Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-025-02651-1

ORIGINAL PAPER

Effectiveness of Algae as a Low-Cost Alternative Input to Stimulate *Sesamum Indicum* L. Growth and Productivity for Sustainable Purposes

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Received: 7 January 2025 / Accepted: 28 July 2025
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Abstract

Purpose This study aimed to investigate how microalgae *Spirulina* (*Arthrospira*) *platensis* and macroalgae (*Padina pavonica*) were used as sources of bio-stimulants instead of chemical fertilizers. The principal goal is increasing various crop plant quality and productivity, particularly in sesame, while reducing environmental impacts.

Methods Both types of algal biomass were applied to *Sesamum indicum* L. plants either as a powder (3 g kg^{-1} of soil) or water extract (9 g of algae 720 mL^{-1} of tap water) during two developmental stages (the vegetative and productive stages).

Results In the vegetative experiment, the application of *S. platensis*, either powder or extract, had stimulative effects on all growth parameters and some metabolites in shoots and roots of sesame plants, while the application of *Padina* and *Spirulina* as a powder or extract induced the antioxidant concentrations. Tracking their effects until the productivity stage showed that the application of all treatments (powder or extract) to the soil improved the productive criteria, such as branch length, capsule numbers, and seed index. Also, similar responses were observed for the mineral composition of different plant parts.

Conclusion The biomass of algae can be used as a biofertilizer in addition to being a source of nutrition to increase crop production to solve the problems of famine in poor countries. FT-IR analysis was used to qualitatively predict the most important chemical components of *P. pavonica* and *S. platensis* as a powder and aqueous extract, which exhibited several active groups that make them effective as bio-stimulants for the sesame plant.

Keywords Bio-stimulants · *Spirulina platensis* · *Padina pavonica* · *Sesamum indicum* L. · Antioxidants · Yield traits

1 Introduction

Green revolution practices should be used to increase agricultural productivity and reduce the risks of using chemical fertilizers, with the goal of producing healthy crops and products that are safe for human, animal, and environmental health. Farmers in developed countries have begun to adopt modern agricultural methods and techniques to combat pests and insects, replacing traditional methods based on chemical fertilizers and pesticides. This approach relies on organic farming or alternative sustainable agriculture (Bhatia 2008; Li et al. 2024).

Bio-stimulants are organic materials, and their application in small quantities enhances plant growth and development; this response cannot be achieved using chemical fertilizers or conventional plant nutrients (El-Shazoly et al. 2024; Rajesaheb et al. 2025). Bio-stimulants activate cellular adaptive responses and enrich the soil with mineral elements (Baltazar et al. 2021). Therefore, bio-stimulants are an alternative or complement to conventional chemical fertilizers and pesticides. In addition to enhancing plant tolerance to abiotic stress and improving productivity, they are also cost-effective for farmers while mitigating environmental challenges (Nephali et al. 2020; Del Buono 2021).

Bio-stimulants are currently being utilized as a part of a sustainable and successful plan to address the urgent need for bioactive alternative products, non-toxic effects on non-target organisms, their suitability for human health as mentioned above, their economic feasibility, and to address the challenges of chemical stimulants (Kocira et al. 2020;

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Published online: 11 August 2025

Pahalvi et al. 2021; Lau et al. 2022). The organic components of bio-stimulants consist of peptides, free amino acids, hormones, phenolic compounds, saccharides, humic compounds, and protein hydrolysates, which are obtained from marine algae or microorganisms (Abou Chehade et al. 2018; Kocira et al. 2019; Distefano et al. 2022).

Macroalgal and microalgal extracts have been utilized as agricultural bio-stimulants (ABs) (EBIC 2012; Colla and Rouphael 2020; Kaleb et al. 2023). Using ABs on crop plants can provide various benefits, such as improved root growth, increased crop and fruit yields, enhanced photosynthesis, and protection against fungi, bacteria, and viruses (Sharma et al. 2014; Goñi et al. 2018; do Rosário Rosa et al. 2021; Łangowski et al. 2022).

Many previous studies have indicated that micro- and macro-algae extracts contain many active compounds, nutrients, amino acids, vitamins, hormones, trace elements, enzymes, and growth-promoting compounds. Consequently, they can be applied to soil as growth promoters to improve the physiological functions of the crop and increase their efficiency (Chiaiese et al. 2018; Ashour et al. 2020; Ma et al. 2022). To meet the increasing demand for alternatives to chemical fertilizers and since the availability of bio-stimulants from one or two sources is no longer sufficient, several viable options need to be explored (Chhaya 1997), and the use of extracts from macroalgae and microalgae as biostimulants or fertilizers is one such great option (Prisa and Spagnuolo 2023; Singh et al. 2025). Unlike chemical fertilizers, seaweed-derived fertilizers (*Padina*, *Fucus*, *Laminaria*, *Ascophyllum*, *Sargassum*, etc.) offer superior benefits as they are biodegradable, non-polluting, and non-toxic to humans, animals, and birds (Dhargalkar and Pereira 2005; Murugesan et al. 2025).

Seaweeds and their products have various agricultural benefits, such as improving seed germination, boosting plant productivity, enhancing stress tolerance, and increasing resistance to pests and diseases (Chanthini et al. 2024). Seaweed products support the plant with all the main nutrients and organic compounds (carbohydrates, amino acids, and vitamins) and trace elements in addition to stimulating anti-growth substances for bacteria or fungi that cause plant diseases (Hassan et al. 2023). The annual production of seaweed is 15 million metric tons (FAO 2006). A considerable percentage of this production is used for bio-stimulants or biofertilizers as plant nutrient supplements to increase their growth and yield. Seaweeds have been successfully used for the preparation of composts, apart from the method of application directly to the soil or extracts either fresh or dried and chopped (Sultana et al. 2011).

Microalgae have fewer agricultural applications compared to macroalgae. The nitrogen-fixing ability of cyanobacteria (blue-green algae) is well-known (~20–30 kg N ha^{-1}), and they are advantageous to many crops, particularly rice fields (Chakdar et al. 2012). Applying gained microalgal biomass to the soil serves as a slow-release biofertilizer and soil conditioner (Dasgan et al. 2010; Garcia-Gonzalez and Sommerfeld 2016). As a fertilizer, *Spirulina platensis* was employed to boost the bio-fortification of red spinach with proteins, carbohydrates, micro- and macronutrients, and vitamin A (Mala et al. 2017). When *Spirulina sp*. is added to the soil, cultivated plants are protected from micro and macronutrient malnourishment (Bhowmik et al. 2010).

Padina pavonica is a brown algae (Phaeophyceae) found worldwide and abundant along the Mediterranean and Atlantic coasts (Gil-Díaz et al. 2014). *P. pavonica* extracts have revealed several biological activities as antimicrobial (Hlila et al. 2017; Al-Enazi et al. 2018), antitumor (Stanojković et al. 2013), anti-osteoporotic (Minetti et al. 2019), anti-inflammatory (Abdelhamid et al. 2018), and anti-acanthamoeba (Abdel-Hakeem et al. 2024).

A traditional oil crop, sesame (*Sesamum indicum* L.), has been grown for many years in tropical and subtropical areas (Bedigian and Harlan 1986). Because of artificial planting and harvesting, developing nations currently account for the majority of sesame production (Andargie et al. 2021). Sesame seeds are a great way to improve human health and have several beneficial effects. These benefits include oil, proteins, fatty acids, vitamins, and minerals (Pathak et al. 2014; Baghery et al. 2023). According to Thanvanathan et al. (2001), the seeds are a great source of minerals (5–7%), sugar (14–16%), and protein (20–28%). Tocopherols, tocotrienols, and lignans in sesame oil, on the other hand, have antioxidative properties that reduce cholesterol and prevent high blood pressure in people (Senila et al. 2020). Given sesame's widespread use in a variety of industries, such as food, medicine, cosmetics, and biodiesel, its significance and importance are increasing (Mahajan and Sadana 2025). Sesame is regarded as a high-yielding, productive plant in desert soil (Bedawy and Moharam 2018). Egypt is the eighth largest producer of sesame globally, with a cultivated area of approximately 34,000 ha. The average yield is 1.29 tons per ha, resulting in a total production of 44,000 tons (FAO 2019, 2020).

Nevertheless, to our knowledge, no investigation has shown the potential of *P. pavonica* and *Spirulina platensis* as bio-stimulants for *Sesamum indicum*, either as aqueous extract or biomass (powder) as a bioagent to promote plant growth and tolerance against abiotic stress. Given the diverse composition and physicochemical properties of bioactive substances, which play a major role in determining the action of biostimulants and which are still under investigation, there is still an urgent need to enhance the bio-stimulants and commercial potential of macro- and/or microalgae extracts, especially in recent times. This study aimed to

determine how *Padina pavonica* and *Spirulina platensis* as bio-stimulants affect the physiological processes of sesame plants under New Valley (Egypt) soil conditions, in addition to plant growth, nutrient use efficiency and plant quality traits towards maintaining higher yields while minimizing environmental impact.

2 Materials and Methods

2.1 Plant Material and Soil Properties

Sesame (*Sesamum indicum* L.) cultivar Shandawil 3, commonly cultivated in New Valley, Egypt, was sown in the greenhouse. Air-dried soil from El-Kharja Oasis, land was placed in one-kilogram and three-kilogram plastic pots enclosed with polyethylene bags. Table 1 displays the physical and chemical characteristics of the used soil.

2.2 Preparation and Application of *Spirulina Platensis* to Soils

The cyanobacterial species *Spirulina platensis* used in this investigation was isolated from EL-Kharja Oasis, and Prescott (1978) was used in identification. A standard growth condition was used to grow *Spirulina* in Zarrock medium at pH 8.3 and a temperature of 30 °C with a constant illumination of 48.4 µmol m^{-2} s^{-1}. The algal biomass was obtained by centrifugation at 6000 rpm for 15 min, then dried, ground into fine powder, and added to the soil, which was sown with sesame seeds (3 g kg^{-1} of soil). To prepare the extract, *S. platensis* powder is mixed well with high-purity water while stirring for an hour and left overnight on the shaker to prepare the fertilizing solution (Kumar and Sahoo 2011). On the day of planting, the solution was supplemented to the soil at a rate of 3 g L^{-1} per pot.

