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Unveiling the potential of seaweed-based biostimulants in modern agriculture: A comprehensive review

G. Abarnadevi*, Senthil Kuppusamy*◆, K. Sakthivel, R.K. Kaleeswari*, P. Aruna*** and Santwana Palai******

* *Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli-620027, Tamil Nadu, India*

** *Genetics and Plant Breeding, Anbil Dharmalingam Agricultural College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli-620027, Tamil Nadu, India*

*** *Post-Harvest Technology, Horticultural College and Research Institute (Women), Tamil Nadu Agricultural University, Tiruchirappalli-620027, Tamil Nadu, India*

**** *Veterinary Pharmacology and Toxicology, College of Veterinary Science and Animal Husbandry, Odisha University of Agriculture and Technology, Bhubaneswar-751003, Odisha, India*

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Abstract

Seaweed extracts have emerged as potent biostimulants in sustainable agriculture, with the aim of boosting plant productivity and resilience to environmental stresses. Seaweed extraction encompasses both conventional and green extraction techniques, such as acid or alkaline hydrolysis, enzyme-assisted extraction, microwave-assisted extraction, and ultrasound extraction. Seaweed extracts regulate hormonal balance, control nutrient transporters, accelerate photosynthesis, and improve stress responses through complex signalling processes and gene expression modifications. Seaweed extracts are rich in bioactives, including polysaccharides, proteins, polyunsaturated fatty acids, vitamins, pigments, polyphenols, minerals, and plant growth hormones. Interestingly, the hydrophilic qualities and chelating abilities of the polysaccharides found in seaweed make them useful in many sectors. The hydrophilic characteristics were instigated by the presence of OH, COOH, CONH, and SO_3H in the polymer structure. Moreover, the indirect effects of seaweed are to enhance soil health by encouraging beneficial microbial populations and nutrient cycling. This review offers fresh insights into seaweed production and its diverse impacts on soil-plant ecosystems, emphasizing their transformative potential in evolving sustainable agricultural practices.

1. Introduction

Indian biostimulants market size is anticipated to grow from USD 3.5 billion in 2023 to USD 6.2 billion by 2027 (Singh *et al.,* 2024). Seaweeds accounted for 30% of the global market in 2018 and are among the most significant sources of natural pharmaceutical ingredients. It was anticipated to exceed USD 10486.8 billion (Rengasamy *et al.*, 2020). The Food and Agriculture Organization (FAO) reported that between 2000 and 2019, the world's production of seaweed, both wild and aquaculture, increased threefold from 118,000 tons to 358200 tons (Zhang *et al.,* 2022). The rising demand for natural products is expected to increase the market in the future. The increasing awareness of the benefits of biostimulants among farmers is expected to drive the market during the forecast period. In India, the dominating seaweed-producing states are Tamil Nadu, Andhra Pradesh, Gujarat, Goa, Karnataka, Lakshadweep, Maharashtra, and Andaman and Nicobar Islands, few species are also found in West Bengal and Odisha (Tandel *et al.*, 2016).

Corresponding author: Dr. Senthil Kuppusamy
Professor, Department of Soil Science and Agricultural Chemistry, TNAU-Anbil Dharmalingam Agricultural College and Research Institute, Tiruchirappalli-620027, Tamil Nadu, India
E-mail: sen7@tnau.ac.in
Tel.: +91-9444488303

Seaweed extracts are one of the most promising biostimulants. The fastest-growing biostimulant business is represented by seaweed extract (Carmody *et al.*, 2020). Unlike terrestrial animals, seaweeds produce various stress-related chemicals that are important for their survival (Shukla *et al.,* 2016). All seaweeds at some stages of their life cycle are unicellular, such as zygotes or spores, and may be temporarily planktonic (Kýlýnç *et al.*, 2013). Courtois (2009) reported thatin coastal and marine environments, seaweeds are multicellular macroscopic organisms' rich in polysaccharides, enzymes, polyunsaturated bioactive peptides, and fatty acids. Many seaweeds exhibit activities that promote plant growth, which has led to their continued and widespread use as organic fertilizers and manure in horticulture and agriculture (Carigie, 2011). This scientific review assesses the present state of knowledge on the benefits offered by the products of seaweed extracts to plants, with a focus on novel chemicals with biostimulant qualities.

