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ORIGINAL PAPER

Dose-dependent Plant-promoting Effect of Macroalgae *Stypopodium schimperi* Extracts in *Solanum lycopersicum* and Detection of Phloroglucinol Composition

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Abstract

This study aimed to investigate using *Stypopodium schimperi*, brown alga extract, as a biofertilizer. Algae can be an essential bio-stimulant that increases plant growth and development. Brown algae especially have critical biological activities due to their high secondary metabolite content. This study also determined the biochemical and physicochemical composition and phenolic content of the *S. schimperi*, an alien brown alga in the Mediterranean Sea.

Dose-dependent effects of these extracts on seed germination, root-shoot growth, seedling vigor index, and genome stability of *Solanum lycopersicum* plant were studied. Inductively coupled plasma mass spectrometry (ICP-MS) analysis revealed the primary elemental composition of the effective extract (10%). Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy showed phloroglucinol composition, the primary structural molecule of a phlorotannin, in the content of the extract. In addition, the phenolic content was determined by the Folin-Ciocalteu method, while the phenol-sulphuric acid method was used to determine carbohydrates by spectrophotometer. Genomic template analysis was conducted by calculating Inter Simple Sequence Repeats (ISSR) profile changes.

Na, Mg, K, Fe, Mo, and Se were determined as elemental compositions of the 10% extract according to ICP-MS analysis. The ATR-FTIR resulted in four different spectral bands at 3350 cm^{-1}, 2936 cm^{-1}, 1636 cm^{-1}, and 1414 cm^{-1}, which were attributed to the phloroglucinol components. Our results showed that the highest phloroglucinol concentration could inhibit root growth and decrease genomic template stability (GST). The GTS difference between the control and 0.5% extract-treated group was approximately 91.38%, as revealed by ISSR analysis. The lowest GTS value (39.66%) was observed in the roots of *S. lycopersicum* treated with 5% extract.

The present study demonstrated for the first time that a low concentration of *S. schimperi* extract could be used as a biofertilizer in agriculture. An alien macroalga that may be harmful to the ecosystem is being transformed into a beneficial one by being brought into the economy.

Keywords FTIR · Phlorotannins · Root growth · Seaweed

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1 Introduction

Many countries lose significant productivity from crop yield caused by abiotic and biotic stress. Climate change is one of the most severe challenges for agriculture worldwide. Besides climate change, increasing environmental pollution due to industrial activities and loss of agricultural lands are the other pressures on crop yields. In agriculture, chemical fertilizers are one of the most common tools to maintain high crop yields. On the other hand, excessive use of chemical fertilizers causes pollution in the soil and the loss of beneficial microorganisms and affects the plants' nutrient intake in the long term (Camargo and Alonso 2006; Gupta et al. 2021). Therefore, avoiding excessive use of chemical fertilizers will also increase sustainability and crop productivity. In this context, algae having a high content of amino acids, vitamins, mineral substances, and plant growth regulators such as gibberellins, abscisic acids, cytokinins, and auxins have been considered valuable sources for plant growth (Ali et al. 2021; Hussein et al. 2021; Khan et al. 2009).

Algae have several biological functions and have been considered an agricultural bio-stimulant since 1940 (Craigie 2011). Farm plant supplementation with macroalgal extracts has been shown to support root development and crop and fruit yield. It also improved photosynthetic activity and resistance to harmful plant-associated fungi, bacteria, and viruses (Agarwal et al. 2016; Gunupuru et al. 2019; Islam et al. 2020; Nagorskaya et al. 2010). Besides, algae are an eco-friendly natural resource, containing unique polysaccharides and various secondary metabolites. Therefore, algae are considered valuable bio-resources with promising multifunctional components that can be used for environment-friendly breeding practices for sustainable agriculture (Castellanos-Barriga et al. 2017; Hussain et al. 2021; Julia et al. 2020; Puglisi et al. 2020). Because of their operative stimulating properties on plants, seaweed extracts account for more than 33% of the total bio-stimulant market worldwide. In 2018, the market value was expected to reach €894 million by 2022 (Eef et al. 2018).

Current research indicates that algae extracts are an essential bio-stimulant that enhances plant growth, development, and seed germination without adverse results (Castellanos-Barriga et al. 2017; Mzibra et al. 2021). Previous studies have reported that algae extract such as *Caulerpa racemosa*, *Gracilaria edulis*, *Kappaphycus alvarezii*, and *Sargassum crassifolium* stimulate seed germination, plant growth and productivity (Dumale et al. 2016; Layek et al. 2018; Sunarpi et al. 2019). Similarly, significant increases in root and stem growth were reported when the liquid extracts of *Gracilaria textorii* and *Hypnea musciformis* were applied to tomato and pepper plants (Rao et al. 2014). Consequently, brown algae are economically significant and widely used in agricultural applications. Although low or moderate doses of algal extracts promote plant growth due to their constituting pigments, polysaccharides, minerals, polyunsaturated fatty acids, hormones, and secondary metabolites, they can also inhibit seed germination and root/shoot growth at high doses (Hong et al. 2007; Kumar et al. 2011). The Phaeophyceae class contains secondary metabolites specific to this group called phlorotannins. Phlorotannin, formed by the oxidative polymerization of phloroglucinol, is a brown algae-specific molecule. Phloroglucinol and phlorotannin have antitumor, antioxidant, antidiabetic, antiallergic, anti-inflammatory, antiproliferative, antityrosinase, antibacterial, and antiviral properties (Amlani and Yetgin 2022; Thomas et al. 2020; Yamagata 2021). Phlorotannins are also bioactive substances that play a role and directly support plant growth and defense (Budzałek et al. 2021). The presence of these substances in the extracts varies according to the class and type of seaweed and the extraction method used (Ali et al. 2021; Li et al. 2017). Phlorotannins, such as phloroglucinol, are also known to inhibit plants' growth, like lettuce and other organisms, microalgae, and invertebrate larvae (Harwanto et al. 2022). According to recent studies, they can also act as auxin hormone and promote plant growth (Rengasamy et al. 2015a, 2016). However, our knowledge about the effects of these compounds on plant growth and genome stability is still limited.