Table 1 Physicochemical properties of the experimental soil

Parameters	Value
EC electrical conductivity dS m^{-1}	1.23
pH	8.65
SP% saturation percentage	42.00
FC% field capacity percentage	22.75
$CaCO_3$%	0.65
OM % organic matter percentage	0.85
CO_3+HCO_3	5.60
Cl	4.30
SO_4	2.13
Ca	3.40
Mg	2.43

2.2.1 Fourier Transform Infrared (FT-IR)

The oven-dried sample (~100 µg) was prepared to identical thickness pellets using potassium bromide (KBr). Infrared transmittance data were measured using Nicolet IS 10 FT-IR wave numbers ranging from 4000−400 cm^{-1}. The sample was analyzed with plain KBr pellet as a blank and the data were compared with a reference to identify the functional groups in the sample.

2.3 Preparing and Applying *Padina pavonica* to the Soils

Padina pavonica (*P. pavonica*) was collected by hand from the Red Sea coast between latitude 27°17′13″N and longitude 33°46′21″E in the summer of 2022. The morphological trait of the macroalga was observed and compared to taxonomic references following the descriptions provided by previous studies (Benita et al. 2018). The samples were washed to remove all unwanted impurities such as adhering sand particles and epiphytes. The biomass was dried in the shade to prevent thermal degradation or photodegradation. The dried *Padina* biomass was ground to a fine powder by the grinder. Even adding it to the soil as a powder at a rate of 3 g kg^{-1} soilor making an aqueous extract from it, as was indicated in the preparation of *Spirulina* extract.

The extraction was prepared using the aforementioned crushed algal biomass of *Padina pavonica* or *Spirulina platensis* at a rate of 9 g of algae to 720 mL of tap water, mixed well and left overnight on the shaker (Kumar and Sahoo 2011). Then, the extracts were filtered and used for irrigation on the first day of planting. Irrigation: Regular tap water was used to maintain the soil field capacity until the end of the experiment.

2.4 Growth Conditions and Experimental Design

The present experiment was conducted in the greenhouse of the Botany and Microbiology Department, Faculty of Science, New Valley University, El-Kharja, New Valley, Egypt. Sesame seeds (*Sesamum indicum* L.) were planted in pots at a rate of 20 seeds/pot. After germination, the seeds were thinned to 7 seedlings in each pot. Seedlings were selected on a quite homogeneous basis.

The experimental treatment consisted of growing plants in five groups. The first group included growth under standard conditions without any soil additives as a control (the control group included pots irrigated with tap water only). The second and third groups were grown by adding *Padina pavonica* powder or its extract, respectively, while the fourth and fifth groups of treatments were *S. platensis* powder or

its extract. The experiment treatments were repeated in three replications.

2.5 Harvesting Plant Growth and Yield

2.5.1 Vegetative Experiment

At the end of the experimental period (30 days), the plants were harvested. For fresh weight (FW) determination, the shoots and roots were quickly weighed separately and, at -80 °C, immediately stored for physiological analysis to determine plant dry weight (DW). An additional fraction of fresh plants was dried in the oven at 70 °C for 48 h. Plant growth parameters were recorded, such as root length and shoot height.

2.5.1.1 Photosynthetic Pigments Chlorophylls (Chl *a* and Chl *b*) as well as carotenoid (Carot.) contents were detected in fresh *Sesamum indicum* leaves using a spectrophotometer; their concentrations were assessed following the Lichthenthale (1987) method. A particular fresh leaf sample (0.05 g) was treated with 5 mL of 95% ethyl alcohol at 60 °C until the photosynthetic pigments were extracted, leaving the leaf sample colorless. A spectrophotometer was used to detect the absorbance measurements. Using the following equations, the concentrations of carotenoids and chlorophylls were determined as mg g^{-1} FW at 663, 644, and 452 nm:

$$Chl\ a = (13.36 * A_{663}) - (5.19 * A_{644})$$

$$Chl\ b = (27.49 * A_{664}) - (8.12 * A_{663})$$

$$Carot. = ((1000 * A_{452}) - (213 * Chl\ a) - (97.6 * Chl\ b)$$

2.5.1.2 Preparation of Plant Extract Fresh shoot and root samples were ground with 5 mL of 50 mM Tris HCl buffer solution (pH 7), containing 3 mM $MgCl_2$ and 1 mM sodium EDTA in a chilled mortar and pestle. After centrifuging the extract for 10 min at 5000 rpm at 4 °C, the resultant supernatant was used for assessing the primary metabolites, the total antioxidants, and enzyme activity according to Padmaja et al. (2011).

2.5.1.3 The Primary Metabolites and Total Antioxidant Activity Total Proteins Total protein contents were determined in the plant extract by Folin reagent according to Lowry et al. (1951). Tissue powder samples (50 mg) were homogenised in 5 mL of 1 N NaOH in a water bath for 30 min. They were then filtered and completed to a certain volume by distilled water. Five mL of the alkaline reagent solution was added to one mL of the plant extract, then mixed and allowed to stand at room temperature for 10 min. Then, 0.5 mL of diluted Folin Ciocalteau's reagent (1:2 v/v) was added and mixed rapidly. After 30 min the extinction against the appropriate blank was determined at 750 nm. Using egg albumin as a calibration curve, one was developed, and the results were expressed as mg protein g^{-1} DW.

Free Amino Acids The free amino acid content in the crude extract was estimated according to the method of Moore and Stein (1948). For two hours, 50 mg of dry tissue samples were boiled in 5 mL of distilled water. After a 20-minute incubation in a boiling water bath, the absorbance at 570 nm was recorded using a spectrophotometer after 0.2 mL of enzyme extract and 1 mL of stannous chloride were added. Traces of proline and hydroxyproline were found using this approach, though. Using glycine, a calibration curve was produced. The free amino acid concentration was expressed as mg g^{-1} FW.

Total Antioxidant Activity (DPPH) DPPH (2,2-diphenyl-1-picrylhydrazyl) stable free radical scavenging activity was determined by the method of Blois (1958). Ascorbic acid and BHT (Butylated Hydroxytoluene) were used as the reference materials.

The extracts and BHT were obtained in separate test tubes at varying concentrations (25, 50, and 100 µL, or 25, 50, and 100 µg, respectively). The addition of MeOH brought the volume to 100 µL. These tubes received five millilitres of a 0.1 mM DPPH methanol solution, which was then forcefully shaken. The tubes were left for twenty minutes at 27 °C. The control was made in the same way but without MeOH or extract. The produced samples' variations in absorbance were measured at 517 nm. The inhibition percentage of radical scavenging activity was measured using the following formula:

$$I = (Abs.\ control - Abs.\ sample)/Abs.\ control \times 100$$

Vitamin E (α-tocopherol) α-tocopherol content in the crude extract of petroleum ether was determined by the method of Pearson (1976) with some modifications. The plant sample was extracted with 10 mL of petroleum ether and concentrated to dryness. The residue was saponified with 5 mL of 0.1 M potassium hydroxide. Ten mL of petroleum ether was used to extract the unsaponified matter and concentrate it to dryness. 10 mL ethanol was added to dissolve the residue. one mL was transferred into three test tubes, one mL of 0.2% ferric chloride in ethanol and 1 mL of 0.5% α-dipyridyl in ethanol were added, and the solution was made up to 5 mL

with ethanol. The absorbance was read at 520 nm using a spectrophotometer and expressed as mg g FW.

2.6 Reproductive Experiment

2.6.1 Seed Yields and their Components

At the end of the experimental period (80 days), plant growth parameters, such as plant height, branch height and yield indexes such as branch number, capsule number, capsule height, seed capsule, and seed index were used. Mineral compositions and total lipid concentrations were assayed in shoots, roots, and the obtained seeds.

2.6.2 Mineral Compositions

The extracts of plant tissues (shoots, roots, and seeds) were prepared using the mixed acid digestion process as stated by Allen et al. (1974). The mixture (60% $HClO_4$, 60% HNO_3, and 60% H_2SO_4) is in a 1:3:1 ratio. After digesting powdered dry plant tissue on a hot plate, which was completed as indicated by white vapours, the sample became colourless, and the volume was completed to a known volume with distilled water. The acid-digested sample was analyzed for Ca, Mg, Fe, Zn, Mn, and Se using atomic absorption spectrophotometry (Buck model 210 Vgp, USA). The data were expressed as mg g^{-1} DW.

2.6.3 Total Lipids

An assay of lipid content in plant tissues (shoots, roots, and seeds) was carried out as described by Van Handel (1985), taking into consideration the modification suggested by Inouye and Lotufo (2006). After preparing the samples and standards in triplicate and allowing the solvent to evaporate in a heating block set at 100 °C, 0.1 mL of concentrated sulfuric acid was added to each sample, ensuring to deposit the acid at the tube's bottom. The samples were vortexed and heated for 10 min at 100 °C. After removing the samples from the heating block set, they were allowed to cool at ambient temperature before being vortexed with 2.4 mL of vanillin reagent (600 milligrams of vanillin, 100 mL of hot water, and 400 mL of 85% phosphoric acid). The pink colour was allowed to develop for 5 min, and samples were read at 490 nm using a spectrophotometer. At this stage, standard curve samples have been made by vortexing tubes with various soybean oil concentrations.