2. Origin and overview of species used for extract production

Seaweeds and macroalgae are thought to comprise roughly 10,000 species (Battacharyya *et al.,* 2015). They were primarily divided into three groups: Phaeophyta (brown), Rhodophyta (red), and Chlorophyta (green). They were classified based on their pigmentation. Approximately 2,000 species of brown seaweed make up the second most abundant group; they are found in temperate zones on rocky shorelines, where their biomass is the highest. Among the brown seaweeds, *Ascophyllum nodosum, Macrocystis pyrifera, Ecklonia maxima, and Durvillea potatorum* are the most frequently used commercially by extraction industries (Khan *et al*., 2009) and other commonly used seaweed species are listed in Table 1. Battacharyya *et al*. (2015) stated that brown seaweed extracts are commonly utilized in horticulture crops as they promote plant development and improve crop tolerance to abiotic challenges such as severe temperatures, flooding, drought, nutrient deficiencies, and salinity.In the case of red algae, which is the largest group of marine macroalgae found in the deep sea. Majority of green seaweed live in freshwater. Blue-green algae are widespread on rocky and temperate sandy shores (Kilinc *et al.,* 2013).

Table 1: List of significant seaweed species of brown, red and green algae (Khan *et al*., 2009; Alí *et al*., 2021)

Brown algae (Phaeophyta)	*Ascophyllum nodosum, Fucus vesiculosus, Ecklonia maxima, Durvillea protatorum, Sargassum* spp, *Durvillea antarctica, Laminaria digitata, Fucus spiralis*
Red algae (Rhodophyta)	*Macrocycstis pyrifera, Porphyra perforate, Kappaphycus alvarezii, Gracilaria edulis, Gracilaria dura, Hypnea pannosa, Gracilaria corticata*
Green algae (Chlorophyta)	*Ulva lactuca, Enteromorpha prolifera, Ulva armoricana, Halimeda opuntia*

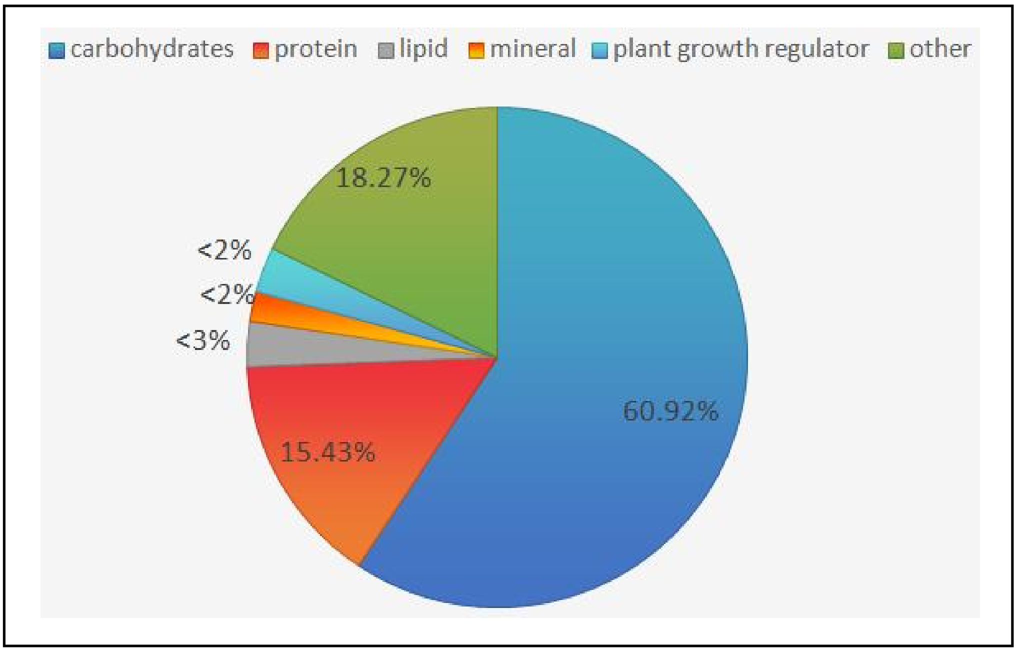

Figure 1: The estimated composition of seaweed extracts in three main classes of seaweed (Alí *et al*., 2021).

3. Chemical composition of seaweed extract

Several bioactive compounds in the seaweed extracts were shown in Figure 1.

