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RESEARCH ARTICLE

Exploring potentials of the physical and biochemical characteristics of *Gracilaria gracilis* and *Gracilaria edulis* for enhancing plant growth under abiotic stress

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Abstract

Seaweed may assist agricultural crops to adapt with abiotic stress and are widely used in agriculture, especially as biostimulants that improve plant growth and resistance to abiotic stressors. The study focuses on the biochemical characteristics of these seaweeds and their effect as plant biostimulant to improve germination and crop growth. Seaweeds were collected from Mandapam area of Ramanathapuram district and identified as *Gracilaria gracilis* and *Gracilaria edulis* from AJC Bose Indian Botanic Garden, West Bengal and their physico-chemical properties were evaluated. Higher protein levels were obtained in *G. edulis* (16.72 %), swelling capacity (SWC) in *G. gracilis* (23.25 mL g^{-1}) is more compared to *G. edulis*, however, water holding capacity (WHC) of *G. edulis* (11.31 g g^{-1}) was higher. The findings demonstrate that *G. edulis* has superior WHC, whereas *G. gracilis* has higher SWC, which improves soil moisture retention and nutrient availability. Further study shows that the two species' mineral compositions differ significantly, with *G. gracilis* being higher in potassium (6413.5 ppm) and sodium (1051.5 ppm), which may help with osmotic management in plants. Growth parameters were significantly improved by the treatment (T2–T5). In comparison to control T1, treatment T5 (10 % papermill effluent + G2 sps @ 7.5 %) exhibited the longest roots (51 ± 0.37 cm) and shoots (34 ± 0.35 cm), remarkable seed vigor index (26.88 ± 0.30) and a high germination percentage (96 ± 0.06 %). Overall, the results provide support to the usage of these seaweeds as organic fertilizers in difficult environmental situations to enhance crop growth.

Keywords: abiotic stress; biostimulant; crop growth and development; seaweed extract; seed germination

Introduction

Marine macroalgae are small, photosynthetic eukaryotic, multicellular organisms that are commonly referred to as seaweeds. They are divided into three categories based on color and taxonomic classification: Chlorophyta (green), Phaeophyceae (brown) and Rhodophyta (red). It is estimated that there are about 164000 species of algae worldwide, including macro and micro. Of these, around 9800 are seaweeds and only 0.17 % have been domesticated for use in commerce. Macroscopic algae called tropical red seaweeds (Rhodophyta) can stimulate plant metabolism and increase plant productivity. The advantageous properties of seaweed extracts have been linked to the presence of phytohormones and a few organic compounds functioning as suitable solutes (1). Red seaweed has also been demonstrated in the past to increase the expression of MAP kinase genes, antioxidative catalase, stress-responsive transcription factor WRKY and superoxide dismutase (SOD) in wheat under abiotic stress conditions. Essential minerals like calcium and potassium have an impact on several physiological and biochemical processes, which in turn affects how plants grow and use energy under abiotic stress (salinity, heat, drought, etc.) (2). Seaweed contains several growth regulators, including auxins, abscisic acid, cytokinins, brassinosteroids and gibberellins. These can function individually or in combination to support plant development, growth and stress tolerance (3). It has been demonstrated that seaweed extracts increase plant development and reduce abiotic stressors by controlling physiological, biochemical and molecular processes.

Seaweed extracts are highly effective in helping crops tolerate salinity and play a pivotal role among organic inputs used in organic agriculture. As macroalgae, seaweeds provide all the vital nutrients needed for plant development and defense. Biochemicals derived from these seaweeds termed biostimulants have an abundance since they include all essential elements and have a good effect on plants. The general growth of plants and environmental circumstances is aided by these biostimulants (4). Proteins, polyphenols and lipids are some of the bioactive compounds found in seaweeds, along with some of vitamins, minerals and polysaccharides. Seaweeds include active functional groups such as amino, hydroxyl, carboxyl, polysaccharides, proteins and sulfate on the surface of their cell walls, they are capable of effective metal biosorption. These collectives serve as metal-binding locations (5). The genus Gracilaria is the most common and potential source of agar and has substantial commercial importance as an agarophyte. In temperate and subtropical regions, it includes more than 150 species. The amino acids that include alanine, aspartic acid, glutamic acid and glutamine are the most common among *Gracilaria* species when it comes to protein concentration. The characteristic of algae is derived from these amino acids, which build up the plants under abiotic stress. Seaweeds, including *Gracilaria*, can concentrate minerals from saltwater, resulting in a mineral concentration that is ten to twenty times greater than the plants found in terrestrial ecosystem (6). The effects of brown seaweed at various NaCl concentrations (5, 10, 25 and 50 %) on wheat germination and growth characteristics were examined in a study. As a result, when 25 % seaweed aqueous extract was applied, seed germination and growth parameters significantly increased. Many studies have investigated the possibility of the function of seaweed-based agricultural biostimulants to mitigate the effects of abiotic stresses like extreme temperatures, drought and high salinity, which pose serious issue to global production of cereals (7). However, seaweeds such as *Ulva rigida*, *Codium decorticatum*, *Gigartina sp*. and *Chondracanthus acicularis*, have been shown to have a positive effect on seed germination and plant development, while *Gigartina pistillata*, a red alga, was found to have an inhibitory effect on seed germination. Globally, the paper board industry ranks sixth in the most polluting industries, producing hazardous effluent on a massive scale following the manufacturing of paper. According to the Central Pulp Paper Research Institute's 2016 annual report, there are approximately 850 paper board units in India. These industries discharge effluent containing complex organic and inorganic compounds; 55–60 % of the waste is lignocellulosic waste from raw materials and only 40-45 % of pulp is obtained during the pulping process (8). Studies indicates that the effects of seaweed polysaccharides of 17 different species in green, red and brown colors on plant growth and germination. The current paper concentrates on the characterization and comparison of two red seaweed species and their potential in maize seed germination under abiotic stress condition.

Material and Methods

2.1. Seaweed (*Gracilaria gracilis* and *Gracilaria edulis*) collection and preservation

The red algae *Gracilaria gracilis* and *Gracilaria edulis* were collected from Mandapam area (Latitude 9.2886 °N; Longitude 79.1329 °E), Ramanathapuram District, Tamil Nadu, India. The collected seaweeds were identified by Central National Herbarium, AJC Bose Indian Botanic Garden, Botanical Survey of India, Howrah, West Bengal. The identified samples were preserved at the Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore for further studies.

Freshly collected *Gracilaria* species were carefully cleaned in saltwater before being transported to the laboratory. The seaweed was then thoroughly washed with fresh water to remove debris and epiphytes, shade dried (at about 25-28 °C), ground using a blender, sealed in an air-tight bag at room temperature and subsequently stored in cold storage at 4 °C.

2.2. Preparation of seaweed aqueous extracts

An Erlenmeyer flask with 100 mL of sterile double-distilled water was filled with approximately 5 g of seaweed powder and heated at 60 °C for 15 min. The crude extract obtained was then centrifuged (8000 rpm, 15 min) and kept at 4 °C for experimental use. The steps involved in the seaweed extraction method are illustrated in Fig. 1.

2.3. Physico-chemical characteristics of the seaweed extract *G. gracilis* and *G. edulis*

2.3.1. Water Holding Capacity (WHC) and Swelling Capacity (SWC) of seaweed powder of *G. gracilis* and *G. edulis*

The WHC of *G. edulis* was measured using an altered centrifugation method. In short, 500 mg of seaweed powder was taken into a pair of centrifuge tubes and added deionized water (20 mL). The tubes were kept in a shaking incubator for 24 hr at 25 °C and 37 °C separately. The supernatant after centrifugation at 14000 × *g* for 30 min was discarded from the tubes. The sample moisture level is reduced by keeping in an

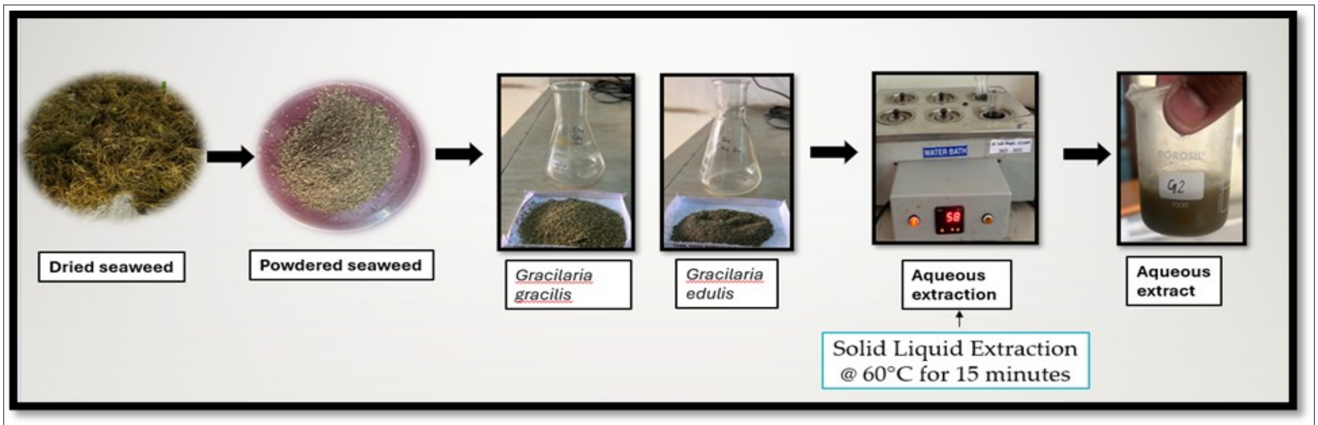

Fig. 1. Method of extraction of red seaweed.

oven at 160 °C for 2hrs and the final dry mass of the seaweed powder sample was noted (9). The values were fitted to the formula below to determine the water holding capacity of given sample and expressed in g g^{-1}.

