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# Effect of liquid seaweed extracts on growth of tomato seedlings (*Solanum lycopersicum* L.)

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**Abstract** Seaweed extracts are used as nutrient supplements, biostimulants, or biofertilizers in agriculture and horticulture to increase plant growth and yield. In this study, we examined the effect of liquid seaweed extracts (LSEs) made from *Ulva lactuca*, *Caulerpa sertularioides*, *Padina gymnospora*, and *Sargassum liebmannii* as biostimulants on the germination and growth of tomato (*Solanum lycopersicum*) under laboratory and greenhouse conditions using foliar and soil drench applications of LSEs. We assessed LSEs at different concentrations (0.2, 0.4, and 1.0 %) on germination parameters (percentage, index, mean time, energy, and seedling vigor index) and growth parameters (plumule length, radical length, shoot length, root length, fresh weight, and dry weight) of tomato seedlings. Our results indicate that seeds treated with LSEs of *U. lactuca* and *P. gymnospora* at lower concentrations (0.2 %) showed enhanced germination (better response in germination rate associated with lower mean germination time, high germination index and germination energy, and consequently greater seedling vigor and greater plumule and radicle length). Application as a soil drench was found to be more effective in influencing the height of the plant (up to 79 cm) than the foliar spray application (75 cm). Plants receiving LSEs of *U. lactuca* and *P. gymnospora* showed increased shoot length, root length, and weight. Furthermore, *U. lactuca* and *P. gymnospora* were found to be more successful and better candidates for developing effective biostimulants to improve the growth of tomato plants. This study provides important information on the identification and utilization of Mexican seaweed resources for agriculture and is the first study to report on the uses of these seaweeds as a source of liquid extracts as biostimulants in agriculture.

**Keywords** Seed germination · Seaweeds · Extract · Nutrient analysis · Biofertilizer · Chlorophyta · Phaeophyta

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## Introduction

Seaweed and seaweed products have been used worldwide to increase plant growth and yield. Modern agriculture is searching for new biotechnologies that would allow for a reduction in the use of chemical inputs without negatively affecting crop yield or the farmers' income. In recent years, the use of natural seaweed as fertilizer has allowed for partial substitution of conventional synthetic fertilizer (Dhargalkar and Pereira 2005; Hong et al. 2007; Khan et al. 2009; Zodape et al. 2010). In addition, a number of commercial seaweed extract products are available for use in agriculture and horticulture and can be used as liquid extracts applied as foliar spray, soil drench, or in granular/powder form as soil conditioners and manure (Blunden et al. 1997; Lingakumar et al. 2004; Thirumaran et al. 2009). These extracts are marketed as liquid biostimulants because a chemical analysis of seaweeds and their extracts has revealed the presence of a wide variety of plant growth-promoting substances such as auxins, cytokinins, and betaines (Khan et al. 2009). These substances can influence shoot and root system development (Durand et al. 2003; Stirk

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et al. 2004). As well, macronutrients and micronutrients can help promote the growth of various vegetables, fruits, and other crops (Blunden 1991; Crouch and van Staden 1993; Moller and Smith 1998). Many beneficial effects have been reported on the use of seaweed extracts. Positive responses include improved germination, root development, leaf quality, general plant vigor, and resistance to pathogens (Khan et al. 2009).

Seaweed is an inexpensive local resource along coastal agricultural areas. In Mexico, seaweeds are abundantly available and represent a great potential for eventual commercial exploitation (Gojón-Báez et al. 1998). However, the only commercial extracts currently produced in Mexico from raw seaweeds are Kelpro and Kelprosoil from *Macrocystis pyrifera* (SAGARPA 2012) and Algaenzims from *Sargassum* spp. (Canales-López 2000; Sunarpi et al. 2010). These products are available for use in agriculture and horticulture. One positive step towards the inclusion of native seaweed resources in Mexico is to use biofertilizers derived from seaweed as an alternative input to improve negative cropping conditions such as the progressive degradation of ecosystems and the contamination of agricultural lands caused by synthetic fertilizers.

Tomatoes (*Solanum lycopersicum*) are one of the most important vegetable crops around the world in terms of human consumption, and they are also the most popular garden vegetable. In 2009, Mexico was among the top ten tomato-producing countries contributing with almost three million tonnes (FAO 2009) to the global production. However, one of the main problems facing tomato production in Mexico is the intensive application of chemical fertilizers causing damage to the soil ecology and agricultural systems (Villarreal-Sánchez et al. 2003). The aim of this study was to examine the effect of liquid seaweed extracts derived from Mexican resources on seed germination and growth of tomato plants.