3.1 Proximate composition

Seaweeds provide critical amino acids such as alanine, glutamic acid, proline, glycine, arginine, and aspartic acid (Gullón *et al.*, 2020). A total of 52.27% and 53.89% of the amino acids were found in the two red seaweeds, *Hypnea pannosa* and *Hypnea musciformis,* respectively, which together contained all the necessary amino acids (Siddique *et al.,* 2013). However, the brown seaweed *Sargassum ilicifolium* had the highest concentration of crude protein compared to the green seaweeds *Ulva lactuca* (Premarathna *et al*., 2022). According to a prior study, Phaeophyta seaweed species had a greater protein content than Chlorophyta and Rhodophyta seaweed species. *Gracilaria corticata* has the lowest protein content in red algae (Seedevi *et al*., 2017). Another recent study found that the green alga, *Halimeda opuntia* had the ultimate ash level, whereas *Ulva lactuca* had the lowest. Both green seaweed (*Chaetomorpha antennina*) and brown seaweed (*Padina antillarum*) contain excessive concentrations of ash (Seedevi *et al*., 2017). Furthermore, the green seaweed *Caulerpa chemnitzia* had the highest dietary fiber content compared to *Acanthophora spicifera, Ulva rigida, Ulva intestinalis* (Chlorophyta), and *Sargassum wightii* (Phaeophyta). Thus, brown seaweed species contain the most protein, and dietary fiber and ash content were more prominent in the seaweed species of Chlorophyta.

According to Vijay *et al*. (2017), more minerals are found in brown seaweeds (*Laminaria*, *Sargassum*, and *Undaria*) than in red seaweeds (*Porphyra*). Similarly, many brown seaweeds have C: N ratios over 15-20, whereas some green seaweeds (*e.g.,Ulva*) have a low ratio of 10 or lower. In addition, Phaeophyta have abundant water-soluble vitamins, such as riboflavin, thiamine, and nicotinic acid (Allen *et al*., 2015).

3.2 Ultimate composition

Rhodophyta is primarily composed of phycoerythrin, which gives it a reddish or purplish color (Manzoor *et al.,* 2024). Hsieh-Lo *et al.* (2019) observed that only chlorophyll a is present in red seaweeds, and since light is only absorbed in the visible spectrum's red and blue areas, there is an absorption gap in the center. Freitas *et al.* (2021)

found that to close this gap and enhance light processing, red seaweeds develop phycobilisomes (PBS) in their thylakoid membrane. Brown algae color from a pigment called fucoxanthin, which is one of the most prevalent carotenoids (comprising approximately 10% of all carotenoids produced in nature) (Matsuno, 2001). Furthermore, the primary cause of the characteristic green hue in Chlorophyta is that it contains the same amounts of chlorophyll a and b as higher plants (Manzoor *et al.,* 2024).

Hydrocolloids, which are usually produced from seaweeds and are mostly extracted from certain species and genera of brown and red seaweeds, are known as alginate, agar, and carrageenan (Kumar *et al*., 2024). Agarose can be produced with good gelling characteristics, and its gelling and melting points fluctuate between 30 and 40°C and 80-90°C, respectively, depending on the concentration, molecular weight, and density of the side group. Agarose is widely used in the textile industry, bakery products, and gel electrophoresis. Moreover, the gelling point of 30-50°C and melting point of 50-70°C of carrageenan make it an excellent thickening, emulsifying, and gelling agent. It is widely used in food and beverages, the paint industry, and as a suspending agent in antacids (Glicksman, 1987; Tuvikene *et al*., 2006; Wüstenberg, 2014; Gade *et al*., 2013; Rhein-Knudsen *et al*., 2015; Zucca *et al*., 2016). Similarly, alginate is a substance with good gelling features that is composed of repeating units of β-1,4-linked d-mannuronic acid (M) and l-guluronic acid (G) in different ratios and generates gels by chemical or physical bonding (Kumar *et al.,* 2024). The hydrophilic characteristics were caused by OH, COOH, CONH, and SO_3H (Ganji *et al.* 2010). Thus, we can deduce that the hydrogel expands in water because water molecules become trapped inside the pores, changing the hydrogen bonding. Additionally, bacteria release different hydrogels and organic debris into soil *via* enzymatic breakdown.

Brown seaweeds contain phlorotannins (Cotas *et al.,* 2020), which are potent plant elicitors that stimulate a variety of metabolic pathways, including the phenylpropanoid/shikimate pathway, which is involved in the production of phenolic compounds (Aremu *et al*., 2015). In brown seaweed, polyuronoides (fucoidans and alginates) are also present, and their hydrophilic properties, gelling, and chelating powers make them valuable constituents in the food processing, agriculture, and pharmaceutical sectors (Cardozo *et al*., 2007). Laminarins are bioelicitors of plant defense responses against fungal and bacterial pathogens (GardeCerdán *et al*., 2017; Pugliese *et al*., 2018). According to Venkatesan *et al*. (2015) and Usman *et al*. (2017), green seaweedsare known to produce the complex, acidic polysaccharide ulvan, which is used in cosmetics and medical industries. Likewise, agar and carrageenan are found in significant amounts in red seaweeds such as *Gracilaria* and *Kappaphycu*s. These industrial polysaccharides are frequently used in antifouling, antimalarial, and antibiotic applications in the culinary, pharmaceutical, textile, paint, and biotechnological sectors (Werner *et al*., 2004).