WHC = Wet weight of the sample (g) - Dry weight of the sample (g)

The bed volume approach was used to determine the swelling capacity of the seaweed powder. To sum up, 500 mg of seaweed powder were mixed with 20 mL of deionized water and strongly swirled. The tubes were incubated overnight at 25 °C and 37 °C to determine the impact of temperature on SWC (9). The values were then fitted to the formula below to determine the swelling capacity of the sample, expressed in mL g^{-1}.

SWC = Initial volume of water (mL) - Volume of water after incubation (mL)

2.3.2. Ash content, moisture content, protein content and fibre content

Five grams of dried and powdered *G. gracilis* and *G. edulis* were placed in a crucible and left overnight at 525 °C in a blast furnace. Using a gravimetric method, the total ash content was calculated as g of ash/100 g of dried sample (10).

The moisture content was evaluated using the oven technique at 105 °C for the whole night (11). The values are expressed in percentage.

The protein content of powdered *G. gracilis* and *G. edulis* was determined using a standard protocol, with a standard of 1 mg/ mL BSA (20).

According to the AOAC enzymatic gravimetric technique, the total fiber content of dried and powdered *G. gracilis* and *G. edulis* were calculated (11).

2.3.3. Determination of chlorophyll content

After extracting *G. gracilis* and *G. edulis* using 96 % methanol, the supernatant was recovered by centrifuging the mixture at 1000 rpm for 1 min. Following filtration, the obtained supernatant was further filtered, centrifuged at 804 × *g* for 10 min and its absorbance was measured at 400-700 nm using a UV-Vis spectrophotometer (12). Chlorophyll A content was then determined using the following formula and expressed as µg/g of fresh weight.

Chlorophyll A = 15.65 (A666) – 7.340 (A653)

2.3.4. Assessment of mineral content

The freeze-dried seaweed extract (*G. gracilis* and *G. edulis*) (1 g) was burned for 24 hr at 550 °C in a muffle furnace to eliminate carbon. Drenched the ash with purified water and mixed it with 1mL of HNO_3. After shaking the mixture, filter paper was used to filter it. Mineral determination was done using the filtrate. The following minerals were identified using a Hitachi Z-5000 atomic absorption spectrophotometer (AAS) and an air-acetylene burner: iron (Fe), zinc (Zn) and copper (Cu) as well as sodium (Na), potassium (K), magnesium (Mg) and calcium (Ca) as macrominerals and trace minerals. Using Perkin Elmer ELAN 9000 inductive coupled plasma mass spectrometry (ICP-MS), selenium (Se) was measured. The calibration curves of the standard were used to calculate the elemental concentrations. Three duplicates of each measurement were made and the data were represented in mg 100 g^{-1} DW basis (13).

2.3.5. Composition of organic compounds and fatty acids in *G. gracilis* and *G. edulis*

G. gracilis and *G. edulis* lipid (75 mg) was immersed in 1 mL of toluene and 2 mL of 1 % H_2SO_4 (in methanol). The esters were then extracted twice with 5 mL of hexane. The outer organic layer was removed and rinsed with 4 mL of 2 % potassium bicarbonate. The solution was dried over anhydrous Na_2SO_4 and filtered. The organic solvent was eliminated and the fatty acid methyl ester (FAME) was subjected to gas chromatography. The initial temperature was maintained at 70 °C, then increased to 250 °C (10 °C/min) and the injection temperature was 220 °C. As the carrier gas, helium was employed at a flow rate of 1 µL/min. By comparing their retention durations with the typical FAME mix, FAME peaks were found (12).

2.3.6. Composition of functional groups in *G. gracilis* and *G. edulis*

According to Gómez-Ordóñez and Rupérez (14), the functional groups of the seaweed extracts of *G. gracilis* and *G. edulis* were identified using Fourier Transform Infrared spectrophotometry (FT-IR), in the range of 4000 to 700 cm^{-1}.

2.4. Germination study (Roll towel method)

Germination test was conducted through roll towel method with three replicates of 100 seeds of maize under controlled conditions (Temperature: 25 °C; Light: 1500 Lux; and RH: 100 ± 5) at Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore. The seeds were soaked overnight in seaweed extract of two different concentration (*Gracilaria gracilis* @ 2.5 and 7.5 %, *Gracilaria edulis* @ 2.5 and 7.5 %). The seeds are wrapped in sheets and sandwiched between two sheets of paper. The rolled towels are positioned vertically in the conical flask containing different concentration of paperboard effluent (10 % and 100 % effluent). Between two sheets of paper, the seeds emerge. The treatment details are mentioned in Table 1.

The germination percentage and germination at the 1^{st} count were assessed using the towel paper roll method at 30 °C by counting the number of normal seedlings on the seventh and fourth days after planting respectively. These parameters were used to assess seed quality, seedling length and dry mass on the fifth day after planting and vigor index, calculated as the product of germination percentage and average seedling length (15).

Results and Discussion

3.1. Initial physico-chemical characteristics of seaweed extract of *G. gracilis* and *G. edulis*

Table 2 illustrates the physico-chemical and biological composition of seaweed powder of *G. gracilis* and *G. edulis* respectively. These powdered seaweed species could potentially be used as growth promoter to agricultural crops to alleviate environmental stress. High swelling capacity (SWC) and water holding capacity (WHC) were observed in *G. gracilis* and *G. edulis*. While *G. edulis* has a higher WHC (11.31 g g^{-1}) than *G. gracilis* (9.7 g g^{-1}), *G. gracilis* has a slightly higher SWC (23.25 mL g^{-1}) than *G. edulis* (21.62 mL g^{-1}). While *G. edulis* exhibited a higher WHC (11.31 g g^{-1}) than *G. gracilis* (9.7 g g^{-1}), *G. gracilis* showed a slightly higher SWC (23.25 mL g^{-1}) compared to *G. edulis* (21.62 mL g^{-1}). This means that extract of seaweed

Table 1. Treatment details for maize seed germination study

T1	Tapwater + untreated maize seeds (Control)
T2	10 % Effluent + (*G. gracilis* 2.5 % extract treated seeds)
T3	10 % Effluent + (*G. edulis* 2.5 % extract treated seeds)
T4	10 % Effluent + (*G. gracilis* 7.5 % extract treated seeds)
T5	10 % Effluent + (*G. edulis* 7.5 % extract treated seeds)
T6	10 % Effluent + untreated maize seeds
T7	100 % Effluent + (*G. edulis* 2.5 % extract treated seeds)
T8	100 % Effluent + (*G. gracilis* 2.5 % extract treated seeds)
T9	100 % Effluent + (G. edulis 7.5 % extract treated seeds)
T10	100 % Effluent + (G. *gracilis* 7.5 % extract treated seeds)
T11	100 % Effluent + untreated maize seeds

Table 2. Physico-chemical characteristics of the seaweed powder *G. gracilis* and *G. edulis*

Parameters	*G. gracilis*	*G. edulis*
SWC (mL g^{-1}) @ 25 °C	23.25	21.62
WHC (g g^{-1}) @ 25 °C	9.7	11.31
Ash content (%)	21.76	8.17
Moisture content (%)	20.71	14.62
Protein (%)	12.59	16.72
Dietary fibre (%)	29.52	67.50
Chlorophyll A (µg g^{-1} DW)	10.21	19.72
Chlorophyll B (µg g^{-1} DW)	-	-

species can improve the intake of water in its own habitat, which might be advantageous for agricultural activities as well as ecological balance (16). These qualities imply that both species might be effective as soil supplements to promote water retention in dry or drought-prone locations, thereby lowering water stress on crops. Particularly in *G. gracilis* (21.76 %), the high ash concentration indicates a significant mineral component. Research indicates that *G. gracilis* has an ash content that is like other seaweeds including *G. changgii* (22.70 %) and *G. salicornia* (38.91 %), indicating that it may be useful as a source of minerals (17). When used as organic fertilizers or soil conditioners, seaweeds can enrich the soil, potentially improve its structure and enhance nutrient availability to crops. Seaweeds such as *G. gracilis* are particularly beneficial in integrated farming systems, as their application has been linked to increased crop yield and improved soil health. *G. edulis* has a high dietary fibre content of 67.50 %, it is possible that these seaweeds are a great source of organic matter for improving soil. This organic matter can improve soil structure, water retention and microbial activity when added to the soil, all of which help crops develop stronger and resilient to stress. *G. edulis* organic matter can increase soil aggregation, which enhances root penetration and aeration. Improved soil structure promotes root development and water circulation, both of which are essential for the health of crop growth. The soil's microbial communities are stimulated by the addition of organic materials. Nutrient cycling depends on robust microbial populations because they decompose organic matter and release nutrients in forms that plants can easily assimilate. By increasing the number of microbes of the soil, increased microbial activity also improves soil health (18). When utilized as fertilizers, the protein content of these seaweeds, 12.59 % for *G. gracilis* and 16.72 % for *G. edulis*, indicates that they may provide slow-release nutritional supplies. This may reduce the risk of nutrient stress by providing a consistent supply of nutrients to crops. Research indicates that *G. edulis* has a higher protein content compared to other seaweed species, making it a valuable resource for sustainable agriculture as a natural fertilizer (6). Both species contain chlorophyll A, with *G. edulis* revealing greater quantities with 13.65 µg g^{-1} of chlorophyll A per dry weight (DW), which may have advantages for the soil health. Studies show that seaweeds like *G. edulis* may greatly improve soil quality when used as amendments. The high chlorophyll content in *G. edulis* contributes to an increase in organic matter and promotes microbial activity in the soil (19).