## Materials and methods

### Preparation of liquid seaweed extracts

Four algal species, two green, *Ulva lactuca* Linnaeus and *Caulerpa sertularioides* Gmelin, and two brown, *Padina gymnospora* (Kützing) Sonder and *Sargassum liebmannii* J. Agardh seaweeds, were collected from the intertidal zone at low tide, in May and November 2009, from the coastal area of Jalisco, Mexico, in Bahia Tenacatita (19° 28″N, 104° 84″W) and Bahia Careyitos (19° 43″N, 105° 02″W). Seaweed species were collected by hand and washed with seawater to remove debris, shells, and sand. Samples were transported to the laboratory in plastic bags, washed with tap water to remove surface salt, oven-dried for 72 h at 60 °C, and then ground in an electric mill (IKA-M 20) to less than 0.50 mm. This milled material (100 g) of each sample was subjected to acid digestion and analyzed by atomic absorption spectrophotometry for mineral analysis of sodium, potassium, calcium, and phosphorus (by colorimetry) following procedures from the Association of Official Analytical Chemists (AOAC 1990). Then, 100 g of each sample was added to 1 L of distilled water with constant stirring for 15 min followed by autoclaving at 121 °C for 1 h at 1.21 kg-cm$^{-2}$. The hot extracts were filtered through a Whatman No. 40 filter paper and stored. The liquid seaweed extracts (LSEs) were designated as stock solution and coded according to the genus and species: *U. lactuca* (UL), *C. sertularioides* (CS), *P. gymnospora* (PG), and *S. liebmannii* (SL). Furthermore, the pH and electrical conductivity (EC) of the LSEs were measured using a pH meter and conductivity meter, respectively, and the latter is expressed as dS m$^{-1}$. Finally, the color of the seaweed extracts was observed visually. All determinations were performed in triplicate.

### Bioassay for germination test

Experiments were conducted using certified tomato seeds (*S. lycopersicum* cv. Rio Fuego; Cal-Oro Vegetable Seeds, United Genetics, Inc., USA). Germination was observed daily over a period of 8 days according to methods of the Association of Official Seed Analysts (AOSA 2005). Four groups of 100 seeds were tested for germination per treatment (AOSA 2005). Experimental units were arranged in a randomized complete block design. Before treatment with LSEs, tomato seeds were surface-sterilized in 4 % sodium hypochlorite solution for 10 min and subsequently triple-rinsed in sterile distilled water prior to soaking in the seaweed extracts. Tested tomato seeds were placed on a Whatman No. 5 filter paper in sterilized 90-mm Petri dishes and then treated with 5 mL distilled water (control) or different concentrations of LSEs (0.2, 0.4, and 1.0 %). The plates were incubated at 25±1 °C and 16-h light/8-h dark regime. Germination was considered to have occurred once the radicle had protruded more than 2 mm.

Measured variables included germination percentage (GP), germination index (GI), mean germination time (MGT), and germination energy (GE), as well as seedling vigor index (SVI), plumule length, radicle length, total plant height, and dry weight of tomato seedlings. After 12 days, the LSEs effects on seed germination and growth of tomato seedlings were measured. Plumule length, radicle length, and total plant height were measured with a vernier caliper. Dry weight was obtained with an electronic balance after oven-drying at 60 °C.

Parameters were calculated as follows: GP=(number of-germinated seeds/total number of seeds)×100. GI was calculated as described by the Association of Official Seed Analysts (AOSA 1983), following the equation: GI=$\sum$(Gt/Tt), where Gt is the number of seeds germinated on day *t* and Tt is the number of days. MGT was estimated according to Ellis and Roberts (1981) and expressed as days. MGT=$\sum(D\times n)/\sum n$,

where $n$ is the number of seeds germinated on day $D$ and $D$ is the number of days counted from the beginning of the test. Seed GE was calculated according to the formula (GE %)=(number of germinating seeds/number of total seeds per treatment after germination for 3 days)×100. SVI was determined according to Orchard (1977) by the following formula: SVI=(seedling length (cm)×germination percentage).

### Greenhouse growth bioassay

Tomato plants were grown in a growth chamber under 16-h light regime at 25 °C and 8-h dark regime at 18 °C in sterilized soil peat moss (Sunshine Mix 3™). Two hundred fifty 15-day-old plants were selected and randomly assigned to different treatment groups and transplanted into pots containing a sand, perlite (Termolita S.A., Mexico), volcanic rock, and peat moss (Sunshine Mix 3™) (1:1:1:1 *w*/*w*) soil mix. Plants were fertilized 1 week after transplanting and treated with 50 mL of 20:20:20 (N–P–K) soil drench solution (Peters Professional; Scotts-Sierra Horticultural Products Co., USA). Thereafter, the plants were irrigated using the LSEs (50 mL every week). Plants were also irrigated separately with water (50 mL every third day). Potted plants were grown for 7 weeks in a greenhouse at ~25±2 °C, in 85 % relative humidity. Morphological characteristics such as shoot length, root length, total height, fresh weight, and dry weight were measured.

The experimental design and treatment were similar to those reported by Crouch and van Staden (1992). A total of 25 different treatments were used with ten replications. The first treatment served as the control in which plants were grown without LSEs. Three factors were randomized for the other 24 LSE treatments. The first factor was LSE applications method (foliar spray versus soil drench). The second factor was the type of seaweed species used to produce the LSEs. The third factor was the concentration (0.2, 0.4, and 1.0 %). The experimental units were arranged in a completely randomized trifactorial design receiving either 50 mL distilled water for the control or 50 mL LSEs for the experimental treatments.

### Statistical analysis

All data were analyzed for significant differences by analysis of variance (ANOVA) with mean separation using least significant difference (LSD). In the first experiment, one-way ANOVA was carried out for each parameter studied to assess significant differences. In the second experiment, three-way ANOVA assessed significant differences at the 5 % level. All statistical analyses were performed with Statistical Package STATGRAPHICS® Centurion XV for Windows.