2.7 Statistical Analysis

Simple completely randomized (SCR) experiments were used. In six pots, each treatment was replicated. Data from three replicates in two different studies were subjected to a one-way ANOVA. Data expressions include mean ± SE. The IBM SPSS 22 and RStudio software packages were used for the analysis. If there were significant discrepancies between the means, Tukey's HSD test was employed at $p \leq 0.05$. Principal Component Analysis (PCA) variance regression ordination was used to analyse all the recorded parameters. RStudio and ggplot packages, integrated into the R software, were used to generate the scatter plot and heatmap, visualizations of corrplot.

3 Results

3.1 Fourier Transform Infrared (FT-IR)

FT-IR analysis was used to qualitatively predict the most important chemical components of *P. pavonica* and *S. platensis* as a powder and aqueous extract (Fig. 1A-D). The infrared spectrum exhibited peaks in the frequency range of 3500–3300 cm^{-1}, which indicates the existence of N-H stretching vibrations in secondary amines (protein, lipid). All samples of both algae exhibited aliphatic C-H stretching vibrations of alkane, which are represented by the frequency ranges between 2925 and 2875 cm^{-1} peak. The N-H bending vibration of the carbonyl β-unsaturated ketone amide, which was seen in all samples of both algae, had the following peaks: 1650–1580 cm^{-1}. The CH_2 bending vibration of halogen compounds (C-Cl) and iodine compounds (C-I) observed in the powder and aqueous extract of *P. pavonica* and *S. platensis* had a peak frequency range of 1435–1405 cm^{-1}. The particular frequency ranges from 1120 to 1030 cm^{-1} present in symmetric C-H stretching. The presence of antioxidant enzymes appeared in all samples of both algae, and only the aqueous extract of *P. pavonica* exhibited the peak value representing 1050–1010 cm^{-1}, exhibited characteristic bands for acids, RSO_3, and ionic sulphonates such as SO_3 symmetric stretching vibration. In samples of powder and aqueous extract of *P. pavonica* and *S. platensis*, the S-O stretching vibration of sulphonic components was represented by peaks with a frequency range of 700–620 cm^{-1}. In samples of powder and aqueous extract of *P. pavonica* and powder of *S. platensis*, the frequency ranges from 620 to 490 cm^{-1} and presents in C-N, C-O, or C-H bonds, inorganic compounds, usually quinoline- or pyridine-based molecules.

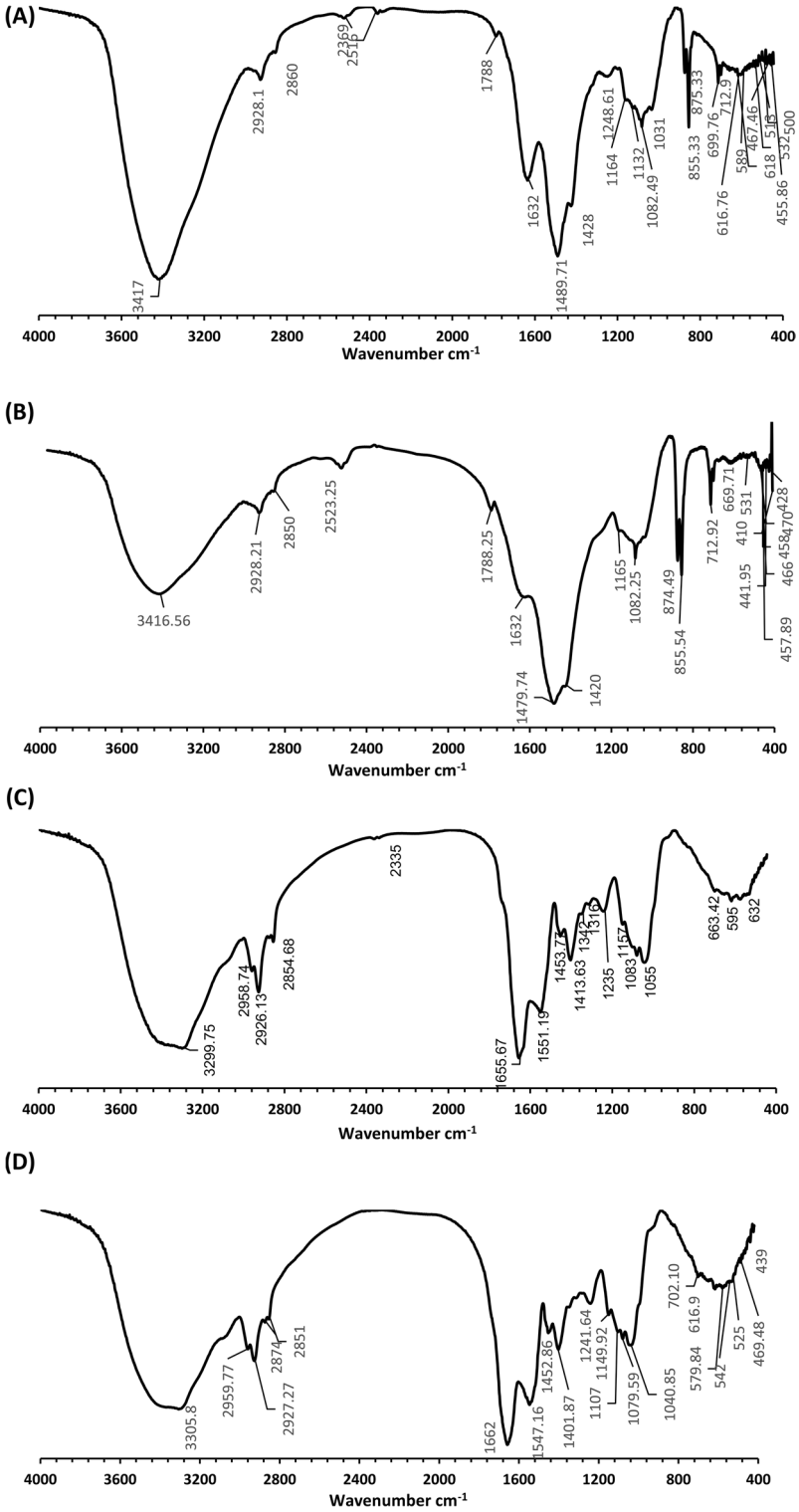

Fig. 1 FT-IR spectra of (**A**) aqueous extract of *Padina pavonica*, (**B**) powder of *Padina pavonica*, (**C**) aqueous extract of *Spirulina platensis*, and (**D**) powder of *Spirulina platensis*

3.2 Vegetative Experiment

3.2.1 Plant Growth and Photosynthetic Pigments

In general, treatments that included the addition of either *Spirulina* or *Padina sp*. in the form of powder (3 g kg^{-1} soil or extract) stimulated *Sesamum indicum* plant growth, represented by increases in plant length of shoot and root and both dry and fresh weights, as shown in Table 2. Priming and treating the sesame plants with the two algae under study, whether in the form of an extract or by mixing the soil with the dry material (3 g kg^{-1} soil), led to a significant

Table 2 Effect of *Spirulina platensis* and *Padina pavonica* application as biostimulants on the photosynthetic pigments (Chl.*a*: chlorophyll a; Chl.*b*: chlorophyll b; and Carot.: carotenoids), growth (FW: fresh weight; DW: dry weight; length), and yield attributes of Sesame plant. The data are given as averages of three replicates ± standard error. The different letters, small for shoot and capital for root, indicate significantly different (one-way ANOVA; Tukey HSD post hoc) at $p \leq 0.05$

Growth stage	Treatme\Paramet		Cont.	*P. pavonica*		*S. platensis*	
				Extract	Powder	Extract	Powder
Vegetative growth	Photosynthetic pigments (mg g^{-1} FW)	Chl. *a*	0.76 ± 0.11^{c}	1.9 ± 0.04^{b}	2.01 ± 0.27^{ab}	2.15 ± 0.38^{b}	2.3 ± 0.23^{a}
		Chl. *b*	0.91 ± 0.09^{A}	1.01 ± 0.42^{A}	0.89 ± 0.07^{A}	0.92 ± 0.33^{A}	1.38 ± 0.16^{A}
		Carot.	0.27 ± 0.01^{d}	1.06 ± 0.02^{ab}	0.85 ± 0.02^{bc}	1.5 ± 0.13^{a}	1.1 ± 0.006^{c}
	Length (cm)	Shoot	9 ± 0.30^{d}	11.2 ± 0.4^{cd}	10.3 ± 0.2^{bc}	12.8 ± 0.2^{a}	12.5 ± 0.3^{ab}
		Root	12 ± 0.80^{C}	13 ± 0.70^{BC}	13 ± 0.8^{BC}	15 ± 0.7^{AB}	17 ± 0.6^{A}
	FW (mg $Plant^{-1}$)	Shoot	0.12 ± 0.004^{c}	0.12 ± 0.002^{c}	0.15 ± 0.006^{bc}	0.17 ± 0.009^{b}	0.2 ± 0.07^{a}
		Root	0.09 ± 0.008^{C}	0.13 ± 0.007^{B}	0.13 ± 0.0003^{B}	0.15 ± 0.002^{AB}	0.17 ± 0.009^{A}
	DW (mg $Plant^{-1}$)	Shoot	0.01 ± 0.009^{c}	0.02 ± 0.001^{bc}	0.01 ± 0.0001^{c}	0.02 ± 0.001^{a}	0.02 ± 0.001^{ab}
		Root	0.01 ± 0.001^{D}	0.02 ± 0.001^{BC}	0.01 ± 0.0001^{CD}	0.02 ± 0.00^{B}	0.03 ± 0.001^{A}
Reproductive growth	Length (cm)	Plants	76.1 ± 2.90^{c}	108 ± 1.4^{b}	108.3 ± 1.70^{b}	122.3 ± 1.70^{a}	1.9 ± 3.0^{b}
		Branches	8.2 ± 0.40^{c}	12 ± 0.60^{bc}	11.5 ± 0.70^{bc}	17.3 ± 1.00^{a}	13.7 ± 1.3^{ab}
		Capsules	1.7 ± 0.20^{c}	2.7 ± 0.17^{b}	3.2 ± 0.10^{ab}	3.1 ± 0.10^{ab}	3.7 ± 0.2^{a}
	Numbers	Branches	28.7 ± 0.7^{a}	31.3 ± 2.4^{a}	32.7 ± 2.4^{a}	36.7 ± 0.7^{a}	38.7 ± 4.0^{a}
		Capsules	13 ± 1.5^{c}	25 ± 0.6^{b}	15 ± 1.7^{c}	27 ± 2^{b}	38 ± 0.6^{a}
		Seeds	39 ± 0.6^{d}	53 ± 1.7^{c}	43 ± 3.6^{d}	78 ± 0.9^{a}	67 ± 1.7^{b}
	g/1000 seeds	Seed index	6.7 ± 0.1^{d}	9.2 ± 0.2^{b}	7.4 ± 0.1^{c}	9.8 ± 0.05^{a}	8.8 ± 0.1^{b}

