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REVIEW ARTICLE

Seaweed derived bioactive metabolites for sustainable agriculture: Phytostimulatory effects, stress mitigation and soil remediation potential

P Niharika[1], PP Mahendran[2*], J Prabhaharan[3], A Gurusamy[3], M Prasanthrajan[4], K Chandrakumar[5] & M Mohamed Roshan Abu Firnass[1]

[1]Department of Soils and Environment, Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India
[2]Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India
[3]Department of Agronomy, Agricultural College and Research Institute, Madurai 625 104, Tamil Nadu, India
[4]Department of Environmental Sciences, Agricultural College and Research Institute, Coimbatore 641 003, Tamil Nadu, India
[5]Department of Renewable Energy and Engineering, Agricultural Engineering College and Research Institute, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - ppmahendran@gmail.com

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Abstract

Marine algae, commonly known as seaweeds, represent a largely untapped bioresource with diverse applications in food, industry, medicine- and traditional botanical practices. Over the past few decades, their role in agriculture has gained significant attention due to the presence of bioactive compounds that confer multiple benefits to plants. Seaweed-derived products exhibit strong phytostimulatory properties, promoting enhanced seed germination, root and shoot development, nutrient uptake and overall crop yield across a variety of horticultural and agricultural field crops. Beyond acting as growth enhancers, these compounds serve as phytoelicitors, activating plant defense mechanisms that improve tolerance to biotic stresses such as pests and diseases, as well as abiotic stresses including drought, salinity and low temperatures. Seaweeds have also been reported as effective bioadsorbents, capable of immobilizing or removing pollutants such as heavy metals and organic contaminants from soils, thereby contributing to soil restoration and environmental remediation. The highly organic nature of seaweed extracts makes them ideally suited for organic and environmentally sensitive farming systems. Furthermore, their compatibility with other fertilizers and crop management practices enables seamless integration into conventional and integrated crop management programs aimed at sustainable agriculture. This review synthesizes current knowledge on metabolite profiles in different seaweed species and evaluates their functional effects in crop production systems. The existing scientific knowledge in this area has been systematically examined to guide further investigations and potential applications.

Keywords: abiotic stress; algal biostimulant; bioadsorbent; bioresource; crop yield; minerals

Introduction

Seaweeds, or marine macroalgae, are autotrophic organisms that inhabit both intertidal and subtidal coastal environments. Algae are among the earliest life forms, with fossil evidence dating back ~3.5 billion years. Algae are a primary source of organic compounds in aquatic ecosystems and play a crucial role in the food chain (1). Seaweeds, as macroscopic multicellular algae, inhabit coastal and marine environments and provide valuable enzymes, polyunsaturated fatty acids, polysaccharides and bioactive peptides. Out of the estimated 164000 algal species globally, seaweeds account for about 9800, yet only a small fraction (approximately 0.17 %) has been domesticated for commercial purposes (2).

Algae are generally categorized into 2 groups: microalgae and macroalgae (commonly referred to as seaweeds), which are mainly found in littoral zones. Based on their pigmentation, biochemical composition and taxonomic characteristics, seaweeds are classified into 3 major divisions: Chlorophyta (green algae), Phaeophyceae (brown algae) and Rhodophyta (red algae). Typically, red seaweeds are more abundant in tropical and subtropical waters, whereas brown seaweeds dominate in temperate regions. Red algal extracts such as *Lithothamnion calcareum* are rich in minerals, making them suitable for applications in both human and animal nutrition (3). Seaweeds are also rich in diverse secondary metabolites, including phenolic compounds, unsaturated fatty acids, carotenoids, phycobiliprotein pigments and polysaccharides (1). These natural compounds exhibit an anticancer, antioxidant and antimicrobial effects against viruses, bacteria and fungi. They also play roles in bioremediation and as organic fertilization. Notably, the majority of these bioactive compounds are synthesized in macroalgae during the later stages of growth or in response to environmental stresses that alter their metabolic pathways.

Beyond their ecological and biochemical importance, seaweeds are gaining recognition for their potential applications in agriculture and further exploration of their potential can offer considerable benefits. Macroalgae are a valuable source of bioactive molecules, including antimicrobial agents, minerals, phytohormones, osmoprotectants, lipids, proteins, carbohydrates and amino acids. Their application in farming provides a wide range of advantages, such as enhancing plant tolerance (frost and salinity), support plant growth promotion (shoot/root elongation, nutrient uptake, seed germination) (4). They also contribute to plant defense by inducing resistance against phytopathogens. In addition, seaweeds play a role in soil and environmental sustainability by facilitating pollutant remediation while simultaneously supplying essential nutrients for plant development. Incorporating seaweed into soil not only enriches the availability of micro- and macronutrients but also enhances both the biological activity and physicochemical quality of the soil (5).

In addition to their agricultural role, seaweeds are now recognized as important functional food resources due to their low caloric value and high nutrient density, including vitamins (A, B1, B2 and C), minerals and trace elements (5). Their versatility extends to emerging sectors such as renewable energy production, wastewater remediation, biofuel generation and carbon sequestration. Thus, seaweeds represent a multipurpose resource with nutritional, environmental and agricultural significance. Against this background, the present paper provides a comprehensive overview of seaweeds, emphasizing not only their nutritional value but also their relatively less-explored role as plant biostimulants that can enhance crop growth and sustainability.

Seaweeds- its origin and types

Brown seaweeds, members of the class *Phaeophyceae,* are among the most widely consumed macroalgae, particularly in Japan, Korea and China where they form a traditional part of their diets (6). The characteristic brown colour is attributed to fucoxanthin, a carotenoid pigment with documented anti-inflammatory, anti-obesity and anticancer effects (6). In addition, brown algae are rich in sodium alginate, a structural polysaccharide that is widely applied in food, pharmaceuticals and cosmetics as a natural thickener, gelling agent and stabilizer.