Table 3 compares the levels of essential nutrients and heavy metals/toxic elements in the two species. In terms of macronutrients, *G. gracilis* exhibits higher concentrations of sodium (1051.580 ppm) and potassium (6413.502 ppm) than *G. edulis*. *G. gracilis* contains high levels of sodium and potassium, which may enhance osmotic regulation within plant cells and improve plant resistance to drought and salt stress (20). The phosphorus (42.914 ppm) and nitrogen (1500 ppm) has been detected in *G. gracilis*, where nitrogen is necessary for protein synthesis and general plant growth, phosphorus aids in the formation of roots and energy transfer activities (21). These variations imply that the two species have different nutritional profiles, which may influence how they are used in agriculture to alleviate environmental stress. But *G. edulis* has higher magnesium (151.714 ppm) and calcium (124.546 ppm) concentrations, *G. edulis* has higher amounts of calcium and magnesium, which support the stability of the cell wall and the synthesis of chlorophyll in plants respectively (20, 21). *G. gracilis* exhibits significantly greater amounts of micronutrients, especially in boron (2.242 ppm), the boron

Table 3. Essential nutrients and heavy metals of seaweed extract (*G. gracilis* and *G. edulis*)

Sl. No.	Parameters	*G. gracilis* (ppm)	*G. edulis* (ppm)
		Essential nutrients Macronutrients	
1	Nitrogen	1500	1160
2	Phosphorous	42.914	36.350
3	Potassium	6413.502	3708.687
4	Sodium	1051.580	945.396
5	Calcium	93.197	124.546
6	Magnesium	145.055	151.714
		Micronutrients	
7	Boron	2.242	2.200
8	Manganese	26.104	23.261
9	Iron	1.623	3.44
10	Copper	0.479	0.451
11	Zinc	0.120	0.122
		Heavy metals/Toxic elements	
12	Aluminium	0.120	0.338
13	Chromium	0.052	0.082
14	Cadmium	0.017	0.017
15	Mercury	0.050	0.016
16	Lead	0.002	0.007
17	Arsenic	0.230	0.219
18	Barium	0.116	0.128
19	Silver	0.006	0.006
20	Nickel	0.089	0.103

deficiency may lead to poor development of plants and reproductive failure since it is essential to produce cell walls and membrane stability. Given that *G. gracilis* contains boron, it may contribute to increased crop resilience, especially in boron -deficient soils. It also contains manganese (26.104 ppm) and copper (0.479 ppm), which play important roles in various physiological processes. Interestingly, *G. edulis* contains more than twice the amount of iron (3.44 ppm) compared to *G. gracilis* (1.623 ppm). This higher iron content may be particularly beneficial for improving the nutritional status of crops susceptible to iron deficiency (6). Both species contain very low levels of heavy metals and toxic substances, which is favorable from an agricultural safety perspective. There are a few noticeable variations, though. In comparison to *G. gracilis*, *G. edulis* has greater concentrations of lead (0.007 ppm), chromium (0.082 ppm) and aluminium (0.338 ppm) still the number of toxic substances is less toxic to the environment, which reduces the risk of negative impact on the agriculture. However, *G. gracilis* has greater levels of arsenic (0.230 ppm) and mercury (0.050 ppm). At certain quantities, both arsenic and mercury are known to be hazardous to plants. Despite having greater concentrations of these metals, *G. gracilis* has also shown resistance to metal stress, as seen by its capacity to reduce oxidative stress and improve metabolic pathways in response to metal stress (22).

Composition of organic compounds in seaweed is presented in the Table 4. Bioactive substances found in these seaweed species, include fatty acids, organic acids and amino acids, which indicate that they may be used as biostimulants to help agricultural crops adapt with environmental challenges such as salt, drought and temperature stress. The high levels of cholesterol in *G. gracilis* (8.39 %) and *G. edulis* (6.67 %) as mentioned in Fig. 2(b), 3(d) is remarkable because it has been proved that plant stress responses include cholesterol and its compounds (23). Tropic acid-TMS (0.70 %) is present in high concentrations in *G. edulis*, which could improve the plant's ability to withstand stress, particularly from salt or drought. Tropic acid use may enhance certain physiological characteristics that support stress tolerance. For instance, in situations of drought, it could promote the development of roots and growth, helping plants to reach deeper soil moisture levels. Furthermore, the protective properties of tropic acid on leaf tissues might lead to increased leaf water retention and decreased transpiration rates (24). In *G. gracilys*, eicosyl benzoate (2.30 %) (Fig. 2a) may be involved in signalling pathways that cause plants' stress response systems to activate, thereby improving the plants' resistance to salt and heat stress (25). The presence of, inositol-6TMS (0.48 %) in *G. gracilis* may play a role in osmoregulation and cellular defense against osmotic stress. Studies show that inositol can affect how genes related to stress response pathways are expressed. For instance, it might activate transcription factors that control how genes responding to drought are expressed, improving the plant's capacity to adjust to varying environmental circumstances (26). Adipic acid-2TMS (0.46 %) in *G. gracilis*, which may act as stress relievers or signalling molecules. Through its interactions with phytohormones like abscisic acid (ABA), adipic acid can function as a signalling molecule that affects the expression of genes that respond to abiotic stress. ABA is referred to be a "stress hormone" since it controls several physiological reactions, like as stomatal closure, which lowers water loss during droughts. Adipic acid may alter ABA signalling pathways, which would improve the plant's capacity to withstand stress by activating the production of genes involved in stress tolerance (27). In *G. gracilis,* compounds such as cinnamic acid (0.57 %) may aid in scavenging reactive oxygen species (ROS), which are often overproduced under extreme conditions such as salt and drought stress (28). Ribose-$13C_5$-meto-4TMS (2.32 %) is another compound (Fig. 2c) that may enhance the antioxidant systems of plants. The commonly used biostimulant melatonin (MET) enhances the activity of antioxidant enzymes (including catalase and superoxide dismutase) under stress, reducing oxidative damage caused by reactive oxygen species (ROS) (29). Hippuric acid-2TMS (1.18 %) (Fig. 2d), may affect how transcription factors and genes associated to stress are expressed in plants. It has been suggested that such substances might alter the action of important phytohormones including abscisic acid (ABA), which is essential for plants to adjust to abiotic stress (salinity and drought). Significant amounts of 2,5-Bis(5-tert-butyl-2-benzoxazolyl) thiophene (2.78 %) in *G. edulis* (Fig. 3a) is detected. This compound maintains lipid bilayers, which may preserve membranes and ensure that cellular structures stand up under environmental stress. Its antioxidant characteristics may help in reducing oxidative damage to membrane lipids, which is crucial in salinity or drought conditions. It has been observed that there are significant amounts of 4-aminobutyric acid (15.07 %) in *G. edulis* (Fig. 3c), which may act as a growth

Table 4. Composition of organic compounds in seaweed extracts (*G. gracilis* and *G. edulis*)

R. Time	*G. gracilis*	Area (%)	R. Time	*G. edulis*	Area (%)
16.755	Cinnamic acid-TMS	0.57	19.278	Saccharopine-4TMS	0.44
37.585	Eicosyl benzoate	2.03	53.835	2,5-Bis(5-tert-butyl-2-benzoxazolyl) thiophene	2.78
40.060	Cholesterol-TMS	0.48	19.780	4-Hydroxybutyric acid-2TMS	0.51
40.670	Inositol-6TMS (2)	0.48	19.985	Acetylglycine-TMS	0.34
41.279	Trichloroacetic acid, undec-2-enyl ester	0.60	28.502	Oleamide-TMS	0.34
43.100	3-Hydroxy-kynurenine-3TMS	0.45	52.580	2-Deoxy-glucose-4TMS (1)	2.87
44.078	Tropic acid-2TMS	0.70	30.016	13-Hexyloxacyclotridec-10-en-2-one	0.36
44.760	4-Cresol-TMS	0.52	33.175	Ornithine-3TMS	0.60
44.890	N6-Acetyllysine-3TMS	0.56	36.387	Tropic acid-2TMS	0.42
45.175	Adipic acid-2TMS	0.46	29.868	Thymidine monophosphate-3TMS	0.71
48.806	Cholesterol	8.39	49.955	4-Aminobutyric acid-3TMS	15.07
52.360	Ribose-13C5-meto-4TMS	2.32	47.077	Anthranilic acid-TMS	0.90
52.636	Hippuric acid-2TMS	1.18	47.740	Uracil-2TMS	0.78
54.607	3,4-Dihydroxymandelic acid-4TMS	0.53	48.804	Cholesterol	6.67