Stypopodium schimperi is a brown alga distributed in the Atlantic and Indian Oceans. This species was first recorded in Israel in 1973 (Galil 2007) and are mainly found in rocky habitats up to 20 m. It is an alien species to the Mediterranean; however, its impacts on native species have not been determined yet (Verlaque et al. 2007). Therefore, more studies are needed to identify its ecological status and effects. Aydın (2021) showed high antibacterial activity of the methanol extract of *S. schimperi* collected from Turkish coasts against *S. aureus*, *B. cereus*, *E. coli*, *P. aeruginosa*, *K. pneumoniae*, *S. typhimurium*, and *P. vulgaris*. Another research (Sampli et al. 2000) revealed the cytotoxic activity of *S. schimperi* extracts on the L16 cancer cell line. Although these macroalgal extracts' antibacterial or anticarcinogenic effects have been determined, their potential in agricultural applications has not been evaluated. The present study aimed to assess the effects of the brown algae extract on the root/shoot growth of the tomato plant and to reveal its concentration-dependent toxicity, as it is rich in carbohydrates and phenolics. For this purpose, the growth parameters such as seed germination, seedling vigor index, and relative root elongation parameters were evaluated in *Solanum lycopersicum*. Moreover,

the physico-chemical parameters like elemental composition, total phenolic, and phloroglucinol contents of the *S. schimperi* extract were measured. Furthermore, the dose-dependent effects of the extract on the DNA obtained from roots were determined.

2 Materials and Methods

2.1 Collection of Algae and Preparation of Algal Extracts for Plant Growth–Promoting Experiment

The brown algae *S. schimperi* (Fig. 1) was collected from Kaş (Antalya) at 0.5 m depth. The samples were washed with seawater, rinsed with distilled water three times, cleaned from epiphytes under a stereomicroscope, and then air-dried for a week at room temperature. The dried samples were stored at +4°C until further analysis.

Ten gram dried algae samples were ground with mortar and pestle until a fine powder was obtained. The sample was boiled in 100 mL of distilled water and incubated in a water bath at 100°C for an hour. The extract was filtered using filter paper (Whatman No 5). The concentration of each algal extract was constructed as 10%. Algal extracts of *S. schimperi* were diluted with distilled water to obtain the different application doses: control group (0%), 0.5%, 1%, 3%, 5%, and 10%.

Fig. 1 Underwater view of the study material, brown macroalgae *Stypopodium schimperi*, collected from Kaş

2.2 The Physico-chemical Composition of Algal Extracts

The total phenolic content of the extracts of *S. schimperi* was determined by modifying the Folin-Ciocalteu method (López et al. 2011). Briefly, each algae extract (100 µL) is mixed by adding 0.5 mL of Folin–Ciocalteu reagent and 1 mL of sodium carbonate (20%) after placing them in test tubes containing 8.4 mL of water. After incubation at room temperature for an hour in the dark, the absorbance at 765 nm was measured using a spectrophotometer. A standard graph determined phenolic content estimation as Gallic Acid Equivalents (GAE). Total protein content was determined spectrophotometrically using Bradford's (1976) method. Total carbohydrate amounts of algae extracts were determined spectrophotometrically using the phenol-sulphuric acid method using starch, maltose, xylose, glucose, and fructose as standards (Dubois et al. 1956). Ascorbic acid was estimated according to Jagota and Dani (1982). It is vigorously shaken after adding 0.2 mL of algae extract to 0.8 mL of 10% trichloroacetic acid. The mixture, kept in an ice bath for 5 min, is centrifuged at 3000 rpm for 5 min. After the extract was diluted to 2.0 mL using double distilled water, 0.2 mL of diluted Folin reagent was added to the extract, and then the tubes were shaken vigorously. After 10 min, measurements were taken with a spectrophotometer at 760 nm absorbance. Ascorbic acid solution (2.5–100 µg) dissolved in water at different concentrations was used as a standard. The amount of ascorbic acid was calculated with the standard graph. The color, Electric Conductivity (EC) value, and pH of the *S. schimperi* extract were recorded.

2.3 Element Analysis of the Algal Extract

5.0 mL of algae extracts was treated with 6.0 mL of concentrated nitric acid and 2.0 mL of concentrated hydrochloric acid. After this process, the samples were placed on the Titan MPS™ microwave sample preparation system by closing the containers and were kept at room temperature. After digestion, the samples were diluted to 100 mL with deionized water. Inductively Coupled Plasma Mass Spectrometry (ICP-MS/OES/Perkin Elmer Avio 200) was used for elemental analysis. Each trial was repeated three times.