The prominent edible species include *Undaria pinnatifida* (Wakame in Japan, Miyeok in Korea), *Saccharina japonica* (Dasima in Korea) and *Saccharina latissima* (sugar kelp). *Undaria pinnatifida* contains fucoidans, polyphenols and bioactive peptides that contribute to metabolic and cardiovascular health. *Saccharina japonica* is particularly known for its polysaccharides, which exhibit immune-modulatory and lipid-regulating properties (7). *Saccharina latissima*, a widely cultivated brown seaweed in the North Atlantic and Alaska (8), is valued for its iodine and polyphenol content, making it suitable for both food and nutraceutical applications.

Beyond their nutritional and industrial relevance, brown seaweeds are increasingly recognized for their biostimulant properties in agriculture. Extracts from species such as *Ascophyllum nodosum*, *Sargassum* spp. and *Laminaria* spp. contain phytohormone-like compounds, including cytokinins, auxins and betaines, which show a prominent effect on plant physiology (9). Their application has been shown to enhance seed germination, promote root and shoot elongation, improve nutrient uptake and increase tolerance to abiotic stresses such as drought, salinity and temperature extremes (10). Moreover, polysaccharides like alginates and laminarins stimulate soil microbial activity, thereby improving soil structure and fertility.

Red seaweeds (Rhodophyta) derive their distinctive red color from phycoerythrin and phycocyanin. Their cell walls contain sulfated polysaccharides such as agar and carrageenans, which are widely exploited in the food, pharmaceutical and biotechnology sectors for their gelling and stabilizing properties. Genera like *Chondrus*, *Porphyra*, *Pyropia* and *Palmaria* are notable for their high nutritional value, with red algae being the most protein-rich among seaweeds, complemented by substantial carbohydrates, fibre and minerals (11, 12). The edible species *Porphyra* and *Pyropia* form the basis of nori in Japan, while large-scale cultivation of *Eucheuma* and *Kappaphycus alvarezii*-pioneered in the Philippines-now contributes significantly to global production. According to Food and Agricultural Organization red seaweeds account for approximately 9 million wet tons annually, representing nearly 47 % of total cultivated seaweed output (13). The 3 types of seaweeds collected along Mandapam coast of Tamil Nadu are given in Fig. 1.

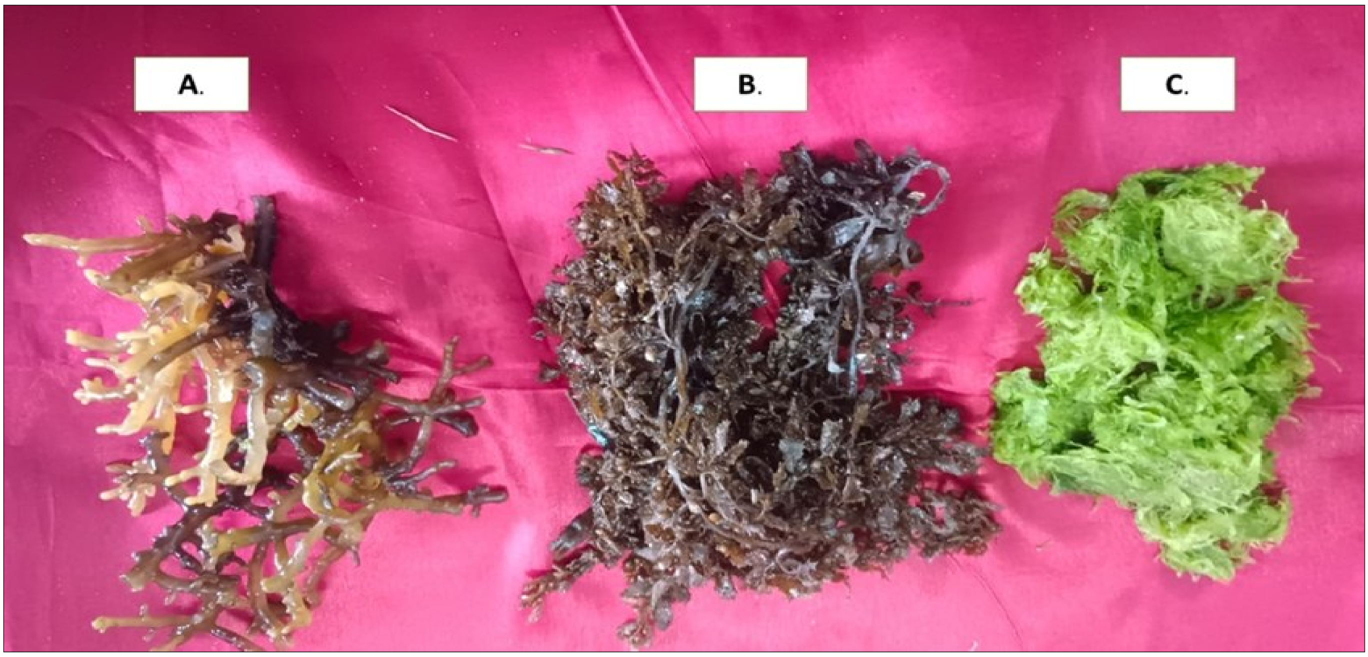

Fig. 1. Three different types of seaweed collected in Mandapam, Tamil Nadu: (**A**). Red algae (Rhodophyta), (**B**). Brown algae (Phaeophyta) and (**C**). Green algae (Chlorophyta).