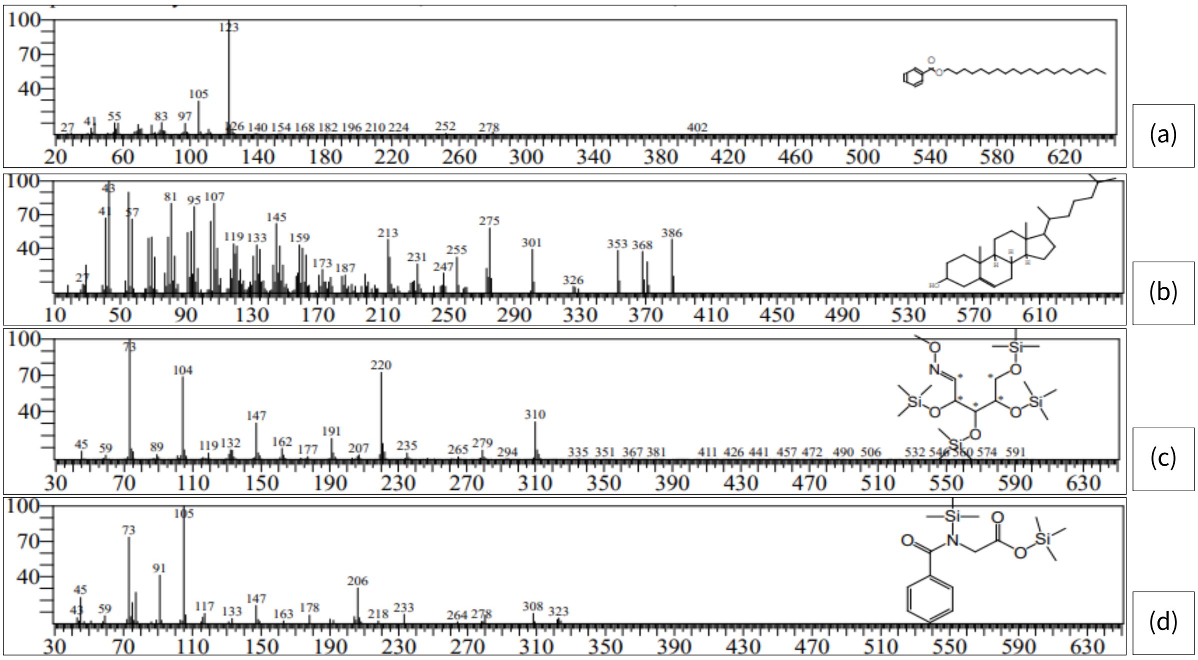

Fig. 2. Different organic compounds in *G. gracilis*.

(a) Eicosyl benzoate, (b) Cholesterol, (c) Ribose-13C5-meto-4TMS, (d) Hippuric acid-2TMS

regulator and reduce the effects of stress (31). The compounds 13-Hexylacyclotridec-10-en-2-one (0.36 %) could have structural characteristics that enable it to interact with ROS and neutralize them, reducing oxidative damage and saccharopine-4TMS (0.44 %) may affect when genes connected to stress response pathways, improving the plant's capacity to adapt to varying environmental conditions. This involves the control of the genes that produce the metabolites and protective proteins (32). *G. edulis* contains a higher amount of 4-hydroxybutyric acid (0.51 %). Research indicates that 4-hydroxybutyric acid can enhance the phosphorus solubilization activity of beneficial soil bacteria, which is critical for nutrient uptake under conditions of limited nutrient availability. This plays a crucial role in stressed plants, as nutrient uptake becomes more difficult under such conditions (33). 2-Deoxy-glucose-4TMS (2.87 %) is a sugar present in *G. edulis* that may help plants withstand abiotic stress (Fig. 3b). Research has been demonstrated that by altering carbon partitioning and improving osmotic control, the use of FDG can increase plants' resistance to abiotic stressors. This is especially important for development in adverse environments and improve activities like photosynthesis in crops (34). Thymidine monophosphate (TMP) (0.71 %) may play a role in regulating metabolism during stress in agricultural crops. TMP is involved in several metabolic pathways essential for cellular function and energy synthesis. By promoting these metabolic activities, TMP helps ensure that plants maintain the energy levels necessary for growth and development under stress conditions. Oleamide (0.34%), present in *G. edulis,* may play a role in signaling pathways and maintaining membrane fluidity under adverse environmental conditions. Oleamide has been shown to interact with various receptors, including gamma-aminobutyric acid (GABA) and serotonin (5-HT) receptors, which are crucial for modulating plant responses to external stimuli. Through the activation of these receptors, oleamide may influence physiological processes such as stomatal regulation and nutrient uptake-both critical to stress responses. Table 5 provides the percentage of fatty acids in *G. gracilis* and *G. edulis*. In *G. gracilis*, the saturated fatty acid hexadecanoic acid (also known as methyl palmitate) has been detected at a concentration of 0.67 %. One of the fatty acid methyl esters that is used as a precursor in the production of jasmonates, especially jasmonic acid, is methyl palmitate. Jasmonic acid (JA) is a crucial plant hormone that regulates growth, development and responses to environmental stressors. Plants respond to abiotic stressors such as drought, salt and high temperatures by activating certain genes involved in biosynthesis to raise the levels of JA. Methyl cis-13,16-Docosadienate (0.47 %) in *G. gracilis*, influences the biochemical parameters of plants, improving their stress tolerance and yields even in unfavourable environmental conditions. It is used as a biostimulant to increase plant growth and production under abiotic stress. In *G. gracilis*, the range of palmitic acid (0.40 %). Studies indicate that palmitic acid levels increase in plants under drought stress. Research in wheat has shown a significant rise in palmitic acid content during drought conditions, suggesting its role in maintaining membrane integrity and supporting post-stress recovery. Under limited water availability, this adaptation helps manage oxidative damage and supports the cellular processes essential for plants survival. The level of azelaic acid (0.57 %) in *G. gracilis* indicates its probable antioxidant activity in plants. Studies have indicated that the use of azelaic acid during stressful circumstances increases the activity of antioxidant enzymes including catalase (CAT) and peroxidase (POD) (Fig. 2). This improvement reduces the harmful effects of oxidative stress by abiotic factors like salinity and drought (38). Methyl palmitoleate can affect the expression of antioxidant enzymes under abiotic stress, including POD, CAT and superoxide dismutase (SOD) (Fig. 4). The pathway to of these enzymes plays role in reducing abiotic stress towards crops. Methyl arachidonate (3.22 %) has been detected in *G. gracilis*. Isopropyl linoleate (8.53 %) was detected in *G. gracilis* (Fig. 5a), at a higher concentration than other unsaturated fatty acids. Bioactive substances like jasmonates, which are implicated in stress signalling pathways, are derived from unsaturated fatty acids like linoleate. These substances aid in the activation of plants' defense systems, which improves their ability to withstand

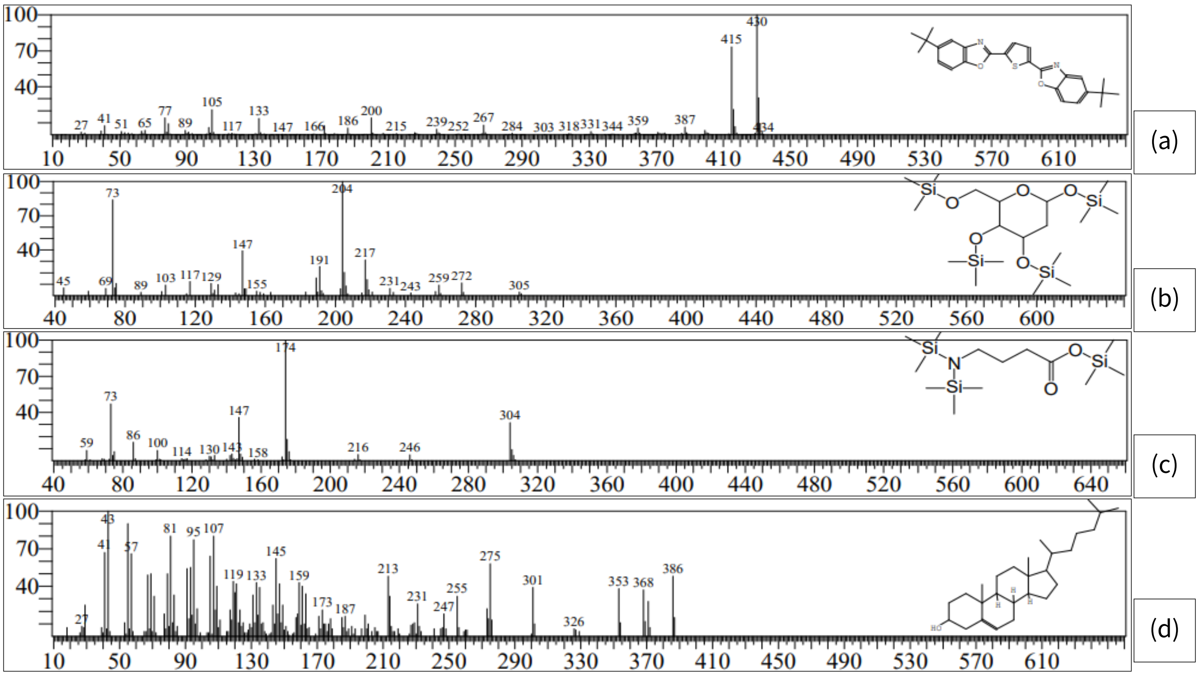

Fig. 3. Different organic compounds in *G. edulis.*

(a) 2,5-Bis(5-tert-butyl-2-benzoxazolyl) thiophene (b) 2-Deoxy-glucose-4TMS (c) 4-Aminobutyric acid-3TMS (d) Cholesterol