Diterpenes and sesquiterpenes such as dictyols, zonarols (Kaeffer *et al*., 1999), and dolabellane (Shimizu *et al*., 2015) are abundant in brown algae belonging to the genera Dictyota and Dictyopteris. These compounds have a diversity of intriguing biological activities, encompassing cytotoxic, antifungal, antiviral, and antibacterial properties. However, the *Laurencia* genus of red algae produces secondary metabolites, primarily terpenoids. Moreover, sesquiterpenes (caulerpenynes) from the green alga *Caulerpa prolifera* have cytotoxic and antimicrobial properties (Yuan and Walsh, 2006).

4. Nutrient uptake and assimilation

Numerous vital nutrients such as micronutrients, trace elements, and growth-promoting hormones are abundant in seaweed extracts. This may aid in improving the nutrition of plants, thereby promoting their growth and development (Ghatas *et al*., 2021). For example, *Ulva linza* contains a variety of nutrients such as Na^+, K^+, Ca^{2+}, Cl^-, and Mg^{2+}. These findings imply that green seaweed may be studied in the future for use in the food, cosmetic, pharmaceutical, or dietary supplement industries (Jiang *et al.,* 2013). According to Elansary *et al.* (2019), adding 225 L ha^{-1} *Saccharina japonica* extract to loamy sand results in increase in total nitrogen and soil organic carbon. Application of *Laminaria* and *Ascophyllum nodosum* extracts in maize showed that the leaves could significantly absorb more Zn, B, S, Fe, Mo, Cu, Mg, Ca, and Mn than the controls (Ertani *et al.*, 2018). Seaweed extracts provide nutrients that are easily absorbed by leaves *via* the stomata and hydrophilic pores in the cuticle (Battacharyya *et al.,* 2015).

Table 2: Impact of seaweed extract on uptake of plant nutrients

Seaweed species	Crop	Mode of application	Observation	References
Ascophyllum nodusum	Grape	Foliar spray	Increased uptake of Cu, Ca^{2+}, and K^+	Turanand Köse, 2004
	Rapeseed	In nutrient solution	Increasing concentration of Cu, Mg, and Mn in the entire plant	Billard *et al.*, 2014
Ecklonia maxima	Tomato	Foliar spray	Increased fruit Ca concentration	Colla *et al.*, 2017
	Mustard	Root application	Increased P&K level	Stasio *et al.,* 2017
Ascophyllum nodusum and *Laminaria* spp.	Maize	Foliar spray	Increased absorption of Zn, Fe, S, Mg, Ca, B, Cu, Mo and Mn	Ertani *et al.*, 2018
Kappaphycus alvarezii and *Gracilaria edulis*	Maize	Foliar spray	Enhanced N, P, K uptake	Basavaraja *et al.*, 2018

The activation of enzymes involved in lignin production and photosynthesis is copper dependent. Lignin strengthens cell walls and provides structural integrity to plants (Printz *et al.* 2016). In particular, applying brown seaweed extract topically to grapevine leaves makes them more susceptible to Cu absorption (Turan and Köse, 2004). Similarly, several enzymes involved in photosynthesis, respiration, and nitrogen metabolism are also stimulated by Mn. According to Chinnasamy *et al*. (2024), seaweed extract @ 3 % showed improved biochemical and physiological characteristics in banana, *viz*., potassium (363.38 mg/100 g), calcium (5.63 mg/100 g), starch (14.30%), reducing sugars (11.15%), total carbs (29.57 g), Total sugar (18.95%), carotene (36.65 µg/g), and non-reducing sugars (7.41%). Likewise, in tomatoes seaweed extract concentration @10% attained higher concentrations of vital minerals such as potassium (563.21 mg/100 g), zinc (0.86 mg/100 g), calcium (152.28 mg/100 g), iron (15.32 mg/100 g), and magnesium (41.44 mg/100 g) than the control (Vinothkumar *et al.*, 2024).Thus, the application of seaweed extract showed increased nutrient uptake in plants and some examples are listed in Table 2.

5. Methods of preparation of seaweed extracts

Seaweeds must be processed into liquid extracts or soluble powders because they decompose slowly when dried and can initially hinder plant growth by producing poisonous sulfhydryl chemicals that can linger for up to 15 weeks (Craigie, 2011). The biological activity of these extracts strongly depends on the extraction method and raw material, which can be acid extraction, alkali extraction, or further technology such as microwave, ultrasound and enzyme assisted extraction (Battacharyya *et al.,* 2015). The bioactive compounds which can be extracted from seaweeds using different methods are tabulated in Table 3.

