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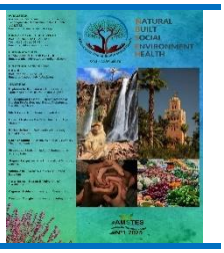

Potential Use of *Sargassum Muticum* as a Source of Plant Biostimulants for the Germination and Growth of Radish (*Raphanus sativus* L.) Through the Application of Eco-Friendly Extracts for Sustainable Agriculture

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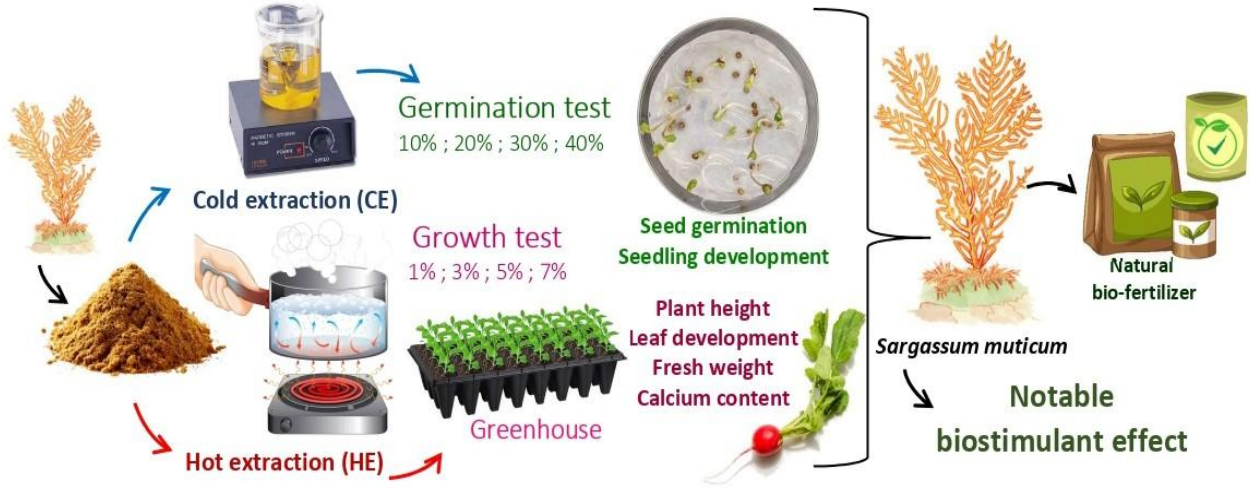
Graphical Abstract

This study demonstrates the biostimulant potential of the alien brown alga *Sargassum muticum*, showing that eco-friendly hot and cold extracts significantly enhance seed germination and early seedling growth of radish at low concentrations under in vitro conditions. Under greenhouse conditions, the cold extract applied at higher concentration promoted plant growth, biomass accumulation, and calcium enrichment in roots, supporting the use of *S. muticum* as a natural and sustainable biofertilizer.



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Abstract: In recent years, seaweed has gained increasing attention for its biostimulatory properties, offering sustainable alternatives to synthetic fertilizers and pesticides. This study evaluated the biostimulant potential of the alien brown alga *Sargassum muticum* on seed germination and the growth of radish plants (*Raphanus sativus* L.) through in vitro assays and greenhouse experiments under natural conditions. Two eco-friendly extracts (hot and cold) were prepared and applied at different concentrations. Low extract concentrations (10% and 20%) significantly enhanced seed germination and early seedling growth, notably stem length and fresh biomass. Under greenhouse conditions, treated plants showed increased total height, leaf development, fresh weight, and calcium content, with the most pronounced effects observed with the high-concentration cold extract (7%). These findings highlight the strong biostimulant potential of *S. muticum* and support its use as a natural biofertilizer for sustainable agriculture.