In addition to their industrial and dietary roles, red seaweeds also demonstrate strong biostimulant potential. Red seaweeds demonstrate notable biostimulant potential due to their sulphated polysaccharides, particularly carrageenans, which act as elicitors of plant defense and growth responses. For instance, foliar application of *K. alvarezii* extract increased wheat grain yield by 22-28 % and improved N, P and K uptake by 15-20 % (14). Similarly, carrageenan treatment enhanced tomato growth and conferred resistance to *Alternaria solani* through activation of salicylic acid and jasmonic acid pathways (15). Another study reported that carrageenan oligosaccharides upregulated defense-related genes in rice, significantly reducing blast disease incidence by approximately 40 % (16). These results highlight the ability of red algae extracts not only to improve crop productivity but also to strengthen stress tolerance, positioning them as promising natural biostimulants for sustainable agriculture.

Green algae (Chlorophyta) are distinctly characterized by their vivid green coloration, as their chlorophyll pigments remain unmasked by accessory pigments. This group exhibits remarkable diversity, encompassing forms that range from microscopic, free-floating unicellular species to large membranous, tubular and bushy macroalgae (17). Their characteristic green coloration arises from the dominance of chlorophyll a and b. Among the commonly reported genera are *Ulva*, *Cladophora*, *Enteromorpha* and *Chaetomorpha*, with *Ulva* species being particularly widespread. Sulfated polysaccharides known as ulvans constitute roughly 9-36 % of the dry biomass of green seaweeds (18). Species such as *Ulva lactuca*, *U. prolifera* and *U. linza* are further noted for their relatively high protein content (often exceeding 15 %), substantial levels of soluble and insoluble dietary fibres (notably glucans) and overall low caloric value (19).

Metabolite composition of seaweed

The nutrient composition of seaweeds is influenced by species, habitat and environmental conditions. In 18 marine macroalgae collected from the Gulf of Kutch, India, the biochemical profile on a fresh weight basis was observed to range as follows: carbohydrates (16-45 %), amino acids (9-20 %), proteins (10-35 %), lipids (8-34 %) and ash (0.4-14 %) (20). The individual nutritional properties of seaweeds from various studies are presented in detail and summarized in Table 1.

Carbohydrates

Polysaccharides are the primary macromolecules in seaweed, constituting approximately 80 % of its total dry weight. These polysaccharides are classified into 2 types based on their location within the seaweed: cell-membrane polysaccharides and storage polysaccharides. While storage polysaccharides are predominantly located in plastids, the majority of polysaccharides occur in the cell wall.

Algal polysaccharides stand out from those in terrestrial plants due to their unique composition, including polyuronides that may undergo pyruvylation, methylation, sulfation, or acetylation, which are integral to seaweed polysaccharides (22). Sulphated polysaccharides such as fucan sulphate, ulvan and carrageenan have gained considerable attention for their antiviral, anticoagulant and antioxidant properties (23). Alginates, extracted from brown seaweeds, has both biostimulant action and medicinal uses. In agriculture, alginates are known for their biodegradability and non-toxic nature, which have been utilized as natural fertilizers due to their exceptional water-retention or superabsorbent properties (24).

Table 1. Nutritional composition of seaweed species (%)

Type of seaweed	Seaweed species	Carbohydrate	Protein	Lipid
Green seaweed	*U. lactuca*	34.7	9.3	2.1
	Ulva intestinalis	36.7	9.0	0.3
	Cladophora sp.	34.8	13.9	3.8
Red seaweed	*Ahnfeltia plicata*	30.2	20.1	N/A
	Brogniartella byssoides	24.0	15.8	N/A
	Ceramium sp.	35.2	15.8	N/A
	C. crispus	52.6	10.3	0.6
	Cystoclonium purpureum	31.5	17.2	
	Delesseria sanguinea	25.9	18.3	N/A
	Dilsea carnosa	79.1	15.2	N/A
	Gracilaria sp.	61.75	24.37	1.8
Brown seaweed	*A. nodosum*	63.3	5.9	3.0
	Chorda filum	87.6	6.3	N/A
	Desmarestia aculeata	75.9	11.5	N/A
	Fucus serratus	77.3	7.1	0.4
	Laminaria digitata	69.9	6.6	2.4
	S. latissima	69.2	6.9	3.7
	Sargassum sp.	33	19	2.9
	Padina sp.	31.6	18.81	1.7

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The highest carbohydrate content was observed in the green seaweed *Enteromorpha intestinalis* (28.58 %), while the brown seaweed *Dictyota dichotoma* recorded the lowest (10.63 %) (25). Other studies have reported maximum carbohydrate levels in green seaweeds such as *U. lactuca* (35.27 %) and *E. intestinalis* (30.58 %) (26). Seaweeds collected from the Maharashtra and Kovalam coasts of India also showed relatively higher carbohydrate content in Rhodophycean members than in Phaeophycean and Chlorophycean members. In the present study, the elevated carbohydrate levels in red algae may be attributed to their higher phycocolloid content in cell walls (27).

The carbohydrate content of seaweeds from the Mandapam coast ranged from 20.47 to 23.9 %, with the highest levels in brown algae (*Turbinaria conoides*, *Sargassum tenerimum*, *S. wightii*), green alga *E. intestinalis* and red algae (*H. valentiae*, *Acanthophora spicifera*), while the lowest was in *Codium tomentosum* (20.47 %) (28). Other reports show carbohydrate content of 22 % in *U. rigida* (29), 2.67 % in *K. alvarezii* (30), 38.94 % in *D. dichotoma* and 56.29 % in *Hypnea musciformis* (31). Overall, seaweeds contained higher carbohydrate levels than *Spirulina* (10-20 %), with *Hypnea* species being particularly rich.

Protein

Protein content in seaweeds varies widely with species, season and location and can reach up to 45 % of dry weight (DW). Generally, red and green seaweeds show higher protein levels (4-50 % DW), whereas brown seaweeds contain comparatively lower amounts (1-29 % DW).