increase in both shoots and the length of roots, especially with *S. platensis* extract and powder increasing by 1.4 and 1.38 fold, respectively. Fertigation plants were verified compared with control plants. *Spirulina* was distinguished in improving the dry weight of sesame plants, recording a significant increase by 1.7- and 2.00-fold in fresh weight of shoot and root extract-treated plants, respectively, 1.6- and 2.7-fold in dry weight of shoot and root of powder *Spirulina*-treated plants respectively over its counterparts in treatments, whether the *Padina* was in the form of extract or powder compared to the control.

The recent investigation displayed that the application of *S. platensis* extract to the soil caused highly significant stimulation of both chlorophyll (Chl. *a*) and carotenoid concentrations in the leaves by 3.1 and 5.1 fold. High stimulation of Chl. *b* were recorded in plants grown with the addition of *S. platensis* powder; it exhibited 1.5-fold stimulation in leaves compared with control plants.

3.2.2 The Primary Metabolites and Total Antioxidant Activity

The effects of applying algal powder or extract as bio-stimulants on sesame primary metabolites (protein, amino acids, vitamin D and total antioxidants) are shown (Fig. 2A). Generally, treating the plant with *Padina* in both of its added forms did not cause a clear change in the concentrations of amino acids while applying *Spirulina* powder stimulated the concentrations of amino acids at a rate of 4.7 and 3.2 fold in the shoot and root respectively, compared to the control ones (Fig. 2A). On the other hand, protein analyses in treated sesame shoots did not show any significant differences in total protein concentration, except for plants treated with *Padina* powder, which recorded a decrease in total protein concentrations. It is worth noting that the addition of *Spirulina* extract to sesame plants caused a 2.8-fold increase in total proteins in roots when compared to control plants (Fig. 2B). The application of *Padina* and *Spirulina* as a powder or extract significantly stimulated the total antioxidant percentage in both the shoots and roots of sesame plants compared with control ones (Fig. 2C). In this investigation, the application of *Spirulina* powder to soil highly significantly elevated the concentrations of vitamin E in the shoots and roots of sesame plants by 1.6 and 3.6 folds, respectively, when compared with control ones (Fig. 2D).

3.3 Reproductive Experiment

3.3.1 Mineral Compositions

In general, all treatments used with plants are recommended to activate calcium concentrations in the different parts of the plant, whether roots, shoots, or seeds, especially *Sesamum indicum* plants enriched with *S. platensis* extract and powder, which induce highly significant calcium in the shoot by 1.6 and 1.5 folds, respectively, compared with control plants (Fig. 3A). It is worth noting that all the treatments used in both forms (extract and powder) led to the accumulation of magnesium in *Sesamum* seeds (the part used in human nutrition), and the highest percentages obtained

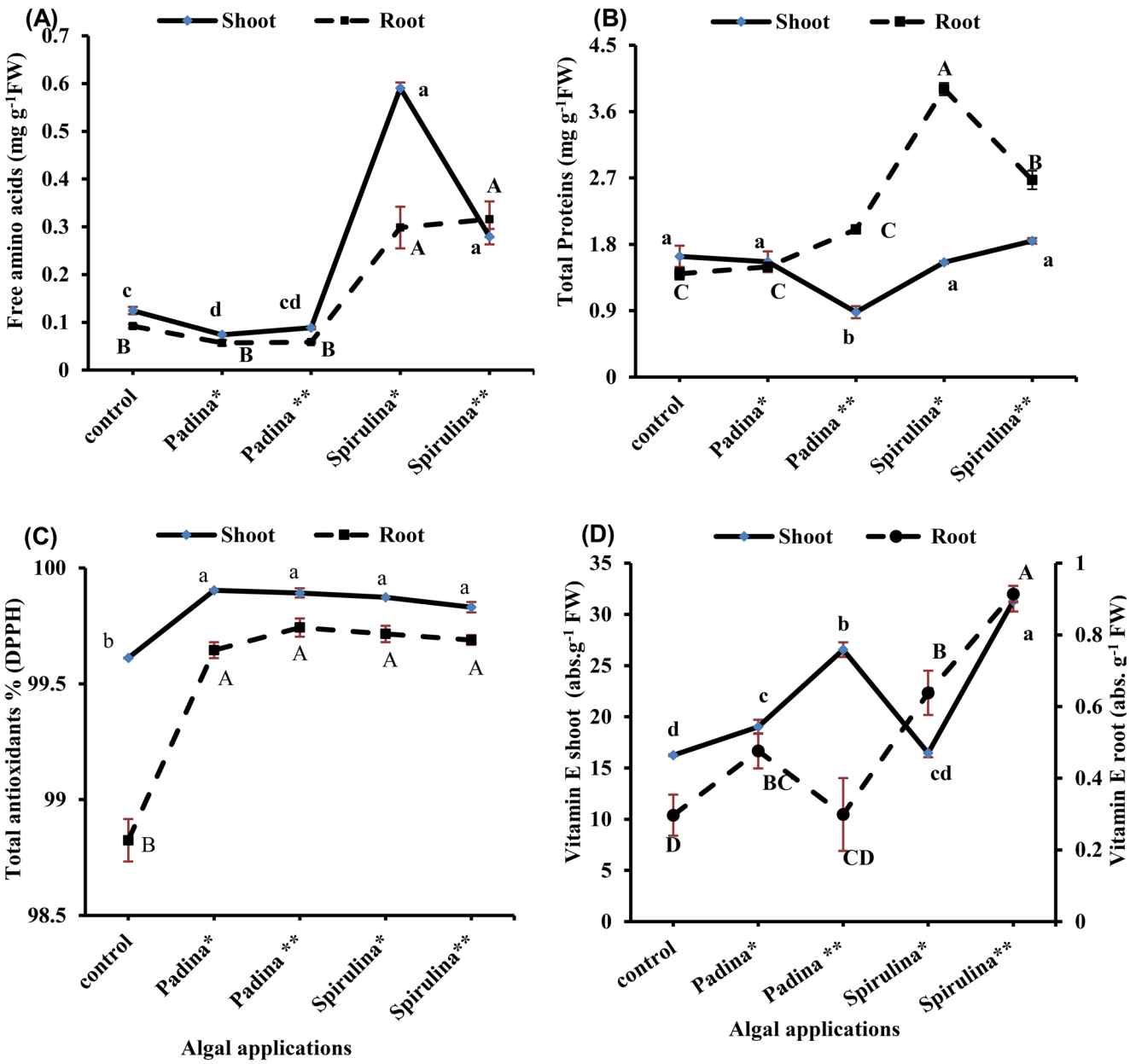

Fig. 2 Effects of in vitro applications of aqueous extract of *Padina pavonica* (*Padina**), powder of *Padina pavonica* (*Padina***), aqueous extract of *Spirulina platensis* (*Spirulina**), and powder of *Spirulina platensis* (*Spirulina***) on primary metabolites (**A**) Free amino acids, (**B**) total proteins, (**C**) total antioxidants (%), (**D**)vitamin E of shoot and root of *Sesamum indicum* seedling as bio-stimulants. The data are given as averages of three replicates ± standard error. The different letters, small for shoot and capital for root, indicate significant differences (one-way ANOVA; Tukey HSD post hoc) at $p \leq 0.05$

were in the plants treated with the addition of *Padina* as a powder or *Spirulina* extract (Fig. 3B). Data presented in Fig. 3C highlighted the significant increase in iron contents due to the stimulative effect of *Padina* extract and *Spirulina* powder application in sesame roots.

The data represented in Fig. 3D showed that application of either *Spirulina* or *P. pavonica* extracts to sesame plants induced manganese content in the shoot and root by 3.6-fold and by 1.3-fold, respectively, under the previously mentioned conditions. The same response to zinc accumulation was observed in the sesame seeds by 5.9- and 6.5-fold, respectively, when compared with control plants (Fig. 3E).

Given the importance of selenium when thinking about using sesame seeds as food material, the data from this study revealed that the highest significant increase in selenium concentrations was recorded in the seeds of *Sesamum* plants fortified with all treatments of the macro- or microalgae used (Fig. 3F).