Keywords: *Sargassum muticum*, Seaweed biostimulant, *Raphanus sativus.*

Introduction

World population growth requires world food production systems to meet demand by increasing supply, especially in Africa, where the population is projected to increase by over 50% by 2050 [1,2]. The increased application of chemical fertilizers to this end has introduced costly but toxic chemicals into the environment with risk to human health [3]. Application of conventional chemical fertilizers can supply crops with mineral nutrients; but their inappropriate use may result in negative effects such as leaching, volatilization, and nutrient fixation in the soil, leading to reduced fertilizer efficiency [4,5]. This scenario is a challenge to develop eco-friendly and innovative methods that increase agricultural yields with minimal inputs [6,7] by adopting sustainable production practices that reduce or replace chemical inputs, including chemical fertilizers and pesticides, with natural or biological substances. Seaweeds are natural marine algae that possess several properties and can act as natural preservatives, extending the shelf life of perishable foods without causing adverse effects [8]. Seaweeds and their derivatives are highly promising biological materials useful as potential plant growth regulators. Several marine algal extracts have been evaluated for their effectiveness in promoting growth and fertilization efficiency in crops such as tomato, alfalfa, basil, parsley, cereals, and pulses [9-13].

Several commercial seaweed extract products are available for use in agriculture and horticulture. Various types of seaweeds are used as liquid fertilizers, applied as foliar sprays, soil drenches, or in granular or powder form as soil conditioners and manure [14]. *S. muticum* is a brown alien seaweed of Japanese origin that was first detected in 2012 during a field trip along the shoreline of Doukkala (Atlantic coast of Morocco, Northwest Africa) [15]. Our bioecological study of *S. muticum* provides recent data on its invasion in Morocco and confirms that its density has increased over the past seven years [16]. Several studies show that *S. muticum* contains a wide range of bioactive compounds, including alginates, sulphated polysaccharides, fucans, steroids, pigments, and flavonoids, as well as minerals and phytohormones (cytokinins and auxins) [17-19]. There is also growing interest in developing effective control and/or eradication strategies for this invasive alga, given its negative impacts on marine ecosystems, human health, and the economy [20]. It is therefore important to develop multiple valorization pathways for the harvested biomass, particularly in agriculture, because it is rich in active substances that may function as effective biofertilizers, e.g., for the *Brassicaceae* family [21].

Raphanus sativus L., commonly known as radish, is a species belonging to the genus *Raphanus*, as supported by phylogenetic studies of the *Brassicaceae* family [22]. Based on the analysis of 63 published papers on the nutritional and phytochemical composition of *R. sativus* L., the review by Gamba *et al.* [23] identified 609 phytochemicals in radish, with major constituents including

flavonoids, non-flavonoid polyphenols, fats and fatty acid-related compounds, terpenes and their derivatives, and glucosinolates, reported at high concentrations in leaves and sprouts. These findings emphasize the contribution of this plant to a healthy and balanced diet. It is nutritious, being rich in dietary fibre, flavonoids, glucosinolates, and vitamin C [24].

Moreover, radishes are low in calories and represent a good source of calcium, magnesium, copper, manganese, potassium, vitamin B6, vitamin C, and folate [24,25]. Dietary fibre promotes intestinal transit, and flavonoids contribute to the prevention of diseases associated with oxidative stress, including cardiovascular diseases and diabetes. Several other medical benefits are attributed to radish or its extracts, such as antidiabetic, anticancer, and hepatoprotective effects, and they may be employed to treat several organ disorders [23,26,27]. The EPIC cohort in Europe provided evidence indicating that radish consumption accounted for 6% of the total intake of *Brassicaceae* vegetables. Radish was ranked fifth in terms of consumption, with cauliflower, broccoli, and white and common cabbage being more widely consumed [28]. To date, there has been no evaluation of the biostimulant effects of *S. muticum* extracts on plant growth promotion in Morocco. The identification of an effective extract is critical to ensuring the economic feasibility of a given project. The use of biostimulant products can help achieve environmental sustainability through the reduction of ecological harm associated with synthetic compounds. This approach also supports ecological diversity by minimizing long-term environmental damage linked to synthetic inputs. In this context, the aim of the present study was to assess the effects of *S. muticum* extracts on seed germination and the growth of radish plants, using two eco-friendly extraction methods.

Materials and Methods

Biological material

Seaweed sampling and powder preparation

In this study, the brown seaweed *S. muticum* was used to evaluate its biostimulant effects on radish. *S. muticum* was collected from Sidi Bouzid (SB), El Jadida, Morocco, during the spring season (33° 13′ 52″, 8° 32′ 51″). At the study site, the alien seaweed *S. muticum* is frequently present and forms an extensive canopy. Thalli were hand-picked and immediately thoroughly washed with seawater (previously collected from the local beach) to remove impurities, then placed in an icebox and transported to the laboratory. Upon arrival at the laboratory, epiphytic material on the thalli was removed using paper towels, without damaging the algal tissues. The samples were then carefully rinsed with tap water and dried at ambient temperature. Finally, the dried seaweed was cut with scissors into small pieces of a few centimetres, then ground into a powder using an electric grinder, and stored at 20 °C for further use.