## Results

### Macroelements in seaweeds and physicochemical content of LSEs

Results obtained from the nutrient analysis showed the presence of the macroelements Na, K, Ca, and P in all samples. The concentration of Na was higher in the green seaweeds *U. lactuca* and *C. sertularioides*, but K concentration was higher in the brown seaweeds *P. gymnospora* and *S. liebmannii*. The concentration of Ca was higher in *P. gymnospora* and *C. sertularioides*. The P concentration was low in all seaweeds (Table 1). The pH values for LSEs of *U. lactuca* and *P. gymnospora* were neutral and slightly acidic than those for LSEs made from *C. sertularioides* and *S. liebmannii*. The value of EC increases in all LSEs with an increase in the concentrations (Table 2).

### Effect of LSEs on seed germination and growth of tomato seedlings under laboratory conditions

Germination occurred in all treatments after 2 days. The effect of the liquid seaweed extracts of *U. lactuca* and *P. gymnospora* at a concentration of 0.2 % gave a significant ($P \leq 0.05$) increase in GP over control after 2 days (Fig. 1a). Data indicated that the same treatments at concentrations of 0.4 and 1.0 % decreased the GP (Fig. 1b, c). Treatments of *C. sertularioides* and *S. liebmannii* had an inhibitory effect on seed germination. All concentrations delayed germination and GP dropped off with a higher concentration (1.0 %) (Fig. 1c).

Seeds treated with *U. lactuca* and *P. gymnospora* LSEs showed higher germination rate associated with lower MGT and greater seedling vigor (Table 3). LSEs of *U. lactuca* and *P. gymnospora* at 0.2 % showed high GP (75 and 76 %, respectively), elevated GI (9.8 and 10, respectively), a reduction in MGT (5.6 days), an increase in GE (88.7 and 87.2 %, respectively), and enhanced SVI (1,026.7 and 1,262.3, respectively). In contrast, seeds treated with LSEs of *C. sertularioides* and *S. liebmannii* at 1.0 % had the longest average delay (high

**Table 1** The content of macroelements in seaweed species (g·100 $g^{-1}$, dry wt.)

| Species | Na | K | Ca | P |
|---|---|---|---|---|
| *U. lactuca* | 5.57±0.80 | 1.85±0.30 | 1.88±0.06 | 0.10±0.08 |
| *C. sertularioides* | 4.42±0.40 | 0.47±0.40 | 3.10±0.50 | 0.20±0.08 |
| *P. gymnospora* | 1.81±0.50 | 4.27±0.60 | 3.65±0.40 | 0.10±0.08 |
| *S. liebmannii* | 1.56±0.40 | 4.54±1.00 | 1.85±0.08 | 0.17±0.05 |

Values are average ± standard error ($n$=3)

**Table 2** Physicochemical content of liquid seaweed extracts (LSEs) treatments of *U. lactuca* (UL), *C. sertularioides* (CS), *P. gymnospora* (PG), and *S. liebmannii* (SL)

| Treatments (%) | Color | pH | EC (dS $m^{-1}$) |
|---|---|---|---|
| Control | | 7.0 | 0 |
| UL 0.2 | | 7.00±0.50 | 0.99±0.11 |
| UL 0.4 | Greenish yellow | 7.30±0.50 | 1.74±0.11 |
| UL 1.0 | | 7.36±0.50 | 3.57±0.11 |
| CS 0.2 | | 6.71±0.50 | 1.01±0.20 |
| CS 0.4 | Dark green | 6.96±0.50 | 1.85±0.20 |
| CS 1.0 | | 6.99±0.50 | 3.93±0.20 |
| PG 0.2 | | 7.10±0.20 | 0.77±0.10 |
| PG 0.4 | Brownish red | 7.60±0.20 | 1.43±0.10 |
| PG 1.0 | | 7.60±0.20 | 2.98±0.10 |
| SL 0.2 | | 6.19±0.50 | 1.01±0.15 |
| SL 0.4 | Brown | 6.26±0.50 | 2.61±0.15 |
| SL 1.0 | | 6.37±0.50 | 3.99±0.15 |

Values are average ± standard error ($n$=3)