Table 5. Composition of fatty acid in seaweed extracts (*G. gracilis* and *G. edulis*)

R. Time	*G. gracilis*	Area (%)	R. Time	*G. edulis*	Area (%)
27.404	Hexadecanoic acid, methyl ester	0.67	7.884	Methyl linolelaidate	0.43
28.137	Methyl cis-13,16-Docosadienate	0.47	9.945	Octanoic acid	0.35
29.699	Palmitic acid-TMS	0.40	38.127	Docosahexaenoic acid-TMS	0.42
51.475	Methyl eicosa-8,11,14-trienoate	5.83	23.600	Methyl cis-11,14-Icosadienoate	0.54
36.195	Elaidic acid-TMS	0.63	33.555	Lysine-4TMS	0.37
36.947	Azelaic acid-2TMS	0.57	24.829	2-Propyl-5-hydroxy-pentanoic acid-2TMS	0.31
49.585	Methyl arachidonate	3.22	52.974	Methyl elaidate	4.28
38.507	2-Octenoic acid-TMS	1.32	25.664	Palmitoleic acid-TMS	1.01
51.955	Isopropyl linoleate	8.53	28.226	Methyl cis-11,14-Icosadienoate	0.42
53.023	Linoleic acid-TMS	1.39	39.691	Octadecanal	1.22
43.246	Stearic acid-TMS	0.82	39.935	Nonanoic acid-TMS	0.37
45.874	Docosahexaenoic acid-TMS	0.75	40.059	Sebacic acid-2TMS	0.57
45.390	Creatinine-3TMS	0.98	42.008	2-Hydroxyisocaproic acid-2TMS	0.51
46.831	Methyl arachisate	0.83	42.906	Palmitic acid-TMS	0.53
47.371	Arachidonic acid-TMS	1.54	33.175	Ornithine-3TMS	0.60
47.910	Methyl linoleate	2.65	47.479	Methyl cis-10-heptadecenoate	1.24
48.071	Methyl linolenate	1.48	24.514	Methyl cis-4,7,10,13,16,19-Docosahexaenoate	0.34
48.385	Docosapentaenoic acid-TMS	2.30	28.792	Methyl palmitoleate	0.91
49.585	Methyl arachidonate	3.22	32.256	Methyl myristoleate	0.45
49.978	Methyl cis-11,14-Icosadienoate	5.01	35.248	Methyl linolenate	0.37
50.346	Methyl elaidate	8.43	38.353	Methyl erucate	0.42
51.235	3-Hydroxyvaleric acid-2TMS	3.25	44.313	Methyl cis-11-icosenoate	0.46

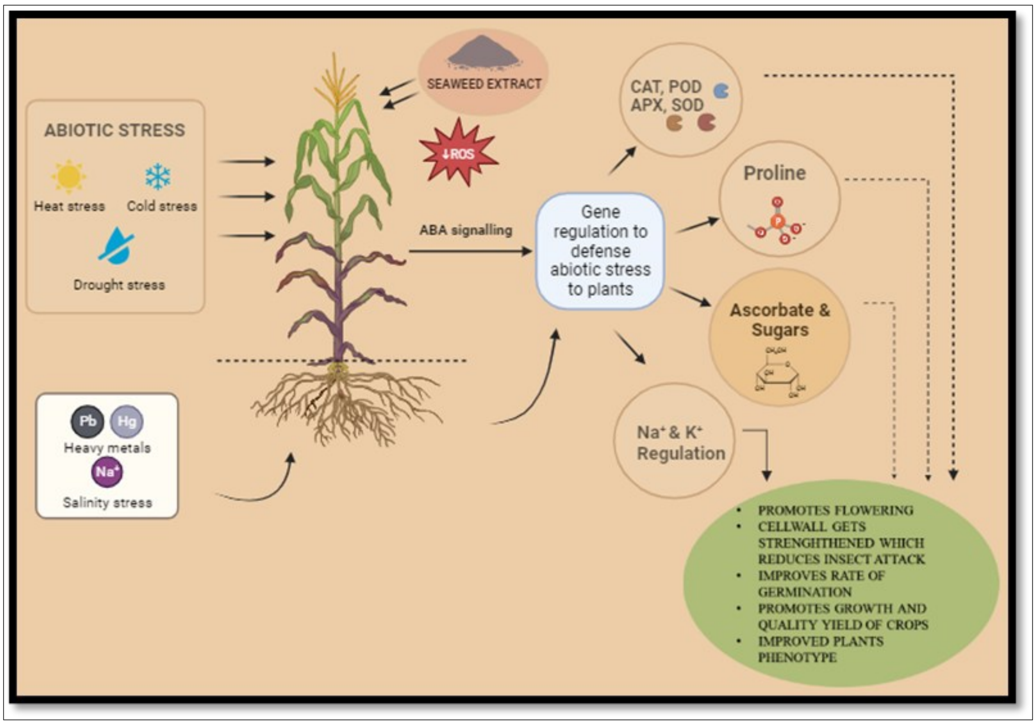

Fig. 4. Mechanism of seaweed based biostimulant to plants under abiotic stress.

abiotic challenges including salinity and high temperatures (35). The omega-3 fatty acid docosahexaenoic acid (DHA) (0.75 %) and methyl arachisate (0.83 %) have been seen in *G. gracilis* recognized for its possible ability to help plants recover from abiotic stress. DHA is involved in the biosynthesis of jasmonates and other phytohormones that control stress responses, as well as in the production of various signaling molecules. These compounds play a key role in activating defense mechanisms and help plants survive environmental stressors (36). Methyl linoleate (2.65), methyl linolenate (1.48 %), docosapentaenoic acid-TMS (2.30 %) and methyl cis-11,14-icosadienoate (5.01 %) is a fatty acid plays a major role as antioxidant activity in crops (Fig. 5b). Due to its antioxidant qualities, this compound might reduce the oxidative stress caused by ROS under stressful environmental situations. Because methyl linoleate scavenges free radicals, it can shield plant cells from oxidative damage and increase their capacity to survive in adverse conditions (37). Methyl elaidate (8.43 %), an elaidic acid methyl ester, has many of potential uses in increasing plant resistance to abiotic stress has been detected in *G. gracilis* in excess amount. Similar to other fatty acid esters, methyl elaidate (Fig. 5c) may improve plants' ability to function as antioxidants. By improving the production of antioxidants, it helps decrease oxidative stress caused by ROS, which may accumulate during environmental conditions like heat and drought (38). Methyl eicosa-8,11,14-trienoate (0.81 %) serves as a precursor for the synthesis of JA is present in *G. gracilis* (Fig. 5d), is an essential phytohormone linked to defense mechanisms in plants. In response to abiotic stress including drought, salinity and high temperatures, plants frequently produce more JA and its derivatives, which aid in the