Seeds collection

In this study, we used radish (*Raphanus sativus* L.), a national variety**,** as plant material. The seeds were obtained from the company BADRA s.a.r.l., Casablanca [29].

Preparation of Seaweed Liquid Fertilizer (SLF)

Seaweed Liquid Fertilizer (SLF) was used to evaluate its effects on germination, growth, and mineral content in *R. sativus* L. (radish). For this purpose, two extracts were prepared using two different eco-friendly extraction methods, referred to as green, according to the following protocols:

Cold extraction (CE)

The crushed seaweed powder was mixed with distilled water at a ratio of 1:20 (w/v)**.** The mixture was incubated for one day (24 h)**.** Thereafter, the extract was filtered through Whatman No. 1 filter paper**,** and the obtained filtrate was considered to be 100%**.**

Hot extraction (HE)

The powder was boiled with water at a 1:1 ratio (w/v) for 2 h**.** The homogenate was filtered using Whatman No. 2 filter paper**,** and the extract was stored in amber-coloured bottles at 4 °C.

Treatment of Radish Seeds

In vitro germination test

The seeds were disinfected with bleach**,** then rinsed thoroughly with distilled water and placed to dry on absorbent paper for a few minutes. The dilutions of the algal extract were prepared with distilled water. Ten seeds of approximately the same size were sown on filter paper (two layers) placed in Petri dishes (10 cm in diameter) containing 10 mL of algal extract at different concentrations (C1: 10%, C2: 20%, C3: 30%, and C4: 40%), and the control contained 10 mL of distilled water (0% algal extract). The experiment was conducted in triplicate (n = 3). Finally, the Petri dishes were incubated in an incubator in darkness at 25 ± 2 °C [30-31]. Germination was monitored for 7 days**,** and the different germination parameters were determined as follows:

- Germination percentage after 3 days: $GP = (N \times 100) / Nt$
- GP: germination percentage; N: number of germinated seeds; Nt: total number of seeds sown.
- Stem and root length: measured using a ruler to assess seedling growth after 7 days of germination.
- Germination kinetics: the number of germinated seeds was counted daily until the 7th day.

- Seedling size: measured using a ruler to assess seedling growth 7 days after germination.
- Fresh weight of seedlings: expressed in grammes (g).

Growth test

- Pot Method

The seeds of radish (*Raphanus sativus* L. var. National**),** certified as homogeneous and of approximately the same size, were disinfected with hydrochloric acid, washed several times with distilled water, and then dried on filter paper for a few minutes before germination in plastic pots containing soil. In each pot, the seeds were watered twice a week with the algal extract (root application) at different concentrations (C1: 1%, C2: 3%, C3: 5%, and C4: 7%), as well as a control (0% algal extract). All the pots were placed in an experimental greenhouse (22 ± 3 °C and 50–60% relative humidity) within the Regional Centre for Agronomic Research in Agadir **(**INRA, Morocco**).** The experiment was conducted in triplicate over a period of 47 days [30-32].

- Growth parameters

To analyse the growth parameters and the biochemical parameters, plants were harvested after 47 days of cultivation. After measuring the growth parameters**,** the radish roots were separated from the leaves and washed with tap water to eliminate surface residues, then stored at −20 °C for the mineral assay [30-32].

-Biometric parameters

To assess the effect of different concentrations of each extract (prepared by decoction or maceration) on the growth of *R. sativus L*. plants, several biometrical parameters were determined, namely:

- Final height of the plants was measured using a graduated ruler.
- Size of Leaves and roots were measured using a graduated ruler.
- Fresh weight of each plant, the fresh weight of the root and the leaves (fresh biomass produced) were measured using a precision balance type PR5003.

To assess the effect of different concentrations of each extract (prepared by decoction or maceration) on the growth of *R. sativus* L. plants, several biometrical parameters were determined, namely:

- Final plant height was measured using a graduated ruler.
- Leaf and root size were measured using a graduated ruler.