2.4 Infrared Spectral Analysis of the Algal Extracts

The spectra of algal extract and anhydrous phloroglucinol ($C_6H_6O_3$) standard (Merck 107069) were collected by an FTIR spectrometer (Frontier FTIR, Perkin Elmer, USA) equipped with a Zn/Se ATR unit. A 2 µL of samples was placed on the crystal plate and dried with a very mild nitrogen gas flux for 5 min to remove excess unbound water. The spectra were collected in the 4000–650 cm^{-1}

at a 4 cm^{-1} with 32 scan repetitions. Before the sample spectra were first obtained, the background spectra of the air were recorded under the same conditions as the samples to eliminate the airborne contribution of molecules. The spectra were recorded using *Spectrum V10.3* software (Perkin Elmer, USA) of the spectrometer. Three extracts, each with two replicates, were scanned, revealing almost identical spectra, and the average spectra of each extract were obtained. These average spectra were offset baseline corrected, normalized concerning the amide A band at 3350 cm^{-1}, and smoothed with a nine-point Savitsky-Golay smoothing function in *Spectrum V10.3* software to detect phloroglucinol-associated bands in the algal extract. The bands of interest were not seen from the raw spectra unless the above-mentioned spectral normalization. The *OPUS 5.5* software (Bruker, USA) was used to determine band positions and area values. The areas under the absorbance bands were calculated from the offset baseline corrected, normalized, and smoothed average spectra using the "integration" option in *OPUS 5.5* software. Total average spectra of 3 average spectra were used to visualize spectral differences. The band area values were shown as % normalized regarding band areas (normalized to 100%) of phloroglucinol standard.

2.5 Plant Experiments

Solanum lycopersicum (tomato) was sterilized with 10% sodium hypochlorite for 8 min and rinsed with sterile distilled water three times before experiments. After the sterilization procedure, the six experimental groups were treated with distilled water (as control), 0.5%, 1%, 3%, 5%, and 10% algal extracts.

2.5.1 Seeds Germination and Growth Bioassay

The germination of *S. lycopersicum* seeds was recorded for 8 days. The following formula determined the germination rate, seed vigor index, and relative root elongation:

(a) germination percentage (GP) = (n/N) × 100

(b) seedling vigor index (SVI) = (seedling length (shoot + root) (cm) × germination percentage)

(c) relative root elongation (RRE) = (mean root length in test solution/mean root length in control) × 100

Each petri dish included ten seeds for each experimental group and was kept in a climate room at 25°C for 15 days. Shoot and root lengths were measured at the end of the experiment period. The chlorophyll content, membrane integrity analysis, and lipid peroxidation assays were conducted to reveal the genotoxic effects of algal extracts. Each experiment was set up independently three times.

2.6 DNA Isolation and Inter Simple Sequence Repeats Polymerase Chain Reaction (ISSR-PCR) Protocol

DNA isolation from *S. lycopersicum* roots was done by the micro-preparation method (Fulton et al. 1995). After DNA yield and quality were measured by BioSpec-Nano (Shimadzu, Japan), isolated DNAs were visualized on 1% agarose gel. ISSR-PCR was modified according to Çekiç et al. (2017). Optimization experiments of the 15 ISSR primers were first performed in the control group, and then the best amplified ten primers were selected. Each analysis was repeated three times.

2.6.1 Genomic Template Analysis

Each observed change in ISSR profiles was awarded a +1 arbitrary score. The average was calculated for each experimental group treated with different concentrations of *S. schimperi* extract. Template genomic stability (%) was calculated as follows;

$$GTS = 100 - \left(100 \times \left(\frac{a}{n}\right)\right)$$

2.7 Statistical Analysis

Statistical analysis was performed using One-way ANOVA with post hoc Tukey HSD Test unless otherwise specified. The critical value for statistical significance was $p < 0.05$ and 0.01. The spectral data were statistically analyzed using the Unpaired *T*-test (One-tailed) in *GraphPad Prism V8.0.1* software (GraphPad, USA). The degree of significance was denoted as less than $p < 0.0001$ ****. The results were expressed as means ± standard error of the mean.

3 Results

3.1 The Physico-chemical Composition of Algal Extracts

The ratio of the algae extract's carbohydrate, protein, ascorbic acid, and total phenolic compounds was calculated as 8.47%, 6.9%, 4.2%, and 12.25% (Table 1). The secondary metabolite ratio in 0.5% algae extract was 4.5 times lower than in 10% algae extracts (Fig. 2). While the EC value of 10% concentration of algae extract was highest, it was observed that the EC value of 0.5% algae extracts was approximately 8.21 times lower compared to

Table 1 The physico-chemical composition of 10% *Stypopodium schimperi* extracts

Element compositions	µg/L	Biochemical compositions (%)	
P	22.913±0.14	Protein	6.9
Mg	1136.57±0.36	Carbohydrate	8.47
K	3777.72±0.23	Phenolic compound	12.25
Na	716.29±0.63	Vitamin C	4.6
Ca	254.07±0.02	Physical parameters	
Si	8.17±0.001	pH	6.24
Mn	0.26±0.0001	Color	Dark Brown
Co	0.04±0.002	EC	5.75± 0.02 dS/m
Mo	15.91±0.01		
B	0.39±0.006		
Fe	0.20±0.01		
Cu	0.25±0.007		
Zn	0.17±0.002		
Se	15.91±0.01		

EC, electric conductivity

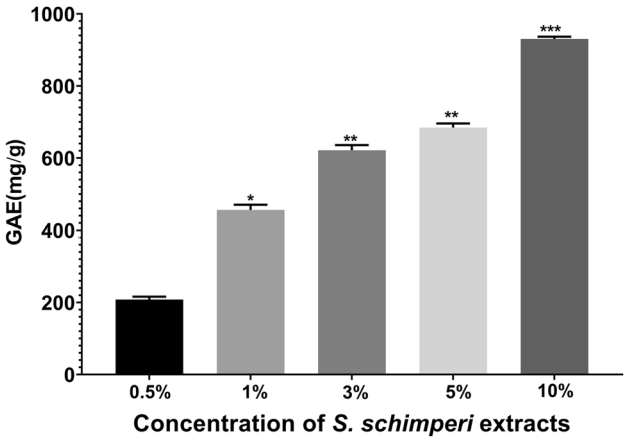

Fig. 2 The total phenolic content of dose-depending *Stypopodium schimperi* extract. *Represents a statistically significant difference of $p < 0.05$ when compared with the control, **represents a statistically significant difference of $p < 0.01$, ***represents a statistically significant difference of $p < 0.001$. GAE: Gallic Acid Equivalents

10% (Table 2). The color of the 10% algae extract was dark brown, and the pH was 6.24 (Table 1).