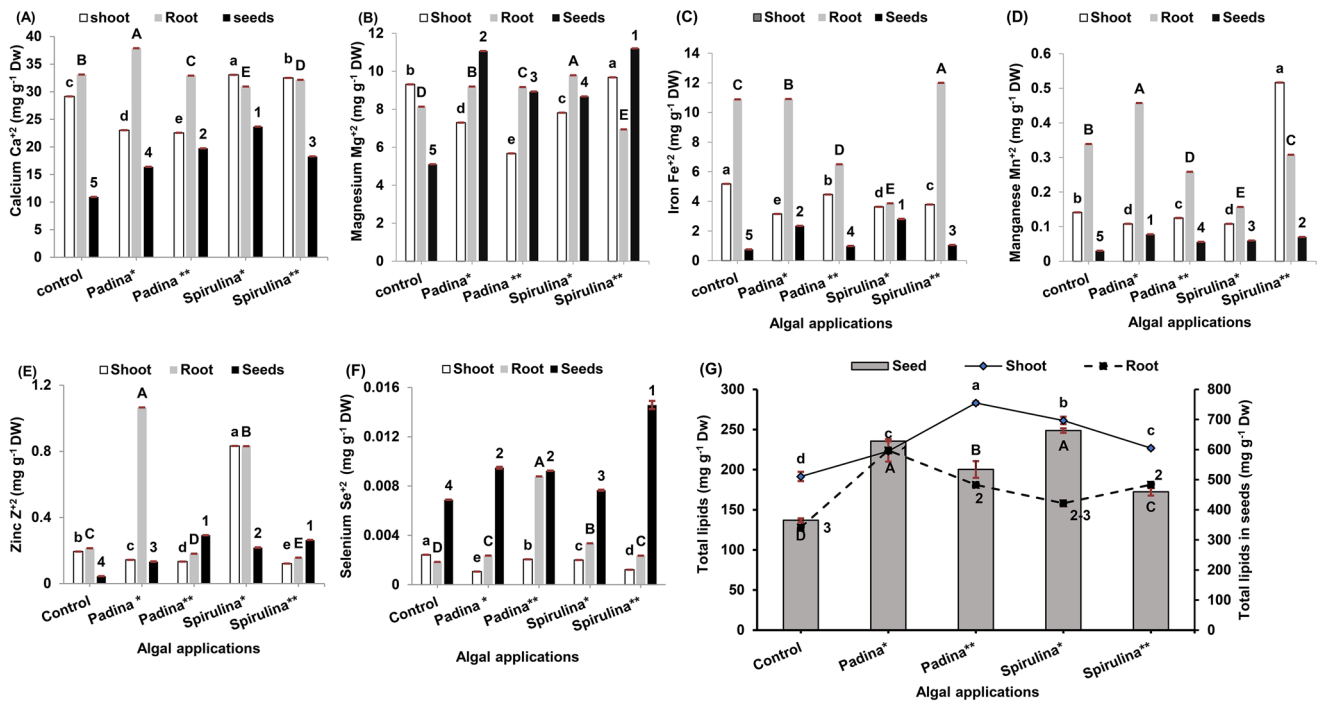

Fig. 3 Effects of in vitro applications of aqueous extract of *Padina pavonica* (*Padina**), powder of *Padina pavonica* (*Padina***), aqueous extract of *Spirulina platensis* (*Spirulina**), and powder of *Spirulina platensis* (*Spirulina***) on minerals component (**A**) Calcium (Ca^{+2}), (**B**) Magnesium (Mg^{+2}), (**C**) Iron (Fe^{+2}), (**D**) Manganese (Mn^{+2}), (**E**) Selenium (Se^{+2}), (**F**) Zinc (Zn^{+2}), and (**G**) total lipids of shoot, root, and seed of *Sesamum indicum* plants as bio-stimulants. The data are given as averages of three replicates ± standard error. The different letters, small for shoot, capital for root, and numbers for seed, indicate significant differences (one-way ANOVA; Tukey HSD post hoc) at $p \leq 0.05$

3.3.2 Total Lipids

In general, sesame seeds were observed to contain higher levels of total lipids than stems and roots. All treatments of the present study induced the accumulation of total lipids in sesame shoots more than in roots, and the highest value was recorded in shoots with the addition of *Padina* as powder compared to the control. Both applications of *Padina* and *Spirulina* extracts had a significant improvement in the concentration of total lipids in sesame seeds by 1.7 and 1.8 times when compared to the control plants (Fig. 3G).

The results of the recent experiment are shown in Table 2 and Fig. 4A-C. All algal applications significantly enhanced the length (plants, branches, and capsules), numbers (branches & capsules), and seed index of sesame. The highest values of length (plants and branches) were observed with the application of *Spirulina* extract by 1.5- and 2-fold, respectively. A similar stimulative effect was recorded with the application of *Spirulina* powder on the length of capsules by 2.2-fold when compared with control plants. Also, the application of *Spirulina* powder caused highly significant values of branches, capsule numbers, and seed index by 1.4, 2.9, and 2- folds, respectively

3.4 Principal Component Analysis, Hierarchical Clustering Pattern, and Correlation Analysis

The principal component analysis (PCA) was computed on the experimental dataset, including 43 physiological variables and 5 treatments, to enhance the discrimination power to group the measured traits based on relationships among treatments (with or without) biostimulant amendment. Since the first two PCs showed the highest percentage of variance, they were used to create a PCA-based biplot (Fig. 5). The subjection of all data of measured parameters to PCA shows clear results about all possible correlations (positive & negative) in all assessed parameters. The level of trend similarity is shown by the distances between the qualities on both axes. The biplot of PCA showed contrariness between all antioxidants, lipids, metabolites, growth and yield indicators (the right-hand half of the biplot Fig. 5) and element contents (selenium, iron, magnesium, and manganese) (the left-hand half of the biplot in Fig. 5). Axis 1 in the PCA biplot catches about 49.3% of the accumulated percentage, while the 2 axis captured about 19.9%.

The right-hand half of Fig. 5 was strongly affected by the following treatments: *Spirulina* biostimulant as an extract and powder. Meanwhile, the left-hand half was greatly affected by control and *Padina* powder as a biostimulant.

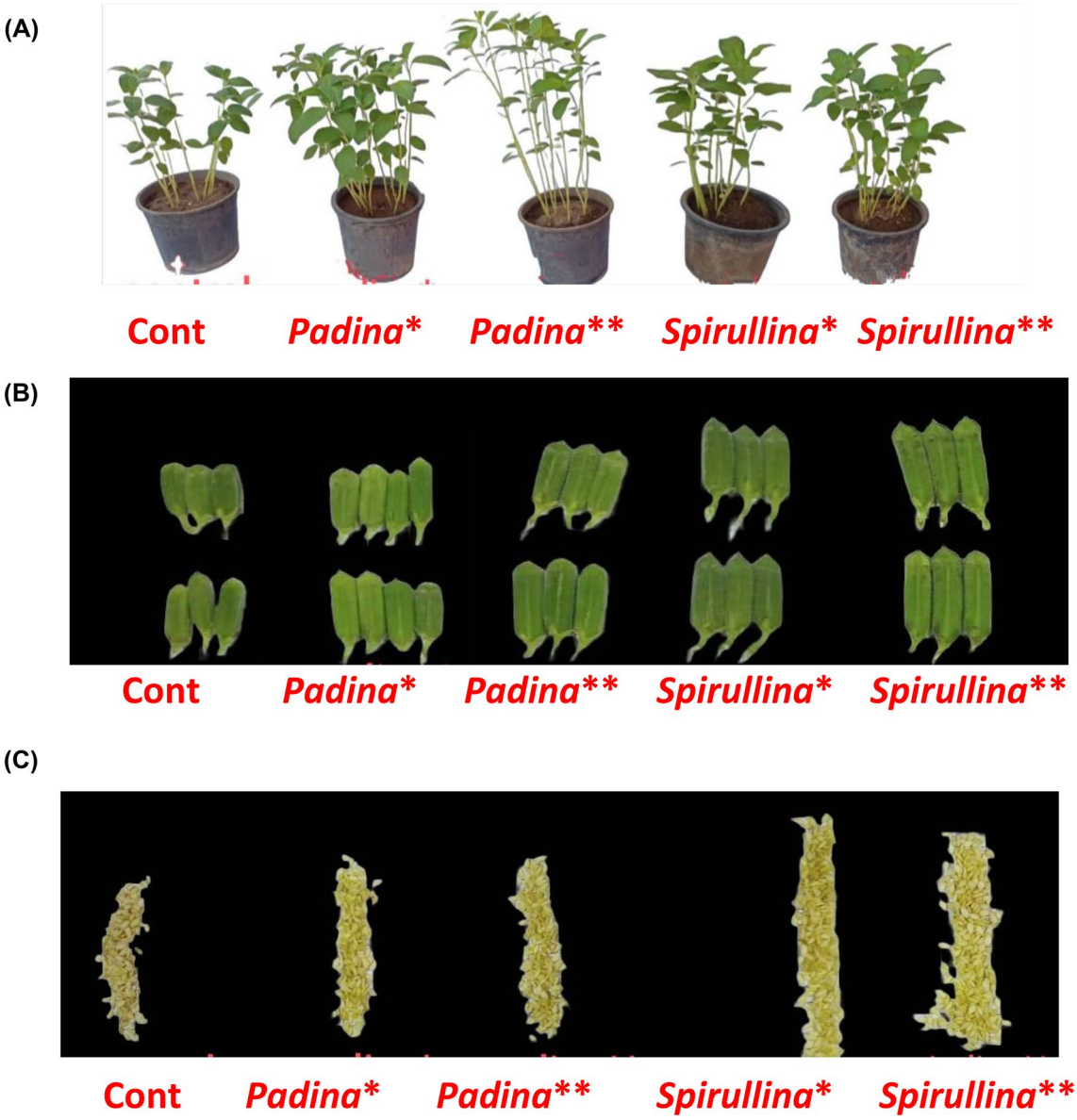

Fig. 4 Effects of applications of aqueous extract of *Padina pavonica* (*Padina**), *Padina pavonica* powder (*Padina***), aqueous extract of *Spirulina platensis* (*Spirulina**), and powder of *Spirulina platensis* (*Spirulina***) on yield attributes (**A**) growth, (**B**) capsules, and (**C**) seeds of *Sesamum indicum* at productivity stage as bio-stimulants

The correlation analysis plot is applied to determine the negative and positive correlations visually among multiple assessed traits under different treatments (Fig. 6). Negative correlations were observed between Fe in the shoot and Se in the shoot and root on one side and almost all growth parameters, yield, and antioxidants on the other. Positive correlations could be noticed among all these parameters, such as root vitamin E, root& shoot F.Wt., root & shoot D.Wt., root length, branch number, Cp number from one side and Mn in root, Ch.b, shoot vitamin E and Se in seeds, branch length, shoot length, and capsules seed number.