*EC* electrical conductivity

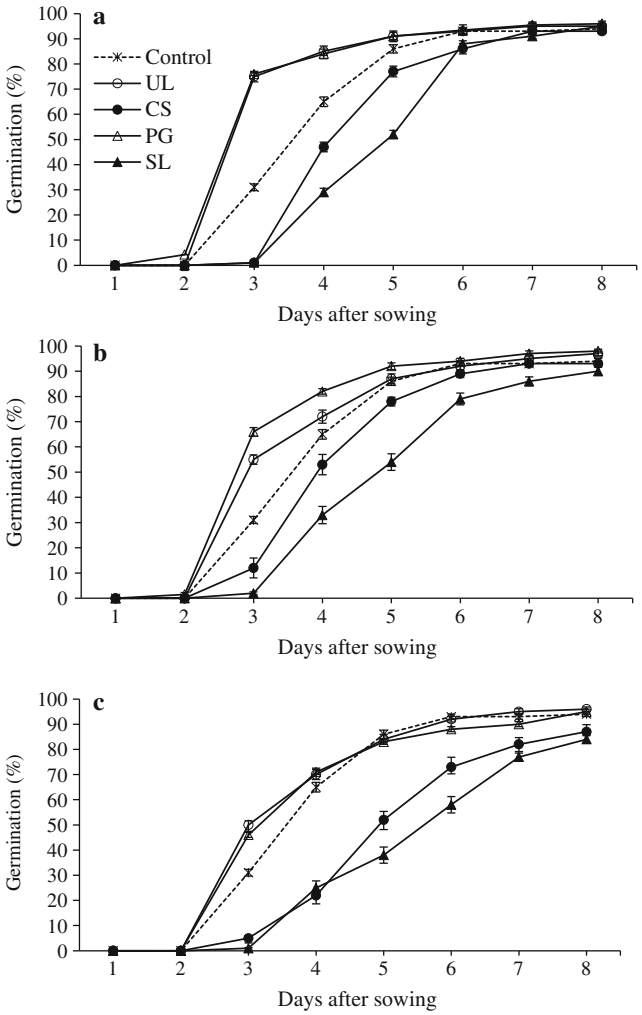


**Fig. 1** Germination percentage of tomato seeds treated with liquid seaweed extracts at concentrations of **a** 0.2 %, **b** 0.4 %, and **c** 1.0 % from *U. lactuca* (*UL*), *C. sertularioides* (*CS*), *P. gymnospora* (*PG*), and *S. liebmannii* (*SL*). Values are presented as average ($n$=400 seeds); *bars* represent standard error

MGT), were the latest to germinate, and had the greatest spread of germination over time (Table 3).

The LSEs had a significant effect ($P \leq 0.05$) on growth of tomato seedlings. All LSEs showed a stimulatory effect on plumule length. The highest average plumule length was found in plants that received LSEs from *U. lactuca* and *P. gymnospora* at 1.0 % (7.3 and 8.3 cm, respectively; Fig. 2a). Moreover, these results indicate that LSEs of *U. lactuca*, *P. gymnospora*, and *S. liebmannii* promoted radicle length. The highest average radicle length was found in plants that received LSEs from *U. lactuca*, *P. gymnospora*, and *S. liebmannii* at 0.2 % (4.1, 5.8, and 5.5 cm, respectively) in comparison to the control. Furthermore, all *C. sertularioides* treatments had an inhibitory effect on radicle length (2.2 to 2.8 cm, Fig. 2b). All *C. sertularioides* and *S. liebmannii* LSE treatments significantly increase dry weight of tomato plants, as did *U. lactuca* and *P. gymnospora* LSEs at (1.0 %). The highest dry weight (0.036 g) was higher for the brown algae LSEs (Fig. 2c).

## Effect of LSEs on tomato seedling growth in greenhouse

In the greenhouse experiment, both foliar spray and soil drench of LSEs showed a significant enhancement ($P \leq 0.05$) on growth of tomato plants. Application as a soil drench was found to be more effective in influencing the height of the plant (up to 79 cm) than the foliar spray application (75 cm).

The interaction between application form, treatment, and concentration demonstrates that plants treated with foliar sprays of *U. lactuca* at 1.0 % and *P. gymnospora* at 0.2 % displayed an increase in shoot length (47 and 49 cm, respectively), but plants receiving the same extracts as soil drench showed no significant difference in shoot length (Fig. 3a, b). Treatments applied as foliar spray of *U. lactuca* and *P. gymnospora* at 0.2 % displayed an increase in root length (25 and 26 cm, respectively) and total plant height (70 and 75 cm, respectively). Similarly, soil drench

**Table 3** Effects of liquid seaweed extracts (LSEs) treatments on germination parameters of tomato seeds: germination percentage (GP), germination index (GI), mean germination time (MGT), germination energy (GE), and seedling vigor index (SVI)

| LSEs (%) | Parameters | | | | |
|---|---|---|---|---|---|
| | GP | GI | MGT (days) | GE (%) | SVI |
| Control | 31±1.40 c | 8.9±0.24 f | 5.9±0.08 ef | 68.8±2.76 d | 763.4±40.8 b |
| UL 0.2 | 75±2.00 g | 9.8±0.89 hi | 5.6±0.06 a | 88.7±2.76 e | 1,026.7±40.8 ef |
| UL 0.4 | 55±1.85 e | 9.4±0.86 gh | 5.8±0.08 b | 74.8±2.76 d | 946.8±40.8 de |
| UL 1.0 | 50±1.62 de | 5.2±0.54 b | 5.8±0.11 bc | 72.9±2.76 d | 1,096.5±40.8 fg |
| CS 0.2 | 1±0.60 a | 8.2±0.72 e | 6.3±0.09 h | 49.8±2.76 c | 805.7±40.8 bc |
| CS 0.4 | 12±3.93 b | 9.0±0.93 fg | 6.2±0.24 g | 56.9±2.76 c | 891.6±40.8 cd |
| CS 1.0 | 5±0.91 a | 3.4±0.75 a | 6.5±0.10 i | 24.5±2.76 a | 622.9±40.8 a |
| PG 0.2 | 76±1.10 g | 10±0.67 i | 5.6±0.06 a | 87.2±2.76 e | 1,262.3±40.8 h |
| PG 0.4 | 66±1.67 f | 9.9±0.57 hi | 5.7±0.05 a | 84.5±2.76 e | 1,229.7±40.8 h |
| PG 1.0 | 46±2.10 d | 9.1±0.92 fg | 5.8±0.09 bcd | 74.2±2.76 d | 888.7±40.8 cd |
| SL 0.2 | 1±0.40 a | 7.9±0.85 de | 5.9±0.13 def | 31.3±2.76 ab | 1,160.6±40.8 gh |
| SL 0.4 | 2±0.57 a | 7.5±1.02 d | 5.9±0.16 cde | 36.0±2.76 b | 873.2±40.8 bcd |
| SL 1.0 | 1±0.31 a | 6.6±1.13 c | 6.0±0.18 f | 28.5±2.76 ab | 635±40.8 a |

Values are average ± standard error ($n$=400). Average followed by the same letter within columns is not significantly different, according to LSD multiple range test ($P \leq 0.05$)

*UL U. lactuca*, *CS C. sertularioides*, *PG P. gymnospora*, *SL S. liebmannii*

applications of *U. lactuca* at 1.0 % and *P. gymnospora* at 0.2 % resulted in an increase in root length (33 and 32 cm, respectively) and total plant length (79 cm) (Fig. 3c–f).