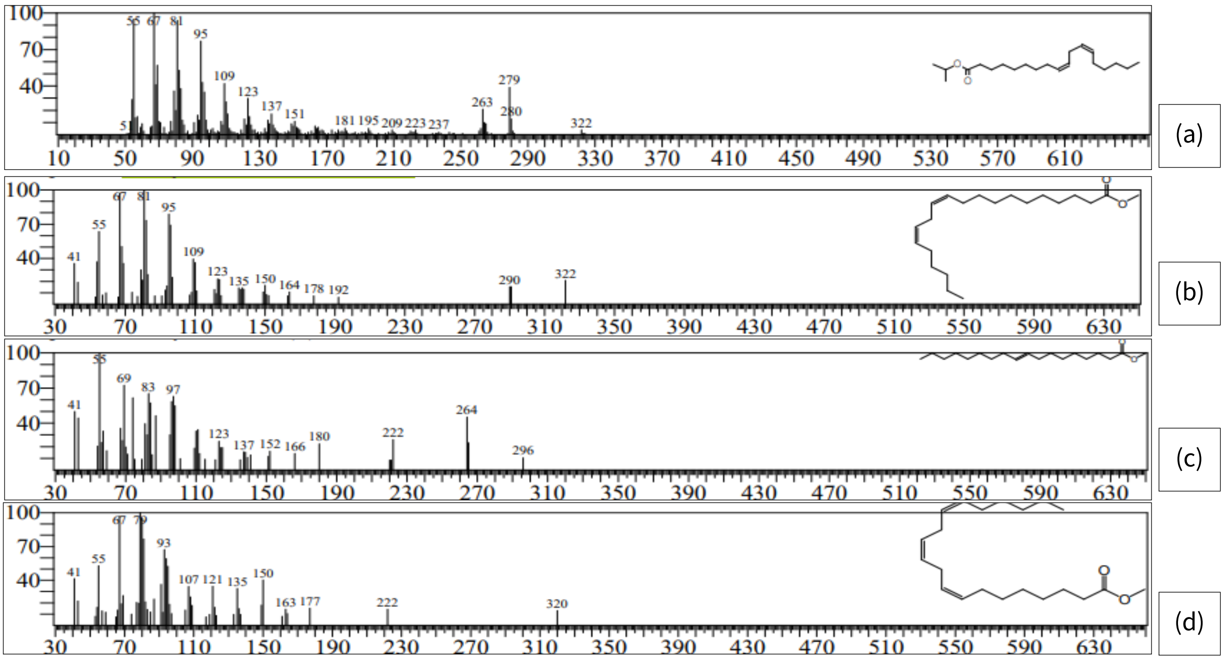

Fig. 5. Different organic compounds in *G. gracilis*.

(a) Isopropyl linoleate (b) Methyl cis-11,14-icosadienoate (c) Methyl elaidate (d) Methyl eicosa-8,11,14-trienoate activation of genes and pathways that are sensitive to abiotic stress (39). In *G. gracilis*, 3-hydroxyvaleric acid (3-HV) (3.25 %) and its trimethylsilyl (TMS) derivative to reduce abiotic stress through various metabolic processes are reported. Studies revealed that a variety of stress tolerance systems in plants can be activated by biostimulants. As a case study, they may promote the accumulation of osmoprotectants such as proline and glycine betaine, which helps stabilize cellular structures and provide protection against salinity stress and dehydration (40).

In *G. edulis*, methyl linolelaidate (0.43 %) has recently gained attention for its potential to enhance plant resistance to abiotic stress. Methyl linolelaidate may support physiological adaptations in plants in response to stress, including improved water retention, enhanced photosynthetic efficiency and increased membrane stability under high-temperature conditions (41). Octanoic acid (0.35 %), also known as caprylic acid, has been reported in *G. edulis*. It is a medium-chain fatty acid that has been studied for its potential role in plant biology, particularly in relation to abiotic stress and antioxidant defense mechanisms (39). Docosahexaenoic acid-TMS (0.42 %) and methyl cis-11,14-icosadienoate (0.54 %), has been found in *G. edulis*. This compound may enhance the antioxidant capacity of stressed plants. By controlling the levels of ROS during abiotic stress conditions, it can help alleviate oxidative damage, therefore requiring better survival and development. Lysine-4TMS (0.37 %) is present in *G. edulis* and is thought to contribute to stress mitigation in plants under abiotic conditions. Studies suggest that serine/arginine-rich (SR) and lysine-rich (LR) proteins enhance plant resistance to abiotic stressors. By regulating gene expression and protein function, these proteins can be engaged in cellular signalling and stress response pathways, helping plants in adapting to adverse climatic situations (42). 2-Propyl-5-hydroxy-pentanoic acid-2TMS (0.31 %) in *G. edulis* plays a role to reduce abiotic stress through different metabolic pathway. Enhancing agricultural procedures like seed priming or foliar spraying using 2-propyl-5 -hydroxy-pentanoic acid-2TMS may enhance features like root growth, water retention and resistance against environmental stressors (48). Palmitoleic acid-TMS (1.01 %) plays an important role in lipid metabolism and signaling pathway to reduce environmental stress has been reported in *G. edulis* (Fig. 6a). Fatty acids, especially palmitoleic acid, may function as signaling molecule which regulate stress response pathways. They might affect the expression of genes related to stress tolerance pathways, improving a plant's capacity to withstand extreme environmental conditions (43). The long-chain aldehyde octadecanal (1.22 %) has been identified in *G. edulis* (Fig. 6b) and is considered important in plant responses to abiotic stress, particularly under drought and high temperature conditions. The physiological adaptations that improve water absorption during drought stress, including decreased transpiration rates or altered root architecture, can be facilitated by the presence of octadecanal. Under stressful conditions, these adaptations support the health and production of plants (44). Trimethylsilyl sebacic acid-2TMS (0.57 %) contributes to the increased resistance of plants against abiotic stress has been reported in *G. edulis*. Genes linked to stress tolerance pathways may be upregulated in the presence of sebacic acid-2TMS. This contains genes linked to metabolic processes that result in the production of osmoprotectants, such as proline and glycine betaine, which aid in the stabilization of cellular structures and proteins under conditions of osmotic stress. The palmitic acid (0.53 %) in *G. edulis* is potential in strengthening plant resistance against abiotic stresses have been explored, especially in relation to its trimethylsilyl (TMS) derivative form. These palmitic acids are involved in antioxidant process and regulation of stress responsive genes to reduce the effect of plants against abiotic stress (heat, drought and salinity). Methyl cis-10-heptadecenoate is one of the fatty acids that has been shown to affect the expression of genes related to stress responses is detected in *G. edulis* (Fig. 6c). The genes that control the generation of antioxidants and other defense mechanisms that improve resistance to abiotic stressors like salinity and drought (45). One important component of plant responses to abiotic stress is monounsaturated fatty acid methyl palmitoleate (0.91 %), methyl elaidate (4.28 %) (Fig. 6d), methyl linolenate (0.37) and methyl myristoleate (0.45 %) has been reported in *G. edulis*. The activity of antioxidant enzymes in plants is modulated by methyl palmitoleate and methyl elaidate. Studies indicate that methyl linolenate may influence the expression of genes associated with stress responses. It can control the expression of genes called fatty acid desaturase, which are involved in the creation of unsaturated fatty acids that enhance membrane function and stability under stress (43). Methyl erucate (0.42 %), a fatty acid methyl ester derived from erucic acid and methyl cis-11-icosenoate (0.46 %), an unsaturated fatty acid, have been identified in *G. edulis* and may contribute to improved plant tolerance to abiotic stress. Additionally, both methyl erucate and methyl cis-11-icosenoate could be involved in stress signalling pathways. Methyl erucate fatty acids can affect the generation of other signaling molecules and ROS, which are involved in regulating stress responses. Plant defense systems against different stressors are known to be regulated by bioactive compounds like jasmonates, which can be synthesized from methyl cis-11-icosenoate (39).

The infrared spectroscopic data of *G. gracilis* and *G. edulis* are presented in Table 6 and Fig. 7 illustrates the peaks corresponding to each functional group present in the seaweed extracts, along with the associated compounds for each group. These seaweed species contain a wide variety of chemical substances, according to the research. The presence of alcohols is indicated by the highest wave numbers, 3828.97 and 3742.19 cm^{-1}, which correspond to O-H stretching vibrations. Use of alcohol particularly ethanol plays major roles in abiotic stress in plants. Ethanol reduce ROS accumulation, enhance antioxidant defense and improve photosynthetic efficiency in plants under abiotic stress (46). The presence of amines is suggested by the N–H stretching peak at 3288.04 cm^{-1}. Amines, especially polyamines play a major role in improving stress tolerance. Their application in plants under abiotic stress has attracted considerable interest. Polyamines are involved in stress response mechanisms, antioxidant activity and gene express regulation (47). Aromatic molecules are indicated by the C–H stretch at 2929.34 cm^{-1}, as well as peaks at 1642.09 cm^{-1} (C=O and C=C stretch) and 1532.17 cm^{-1} (C=C stretching). Aromatic compounds, particularly secondary metabolites such as phenolics and phytohormones, play a critical role in strengthening plant tolerance to abiotic stresses such as