5.1 Acid hydrolysis

In the process of acid hydrolysis, freshly chopped seaweed (*Ascophyllum)* biomass was exposed to sulfuric or hydrochloric acid at 40-50°C for 30 min (Sharma *et al.*, 2014). Acid hydrolysis has been reported to promote polysaccharide depolymerization and eliminate complex phenolic compounds (Flórez Fernández *et al.*, 2018). For instance, the green seaweed *Valonio psispachynema* could provide a large quantity of total sugar (38.5 ± 0.2 mg/g) by hydrolysis with diluted 3% sulphuricacid, which greatly increased algal biomass and lipid production (Lakshmikandan *et al.*, 2021). In addition, Kadimpati *et al.* (2021) achieved the maximum sugar extraction (153.00 ± 5.96 mg/g biomass) using 3.5% w/v HNO_3 for 10 g dried *Sargassum cinereum* biomass.

5.2 Alkaline hydrolysis

In Alkaline hydrolysis, the biomass of *A. nodosum* is removed in KOH or NaOH solutions at "relatively low" temperatures ranging from 70 to 100°C (Craigie, 2011). For instance, a maximum yield of 51.84% sodium alginate was obtained via alkaline extraction at 80°C for 195 min of extraction time, demonstrating the viability and cost-effectiveness of the process (Nogueira *et al.*, 2022).

5.3 Microwaveassisted extraction (MAE)

In microwave-assisted extraction, microwave radiation is used to heat a slurry prepared from dried algal biomass in either water or a solvent supported by microwaves, to extract bioactive chemicals (Magnusson *et al.,* 2017; Flórez Fernández *et al.,* 2018). The microwave heating mechanism relies on the ionic conduction of bioactive chemicals produced from seaweed into the solvent along with dipole polarization (Lucchesi *et al.,* 2004). Le *et al.* (2019) found that the maximum yield of ulvan (41.9%) from *Ulva pertusa*, which had significant antioxidant properties, was obtained *in vitro* when an MAE of 600 W of microwave radiation was applied for 43.63 min, with a water-to-raw-material proportion of 55.45 ml/g and a pH of 6.57.

Table 3: List of bioactive compound present in seaweed species extracted by different methods

Seaweed species	Extraction process	Bioactive compound	Extraction yield(% of bioactive compound)	References
Undaria pinnatifida	Enzyme assisted extraction	Fucoxanthin	94%	Billakanti *et al.*,2012
Kelp	Enzymatic hydrolysis	Alginic acid	20.16 g/l of seaweed	Chen *et al.*, 2021
		Polyphenol	205.56 mg/l of seaweed	
		Oligosaccharide	4.00 g/l of seaweed	
		Mannitol	12.10 g/l of seaweed	
		Free amino acid	5.00 g/l of seaweed	
Sargassum cymosum	Alkaline extraction	Sodium alginate	45.79%	Nogueira *et al.*, 2022
Undaria pinnatifida	Microwave assisted extraction	Fucoidan	12.3%	Sasaki *et al.,* 2024
Ecklonia maxima	Sub critical water extraction	Phenolics (Phloroglucinol)	26.02 ± 0.05 mg/g of seaweed	Park *et al.*, 2024
	Acid extraction	Sodium alginate	58.7%	Park *et al.*, 2024
Kappaphycus alvarezii	Ultrasound-microwave assisted extraction	Polysaccharides	61.25 ± 0.70%	Kapahi *et al.,* 2024
Saccharina lactisima	Solvent extraction	Protein	10.6%	Moldes *et al.*, 2024
Ascophyllum nodosum	Alkaline sub critical water extraction	Crude	80.52 %	Zhang *et al.*, 2024
		Alginate	38.25 %	
		Fucoidan	39.38 %	

5.4 Ultrasound assisted extraction (UAE)

In UAE, ultrasonic waves travel through liquid, solid, and gaseous media at high frequencies (over 20 kHz) by rarefactions, which causes the longest gap between wave particles and compression, which causes the lowest space between wave particles. Under ultrasonic waves, the extraction solvent cavitates, allowing the release of bioactive compounds from a range of seaweed biomass (Kadam *et al.*, 2013). For instance, the yields achieved using UAE ranged from 20.4-36.9%, whereas those obtained with traditional extraction were between 10.5% and 19.3%. The extraction yield increased from 1.5-fold to 2.5-fold under UAE conditions (35 kHz, 50% ethanol, and 30 min) (Ummat *et al.*, 2020). Another study reported that under ideal ultrasound settings (15 min and buffer solvent), the maximum phycoerythrin yield (33.85 mg/g) for *Padina cruentum* was achieved (Ardiles *et al.*, 2020). Wen *et al.* (2020) state that, using NaOH as a solvent, UAE achieved a 3.4% protein yield (w/w) from *Neoporphyra haitanensis* after 20 min of ultrasound treatment at ambient temperature.