Inductively coupled plasma mass spectrometry analyzed P, Mg, K, Na, Ca, Si, Mn, Ni, Co, Mo, B, Fe, Cu, Zn, Se, and Cd analysis. According to the results as represented in Table 1, the main element of the extract revealed as K (3777.72 mg/mL), Mg (1136.57 mg/mL), Na (716.29 mg/mL), and Ca (254.07 mg/mL). Mo and Ni elements appeared to be non-detectable (ND). Fe, Mn, Zn, and Cu were the least abundant elements, with 0.39 mg/mL, 0.26 mg/mL, 0.25 mg/mL, and 0.20 mg/mL concentrations, respectively.

ATR-FTIR spectroscopy was used to determine phloroglucinol composition and quantity in the extracts. The production of algal phloroglucinol was detected based on the quantification of integrative band areas, that is, the concentration of specific spectral bands in algal extract spectra regarding the infrared (IR) spectrum of anhydrous phloroglucinol standard. Figure 3 shows the average absorbance spectra of phloroglucinol standard (straight line) and algal extract (dashed line). As depicted, many phloroglucinol-related bands existed in the IR spectrum of the phloroglucinol standard over the 4000–650 cm^{-1} IR region (straight line). However, most were absent in the algal extract spectrum (dashed line) except for the bands at 3350 cm^{-1}, 2936 cm^{-1}, 1636 cm^{-1}, and 1414 cm^{-1} positions. The % quantities of these spectral bands are given in Figure 4, where the chosen bands of phloroglucinol standard were normalized to 100%, and deviations in the same bands in the algal extract were evaluated, respectively. The % quantities of bands at 3350, 2936, 1636, and 1414 cm^{-1} were sequentially calculated as 89.2, 0.5, 36.2, and 4.2% (Fig. 4).

3.2 Effect of Algal Extracts on Growth Parameters of *S. lycopersicum*

With this study, we observed the outcomes of different concentrations of *S. schimperi* extracts on germination rate (Fig. 5). While 0.5% and 1% extract concentrations did not significantly affect the germination rate compared

Table 2 15-day growth and development parameters of *Solanum lycopersicum* seeds treated with different concentration of *Stypopodium schimperi* extracts

	Mean germination time X±SD	Seedling vigor index X±SD	Relative root elongation X±SD	EC value of extract (dS/m)
control	4.83±0.04	1337.30±0.12	100	0
0.5 %	4.83±0.09	1577.38±0.09*	111.30±0.08*	0.791±0.02
1%	4.67±0.06	1194.14±0.09*	83.64±0.15*	1.228±0.01
3%	1.83±0.08**	386.46±0.07**	67.98±0.08*	3.85±0.02
5%	1.76±0.02**	155.24±0.05***	26.11±0.06**	4.92±0.09
10%	ND	ND	ND	5.75±0.02

*Represents a statistically significant difference of $p < 0.05$ when compared with the control, **represents a statistically significant difference of $p < 0.01$, and ***represents a statistically significant difference of $p < 0.001$. *EC*, electric conductivity; *SD*, standard deviation

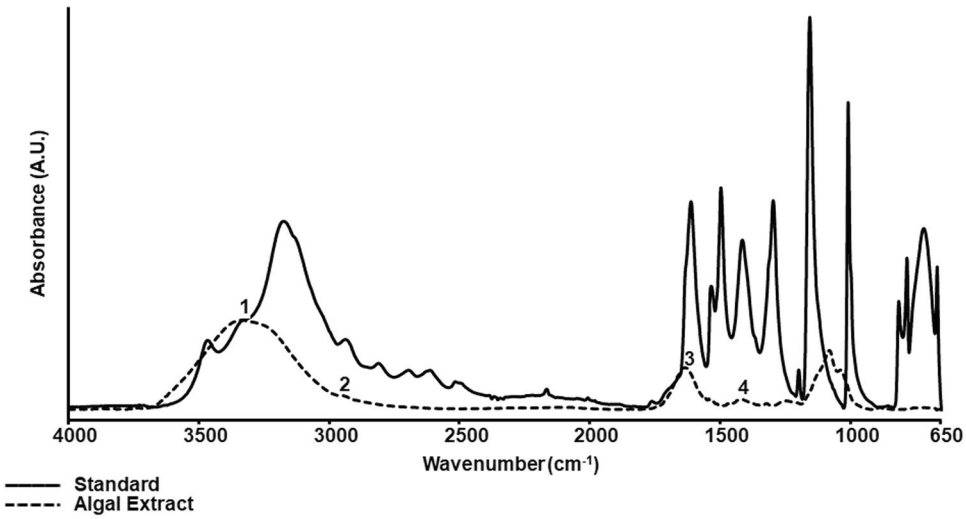

Fig. 3 The average absorbance spectra of both phloroglucinol standard (straight line) and algal extract (dashed line) at the whole (4000–650 cm^{-1}) infrared region. The spectra were offset baseline corrected, normalized concerning the amide A band at 3350 cm^{-1}, and smoothed with nine-point Savitsky–Golay smoothing function in *Spectrum V10.3* software (Perkin Elmer, USA)