In addition, positive effects on fresh weight were observed with application as foliar spray of *P. gymnospora* at all concentrations (9.9, 10.1, and 10.7 cm) and with application as soil drench of *U. lactuca* and *C. sertularioides* at 1.0 % (14 and 14.6 cm, respectively) (Fig. 4a, b). Dry weight of tomato plants was unaffected by treatment with LSEs, except for *S. liebmannii* that produced negative effects (Fig. 4c, d).

## Discussion

Previous papers reported that seaweeds contain high macroelement levels (Ca, K, P), especially those from the Phaeophyta (Hong et al. 2007). The content of minerals in the seaweeds used in this research was in general agreement with the typical values for these marine algae from other countries (Gireesh et al. 2011; Hong et al. 2007; Kalaivanan and Venkatesalu 2012; Sivasangari et al. 2010) and Mexico (Carrillo-Domínguez et al. 2002; Robledo and Freile Pelegrin 1997). The quantitative ranges for the various components in seaweed can vary due to season, location, and analytical methods (Castro-González et al. 1996; Ito and Tsuchiya 1981).

The pH and EC from LSEs affected germination in tomato. The beneficial effects of seaweed extracts may arise from higher seed moisture after the drying phase (Weges and Karsssen 1990). Additionally, changes in pH and EC of acidic and neutral extracts can affect bioactivity (Booth 1969; Henry 2005). According to Reinhardt and Rost (1995), most plants are more sensitive to salinity during germination and seedling growth. This is in agreement with our study whereby a higher germination percentage was found with treatments of *U. lactuca* and *P. gymnospora* (0.99 and 0.77 dS $m^{-1}$ with 0.2 %) at low concentration. This may be due to the absence of salts in the medium, thereby allowing seeds to more efficiently imbibe water. In contrast, LSEs of *C. sertularioides* and *S. liebmannii* (3.9 $dSm^{-1}$ with 1.0 %) at higher concentration showed a significant negative effect on the germination of tomato seeds, by inhibiting the seeds' ability to imbibe water.

Similar results have been reported by Basher et al. (2012). They evaluated the effect of seaweed, salt water, and drainage water on germination percentage, rate, and seedling growth of tomato (*Lycopersicum* spp.). The combination of water with seaweed treatments shows the highest rate for 2.7 $dSm^{-1}$ with 0.1 % seaweed concentration and lowest rate for 5 $dSm^{-1}$ with 0.05 % seaweed concentration compared to control. Salt stress reduced the growth of the plumule and radicle in tomato seedlings, and there was a direct adverse relation between NaCl concentration and reduction in growth (plumule and radicle) (Nyagah and Musyimi 2009). Tomato seedlings are moderate sensitive to NaCl salinity. However, during imbibition, the effect of salt is merely osmotic until a hydration threshold is surpassed (Almodares et al. 2007). Tomato seeds treated with low concentrations of *U. lactuca* and *P. gymnospora* responded better in terms of germination rate associated with lower MGT, high GI and GE, and consequently greater seedling vigor and