- Fresh weight of each plant, including root and leaves (fresh biomass produced), was measured using a precision balance (PR5003)

Biochemical parameter

Chlorophyll content

The total chlorophyll contained in the leaves of radish plants was measured using the CCM-300 device.

Mineral content

Trace elements such as potassium and calcium contained in the roots were measured using a flame photometer [33].

Statistical analysis

Statistical analysis was performed using one-way ANOVA with the R software. The means of the three replicates were compared using the Kruskal–Wallis test (rank-sum test, a non-parametric test analogous to ANOVA) and the pairwise test **(**pairwise comparisons) at a significance threshold of 5%**,** and results were considered significant when P was less than or equal to 0.05**.** Spearman correlation and cluster analyses were conducted using the PRIMER/PERMANOVA statistical software package on the different concentrations of the two types of extracts to assess their impact on the germination and growth parameters of radish plants. The data presented in the figures represent the means of three replicates (n = 3) with their corresponding standard deviations.

Results

In vitro germination test

In this experiment, two types of *S. muticum* extracts were formulated using environmentally friendly extraction methods. The first extract was obtained through cold maceration (M), and the second was produced by thermal extraction (D). For each extract type, **f**ive treatment concentrations were prepared: control (T, 0%), C1 (10%), C2 (20%), C3 (30%), and C4 (40%). These treatments were applied to radish seeds to evaluate their potential biostimulant effects. The assessment focused on key germination and early growth parameters, including germination percentage (%G), germination kinetics (GK), plant size (PS), root length (RL), stem length (SL), and fresh plant weight (FPW).

Germination rate

The germination rate of *R. sativus* (radish) seeds was measured after three days of germination (Figure 1). These results indicate that the tested extracts exert a positive effect on the germination of radish seeds. Specifically, concentrations C1M (10%), C3M (30%), and C1D (10%) resulted in a maximum germination percentage of 100%**,** suggesting that these concentrations are optimal for promoting radish seed germination**.** By contrast**,** the C4D treatment exhibited the lowest germination rate (87%)**,** whereas the control treatment showed a germination rate of 93.3%**.** No significant difference (P > 0.05**)** was observed among the different concentrations and the control (0%)**,** as determined by the Kruskal–Wallis test**.**