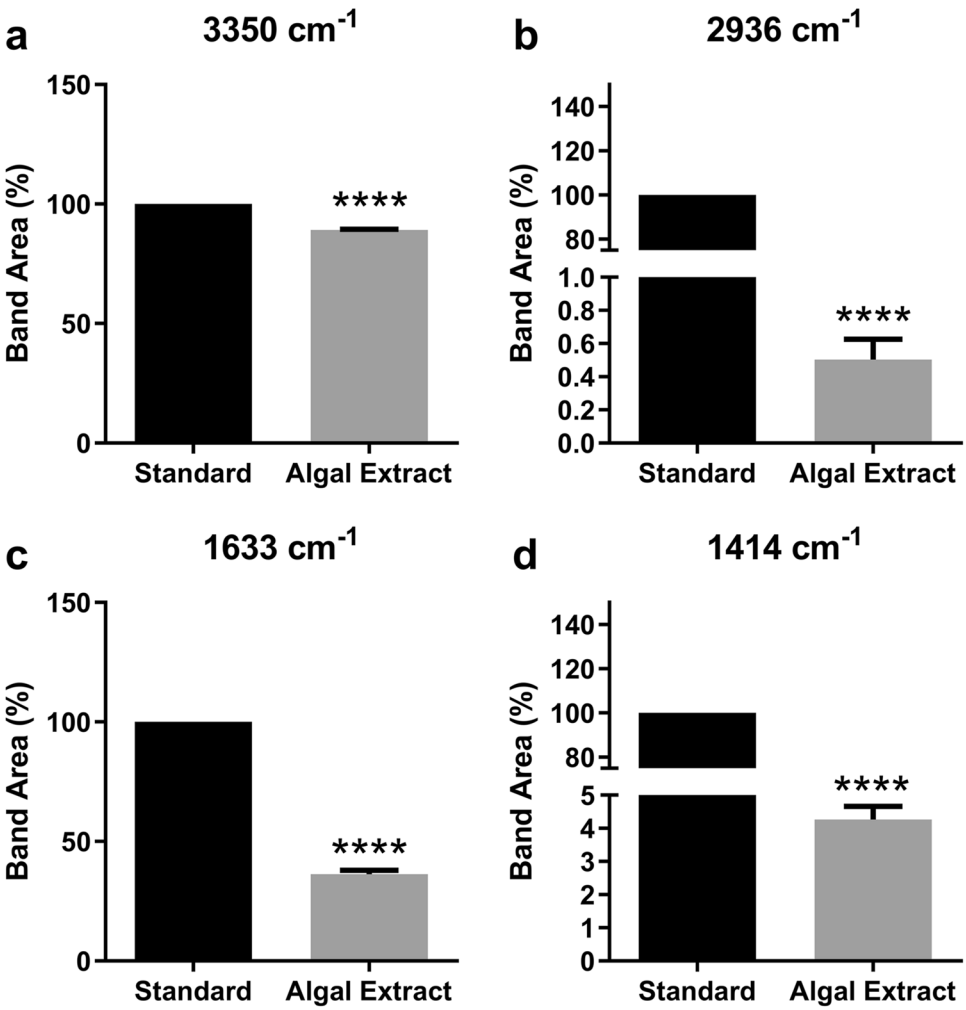

Fig. 4 The percent quantities of spectral bands at (**a**) 3350 cm^{-1}, (**b**) 2936 cm^{-1}, (**c**) 1636 cm^{-1}, and (**d**) 1414 cm^{-1} positions attributed for phloroglucinol components of algal extracts. In the analysis, the chosen bands of phloroglucinol standard were evaluated, respectively. The degree of significance was denoted as less than $p < 0.0001^{****}$. The results were expressed as means ± standard error of the mean

to the control group, 54.67% and 60.07% inhibitions were determined with 3% and 5% extract concentrations, respectively. A 10% extract application totally (100%) inhibited *S. lycopersicum* seeds (Fig. 5). Similarly, there is no evident difference determined with 5% and 1% concentrations on the germination time of the seeds (Table 2).

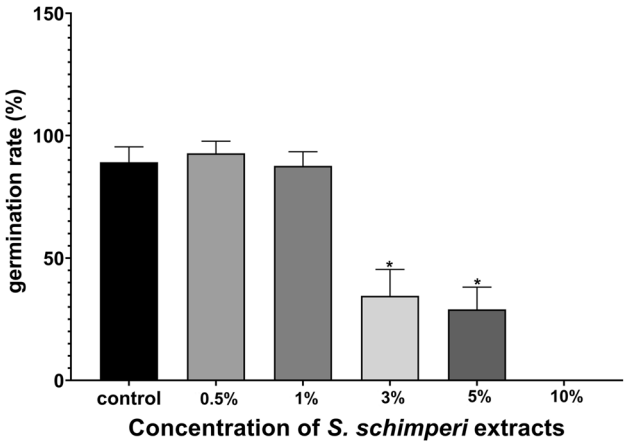

Fig. 5 The seed germination rate of *Solanum lycopersicum* treated with different concentrations of *Stypopodium schimperi* extracts. *Represents a statistically significant difference of $p < 0.05$ compared to the control

Shoot and root growth rates varied depending on the concentration of the extract. Approximately 1.33 and 1.2 times increase in shoot length was determined in seeds treated with 0.5% and 1% *S. schimperi* extract, respectively (Fig. 6). In addition, the seedling vigor index increased by 17.95% in the samples treated with 0.5% algae extract (Table 2).