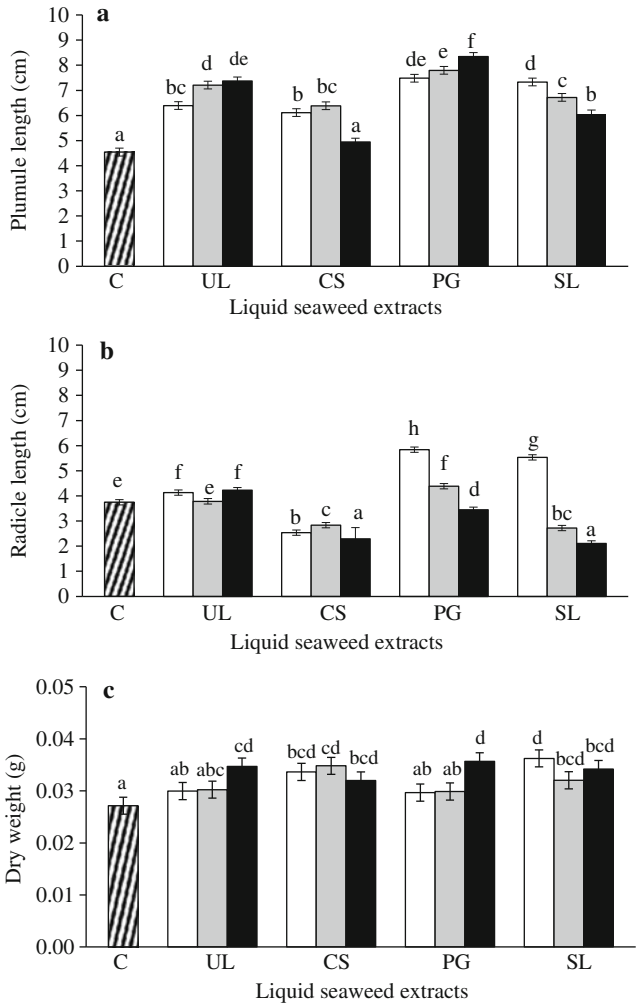


**Fig. 2** Effect of liquid seaweed extract treatment applications on **a** plumule length, **b** radicle length, and **c** dry weight of tomato seedlings at different concentrations: 0.2 % (*white columns*), 0.4 % (*gray columns*), and 1.0 % (*black columns*). Treatments: control (*C*), *U. lactuca* (*UL*), *C. sertularioides* (*CS*), *P. gymnospora* (*PG*), and *S. liebmannii* (*SL*). Columns denoted by a *different letter* are significantly different at $P \leq 0.05$. Values represent average ($n=300$ seedlings); *bars* represent standard error

higher plumule and radicle length. The higher concentration showed a decreasing trend, particularly with *C. sertularioides* and *S. liebmannii* treatment at 1.0 %.

In tomato, high concentrations of salt in the germination media significantly delayed the onset, reduced the rate of germination (Foolad and Lin 1997, 1998), and reduced the germination percentage (Hajer et al. 2006). In this study, the reduction in germination and growth (plumule length and radicle length) following applications of LSEs of *C. sertularioides* and *S. liebmannii* could be a result of high-salinity extracts. Seed germination of tomato lines (LA3770, R205, CT6, FLA, and ME) was delayed by salinity increasing from 2.5 to 10 dS $m^{-1}$ (Kaveh et al. 2011). In addition, germination rate decreased in tomato cultivars (Pascal, Red Stone, Shohba, Super Marmand, and Tanshet Star) at high salt concentration in proportion to the control application (Al-Harbi et al. 2008).

Salt stress decreased germination by preventing the germination processes due to the accumulation of a high concentration of $Na^+$ and $Cl^-$ ions, which might be toxic to the embryo or the developing seedlings (Almodares et al. 2007), and can affect many vegetable crops, leading to uneven stand establishment and reduction of crop yields (Yildirim and Guvenc 2006). The mechanisms for salt damage during germination are not completely understood (Almodares et al. 2007). However, the effect of salinity on plant growth is a complex syndrome that involves osmotic stress, ion toxicity, and mineral deficiencies (Musyimi et al. 2007).

In the present study, higher concentrations of seaweed extract from *C. sertularioides*, *P. gymnospora*, and *S. liebmannii* at 1.0 % had toxic effects on tomato seedlings and caused detrimental effects such as radicle browning and disintegration of plumules. This detrimental effect for tomato growth has been reported previously by Arnon and Johnson (1942) and is caused by higher pH in the growth medium. Higher concentrations of seaweed extracts from *S. johnstonii* (2.0 to 10 %) caused the same detrimental effects in black gram (*Vigna mungo*) seedlings (Kumari et al. 2011). Indeed, several studies have examined seaweed extracts on seed germination of various species such as table beet (Wilczek and Ng 1982), lettuce (Moller and Smith 1998), tomato (Demir et al. 2006), green gram (Ashok-Kumar et al. 2012), and black gram (Kalaivanan and Venkatesalu 2012; Ganapathy Selvam et al. 2013). The increased germination percentage at low concentrations could be due to the presence of growth-promoting substances such as indole acetic acid, indole-3-butyric acid, gibberellins, cytokinins, micronutrients, vitamins, and amino acids (Challen and Hemingway 1965).

Seaweed products exhibit growth-stimulating activities, and the use of seaweed formulations as biostimulants in crop production is well established. Seaweed ingredients include macro- and microelement nutrients, amino acids, vitamins, cytokinins, auxins, and abscisic acid that affect cellular metabolism in treated plants, leading to enhanced growth and crop yield (Crouch and van Staden 1993; Stirk et al. 2004; Wightman and Thimann 1980). In addition, seaweeds contain precursors of elicitor compounds that promote germination (Stephenson 1974), growth, and maintenance of plant health (Kloareg et al. 1996). Another possibility is the presence of polysaccharides in LSEs, as sugars that are known to improve plant growth in a similar way to hormones (Rolland et al. 2002). Zeatin is another candidate for induction of rooting in plants by seaweed (Finnie and van Staden 1985).

Furthermore, brown and green seaweed extracts contain various betaines and betaine-like compounds (Blunden et al. 1986; Ghoul et al. 1995). In plants, betaines serve as a compatible solute that alleviates osmotic stress induced by salinity and drought stress. However, other roles have also been