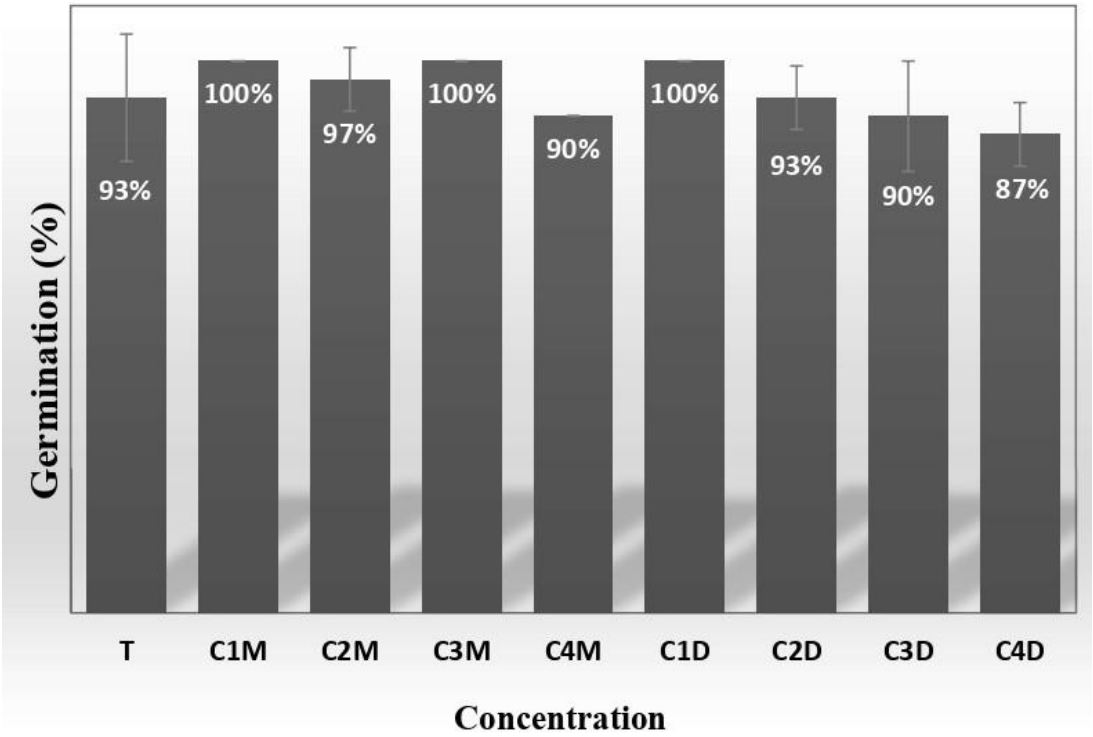

Figure 1. Effect of two *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D) at different concentrations (0%, 10%, 20%, 30%, and 40%) on the germination rate of *Raphanus sativus* L. seeds after 72 h. Values represent means ± standard deviation (n = 3).

Germination kinetics

The germination kinetics (Figure 2) demonstrates the daily monitoring of radish seed germination.

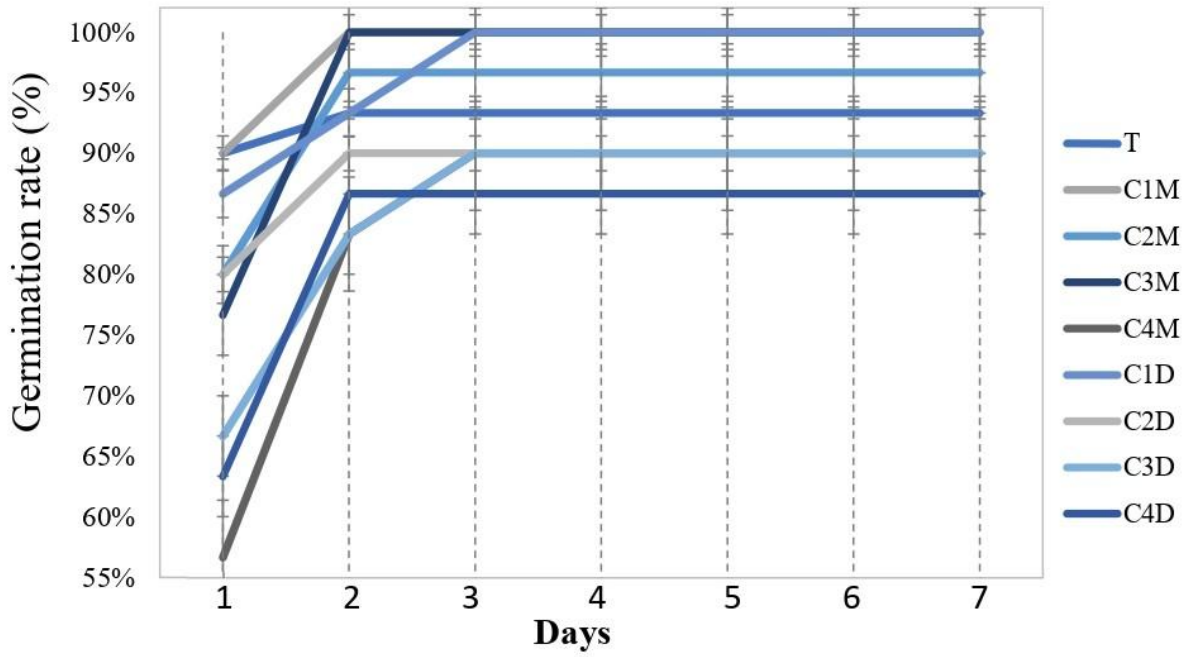

Figure 2. Germination kinetics of *Raphanus sativus* L. seeds over a 7-day period following treatment with *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D) at different concentrations (0%, 10%, 20%, 30%, and 40%).

In terms of germination rate, the cold extraction method at 10% and 30% concentrations achieved a 100% germination rate within 48 hours**.** By comparison**,** the hot extraction method at 10% concentration required 72 hours to reach the same result.