The two-sided dendrogram obtained from the cluster analysis showed that all investigated treatments and measured traits were grouped into different subclusters (Fig. 7). The heat map plot is used to determine complex associations between multiple parameters under different treatments. It is very useful to add hierarchical clustering to a heat map as an attempt to arrange items in a hierarchy according to similarity among them. Hierarchical clustering analysis and heatmap identified the significant differences among treatments on the left side and parameters on top (Fig. 7). Application of *Spirulina* and *Padina* biostimulants as extract or powder affected the response of all studied physiological, growth, and yield attributes (Fig. 7). It was noticed that attributes of growth clustered with total antioxidants and chlorophyll a&b. On the other hand, spirulina

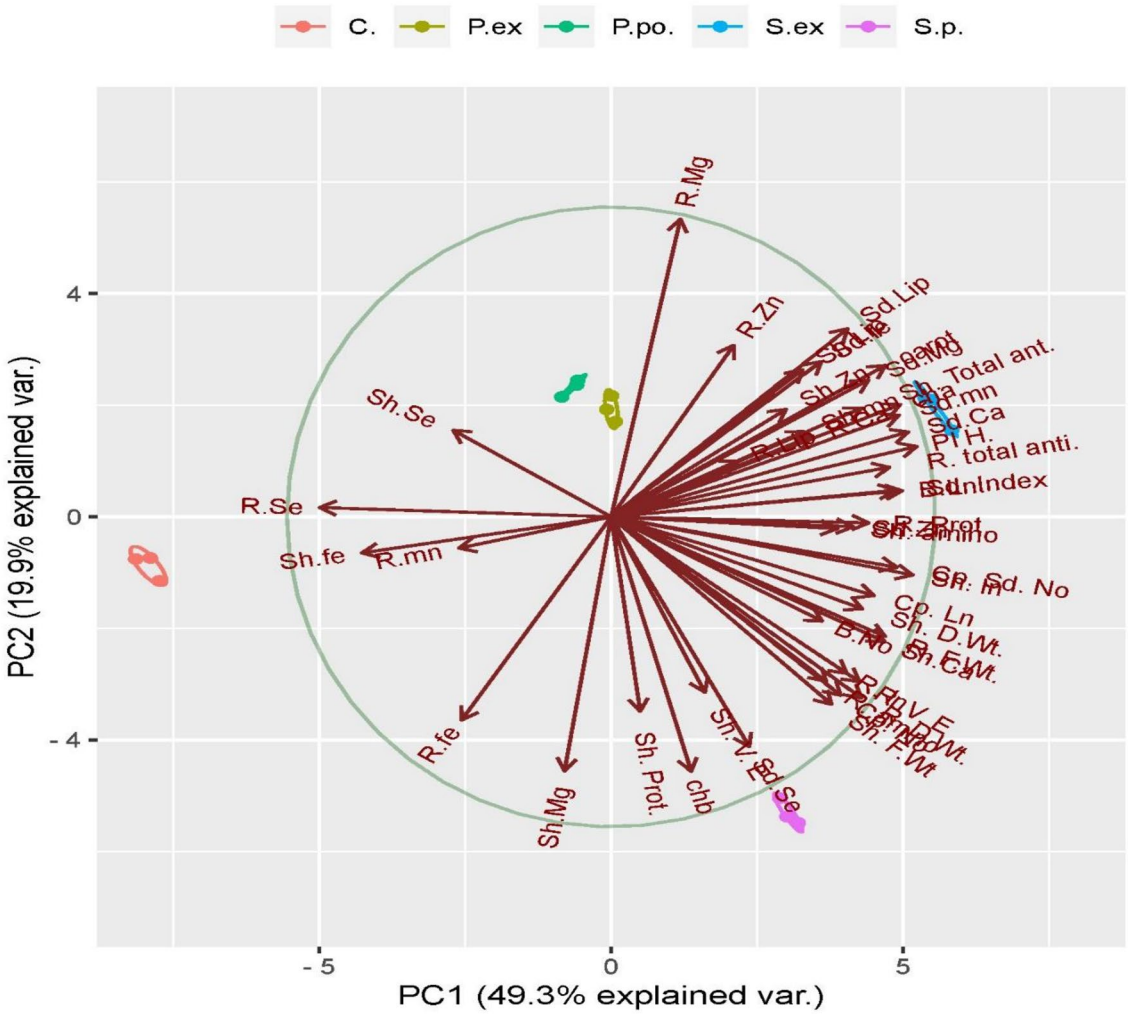

Fig. 5 Loading plot of different studied attributes under *Spirulina platensis* and *Padina pavonica* bio-stimulants correlations to the first two principal component analysis (PCA) axes. Horizontal and vertical arrows indicate the rise direction different treatments. C.=control, P.ex=*Padina* extract biostimulant, P.Po.= *Padina* powder bio-stimulant, S.ex.= *Spirulina* extract bio-stimulant, S.p.= *Spirulina* powder bio-stimulants. **Parameters**: Cha=chlorophyll a, chb=chlorophyll b, carot=carotenoids, Sh. Ln=shoot length, R. ln=root length, Sh. F.Wt=shoot fresh weight, R. F.Wt.=root fresh weight, Sh. D.Wt.=shoot dry weight, R. D.Wt.=root dry weight, Sh. Amino=shoot amino acids, R. amino=root amino acids, Sh. Prot.=shoot proteins, R. Prot.=root proteins, Sh. Total ant.=shoot total antioxidants, R. total anti.=root total antioxidants, Sh. V. E=shoot vitamin E, R. V. E=root vitamin E, Sh.Ca=shoot Calcium, Sh.fe=shoot iron, Sh.Mg=shoot magnesium, Sh.mn=shoot manganese, Sh.Se=shoot selenium, Sh.Zn=shoot zinc, R.Ca=root calcium, R.fe=root iron, R.Mg=root magnesium, R.mn=root manganese, R.Se=root selenium, R.Zn=root zinc, Sd.Ca=seed calcium, Sd.fe=seed iron, Sd.Mg=seed magnesium, Sd.mn=seed manganese, Sd.Se=seeed selenium, Sd.Zn=seed zinc, Pl H.= plant height, B.Ln.=branch length, B.No=branch numbers, Cp. No=capsule number, Cp. Ln=capsule length, Cp. Sd. No=capsule seed numbers, Sd. Index=seed index, Sh.Lip=shoot lipids, R.Lip=root lipids, Sd.Lip=seed lipids

extract positively correlated with all parameters clustered in subcluster b (shoot DW, shoot length, shoot amino acids, carotenoids, Zn, and Mn elements in the shoot as observed in the heat map.

4 Discussion

Sesamum indicum is the queen of oil seeds and is widespread in many parts of the world, although its original homeland is Africa, China, and India. *Sesamum* is used as a nutritional supplement, providing nutritious protein, and as a treatment for many diseases such as skin lesions, aging, oxidative stress, atherosclerosis, hypertension, and cataracts (Miraj and Kiani 2016; Fuji et al. 2018). Given the extreme benefits of sesame in food and oil, as mentioned above, it is