Protein content in Indian macroalgae exhibits considerable variation among species and locations. Along the Mandapam coast, it ranged from 3.25 % in *U. lactuca* to 17.08 % in *Padina gymnospora*, with intermediate values in *E. intestinalis* (16.38 %), *S. tenerimum* (12.42 %), *Gracilaria folifera* (6.98 %), *C. tomentosum* (6.13 %) and *H. valentiae* (8.34 %) (32). In the Tuticorin region, *Turbinaria ornata* and *Gracilaria verrucosa* contained 14.68 % and 9.47 % protein respectively (25). *Ulva rigida* from Chilka lake exhibited 6.64 %, while the red alga *K. alvarezii* from Rameshwaram reached 18.78 % (30). *Padina tetrastromatica* (Phaeophyta, Dictyotales) was reported to be rich in amino acids, including lysine, phenylalanine, aspartic acid and histidine (31). These differences are primarily attributed to environmental conditions, spatial and temporal variations and water quality.

Lipids

Lipids, predominantly fatty acids (FAs), are essential biomolecules that function as structural components of membranes, energy reserves and signaling molecules. Certain seaweeds contain over 10 % lipids on a dry weight basis, with roughly half present as extractable fatty acids, as reported for the brown alga *Spatoglossum macrodontum*. Marine algae are particularly rich in polyunsaturated fatty acids (PUFAs), especially ω-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids are well known for their health benefits, including cardioprotective effects, anti-inflammatory properties and support for brain and visual development (33). Red algae exhibit higher levels of EPA, palmitic, oleic and arachidonic acids, brown algae are richer in oleic, linoleic and α-linolenic acids, while green algae are abundant in linoleic, α-linolenic, palmitic, oleic acids and DHA (33). Algal lipids have significant pharmaceutical relevance and are also a notable source of phytosterols (C28 and C29), precursors for bioactive compounds and vitamins. Brown algae, including *L. japonica*, *Agarum cribosum* and *U. pinnatifida* are particularly rich in fucosterol, comprising 83-97 % of total phytosterol content (34).

The fatty acid profile of seaweed products is characterized by high levels of ω-3 fatty acids and a nutritionally favorable ω-6/ω-3 ratio, which is important for maintaining physiological balance between pro-inflammatory and anti-inflammatory pathways and for reducing the risk of chronic diseases (34). Lipid content in seaweeds varies widely, ranging from 1.33 % in *E. intestinalis* to 4.6 % in *Eisenia clathrata*, with intermediate values in *G. folifera* (3.23 %), *C. tomentosum* (2.53 %), *Colpomenia sinuosa* (2.34 %) and *S. wightii* (2.34 %) (28). *Padina gymnospora* (1.4 %), *S. tenerimum* (1.46 %) and *U. lactuca* (1.6 %) exhibited lower lipid contents. Other reports indicate 12 % lipid in *Ulva rigida* (30) and 1.09 % in *K. alvarezii* (29). Along the Tuticorin coast, total lipid content ranged from 3.15 to 5.30 %, with the green alga *E. intestinalis* showing the highest values and the red alga *G. verrucosa* the lowest, consistent with earlier findings of 7.13 % in *E. intestinalis*. Such regional variability in lipid content can be attributed to differences in species, seasonal fluctuations and environmental factors such as temperature, salinity and nutrient availability (26).

Mineral profiling of seaweeds

Seaweeds are a valuable source of organic matter and essential nutrients that improve plant growth and contribute to soil fertility under field conditions (28). Macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) and even traces of micronutrients like Fe, Cu, Zn and Mn play a key role in improving soil quality. Seaweeds are widely consumed in coastal regions due to their nutritional value. For example, *Padina tenuis* and *Hypnea* spp. are often eaten whole as good sources of minerals. In *Hypnea pannosa*, sodium content is particularly high (127.65 mg/g), whereas *P. tenuis* contains higher levels of calcium (48.00 mg/g), magnesium (44.13 mg/g) and iron (6.64 mg/g) (35). The mineral composition of different seaweed groups is summarized in Table 2. The bioactive metabolites present in seaweeds are depicted in Fig. 2.

Biostimulant action of seaweeds on plants

Biostimulants are defined as biologically derived substances or microorganisms that, when applied to plants through root drenching, foliar spraying, or combined methods, stimulate natural physiological processes. These processes improve nutrient use efficiency, stimulate plant growth and strengthen tolerance to both abiotic and biotic stresses, irrespective of the intrinsic nutrient content of the biostimulant (5). Historically, seaweeds have been utilized either directly or in composted form as soil amendments, particularly in coastal agriculture and in the reclamation of alkaline soils characterized by nutrient deficiencies. They are recognized as a rich source of plant growth regulators- including cytokinins, indole-3-acetic acid and gibberellins, betaines, amino acids and polysaccharides (e.g., laminarins, alginates, fucoidansas well as vital macro- and micronutrients (9).

In modern agriculture, seaweed extracts are primarily employed in liquid form as foliar sprays and biostimulants, with water-based extracts being especially cost-effective and widely adopted. Application of seaweed liquid fertilizers (SLF) has been shown to promote branching and enhance photosynthetic pigment levels (5). Moreover, the integration of organic fertilizers such as SLF contributes to the build-up of beneficial soil residues, which in turn improve the physical and chemical properties of soil, thereby fostering microbial activity and supporting long-term soil fertility (36).

Seaweed liquid extracts (SLE) can be applied to crops through multiple methods, the most common being root-zone application via drip irrigation and foliar spraying (37). Foliar application is often considered particularly effective when carried out in the morning, as stomatal opening facilitates absorption. The

Table 2. Mineral composition of three different genera of seaweed (3)

Mineral compounds (pg/g of extract)	**Red alga (*L. calcareum*)**	**Green alga (*U. lactuca*)**	**Brown alga (*Stoechospermum marginatum*)**
Copper	4.89	0.32	8.64
Manganese	57.50	0.38	8.75
Zinc	15.80	62.00	19.92
Iron	915.00	1.01	858.50
Potassium	5.16	0.37	29.65
Magnesium	25.80	113.00	9.60
Cobalt	0.80	18.30	3.47
Chromium	0.82	0.06	16.60
Lead	0.15	Nd	0.40
Nickel	1.84	Nd	25.20
Sodium	4.15	185.00	39.11
Calcium	351.50	195.26	2053.43

Nd- not detected.