3.3 Determination of the Genotoxic Effect of *S. schimperi* Extracts Using ISSR-PCR

This study, 15 ISSR primers were used in ISSR-PCR analyses, and 10 of these primers displayed polymorphic bands. Band differences (appearance/disappearance and decrease/increase in band intensities) observed in ISSR profiles are given in Table 3. As the concentration of *S. schimperi* extracts increased, different DNA amplification profiles were observed in the roots of the tomato plant (Fig. 7). In the samples treated with 3% and 5% extract, 11 and 16 new bands were detected, respectively. The highest polymorphic bands in all ten primers were detected in roots treated with 5% alga extract. Accordingly, the GTS difference between the control and 0.5% *S. schimperi* treatment was approximately 91.38%. The lowest GTS value (39.66%) was observed in the roots of *S. lycopersicum* treated with 5% extract (Table 4**).**

4 Discussion

Marine algae are mainly rich in chemical compounds belonging to the following groups: polysaccharides, polyphenols, phlorotannins, plant pigments, unsaturated fatty acids, sterols, and plant hormones. In addition, previous studies have determined that the total polysaccharide content of seaweeds in dry weight is between 4% and 76% (Górka et al. 2018). Macro and microelements are essential for proper functioning plant metabolism, development, and growth (Jones 2012). Previous research has shown that seaweed extracts are a rich source of critical macronutrients (N, K, and P) and trace elements such as Fe, Mg, Mn, and Zn (Craigie 2011; Michalak and Chojnacka 2015; Sethi 2012; Soares et al. 2020). A previous study demonstrated that aqueous extracts of the brown algae *Saccharina japonica* contains Ca, Mg, P, K, and Na as the main macro-minerals and Fe, Mn, Zn, and Al as the main micro-minerals in their chemical composition (Saravana et al. 2016). Like the extraction process used in this study, Uthirapandi et al. (2018) also attained liquid extracts by boiling the brown and green algae in distilled water for an hour and determined Na, Mg, K, Fe,

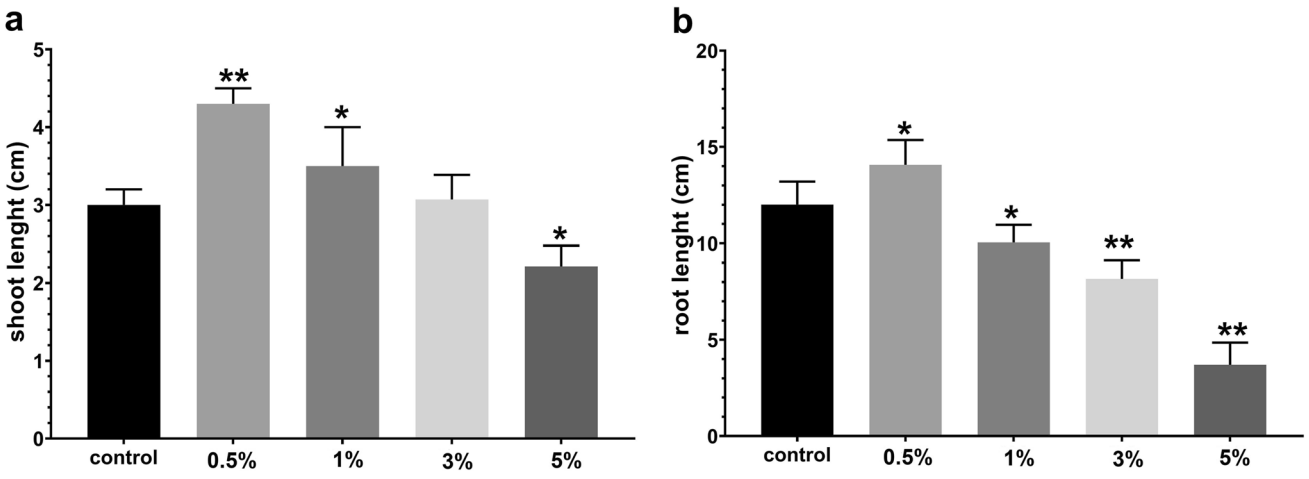

Fig. 6 The root and shoot length of *Solanum lycopersicum* treated with different concentrations of *Stypopodium schimperi* extracts. *Represents a statistically significant difference of $p < 0.05$ compared to the control, and **represents a statistically significant difference of $p < 0.01$

Table 3 Changes of total bands in control and polymorphic bands in treated with different concentrations of *Stypopodium schimperi* extract, **a**; appearance band number, **b**; disappearance band number, **c**; decreased band intensity, **d**; increased band intensity. ISSR: Inter Simple Sequence Repeat

		0.5%				1%				3%				5%			
	C	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
ISSR809	6	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	1
ISSR810	6	0	0	0	0	0	0	1	0	5	0	0	0	6	0	1	0
ISSR818	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ISSR842	4	0	0	0	0	1	0	0	1	2	1	0	0	2	1	0	0
ISSR868	9	0	0	0	0	0	2	0	0	0	8	1	0	0	0	0	0
ISSR890	6	0	0	0	0	1	0	1	0	1	0	1	0	3	0	0	3
ISSR873	2	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	1
ISSR866	5	1	0	0	3	0	1	0	2	1	0	0	3	1	0	0	3
ISSR807	8	1	0	0	0	0	0	0	1	1	0	0	1	0	2	2	2
ISSR880	10	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	2
Total bands	58	2	0	0	3	2	4	3	5	11	9	2	6	16	4	3	12
a+b+c+d		5				14				28				35			