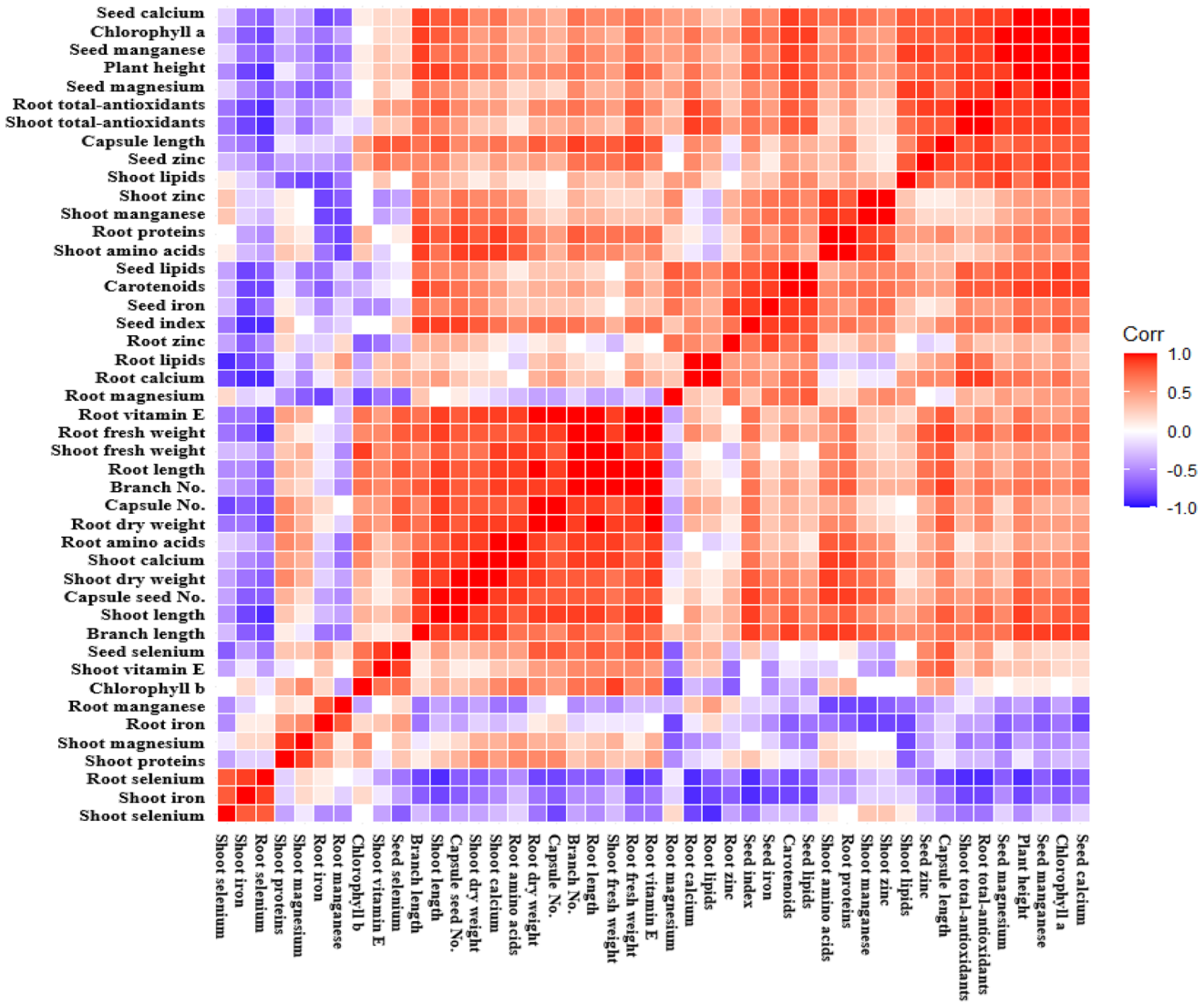

Fig. 6 Correlation matrix of the measured traits of the studied parameters in shoot, root, and seed of *Sesamum indicum* plants treated with *Spirulina platensis* and *Padina pavonica* (powder and water extracts) as bio-stimulants. The increasing colour intensities illustrate a higher correlation coefficient

important to search for new strategies to increase its production in line with the excessive increase in population and its increasing needs. In this regard, excessive use gives chemical fertilizers a bad reputation. The consequences of the overuse of chemicals are as follows: water contamination, acceleration of climate change, and increased acidity levels. To avoid these risks and for low costs and economic feasibility, we have resorted to using biological fertilizers by applying the microalgae (*Spirulina platensis*) and macroalgae (*Padina pavonica*) as bio-stimulants of sesame plants.

Applying fresh, dried, and chopped seaweeds or microalgae as a soil supplement or as fertilizers is one of the techniques used to enhance plant growth and their nutritional and thus economic values. Algae contain vitamins and macronutrients such as phosphorus, potassium, magnesium, calcium, and many other trace elements (boron and zinc) that are beneficial to plants (Prakash and Nikhil 2014; Uysal et al. 2015; Vasileva et al. 2016; Patel et al. 2021). Seaweeds affect crops by stimulating the growth of plants, seedlings, root hairs, and secondary roots. Moreover, they can enhance and incorporate nutrients, resist diseases and pests, and manage abiotic stresses such as salinity, drought, and temperature (Mukherjee and Patel 2020). They contain multiple growth-promoting substances such as cytokinins, auxins, gibberellins, and other macro- and micronutrients necessary for plant growth and development (Begum et al. 2018).

For the detection and identification of the main components of algal colloids, such as polysaccharides and proteins. Mishra and Jha (2009) confirmed that the vibration of the adjacent group and the number of substitutions occurring

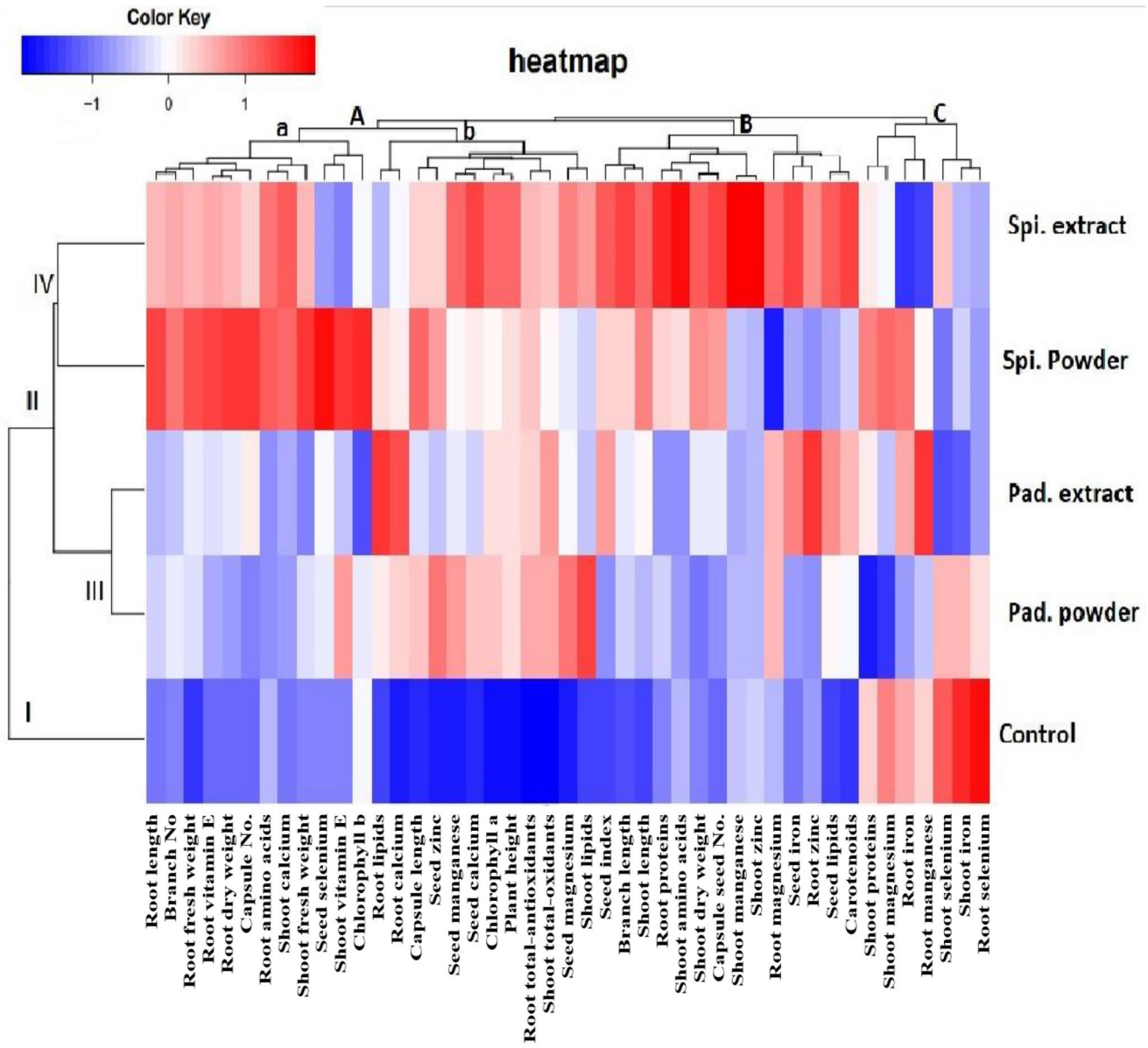

Fig. 7 Heatmap showing the saturation of colors indicating the effects of *Spirulina platensis* and *Padina pavonica* (powder and water extracts) on the studied parameters in *Sesamum indicum* plants as bio-stimulants

on the same molecule are typically related to differences in the vibrational stretching and bending patterns of individual functional groups. Applying this approach to the algal extract under study to identify individual functional groups confirmed that.

The obtained results are in line with earlier research on marine microalgae, which has looked into and identified more than 15,000 different components, such as fatty acids, sterols, phenolic compounds, terpenes, enzymes, polysaccharides, alkaloids, and flavonoids (Ahmed et al. 2024). Furthermore, it has been observed that marine algae contain antioxidant molecules that can scavenge free radicals (Viswanathan et al. 2014). In addition, fucoidans and alginates were the primary components found in water extracts from *P. pavonica* brown alga, according to an investigation into the biochemical composition of numerous Phaeophyceae (brown seaweeds) extracts (Mohamed and Borik 2013; Drira et al. 2021). Also, the previous study by Venkatesan et al. (2012) confirmed the current FT-IR analysis of freshwater algae *Spirulina* powder.

This investigation revealed that *Spirulina* or *Padina sp.* in the form of powder stimulated *Sesamum indicum* plant growth represented by increases in plant length of shoot and root and both dry and fresh weights. This is consistent with the results of Supraja et al. (2020) that the application of varied doses of microalgae mixture, mainly consisting

of *Spirulina sp.*, *Scenedesmus sp.*, *Synechocystis sp.*, and *Chlorella sp.*, led to a boost in the total biomass content of plants, shoot height, and root length in comparison with the control plants. Several previous studies have shown that seaweeds can be used as bio-organic and environmentally friendly fertilizers to enhance the growth of many economically valuable crops (Ansari et al. 2019). Likewise, Rayorath et al. (2008) reported the growth enhancement of the shoot and root of the model plant *Arabidopsis thaliana* by treatment with algal extracts.

These findings are in harmony with the obtained results of recent investigations declaring that the application of *S. platensis* extract to the soil caused highly significant stimulation of both Chl. *a* and carotenoid concentrations in the leaves. Also, the highest stimulation of Chl. *b* concentrations were recorded in plants grown with the addition of *S. platensis* powder in leaves compared with control plants. Earlier studies by Mukherjee and Patel (2020), Mutale-Joan et al. (2021), and Gitau et al. (2022) found that the chlorophyll content in plants increased significantly with early seaweed application linked with enhanced osmotic adjustment and PSII stability.

In the current investigation, applying *Spirulina* powder increased amino acid levels in sesame shoots and roots, while *Padina* powder reduced total protein concentrations. *Spirulina* extract boosted root protein levels, and both *Padina* and *Spirulina*, whether in powder or extract form, enhanced antioxidant percentages. Additionally, *Spirulina* powder significantly raised vitamin E concentrations in shoots and roots when compared to control plants.