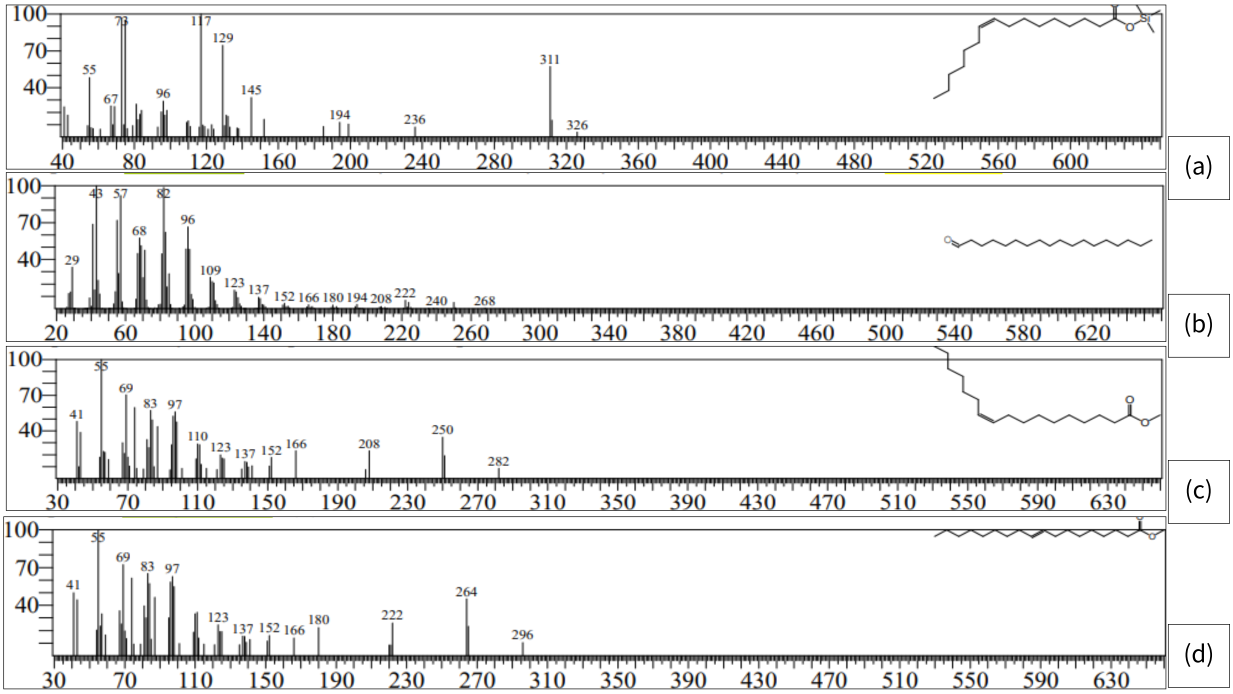

Fig. 6. Different organic compounds in *G. edulis.*

(a) Palmitoleic acid-TMS (b) Octadecanal (c) Methyl cis-10-heptadecenoate (d) Methyl elaidate

Table 6. Functional groups of seaweed extracts (*G. gracilis* and *G. edulis*)

***G. gracilis* & *G. edulis* (Position cm^{-1})**	**Functional groups**	**Compounds**
3828.97 and 3742.19	O–H stretch	Alcohols
3288.04	N–H stretch	Amines
2929.34	C–H stretch	Aromatic compounds
1642.09	C=O and C=C stretch	Aldehydes Aromatic compounds
1532.17	C=C stretching	Aromatic compounds
1462.74	C–H bend	Alkenes Alkynes
1010.52	C–O stretch	Esters
748.24 and 647.96	C–H bend	Alkenes

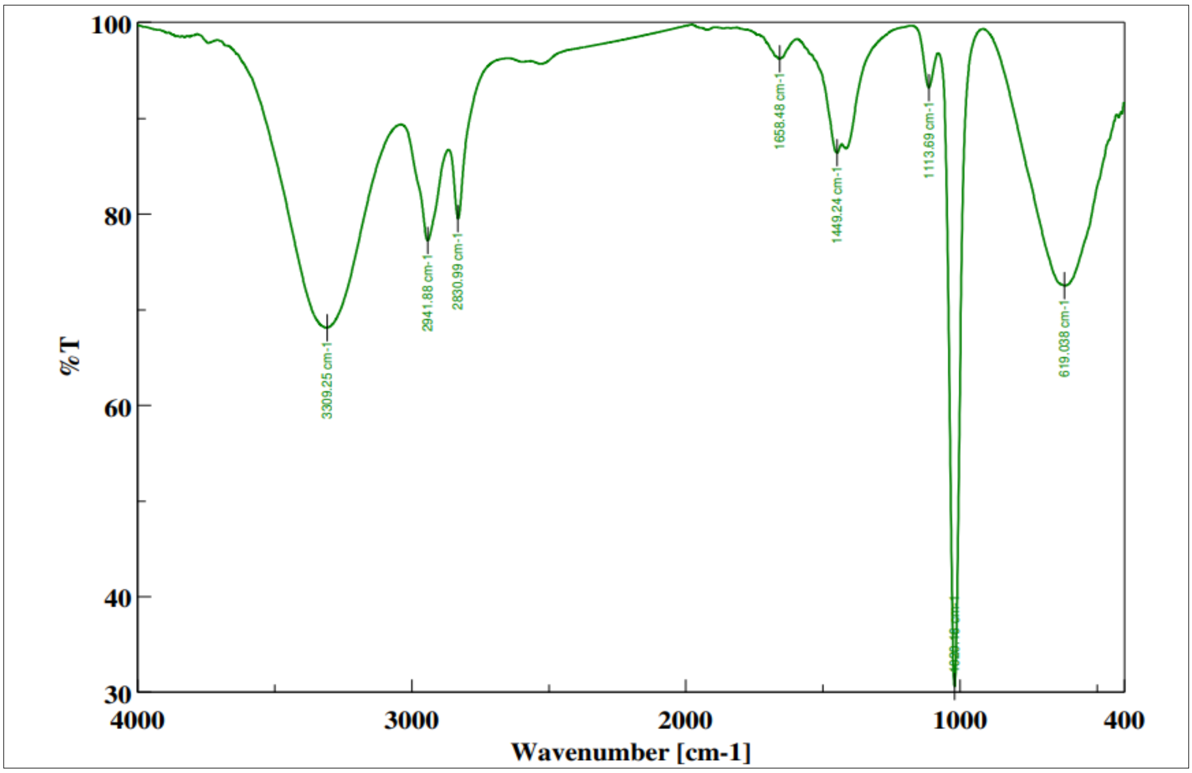

Fig. 7. FT-IR spectrum of seaweed extracts (*G. gracilis* and *G. edulis*).

drought, salt, heat and cold. It involves antioxidant activity, stress related mechanism and metal chelation ability (48). In addition, the spectrum reveals the presence of esters with a C-O stretch at 1010.52 cm^{-1} and alkenes and alkynes with a C-H bend at 1462.74 cm^{-1}. With wave numbers of 748.24 and 647.96 cm^{-1}, alkenes exhibit C-H bending. As unsaturated hydrocarbons, alkenes and alkynes play important roles in plant responses to abiotic stress. It involves mechanism in signaling stress (49), metabolic alterations and protective mechanisms. According to this detailed spectroscopic study, the complex array of organic compounds presents in *G. gracilis* and *G. edulis* -characteristic of marine algae and indicative of their rich biochemical composition-includes alcohols, amines, aromatics, aldehydes, alkenes, alkynes and esters.

3.2. Effect of different concentration of seaweed extract of *G. gracilis* and *G. edulis* on agricultural crops under abiotic stress

Seaweed extracts have emerged as important biostimulants in agriculture, offering several benefits for plant growth, development and resilience. Research indicates that seaweed-based products can significantly enhance plant productivity and tolerance to abiotic stresses such as salinity and drought by activating protective mechanisms within the plant. Furthermore, seaweed extracts have a beneficial effect on the soil microbiome and enhance soil fertility and health, while integrating well with other crop inputs, all of which support sustainable farming practices. This study examined the germination of maize under different concentrations of papermill effluent and evaluates the effect of various concentrations of red seaweed extract as a plant biostimulant to alleviate environmental stress. The results of the experiment demonstrated significant variations in the growth parameters of maize under several treatments that include papermill effluent and seaweed extracts of two red seaweed species (*G. gracilis* and *G. edulis*) mentioned in Table 7. The tap water (control) treated maize seedling showed a shoot length of 22 ± 0.28 cm, a root length of 29 ± 0.02 cm and a germination percentage of 84 ± 0.69 %. Treatments T2 to T5 showed significant improvements in these growth parameters. The treatment T5 (10 % Papermill effluent + G2 sps @ 7.5 %) when compared to control T1, had the longest shoots (34 ± 0.35 cm) and roots (51 ± 0.37 cm) as shown in Fig. 8. Additionally, the remarkable seed vigor index (26.88 ± 0.30) and ideal germination percentage (96 ± 0.06 %) were observed in the seaweed extract treated maize seed. The favourable effects of seaweed extract treated maize seeds demonstrated a mutually reinforcing relationship that supports plant growth and development under abiotic condition, which showed that the seaweed extract has several growth hormones that induce the growth and development in plants. Growth measurements were considerably lower in treatments using 100 % papermill effluent (T7–T11), indicating that the stress-inducing effects of paperboard effluent. T11 (100 % papermill effluent + untreated maize seeds) consistently had the lowest results, with fresh weight of 0.97 ± 0.01 g, shoot length of 13 ± 0.14 cm and root length of 25 ± 0.37 cm. Even at high effluent concentrations, however, the addition of seaweed extracts especially G2 (*G. edulis*) species showed impressive stress-mitigating benefits. This is supported by the fact that treatments with seaweed extracts performed comparatively better than those without, indicating the seaweed extracts' biostimulant qualities under stress.