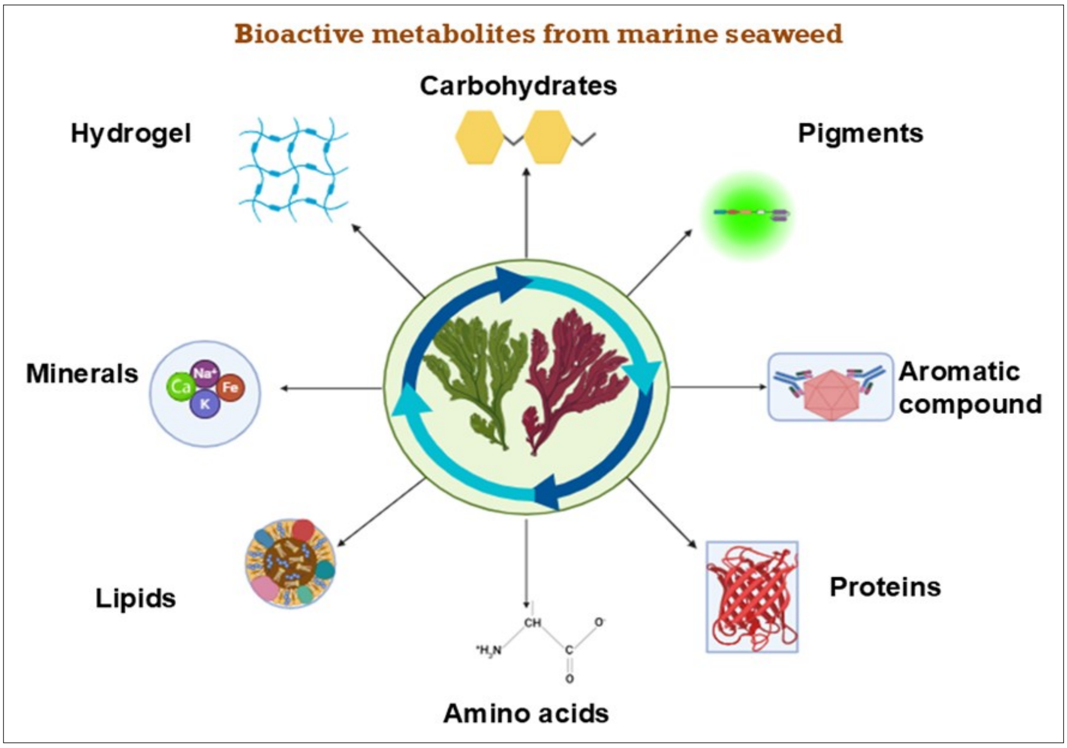

Fig. 2. Bioactive metabolites from marine seaweed.

effectiveness of SLEs, however, is strongly influenced by the developmental stage of the plant. The potato yield was improved most significantly when seaweed extract was applied within two weeks after tuber initiation. In addition to foliar and root applications, seaweed extracts are also widely employed to break seed dormancy and to stimulate germination, thereby functioning as biostimulants across various stages of crop development (38). The biostimulant action of seaweeds on crops and soil rhizosphere is pictorially represented in Fig. 3.

Effect on plant growth

The beneficial influence of seaweed extracts on plant growth has been well documented. Extracts from *A. nodosum* have been shown to stimulate root development in *Arabidopsis* even at very low concentrations (0.1 g L^{-1}), while higher doses (1 g L^{-1}) significantly increased plant height and leaf number. Treated plants consistently progressed through developmental stages more rapidly than untreated controls, with growth enhancement showing a clear concentration-dependent response on the applied concentration