These results are consistent with the findings of Chojnacka et al. (2015) and Fan et al. (2013), who demonstrated that applying a commercial algae-based extract to some plants increased total soluble proteins and amino acids, which were then strongly correlated with higher transcription levels of regulatory enzymes associated with nitrogen metabolism. Consequently, the nitrate content in the plant will drop and yields will rise. Also, Pei et al. (2024) concluded that crop yield increased by 15.17% with the application of seaweed as fertilizer. Quality indexes such as the contents of sugar, protein, and vitamin C increased.

Whereas the mechanism by which seaweed application induces plant stress tolerance is not well understood, research findings indicate that some bioactive substances coming from seaweed, such as cytokinins and betaines, are involved in stress management (Blunden et al. 1996; Zhang and Ervin 2004). It has been previously reported that seaweed extract (SWE) enhanced total antioxidant activity (TAA) in lettuce, cowpea, and pepper plants, which is attributed to the stimulation of antioxidant enzyme production in the host plant by SWE (Ashour et al. 2021). Furthermore, it has been observed that after applying seaweed extract, the plant's endogenous content of stress-related components, including proline, cytokinins, and antioxidants, increased (Aziz et al. 2011; Fan et al. 2013).

Additionally, vitamins also occupy a certain proportion of the nutrient composition of sesame, of which vitamin E is the richest (Mili et al. 2021). According to Wei et al. (2022), the main type of vitamin E found in sesame seeds is γ-tocopherol. Tocochromanols, another name for vitamin E, are essential micronutrients for humans created by phototrophs like plants and certain types of algae (Falk and Munné-Bosch 2010). These substances have antioxidant properties and are present in thylakoids and chloroplast membranes (Muñoz and Munné-Bosch 2019). Bao et al. (2020) believe that tocochromanols are significant antioxidants that can be highly concentrated in response to a variety of biotic and abiotic stresses. Low tocochromanol levels make plants more susceptible to various stresses, underscoring the critical function of vitamin E in plant environmental adaptation. Because of the information mentioned, some scientists who discovered algal vitamins may have a bio-stimulatory effect on crops despite limited evidence to support this view (Mahapatra et al. 2018). Beyond containing the typical mineral and small molecular organic nutrients found in terrestrial plants, seaweeds are enriched with distinct marine minerals and bioactive compounds (active biological compounds). The seaweed concentrations of mineral, trace, and ultra-trace elements are higher than those in continental plants (Rohani-Ghadikolaei et al. 2012). Although seaweed extract, as a bio-stimulant, has minimal mineral concentrations that plants can readily absorb, its key value comes from its capacity to activate several plant system processes, ultimately leading to improved plant growth and production (Ali et al. 2019; Pei et al. 2024).

Sesamum indicum plants enriched with *S. platensis* extract and powder induced a highly significant increase in calcium in the shoot when compared with control plants. It is worth noting that all the treatments used in both forms (extract and powder) led to the accumulation of magnesium in *Sesamum* seeds, and the highest percentages obtained were in the plants treated with the addition of *Padina* as a powder or *Spirulina* extract. This is matched with previous studies that have shown that *Spirulina* extract application as a foliar spray can increase magnesium levels in tomato plants, leading to enhanced overall plant vigour as well as chlorophyll synthesis (Mostafa et al. 2024) and in the amount of Mg in rape oilseed treated with seaweed extract (Billard et al. 2014). Natural growth hormones and bioactive compounds derived from seaweed application have been proven to enhance root development and nutrient absorption, allowing plants to uptake magnesium from the soil more effectively (La Bella et al. 2021). Also, Khan et al. (2009) demonstrated that applications of seaweed as

foliar extracts derived from *Ascophyllum nodosum* significantly increased magnesium levels in spinach and broccoli plants, which in turn improved photosynthetic efficiency and growth.

Also, the findings obtained in this study revealed a significant increase in iron concentrations due to the stimulative effect of *Padina* extract and *Spirulina* powder application in sesame roots, which are particularly important as iron is a critical element for influencing chlorophyll synthesis, plant health, and overall growth. Additionally, *Spirulina* itself contains a notable amount of iron, constituting about 14% of its dry weight, which can contribute to the iron content in plants when used as a fertilizer (Wuang et al. 2016). Some scientists, Craigie (2011), reported that *Ascophyllum nodosum* extract applications as seaweed foliar spray enhanced iron uptake and content, resulting in improved tomato and lettuce plant health and productivity. Furthermore, plenty of natural growth regulators contained in seaweeds, such as auxins and cytokinins, not only enhance plant growth but also stimulate the plant's ability to absorb nutrients, including iron, from the soil. On the other side, seaweed-derived bio-stimulants have been proven to significantly increase the availability of essential micronutrients, including iron, in tomato and lettuce plants (Youssef and El-Habbak 2021). In addition, Kaur and Gupta (2019) have linked the *Spirulina* application to the increase in micronutrient content, like iron, copper, zinc, and manganese. This agreed with the current investigation that showed the application of either *Spirulina* or *P. pavonica* extracts to sesame plants induced manganese and zinc content in the shoot and root. Selenium at the highest significant content was recorded in the seeds of *Sesamum* plants fortified with all treatments of the macro- or microalgae used. Selenium is an essential mineral for human health, having structural and enzymatic roles as an antioxidant and stimulator of the production of active thyroid hormone. Selenium is essential for the proper functioning of the immune system, appears to be an essential nutrient for sperm motility, and may reduce the risk of miscarriage. Its deficiency has been linked to poor moods. High selenium intake may be associated with a reduced risk of cancer (Wei et al. 2022). In the context of these health effects, the low or decreasing levels of selenium in some parts of the world are a cause for concern, so its proportion in food plants the must be taken into account (Rayman 2000; Genchi et al. 2023).

All treatments of *Padina* and *Spirulina* used in the present study induced the accumulation of total lipids in sesame shoots more than in roots, and the highest value was recorded in shoots with the addition of *Padina* as powder compared to the control. According to Kasim et al. (2016), the seaweed extract increased the stabilizing effect on membrane lipids, increased lipid-synthesizing enzyme activity, and reduced the generation of reactive oxygen species (ROS), which causes lipid peroxidation and disruption of enzyme activity which may cause the raised lipid accumulation in seaweed-treated seedlings. Sesame seeds are a great source of oil, proteins, fatty acids, vitamins, minerals, and other health-promoting substances for humans (Wei et al. 2022).

According to numerous scientific reports, soybeans sprayed with *Ecklonia maxima* aqueous extract showed higher productivity, which was associated with more pods, seeds, and seed weight (Kocira et al. 2019). Based on Engel et al. (2023) research, biostimulant-treated soybean plants that received aqueous extract 0.25% and 0.50% (application of seed and leaves) produced more leaves and pods than the control plants.

All algal applications significantly enhanced the length (plants, branches, and capsules), numbers (branches and capsules), and seed index of sesame. The highest values of length (plants and branches) were observed with the application of *Spirulina* extract. A similar stimulative effect was recorded with the application of *Spirulina* powder on the length of capsules, branches, capsule numbers, and seed index when compared with control plants. The findings shown here are in line with those of Shedeed et al. (2022), who noticed that the maximum values of growth and yield components were obtained following the topical application of 0.25% *Spirulina* extract to *Lupinus luteus*. Consequently, seaweed extracts (SEs) were found to increase plant development (Singh et al. 2025). Seaweed plays a crucial role in both agricultural systems and human welfare (Dawes and Ridd 2020; Singh et al. 2025). Despite the abundant seaweed resources available along global coastlines, there's a pressing need for more efficient and strategic utilization to prevent the wastage of these valuable materials (Parmar et al. 2017). Historical evidence shows that farming communities, particularly in coastal areas, have long recognized seaweed's agricultural value, using it either in its raw form or as compost to enhance crop yields (Cole et al. 2016). The effectiveness of seaweed as a biofertilizer is well-documented, particularly in addressing soil nutrient deficiencies. What makes seaweed especially valuable is its rich composition of beneficial compounds, including growth regulators, hormones, carbohydrates, auxins, gibberellins, and vitamins, all of which contribute to improved crop productivity and sustained soil health (Cole et al. 2016; Raja and Vidya 2023).

Finally, seaweeds, as natural biocontrol agents, play a crucial role in improving soil health by adding beneficial elements and important compounds, as mentioned above. They increase soil resistance to pests, diseases, and abiotic environmental factors, such as salinity, drought, and others. Their ability to stimulate plant defence mechanisms and promote root growth makes them an environmentally

friendly alternative to synthetic agrochemicals (Singh et al. 2025).

5 Conclusion

Both the microalga (*Spirulina platensis*) and the macroalga (*Padina pavonica*) used in this work have shown promising results in stimulating the vegetative growth and productivity stages of sesame plants, which may be because they contain, like other algae, many important micro- and macronutrients. FT-IR analysis showed several active groups that make them effective as bio-stimulants to sesame plants. Therefore, the biomass of algae can be used as a biofertilizer. Using these biological fertilizers as an alternative solution to confront the challenges and harmful effects of chemical fertilizers, or at least to limit their use due to their severe negative effects on the environment, plant communities, and humans. In addition to being a source of nutrition to increase plant productivity or crops to solve the problems of famine in poor countries and to meet the challenges facing the world due to the lack of nutrients that do not meet the requirements of the increasing population. Also, the same responses were observed for the mineral composition of different parts of these plants.

Author Contributions El-Shazoly R. M., Hifney A. F., and Abdel Wahab D. A. participated in the experimental design; El-Shazoly R. M., Yousef S. M. and Abdel Wahab D. A. collected experimental materials; El-Shazoly R. M. and Abdel-Wahab, D.A. participated in the experimental analysis; El-Shazoly R. M., Hifney A. F., and Abdel Wahab D. A. discussion part of the paper and prepared the manuscript. All of the authors read and approved the manuscript.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). This research did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability Data will be made available on request.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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