Table 7. Effect of seaweed extracts (*G. gracilis* and *G. edulis*) on growth parameters and seed vigor index of maize grown under paperboard effluent

Treatments	Shoot length (cm)	Root length (cm)	Germination percentage	Maize weight (g)		Seed vigor index (SVI)
				Fresh weight (g) (7^{th} day)	Dry weight (g) (after 24 hr in oven @ 85 °C)	
T1 - Tap water (control)	22 ± 0.28^{d}	29 ± 0.02^{e}	84 ± 0.69^{cd}	1.29 ± 0.02^{de}	0.244 ± 0.01^{c}	19.54 ± 0.12^{c}
T2 - 10 % of papermill effluent + G1 sps @ 2.5%	28 ± 0.19^{c}	40 ± 0.02^{c}	92 ± 0.83^{ab}	1.35 ± 0.02^{cd}	0.160 ± 0.01^{e}	14.72 ± 0.17^{e}
T3 - 10 % of papermill effluent + G2 sps @ 2.5 %	29 ± 0.16^{c}	41 ± 0.44^{c}	90 ± 0.62^{b}	1.29 ± 0.01^{e}	0.176 ± 0.01^{d}	15.84 ± 0.10^{d}
T4 - 10 % of papermill effluent + G1 sps @ 7.5 %	31 ± 0.37^{b}	48 ± 0.55^{b}	96 ± 0.32^{a}	2.01 ± 0.01^{a}	0.282 ± 0.01^{a}	27.07 ± 0.24^{a}
T5 - 10 % of papermill effluent + G2 sps @ 7.5 %	34 ± 0.35^{a}	51 ± 0.37^{a}	96 ± 0.06^{a}	1.69 ± 0.01^{b}	0.280 ± 0.01^{a}	26.88 ± 0.30^{a}
T6 - 10 % of papermill effluent + untreated maize seeds	23 ± 0.04^{d}	30 ± 0.35^{e}	80 ± 1.15^{d}	1.36 ± 0.01^{c}	0.269 ± 0.01^{b}	21.52 ± 0.11^{b}
T7 - 100 % of papermill effluent + G1 sps @ 2.5 %	14 ± 0.05^{g}	29 ± 0.32^{e}	84 ± 0.21^{cd}	1.09 ± 0.01^{h}	0.148 ± 0.01^{f}	12.43 ± 0.14^{g}
T8 - 100 % of papermill effluent + G2 sps @ 2.5 %	16 ± 0.09^{f}	32 ± 0.44^{d}	84 ± 0.45^{cd}	1.16 ± 0.02^{fg}	0.156 ± 0.01^{ef}	13.10 ± 0.14^{fg}
T9 - 100 % of papermill effluent + G1 sps @ 7.5 %	16 ± 0.03^{f}	30 ± 0.02^{e}	88 ± 1.19^{bc}	1.11 ± 0.01^{gh}	0.152 ± 0.01^{ef}	13.37 ± 0.17^{f}
T10 - 100 % of papermill effluent + G2 sps @ 7.5 %	18 ± 0.03^{e}	33 ± 0.36^{d}	88 ± 0.16^{bc}	1.20 ± 0.01^{f}	0.149 ± 0.01^{f}	13.11 ± 0.19^{fg}
T11 - 100 % of papermill effluent + untreated maize seeds	13 ± 0.14^{g}	25 ± 0.37^{f}	80 ± 0.89^{d}	0.97 ± 0.01^{i}	0.131 ± 0.01^{g}	10.48 ± 0.15^{h}
Mean	22.18	35.27	87.45	1.32	0.19	17.09
SE(d)	0.56	0.84	1.54	0.02	0.004	0.45
CD (0.05 %)	1.16	1.74	3.19	0.04	0.009	0.95

G1- *G. gracilis*, G2- *G. edulis*

* Treatments with same letters are not significantly different

CD - Critical difference ($p < 0.05$)

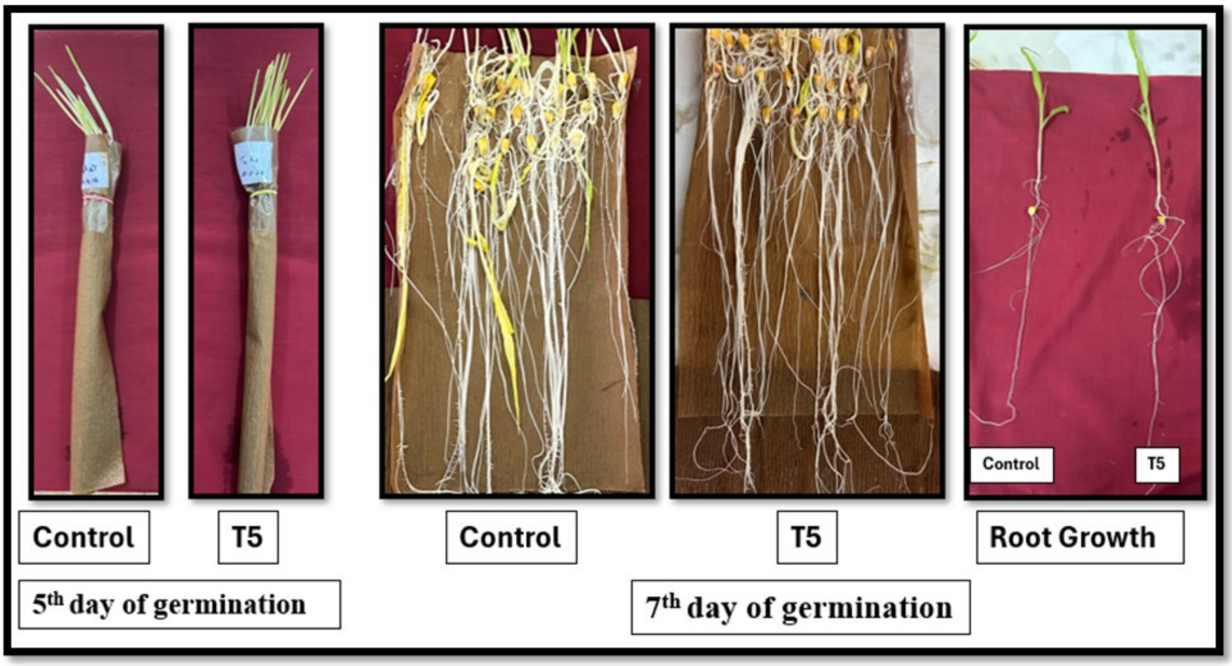

Fig. 8. Effect of seaweed extract of *G. edulis* in maize grown in paperboard.

*Control (Tap water), *T5 (10 % papermill effluent + G2 sps @ 7.5 %)

The stress-reducing effects of seaweed extracts are further supported by measurements of fresh and dry weight. Treatment T4 (10 % papermill effluent + G2 sp. @ 2.5 %) demonstrated improved biomass accumulation and stress tolerance, with the highest fresh weight (2.01 ± 0.01 g) and dry weight (0.282 ± 0.01 g). Compared to treatments with concentrated effluent (10 % and 100 %), the combinations of paperboard effluent and seaweed extracts (especially T4 and T5) showed considerably higher seed vigor index (SVI) values (27.07 ± 0.24 and 26.88 ± 0.30 respectively) which are strongly correlated with other growth parameters.

The overall findings indicate that seaweed extracts, particularly G2 (*G. edulis*) can effectively reduce abiotic stress in maize plants exposed to papermill effluent at concentrations ranging from 2.5 to 7.5 %. Improved hydration retention, enhanced nutrient uptake and the activation of stress tolerance pathways are likely involved in this response. The study shows that adding seaweed extracts at the right amounts to properly diluted industrial effluents can improve maize plant growth and development while also reducing stress. This process has significant implications for sustainable agriculture, especially in regions where agricultural plants are subjected to abiotic stressors like salinity and drought. The study provides a viable strategy for boosting crop resilience and yield under stressful situations using natural biostimulants for crop growth and development.

Conclusion

According to the study's findings, *Gracilaria gracilis* and *Gracilaria edulis* show significant potential as biostimulants in agriculture, especially when it comes to boosting crops' resistance to environmental stresses like heat, salinity and drought. These two red seaweed species differ in their physico-chemical characteristics, which may provide distinct advantages for plant development and soil health. *G. gracilis* exhibits increased mineral concentrations, particularly potassium and sodium and greater swelling capacity, which may improve plant osmotic management. Both species are rich in vital nutrients and bioactive compounds that enhance plant metabolism and resilience to stress. The function of phytohormones in stimulating plant growth and development is further supported by the presence of minerals like calcium and magnesium. The research suggests that incorporating these seaweeds to agricultural operations can improve overall soil health, microbial activity and nutrient availability. Therefore, using *G. gracilis* and *G. edulis* as organic fertilizers presents a sustainable strategy to reduce environmental stress and increase crop yields. Future research needs to examine the long-term impacts of these algae on different crop growth under abiotic stress.

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Authors' contributions

RR contributed to conceptualization, methodology, validation, formal analysis, data collection and interpretation, writing the original draft and concluding results and discussion of the article. JR contributed to correction of the article, validation, technical data analysis and finalizing the topic. DP and DV contributed to correction and validation of the article. CK and TK contributed to correction and editing of the article.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to declare.

Ethical issues: None

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