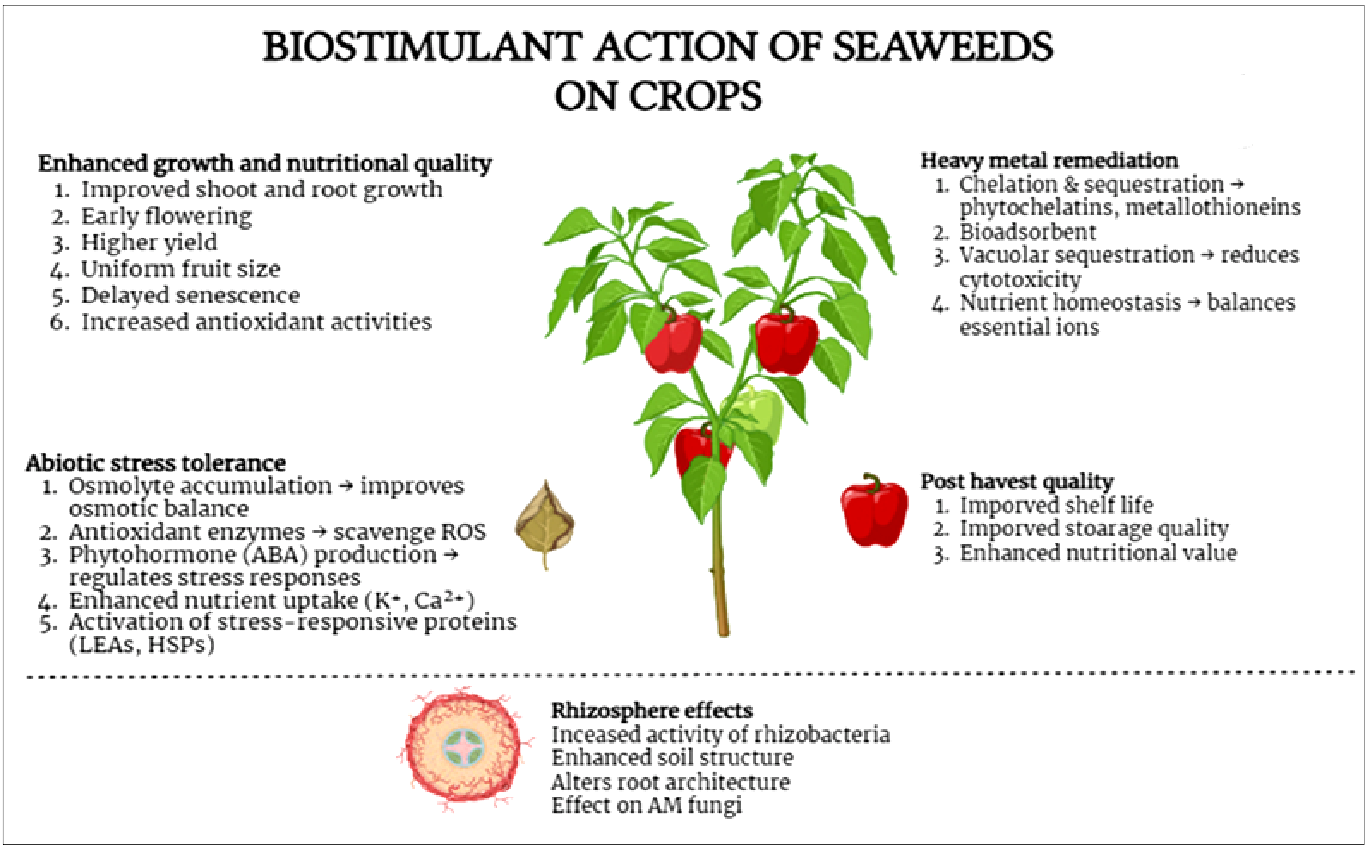

Fig. 3. Biostimulant action of marine algae (seaweeds) on crops and soil rhizosphere.

(39). Similarly, seaweed extracts are widely recognized for promoting root initiation and elongation, particularly during the early growth stages of maize, where their effects are comparable to those of auxins, the hormones responsible for root proliferation (40). Seaweed-derived polysaccharides have also demonstrated positive effects on seed germination and early seedling growth in *Brassica napus* L. Among the tested polysaccharides, carrageenan extracted from *Chondrus crispus* produced the most pronounced improvements, while alginate from *Saccorhiza polyschides* and agar from *Gracilaria gracilis* were comparatively less effective. These differences were attributed to variations in structure, physicochemical traits (pH, electrical conductivity) and mineral composition (41).

In addition to growth and germination responses, seaweed extracts have been reported to improve chlorophyll content and photosynthetic efficiency. Foliar application of *Sargassum* spp. extracts, prepared under different conditions of temperature, extraction time and ethanol concentration, demonstrated significant benefits in tomato seedlings when applied at a 1.5 % dose. The extract obtained at 160 °C for 30 min using 50 % ethanol was especially effective, leading to increased biomass in shoots and roots as well as elevated pigment and antioxidant levels. The rise in chlorophyll concentration was attributed to reduced degradation, likely influenced by the presence of betaines in the extract (42).

Furthermore, aqueous extracts from brown algae (*Sargassum vulgare*) and red algae (*Osmundaria obtusiloba*) were evaluated for their effects on bean seed germination and early vegetative growth. Among the treatments, the 25 % red algal extract produced the most favourable outcomes. Biochemical analysis of the extracts revealed higher concentrations of proteins and carbohydrates in the red algae, which likely contributed to its superior performance. These outcomes also reflect the influence of environmental conditions on macroalgal growth, as spatial variations in ecological parameters affect their biochemical composition (43). Consequently, the concentration of active constituents differs both between and within species leading to variable crop responses upon application (44).

Effect on crop yield and quality of crops

The application of seaweed extracts has been reported to stimulate early flowering and fruit set in several crops. For instance, tomato seedlings treated with seaweed concentrate produced flowers earlier and in greater numbers compared to untreated controls and this effect was attributed to growth promotion rather than a stress-induced mechanism (45). Yield increases in seaweed-treated plants are often linked to the presence of hormonal substances, particularly cytokinins, which play a key role in regulating reproductive development. The application of a commercial extract of *A. nodosum* as a soil drench (2.5, 5 and 10 L ha^{-1}) significantly improved growth, yield, physiological traits like root length, shoot length and total soluble solids and fruit firmness in tomato (46). These effects were attributed to the sulfated polysaccharides present in the extracts, which are known to activate multiple signaling pathways, enhance nutrient-use efficiency and stimulate nitrogen metabolism, thereby contributing to improved crop growth, yield and quality. Similarly, foliar application of seaweed extracts during the vegetative stage has been shown to enhance fruit yield and quality in tomato, resulting in larger fruits with up to a 30 % increase in fresh fruit weight compared to untreated controls (45).

Seaweed-derived biostimulants have been demonstrated to significantly enhance reproductive and yield-related traits in diverse crops. In marigold, application of the commercial formulation Kelpak immediately after transplanting increased the number of flowers and seeds per head by up to 50 % relative to untreated controls (47). Similarly, foliar application of *A. nodosum* extract at 0.5 % in bell pepper improved plant growth parameters, including plant height (40 %), leaf number (50 %), plant dry biomass (52 %), root length (59 %) and chlorophyll content (20 %) compared to control. These effects were attributed to the complex composition of the extract, which provides dissolved nutrients together with functional organic molecules, including phytohormones, carbohydrates and proteins that stimulate growth and reinforce antioxidant defences (48). In legumes, foliar treatments with extracts from brown (*Sargassum swartzii*) and red (*K. alvarezii*) seaweeds revealed notable benefits in cowpea, with the brown seaweed extract (3 %) producing superior improvements in yield and nutraceutical quality, likely due to its higher content of macro- and micronutrients. On an average, liquid seaweed fertilizers have been reported to increase crop yield by approximately 20-30 % compared with untreated controls (49).