The results indicate that the germination rate of radish seeds treated with extract concentrations obtained via cold extraction (10% and 20%) was significantly higher than that of the control (0%), which achieved a final germination rate of 93%**.** This response was not recorded for the other concentrations of both extract types. Seeds treated with C1M, C3M, and C1D reached a final germination rate of 100%**,** whereas the control seeds exhibited a germination rate of 93%.

These results indicate that the lowest concentration of the cold extract reduced the time required to reach 100% germination to only 2 days**,** compared to the control and the higher concentrations. For the hot extract, the C1D concentration resulted in a 100% germination rate after 72 hours.

Fresh plant weight

The application of the two *S. muticum* extracts showed a positive effect on the fresh weight of seedlings (FPW) after 7 days of germination**.** This effect was more pronounced at lower extract concentrations (Figure 3).

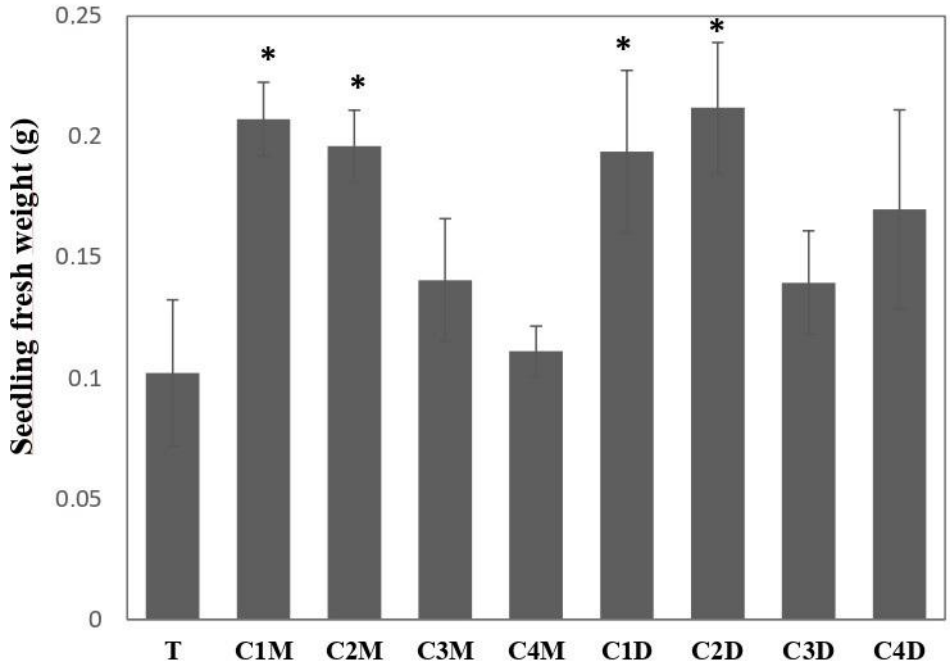

Figure 3. Variation in seedling fresh weight of *Raphanus sativus* L. under different treatments. C1 (10%), C2 (20%), C3 (30%), and C4 (40%) correspond to increasing concentrations of *Sargassum muticum* extracts obtained by cold maceration (M) or hot extraction (D). Values represent means ± standard deviation (n = 3). * indicates a significant difference compared with the control (T, 0%), according to the Kruskal–Wallis test ($P \leq 0.05$).

The two concentrations of cold extraction **(**C1M: 10% and C2M: 20%**)** significantly increased the fresh biomass of the seedlings by 5% compared to the control (0%). The mean values of the seedling fresh weight were 0.207 g and 0.196 g for C1M and C2M, respectively, whereas the control recorded the lowest value (0.102 g). Similar results were obtained for the C2D and C1D treatments**,** with fresh weight values of 0.212 g and 0.139 g**,** respectively.

Radish seedlings treated with 10% and 20% extracts**,** prepared by cold or hot extraction**,** showed improved responses compared to the control **(**$P < 0.05$**).** As the concentration of both extract types increased**,** a reduction in seedling fresh weight was observed**,** reaching minimum values of 0.111 g for cold extraction (M) and 0.139 g for hot extraction (D)**.**

These results suggest that seedling fresh weight is not significantly influenced by extract concentrations above 20%**.** No significant differences were recorded for C3 and C4 of both extract types **(**D and M**)** compared to the control**.**

Size of seedling, stem and roots of radish

Seedling size (SZ) was measured to assess the impact of the two extracts (D and M) at various concentrations on seedling growth after 7 days of germination (Fig. 4).