5.5 Enzyme assisted extraction (EAE)

Digestive enzymes such as carbohydrases and proteases extract bioactive compounds from seaweeds (*Sargassum fulvellum, Ecklonia cava, Sargassum horneri,* and *Sargassum thunbergii)*. These enzymes can transform water-insoluble compounds in seaweed into water-soluble compounds (Ahn *et al.* 2004; Park *et al.* 2004; Heo *et al.* 2005). Khalil *et al.* (2017) reported that this technique is important for the synthesis of seaweed gel with an average yield of 28.65% because it can also produce soluble materials that are insoluble in water. Enzymatic hydrolysis, specifically utilizing the "Miura" enzymatic cocktail (glycoside, β-glucanase, hydrolase, xylanase, and cellulase), demonstrated enhanced outcomes in the extraction of soluble proteins, carbohydrates, phycocyanin, and phycoerythrin, with increases of approximately 890%, 65%, 510%, 195%, respectively, in comparison to the optimal alkaline hydrolysis extraction (2.5% Sodium carbonate and 80°C) (Pereira *et al.*, 2024).

Alkaline extraction at high pressure is the most popular extraction method. The advantage of this approach is its prominent level of extractability and mild polysaccharide degradation into oligomers, which are the physiologically active components of seaweed extracts (Shukla *et al.*, 2019; Jayaraj, 2018).

6. Mechanism of action: Molecular and metabolic pathway

Seaweed extracts regulate hormonal balance, control nutrient transporters, accelerate photosynthesis, and improve stress responses via complicated signaling processes and gene expression modifications (de Saeger *et al.,* 2019). Seaweed extracts also improve carbon and nitrogen metabolism by activating defense systems and modifying metabolite profiles, such as TCA cycle metabolites and secondary metabolites, which modulate plant metabolic pathways (Tran *et al*, 2023). For example, the application of *Ascophyllum nodosum* extract in Arabidopsis downregulates the degradation of chlorophyll genes (AtCLH1 and AtCLH2) and upregulates drought-responsive genes in soybean (Shukla *et al.*, 2018), which prevents cold stress and drought stress. In addition, upregulation was associated with transcription genes (COR78/RD29A and DREB1A), which regulate cold stress tolerance by cryoprotecting chloroplasts (Nair *et al.,* 2012). Sangha *et al.* (2011) found that in *Arabidopsis thaliana*, treatment of extremely sulphated λ-carrageenan (35% sulphation) was linked with a higher activity of oxalate oxidase and expression of Jasmonic acid signalling linked genes, such as, plant defense (PDF1.2), pathogenesis related (PR-3), and alleneoxide synthase (AOS).

Ali *et al.* (2021) reported that *S. vulgare* extract decreased the infection level of *Alternaria solani, Xanthomonas campestri* sp. *Vesicatoria* in Sweet pepper and tomato, thereby increasing defense enzyme activity, including peroxidase, ammonia-lyase, β-1,3-glucanase, phenylalanine, polyphenol oxidase, and also upregulating the PR1-a, ETR-1, and PinII genes linked to ET and Jasmonic acid mediated signaling. Furthermore, the mechanism by which Na^+ is bound to roots is due to an increase in the concentration of Na^+ in the soil solution, which stimulates passive Na^+ transport via a group of non-selective cation channels in root cells, which is carried by mass flow via the xylem to the shoots (Almeida *et al.*, 2017). Consequently, the loss of the Na^+ transporter HKT1 gene in Arabidopsis causes hypersensitivity to salt in mutant lines, resulting in elevated Na^+ levels in the leaves (Moller *et al.,* 2009). Despite this, the pretreatment of Arabidopsis with *Ascophyllum nodosum* extract (Super fifty) resulted in considerable upregulation of genes in hormonal signaling, precise photosynthesis, and growth under both oxidative stress and control conditions (Omidbakhshfard *et al.*, 2020). Recently, Kapur *et al.* (2024) suggested that use of a seaweed extract under water stress conditions resulted in a substantial rise in the content of syringic acid, pelargonidin-3-rutinoside, cyanidin-3-glucoside, chlorogenic acid, rutin, p-coumaric acid, epicatechin, and pelargonidin-3-glucoside while, quercetin, catechin, sinapic acid, caffeic acid, epigallocatechin gallate, and ellagic acid were dramatically reduced.