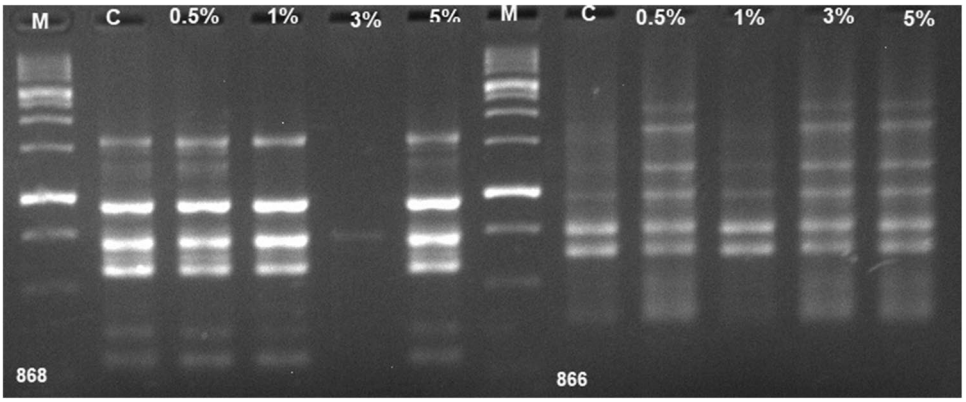

Fig. 7 The Inter Simple Sequence Repeat-Polymerase Chain reaction (ISSR-PCR) results of *Solanum lycopersicum* root treated with different concentrations of *Stypopodium schimperi* extracts

Table 4 Changes of Genomic Template Stability (GTS%) for 10 Inter Simple Sequence Repeat (ISSR) primers in treated with different concentrations of *Stypopodium schimperi* extract

Treated groups	Genomic Template Stability (GTS%) Ratio
0.5%	91.38
1%	75.86
3%	51.72
5%	39.66

Mo, and N elements in these extracts. When we performed the elemental analysis from the 10% extract, it was revealed that it contains high K, Mg, Na, and Ca levels and low Mn, Fe, Cu, and Zn levels.

Interestingly, the Se element was also detected in these extracts. Besides, Michalak et al. (2015) determined B, Ca, Cu, Co, Fe, Mg, Na, K, P, Si, S, Mn, Mo, Ni, and Zn elements obtained from the extracts by microwave-assisted extraction method. Soares et al. (2020) identified essential microelements (B, Cl, Zn, P, Mo, V, Se, and I) in the brown alga *Saccorhiza polyschides* extracts using the subcritical water extraction method. In this study, it was observed that there are many minerals that can support plant growth and development in *S. schimperi* extracts obtained by using the boiling method. In this respect, the boiling approach is suitable for agricultural use, as stated in the literature and our study. This finding is significant because no chemical solvents are used to convert algae, a natural substance, into natural fertilizer.

Previous studies indicated that changes in pH and EC of seaweed extracts might affect bioactivity (Booth 1969; Henry 2005). Carrasco-Gill et al. (2018) showed that the pH of the extract obtained by alkaline hydrolysis of commercially used brown algae *Ascophyllum nodosum* was 6.3. Sivasankari et al. (2006) determined the pH of the extracts from brown algae *Sargassum wightii* obtained by water boiling as 6.2. The EC value is accepted in the literature as an indicator of salinity (Baroud et al. 2021). Studies indicate that a low EC value increases germination and plant growth due to low salinity (Baroud et al. 2021; Hernández-Herrera et al. 2014). Hernández-Herrera et al. (2014) also showed lower EC values of *Ulva lactuca* and *Padina gymnospora*

extracts (0.99 and 0.77 dS m^{-1}, respectively) in tomato plants, leading to a higher germination percentage. Baroud et al. (2021) reported that the extracts of three different brown algae species (*Cystoseira gibraltarica*, *Fucus spiralis*, and *Bifurcaria bifurcata*) with low EC values promote tomato seed germination. Similarly, in the present study, *S. schimperi* extracts with the highest EC values inhibited seed germination, possibly due to the salt content of the alga extracts.

Seaweed extracts have a complex composition. It has been reported that the phenolic compounds of seaweeds may also have plant growth-enhancing effects (Kocira et al. 2019). In this respect, secondary metabolites, another factor that may affect plant growth, should also be considered. The present study determined that phenolic content is higher than proteins and carbohydrates in 10% algae extract (Table 1). Moreover, the 0.5% *S. schimperi* extract had the lowest phenolic acid content (Fig. 2). Previous studies indicated that low concentrations of algae extracts could promote plant germination and growth, and vice versa at high concentrations (Baroud et al. 2019; Hernández-Herrera et al. 2014; Kalaivanan and Venkatesalu 2012; Kumari et al. 2011; Selvam and Sivakumar 2013; Sridhar and Rengasamy 2010). In our study, 0.5% and 1% extract concentrations did not significantly affect the germination rate. In comparison, 10% extract application totally (100%) inhibited *S. lycopersicum* seeds. Similarly, Baroud et al. (2019) reported that the three different brown algae extract at 2% concentration diminished the seed germination rate. In this respect, our results were consistent with the literature proposing that high amounts of phenolic compounds could inhibit seed germination.