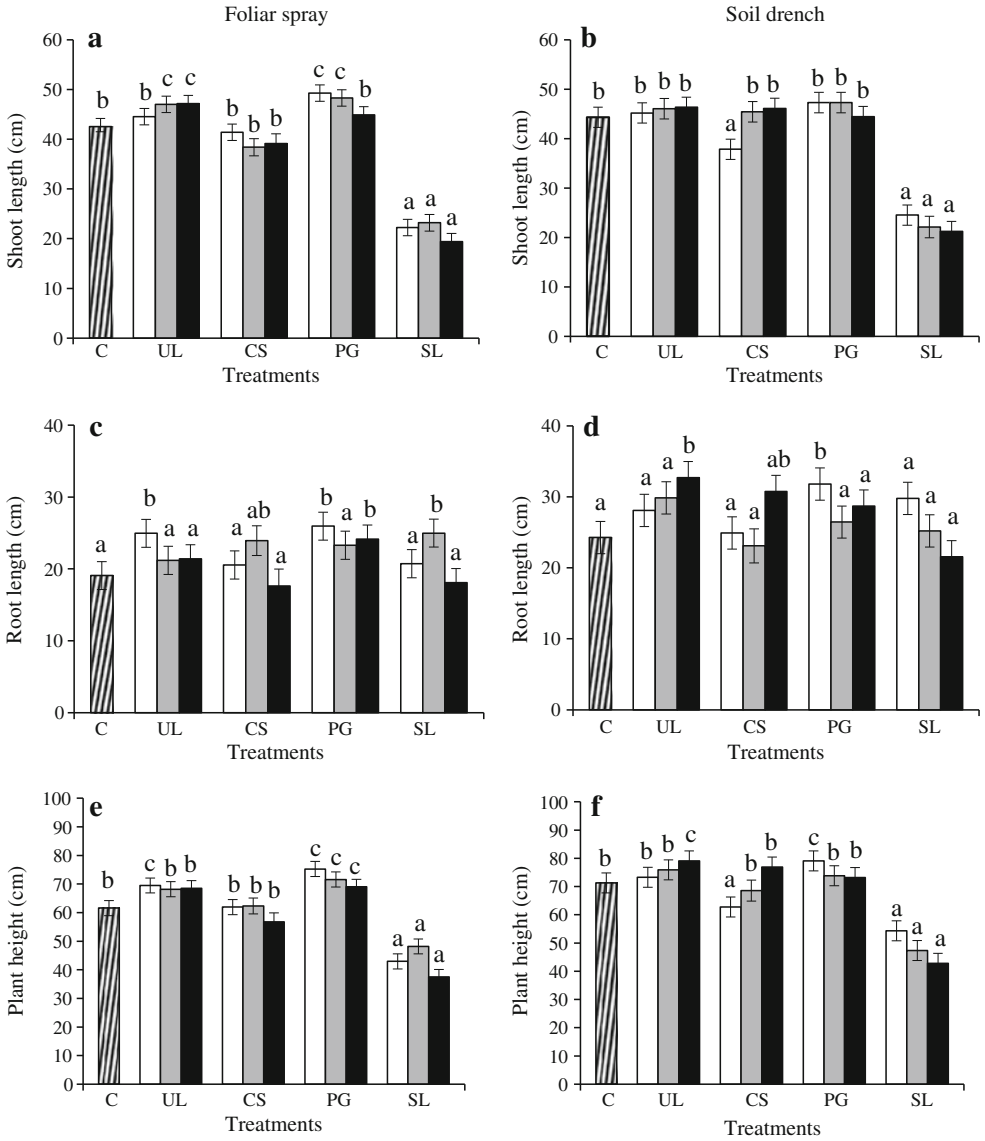


**Fig. 3** Effect of liquid seaweed extracts treatments applied as foliar spray and soil drench on **a**, **b** shoot length, **c**, **d** root length, and **e**, **f** total plant height of tomato at different concentrations: 0.2 % (*white columns*), 0.4 % (*gray columns*), and 1.0 % (*black columns*). Treatments: control (*C*), *U. lactuca* (*UL*), *C. sertularioides* (*CS*), *P. gymnospora* (*PG*), and *S. liebmannii* (*SL*). Columns denoted by a *different letter* are significantly different at $P \leq 0.05$. Values represent average ($n=10$ plants); *bars* represent standard error

suggested (Blunden and Gordon 1986). It has been indicated that betaine may work as a nitrogen source when provided in low concentration and serve as an osmolyte at higher concentrations (Naidu et al. 1987). Betaines have been shown to play a part in successful formation of somatic embryos from cotyledonary tissues and mature seeds of tea (Akula and Bateson 2000). All that information supports our results about seed germination and developed seedlings with LSEs.

Our results relate with those in the literature (Ashok-Kumar et al. 2012; Ganapathy Selvam et al. 2013; Kalaivanan and Venkatesalu 2012; Kumari et al. 2011; Sridhar and Rengasamy 2010, 2011), where seaweed extract at low concentration was used for a variety of plants without any harmful effects. Effect of seaweed extract on tomato seedlings was successfully demonstrated by Crouch and van Staden (1992, 1993). Tomato plants treated with LSE from *Ecklonia maxima* as a soil drench at 1.0 % increased root length and fresh weight, whereas foliar applications of the same product had no significant effect on shoot growth but showed effect on fresh weight at a concentration of 0.4 %. Also, seaweed extracts enhance nutrient uptake by roots (Crouch et al. 1990), resulting in root systems with improved water and nutrient uptake efficiency, thereby causing enhanced general plant growth and vigor. Our results agree with these trends. We showed that applications of LSEs from *U. lactuca* and *P. gymnospora* as a soil drench and foliar spray increased shoot length and root length of tomato plants. In another study, Kumari et al. (2011) reported an increase in root length, shoot length, and fresh weight in tomato treated with drench and foliar applications of LSE from *S. johnstonii*. Enhanced vegetative growth in tomato plants treated with a higher concentration of seaweed extract could be due to the mineral nutrients