7. Influence of seaweed extract on plant growth and development under biotic stress

The *Ascophyllum nodosum* extract provides elicitor chemicals that encourage increased enzyme activity to alleviate stress, thereby strengthening the plant's defense system against biotic stressors (Ali *et al.*, 2016). In *Ascophyllum nodulosum* extract treatment, betaines may support healthy plant growth by acting as stress-induced osmoprotectors in plant cells. Seaweed extracts promote early flowering and boost fruit development in various agricultural plants, including tomatoes and peppers (Dookie *et al.*, 2021). Seaweed extracts trigger plant defense mechanisms against devastating bacterial, viral, and fungal infections, shielding crops from diseases that may result in significant financial losses (Fei *et al.*, 2017).

The impact of powdery mildew, late blight triggered by *Phytophthora infestants*, and gray mold caused by *Botrytis cinerea* decreased by 37%, 36%, and 80%, respectively, after foliar application of *Sargassum fusiforme* extract on tomato plants (Sbaihat *et al.*, 2015). El-Sheekh *et al.* (2020) found that the methanolic extracts of *Cystoseria myrica* and *S. cinereum* exhibited the greatest antifungal activity by increasing the total free amino acid content and antioxidant enzyme activities of *Fusarium oxysporum* infected roots and shoots. Yao *et al.* (2020) identified that the application of *Sargassum horneri* extract increases the photosynthetic ability of tomatoes and boosts tomato yield by 4.6 to 6.9%. In addition, the application of *Sargassum tenerrimum* extract on *Macrophomina* treated tomato plants showed a considerable increase inindole acetic acid and kinetin levels throughout the vegetative and generative phases (Khedia *et al.,* 2020). In the investigation, Raja and Vidya (2023) reported that, the extract of *Gelidium serrulatum* evoked salicylic acid and jasmonate signalling and reduced the bacterial and fungal diseases. The impact of different species of seaweed extract on plants against plant pathogens are listed in Table 4.

Table 4: Effect of some seaweed species in different plants against plant diseases

Crop	Seaweed species	Disease	Causal organism	Findings	References
Arabidopsis	*Ascophyllum nodusum*	Bacterial disease	*Pseudomonas syringae and Xanthomonas. campestris*	Expression of defense -related genes is stimulated	Cook *et al.*, 2018
Strawberry	*Ascophyllum nodusum*	Powdery mildew	*Podosphaera aphanis*	Defence enzymes and secondary metabolites expression is increased	Bajpai *et al.*, 2019
Grape	*Ascophyllum nodusum*	Bunch rot	*Botyrtis cinerea*	Defence-related gene expression is increased	Frioni *et al.*, 2019
Wheat	*Ascophyllum nodusum*	*Septoria tritici* blotch	*Zymoseptori atritici*	Enhanced expression of antioxidant metabolism, octadecanoid-based pathways, phenylpropanoid and defense-related PR protein,	Somai-Jemmali *et al.*, 2020
Tomato	*Sargassum tenerrimum*	Charcoal rot	*Macrophomina phaseolina*	Stimulate the defence-related hormones and genes	Khedia *et al.*, 2020
Sesame	*Sargassum tenerrimum*	Charcoal rot	*Macrophomina phaseolina*	Stimulate physio-biochemical pathways	Dangariya *et al.*, 2024
Potato	*Ascophyllum nodosum* and *Laminaria digitata*	Potato cyst-forming nematode	*Globodera rostochiensis*	Hatching of juvenile nematode is delayed and reproductive capacity is reduced	Matveeva *et al.*, 2024