These phenolic compounds may be tannins, which are predominantly specific to brown algae. Tannins are polyphenolic compounds naturally synthesized in photosynthetic organisms and are commonly found in terrestrial and marine plants (Waterman and Mole 1994). Phlorotannins, a tannin type, are only found in brown marine algae. The most widely known phlorotannins are eckol, dieckol, and phloroglucinol. Besides, many phlorotannins are the predominant secondary metabolite in algae extracts. In this study, the presence of phloroglucinol in *S. schimperi* extract was determined by IR spectral analysis. The four spectral bands located at 3350 cm^{-1} (O-H groups; N-H stretching), 2936 cm^{-1} (aliphatic C–H stretching), 1636 cm^{-1} (C=O; C=N stretching; C-C ring vibrations), and 1414 cm^{-1} (C-OH deformation, O-H or C-H in-plane bending vibrations) were present in both phloroglucinol standard and extract spectra and thus attributed for phloroglucinol components of algal extracts (Cantarutti et al. 2020; D'Souza et al. 2008; Feldscher et al. 2010; Ito et al. 2017; Ma et al. 2017; Peng et al. 2021; Selvaraj et al. 2018; Ye et al. 2020; Zeng et al. 2019a, b). Leyton et al. (2016) also showed the primary IR band range of phloroglucinol as 1618–536 cm^{-1} in *Macrocystis pyrifera* extracts using FTIR spectroscopy.

The promoting properties of phlorotannins on plant growth and development have been reported in recent studies (Rengasamy et al. 2015a, 2016; Teixeira da Silva et al. 2013). *Ecklonia maxima* is one of the best-known commercial brown alga widely used to improve plant growth and crop protection (Rengasamy et al. 2015a). In a study, eckol isolated from *E. maxima* was found to act as a bio-stimulant by increasing the growth and development of maize (Rengasamy et al. 2015a, 2016). However, there is limited information on the effectiveness of phloroglucinol in plant tissue culture (Teixeira da Silva et al. 2013) and crops. A study reported that eckol from brown algae also has a solid auxin-like activity (Rengasamy et al. 2015b). Although *S. schimperi* extracts positively affected tomato plants at low concentrations, they inhibited plant development and growth as the concentration increased. The shoot length decreased approximately 1.36 times in *S. lycopersicum* seeds treated with a 5% algae extract. It was determined that 0.5% algae extract, a low concentration, increased root length approximately 1.2 times. However, the root growth was inhibited significantly at higher extract concentrations. Similarly, a significant decrease in the seedling viability index of *S. lycopersicum* was observed in the groups treated with high extract concentrations. This increase in plant seedling vigor index may be associated with the auxin-like behavior of phlorotannins.

This study also investigated whether or not *S. schimperi* extracts applied to seeds at different concentrations cause genetic instability in the *S. lycopersicum* plant. The changes in a plant's genome could result from transposable elements, chromosomal aberrations in number and/or structure, or possibly pre-existing genetic imbalance (Isah 2015). Somaclonal variations or the application of exogenous substances such as algae extracts can cause changes in plant morphology and chromosome number, differences in gene expression, protein profile, and DNA sequences. In general, the evaluation of genetic stability in plants is based on a variety of analyses, such as cytological, biochemical, and molecular analyses (Garcia et al. 2019; Vitamvas et al. 2019). One of the most common techniques is the ISSR-PCR method. According to the results, high concentrations of algae extract caused a decrease in genome stability. Similarly, Hamouda et al. (2022) determined that high concentrations of *Ulva linza* and *Corallina officinalis* extracts changed genome stability in the wheat plant using the RAPD-PCR (Random Amplified Polymorphic DNA) technique. They pointed out that phenols, which have antioxidant characteristics, can damage important biomolecules at high concentrations and cause changes in the nucleotide sequence. The present study showed a decrease in genome stability due to increased phenolic compounds. IR spectral analysis of *S. schimperi* extracts revealed that they contain

phloroglucinol. Thus, these phlorotannins could be implicated in altered genome structure. This study suggests that low concentrations of *S. schimperi* extracts can promote the growth and development of the tomato plant.

5 Conclusions

Alien invasive species in this situation, algae, significantly threaten native ecosystems and biodiversity. Collecting these species and bringing them into the economy is important from another point of view. For this purpose, this study determined for the first time that the extracts of *S. schimperi* contain beneficial elements for plant nutrition and development processes. On the other hand, these extracts also contain high salinity, phenolic acids, and phloroglucinol which are valuable substances for many pharmaceutical and industrial purposes. Therefore, they can also exert an inhibitory effect on the seeds depending on the concentration levels. The study findings suggest that a high concentration of phlorotannin can affect DNA stability and cause changes in the genome. Nevertheless, a low concentration of *S. schimperi* extract increased the plant vigor index and promoted root growth. Based on these findings, this study proposes that the invasive species *S. schimperi* could be a good candidate as a stimulator for plants if used at appropriate doses. In conclusion, we are contributing to three goals of the 'United Nations' Sustainable Development Goals (SDG); Zero Hunger (SDG2), Climate Action (SDG13), and Life Below Water (SDG14) by adding an economic value to an alien aquatic species, removing them from the aquatic ecosystem and by obtaining potential bio-fertilizer from a natural source for sustainable and chemical-free agriculture.

Author contributions DU: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing—Original Draft, Review & Editing, Visualization. RG: Investigation, Resources, Data Curation, Writing—Original Draft GS: Investigation, Methodology GS: Investigation, Methodology GV: Investigation, FOK: Investigation, Writing—Original Draft, Review & Editing, ITK: Methodology, Investigation, Writing—Original Draft, Review & Editing, Visualization

Data availability All data generated during this study are included in this published article. The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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