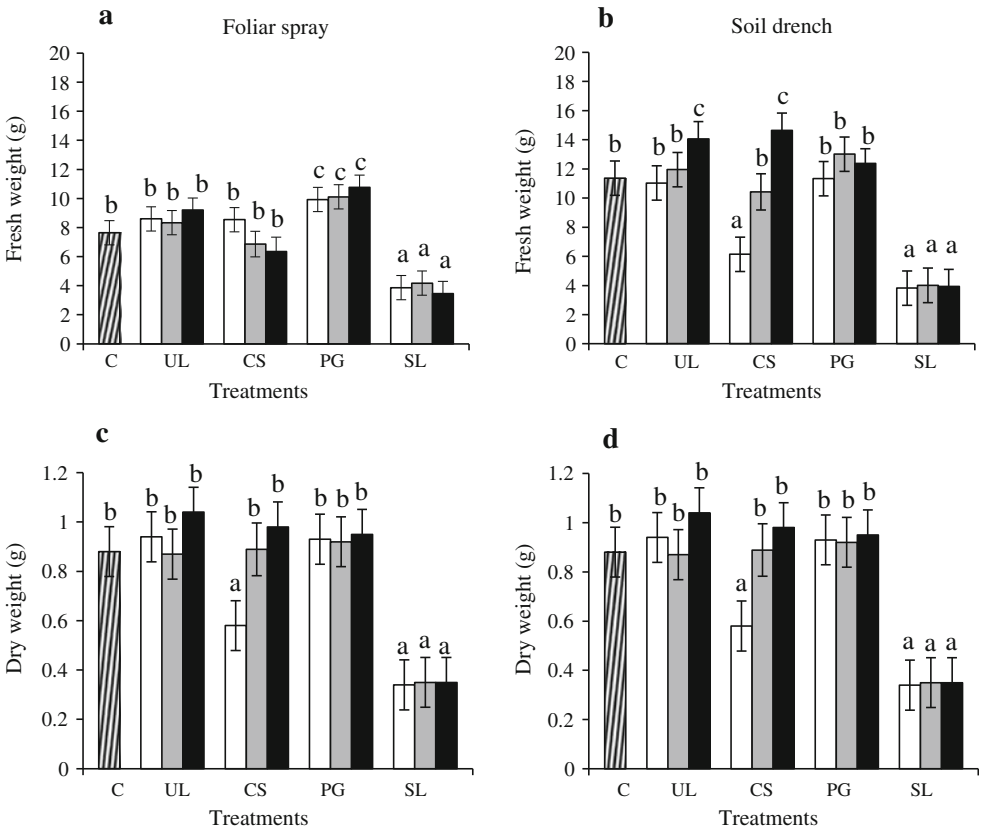


**Fig. 4** Effect of liquid seaweed extracts treatments applied as foliar spray and soil drench on **a**, **b** fresh weight and **c**, **d** dry weight of tomato at different concentrations: 0.2 % (*white columns*), 0.4 % (*gray columns*), and 1.0 % (black columns). Treatments: control (*C*), *U. lactuca* (*UL*), *C. sertularioides* (*CS*), *P. gymnospora* (*PG*), and *S. liebmannii* (*SL*). Columns denoted by a *different letter* are significantly different at $P \leq 0.05$. Values represent average ($n=10$ plants); *bars* represent standard error

present in the LSE. The beneficial effect of seaweed extract application can be attributed to its many components working synergistically at different concentrations (Fornes et al. 2002). Similar, studies conducted with LSEs applied by sprays under controlled experiments resulted in increased height and improved root growth in tomatoes (Verkleij 1992; Zodape et al. 2011). Other positive results were reported in spinach and tomatoes (Featonby-Smith and van Staden 1983; Finnie and van Staden 1985). This enhanced growth effect is thought to be due to various organic compounds present in the seaweed extracts. In the present research, it was not possible completely establish the relationship between minerals and growth of tomato plants. However, a possible explanation for these results may be due to the presence of P in LSEs. The LSEs or liquid seaweed fertilizers can help stimulate root proliferation and enhance root-to-shoot ratio, thereby making the plants more able to mine adequate nutrients from the deeper soil layers and influence crop maturity as a whole. Since liquid seaweed fertilizer is a very good source of K, it helps in regulating the water status of the plants, controls the opening and closing of stomata, and thereby, to a large extent, controls the photosynthesis. Meristematic growth, translocation of photosynthates, and disease resistance are also influenced by the presence of K. The Ca in seaweed extracts helps in enzyme activation, cell elongation, and cell stability. The organic constituents of seaweed extract include plant hormones which elicit strong physiological responses in low doses (Pramanick et al. 2013).

In conclusion, this study shows that liquid seaweed extracts from *U. lactuca* and *P. gymnospora* were more effective at stimulating the growth of tomato seedlings, and therefore, they are potential candidates for the production of effective biostimulants. Surprisingly, the extracts of both species showed better results when they were applied at lower concentrations than more concentrated extracts. This shows that only a small amount of seaweed extract can be used or even could be mixed with commercially available fertilizers to enhance plant growth. In places where inorganic fertilizers are limited, LSEs may provide a powerful and environmentally friendly approach to nutrient management. This study provides valuable information on the identification and utilization of Mexican seaweed resources for agriculture. The presence of inorganic minerals in LSEs makes them an excellent choice as organic fertilizers. The practice of applying eco-friendly seaweed extract can therefore be recommended to growers to help attain better germination and growth of tomato or other crops. Future studies on specific mechanisms attributed to plant growth are required to determine the potential of *U. lactuca* and *P. gymnospora*

as commercial growth biostimulants which can be promoted as eco-friendly biofertilizers across Mexico.

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