Table 5: Impact of seaweed extract on plants under abiotic Stress

Stress	Crop	Seaweed species	Findings	References
Freezing stress	Arabidopsis	*Ascophyllum nodusum*	Lipophilic compound preserves membrane integrity and modifies the expression of genes that are sensitive to freezing stress, improving freezing tolerance.	Rayirath *et al.*, 2009
Salt Stress	Turf grass	*Ascophyllum nodusum*	Enhanced the growth by maintaining the K^+/Na^+ ratio higher.	Elansary *et al.*, 2017
	Arabidopsis	*Ascophyllum nodusum*	Decreased oxidative damage caused by salinity by promoting glutathione S transferase expression.	Jithesh *et al.*, 2019
	Avocado	*Ascophyllum nodusum*	Reduced the impact of salt stress on avocado growth and yield by increasing nutrient absorption.	Bonomelli *et al.*, 2018
	Canola	*Gelidium crinale, Cystoseira* spp., and *Ulva lactuca,*	Alleviated the growth inhibition caused by NaCl by dramatically lowering the inhibition of total carbohydrate accumulation, chlorophyll a and b.	Hashem *et al.*, 2019
	Tomato	*Padina gymnospora*	Under salt stress, seaweed-treated plants shown a 3.4% decrease in production, whereas untreated plants exhibited a 28.7% decrease as seaweed compared to treated plants.	Hernández-Herrera *et al.*, 2022
Drought Stress	Tomato	*Ascophyllum nodusum*	Increased resilience to drought stress by regulation of dehydrin expression.	Goni *et al.*, 2018
	Phaseolus vulgaris	*Ascophyllum nodusum*	Enhanced resistance to the stress of drought through an impact on proline metabolism.	Carvalho *et al.*, 2018
	Tomato	*Ascophyllum nodusum*	Fruit produce was enhanced by 225% and 271% at 50% field cap acity by soil drenching and foliar spray at 5 ml/l, respectively.	Ahmed *et al.*, 2022
	Maize	*Ecklonia maxima*	Plant metabolism was altered by foliar treatment, which also increased plant diameter and height while lessening drought stress.	Tinte *et al.*, 2022
	Sugarcane	*Ascophyllum nodosum*	Increased stalk yield by 3.08 Mg/ha and sugar yield by 3.4 Mg/ha.	Jacomassi *et al.*, 2022
Heat stress	Spinach	*Ascophyllum nodusum*	High germination%, seedling vigor, germination rate, antioxidant metabolism, and low malondialdehyde, hydrogen peroxide.	Anjos *et al.*, 2020

8. Consequences of seaweed extract on plant growth and development under abiotic stress

Seaweed extract treatment may promote plant development, yield, and quality by promoting the buildup of secondary metabolites such as simple sugars, abscisic acid, proline, alcohols, and antioxidant chemicalsand/or stimulating metabolic pathways, thereby minimizing the detrimental impacts of salinization (Bose *et al.*, 2014; Rai *et al.*, 2021; Khan *et al.*, 2022) and their impact on some of the plant under abiotic stress (Table 5). Hormone pathways also mediate various aspects of plant growth and development, including as nutrient uptake, and the molecular and physiological reactions to abiotic stress (Ryu and Cho, 2015). Plants exposed to salt and drought that are treated with seaweed extracts show increased proline and sugar (glucose, fructose, and sucrose) (Goñi *et al.*, 2018). In addition, seaweed extract-treated crops showed enhanced growth and survival in drought and salinized environments, recovering from the detrimental impacts of frost and heat (Shukla, *et al.*, 2019). Moreover, Seaweed extracts diminish abiotic stressors by boosting the antioxidant capacity of enzymes that scavenge reactive oxygen species (ROS), such as catalases, superoxide dismutase, peroxidases, and phenolic antioxidants (Latef *et al.*, 2017; Hussein *et al.*, 2021). When crops were subjected to abiotic stress, seaweed extracts increased the expression of genes that respond to stress, including Na^+/K^+ transporters and late embryogenesis abundant (LEA) proteins like dehydrins and aquaporins (Goñi *et al.*, 2018; Zou *et al.*, 2018: Rasul *et al.*, 2021;). Genes that respond to drought, including LEA4-5, LEA4-6, and LEA7, were also strongly upregulated after treatment with a biostimulant based on *Ascophyllum nodusum* (Rasul *et al.*, 2021). Therefore, we can find that seaweed bioactive compound and mechanism helps plant to grow under stress conditions.

9. Conclusion

Seaweedbased biostimulants hold great promise for sustainable agriculture due to their rich composition of nutrients, plant hormones, and bioactive compounds like polysaccharides, polyphenols, and antioxidants. These extracts enhance plant growth, improve nutrient uptake, and boost tolerance to both biotic and abiotic stresses such as drought, salinity, and temperature extremes. They also strengthen plant immunity by activating defense-related genes and metabolic pathways. Furthermore, seaweed applications improve soil health by promoting beneficial microbial activity and nutrient cycling. Modern extraction techniques-such as alkaline, enzymatic, microwave, and ultrasound methods-help preserve the functional compounds and increase the effectiveness of these biostimulants. Different seaweed types (brown, red, and green) offer unique benefits, and their application has proven successful in crops like maize, tomato, sugarcane, and grape. In addition to improving crop yield and quality, seaweed extracts offer an eco-friendly alternative to chemical fertilizers and pesticides. As agriculture faces challenges from climate change and resource limitations, seaweed biostimulants present a viable solution. However, further research is needed to refine extraction methods, understand molecular mechanisms, and explore broader applications in agroecosystems.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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