Recent evidence indicates that seaweed extracts and their bioactive constituents can regulate the expression of genes namely YUCCA gene family involved in the biosynthesis of major phytohormones, including auxins, cytokinins and gibberellins. Such regulatory effects have been documented in tomato and sweet pepper treated with extracts from *A. nodosum*, *S. vulgare* and *A. spicifera* (48). Beyond yield enhancement, seaweed application has also improved the nutritional quality of various crops, such as lettuce and cucumber (50, 51). For instance, treatment of cucumber with *Macrocystis pyrifera* extract significantly increased total phenols, antioxidant capacity and vitamin C (51). Similarly, *A. nodosum* extracts enhanced anthocyanin and total phenolic content in grapevines and berries (52), while strawberry fruits treated with *A. nodosum* extract exhibited higher levels of total soluble solids, sucrose, fructose and quercetin-a bioactive flavonoid associated with cardiovascular protection and anticancer properties (53). Furthermore, postharvest application of *C. tomentosum* extract to apple fruit reduced enzymatic browning by suppressing peroxidase and polyphenol oxidase activity (54).

Effect of seaweed extraction mitigating abiotic stress

Abiotic stresses such as drought, salinity and extreme temperatures severely reduce crop yield and threaten global agricultural productivity. These stresses often trigger secondary effects such as oxidative stress, causing excessive accumulation of reactive oxygen species (ROS), including superoxide anion (O^-_2) and hydrogen peroxide (H_2O_2), which damage cellular components such as DNA, lipids, proteins and carbohydrates (55). The negative consequences of abiotic stress on plant growth and productivity present a significant challenge for sustainable agriculture, necessitating immediate and effective solutions. In this context, seaweed-derived bioactive compounds have emerged as promising natural agents to alleviate stress impacts and improve plant resilience.

Frost damage poses a major challenge to food production, particularly in temperate regions. Cold stress alters the fluidity of membrane lipids and disrupts the structural integrity of cell membranes. Bioactive substances present in seaweed extracts have been shown to mitigate such effects, enhancing plant tolerance to freezing stress. For instance, foliar applications of *A. nodosum* extracts improved freezing tolerance in grapes by reducing leaf osmotic potential, an important marker of osmotic adjustment (37). Similarly, winter barley (*Hordeum vulgare* cv. Igri) treated with *A. nodosum* extract exhibited improved winter hardiness and frost tolerance (56). The mechanisms underlying this response are increasingly understood, with studies highlighting the role of proline and other osmo-protectants. *Ascophyllum nodosum* with lipophilic contents enhanced freezing tolerance in *Arabidopsis* through a dual mechanism involving elevated proline accumulation and altered cellular fatty acid composition (15).

Soil salinity is one of the most pressing environmental challenges restricting agricultural productivity worldwide. Although research on the role of seaweed extracts in mitigating salinity stress remains limited, existing evidence indicates significant potential. Studies have demonstrated that seaweed applications can reduce sodium uptake and improve salt tolerance in grasses and turf species, highlighting their ability to buffer plants against ionic stress. The detailed impacts of seaweed treatment on plants under salinity stress are summarized in Table 3.

Drought is another major abiotic stress that poses a global threat to food security due to declining water availability. Drought stress disrupts plant physiology primarily through the accumulation of abscisic acid (ABA), which induces stomatal closure and reduces photosynthetic efficiency. Despite advances in genetic engineering, the complexity of drought-responsive pathways has limited success in developing tolerant crop varieties. As a result, biological approaches such as seaweed-based treatments are gaining prominence. Seaweed extracts enhance plant resilience to drought by strengthening the antioxidant defense system and stimulating the synthesis of osmolytes, thereby alleviating yield losses under water-limited conditions. Scientific evidence supporting these effects is presented in Table 3.

Effect of seaweed on heavy metal pollution remediation

Heavy metal contamination has emerged as a serious environmental challenge, primarily driven by industrial activities. Operations such as mining, metallurgical processing, fertilizer and pesticide production, leather tanning, electroplating and energy generation are among the major sources of heavy metal release. These industries discharge substantial quantities of toxic elements into soils, surface water and groundwater, resulting in persistent ecological disturbances. The accumulation of heavy metals in the environment not only deteriorates soil and water quality. Additionally heavy metals pose long-term risks to agricultural sustainability, ecosystem balance and human health through bioaccumulation and food chain transfer (68). Conventional remediation techniques, such as chemical precipitation, ion exchange, membrane filtration and electrochemical treatment, are often expensive and generate secondary pollutants, highlighting the need for sustainable alternatives. In this context, biosorption has emerged as a promising, low-cost and eco-friendly strategy for removing toxic metals from aqueous solutions. Among various biosorbents, dried seaweed biomass stands out due to its rich composition of polysaccharides, proteins and functional groups with strong metal-binding capacities (69). Moreover, the macroscopic structure of seaweeds provides an inherent advantage, allowing to produce biosorbent particles well-suited for practical applications in wastewater treatment and environmental remediation (70).

Recent research has employed innovative strategies to elucidate the mechanisms through which seaweeds facilitate the removal of heavy metals from aqueous systems. For example, the integration of brown seaweeds with the green synthesis of iron oxide (Fe_3O_4) nanoparticles has been demonstrated to significantly enhance lead removal efficiency (71). Similarly, adsorption studies using *Kappaphycus* sp. demonstrated its potential as an economical biosorbent for heavy metal remediation (72). Other seaweed species, including *Gracilaria corticata* var. *cartecala* and *Grateloupia lithophila*, have been reported to effectively sequester metals such as Cr (VI), Cr (III), Hg (II), Pb (II), Co and Cd (II) via biosorption processes (68). In addition, a mixed consortium of green, red and brown algae was successfully employed for the mitigation of chromium pollution, with evidence suggesting that polysaccharide functional groups on algal cell walls were primarily responsible for metal binding (73). Further studies have highlighted the effectiveness of *K. alvarezii* and *Eucheuma denticulatum* in cadmium biosorption, while extracts of red algae, such as the commercial formulation obtained in markets "Acadian," have shown promise in lead remediation (74).

Table 3. Impact of seaweed application on mitigating abiotic stress

Name of Seaweed	Crop or plant	Abiotic stress	Mechanism of action	References
A. nodosum	*Lactuca sativa*	Salinity	Increased the plant growth and tolerance to abiotic stresses	(57)
U. lactuca	*Triticum aestivum*	Salinity	Growth and yield were enhanced	(58)
A. nodosum	*K. alvarezii*	Frost stress	Acted as a remedial to stress, increasing daily growth rate and stem strength on red seaweed	(59)
A. nodosum	Eggplant	Salinity	Enhanced phenolic antioxidant through activation of ROS scavenging	(60)
Seaweed extract	*Zea mays*	Cold stress	Enhanced the cold tolerance and improved Zn and Mn supply to plants	(61)
A. nodosum	*Paspalum vaginatum*	Salinity	Improved the regulation of osmotic adjustment and antioxidant defense system	(62)
A. nodosum	*A. thaliana*	Drought	Enhanced photosynthesis and optimized water utilization by modulating stress-related gene expression	(63)
A. nodosum	*Lycopersicon esculentum*	Drought	Upregulated dehydrins through stress-responsive pathways	(64)
A. nodosum	*Phaseolus vulgaris*	Drought	Enhanced osmotic adjustment via proline metabolism	(65)
A. nodosum	*Glycine max*	Drought	Alter transcription of stress-responsive genes	(66)
A. nodosum	*Petunia sp.*	Drought	Stimulated root elongation, shoot development	(67)

Beyond metals, seaweed amendments have also been found to influence the environmental behavior of persistent organic pollutants. For instance, the incorporation of seaweeds into soil enhanced the biodegradation of DDT (1,1,1-trichloro-2,2-bis (p-chlorophenyl) ethane, a persistent organochlorine pesticide. This effect was attributed to increased levels of dissolved organic carbon (DOC) released by seaweeds, which modified soil physicochemical properties such as ionic strength, redox potential and pH, thereby altering contaminant bioavailability and transformation pathways (75).

Collectively, these studies underscore the capacity of seaweeds to adsorb toxic metals including cadmium, lead, chromium and mercury through biosorption mediated by polysaccharide functional groups that provide abundant binding sites. Moreover, emerging strategies, such as nanoparticle-seaweed composites, have been shown to further enhance remediation potential. These findings highlight a promising avenue for future research aimed at utilizing seaweeds for the sustainable mitigation of heavy metal and organic pollutant contamination.

Potential drawbacks of seaweed application in agriculture

In general, the use of seaweeds as biofertilizers has shown generally safe, but some considerations are important. Their naturally high salt content (Na^+, Cl^-, K^+, Ca^{2+} etc.) may under long-term or excessive use, contribute to soil salinization and salt accumulation in plant tissues. This risk can be minimized by alternating application periods, allowing natural rainfall to leach salts, or by using refined extracts instead of crude biomass. Since seaweeds are known to bioaccumulate heavy metals and pollutants, materials harvested from contaminated waters may transfer these elements into soils and crops. Hence, routine screening for contaminants is essential, with techniques such as inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) commonly employed for trace metal detection. Additionally, anaerobic breakdown of sulfated seaweed compounds may generate sulfides, which upon microbial oxidation, can increase soil acidity.

The unique polysaccharides in seaweeds (e.g., carrageenans, laminarins, ulvans, alginates) differ from terrestrial plant polymers and may influence soil microbial communities by introducing compounds less readily degradable. Alginate, in particular can alter water distribution in soils. Therefore, long-term impacts on microbial diversity and soil health should be evaluated using modern sequencing tools such as 16S rRNA. Finally, as seaweeds harbour diverse microbial consortia, including antimicrobial-producing strains, their persistence and role in reshaping soil microbial ecology need careful assessment. Interestingly, these shifts could also enhance nutrient cycling, indirectly supporting plant growth and soil fertility.

Conclusion

Seaweeds and their derivatives show strong potential as sustainable agricultural inputs, consistently improving plant growth, stress resilience and yield across laboratory, greenhouse and field studies. Their benefits arise from bioactive compounds that influence plant physiology, soil properties and microbial communities, though responses remain context-dependent and influenced by species, formulation, dose and environmental conditions. To fully realize their potential, research must clarify underlying mechanisms using omics tools, optimize application strategies and ensure quality, safety and sustainable sourcing. Future priorities include standardized characterization and labelling, multi-site dose-response validation, integration with precision inputs and biologicals, monitoring of long-term soil effects and comprehensive life-cycle and economic assessments. With these guardrails, seaweed-based products can serve as climate-resilient, circular-economy tools that elevate productivity while restoring soil and environmental quality.

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Authors' contributions

PN performed conceptualization and writing of the original draft. PPM carried out conceptualization, supervision, writing, review and editing. AG made writing, original draft, methodology and validation. JP contributed for writing, original draft and editing. MP, KC and MMRAF carried-out writing, review and editing. MMRAF performed editing and generating figures. All authors read and approved the final manuscript.

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