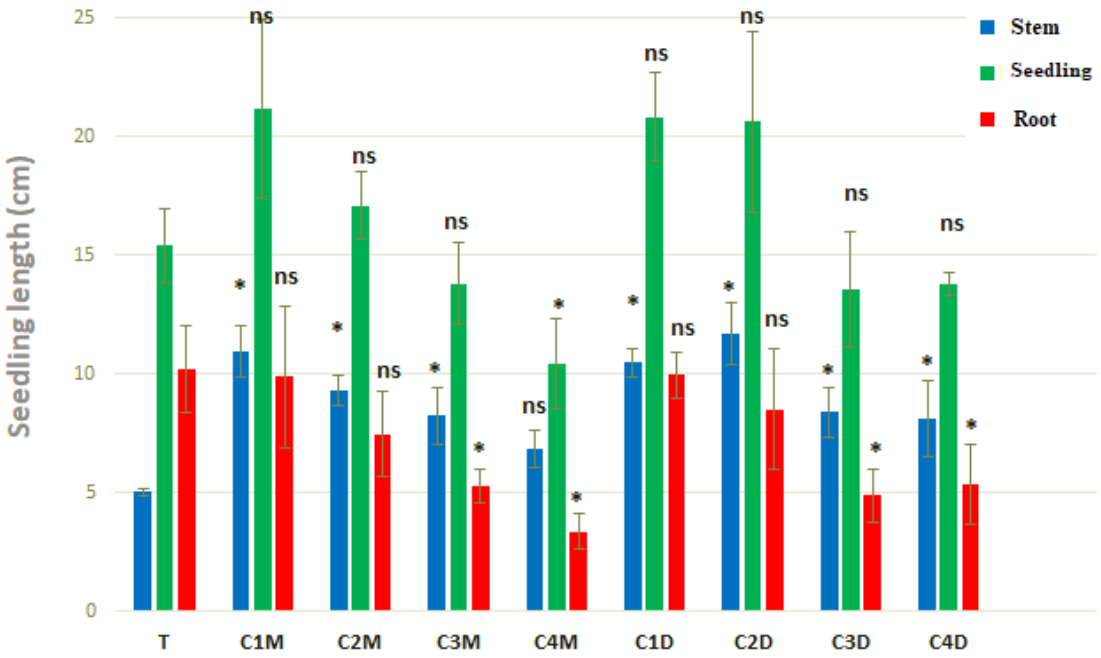

Figure 4. Variation in seedling, stem, and root length of germinated *Raphanus sativus* L. seeds under different treatments with *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D) at increasing concentrations. Values represent means ± standard deviation (n = 3). * indicates a significant difference compared with the control (T, 0%), according to the Kruskal–Wallis test ($P \leq 0.05$); ns indicates no significant difference.

Compared to the control group, a positive effect was observed for treatments using both extracts (M and D) on seedling and stem size**,** whereas a negative effect was observed on root growth**.** The analysis of the results indicates that the size of the seedlings and their stems in the Petri dishes treated with the concentrations C1M, C1D, C2M, and C2D was greater than that of the control**.** Above C2M, a decrease in seedling size was recorded**,** indicating an inhibitory effect of the extracts at higher concentrations**.**

There was no significant difference in seedling size among the different treatments of the two extracts and the control group ($P > 0.05$). At lower concentrations, C1 and C2 (10%), the extracts stimulated radish seedling growth, as shown by the increased and optimal size of the stem and seedlings, together with higher fresh weight.

Understanding treatment-variable interactions using hierarchical clustering and Spearman correlation analysis

Spearman correlation was performed to assess the correlation between various germination parameters, Figure 5 shows the results.

The cluster analysis and Spearman correlation test of the entire dataset (Fig. 5a and b) show that

the different treatments are generally classified into four groups according to their effects on the germination of radish seeds**.** G1: the control group, treated with distilled water, is clearly distinct from all other treatments. G2: low concentrations **(**C1: 10% and C2: 20%**)** of extracts obtained by cold and hot extraction resulted in optimal germination performance compared with the control. G3: intermediate concentrations of both extract types led to moderate germination responses, with values close to those of the control**.** G4: high concentrations, obtained using both extraction methods, exhibited reduced germination effects compared to the control.

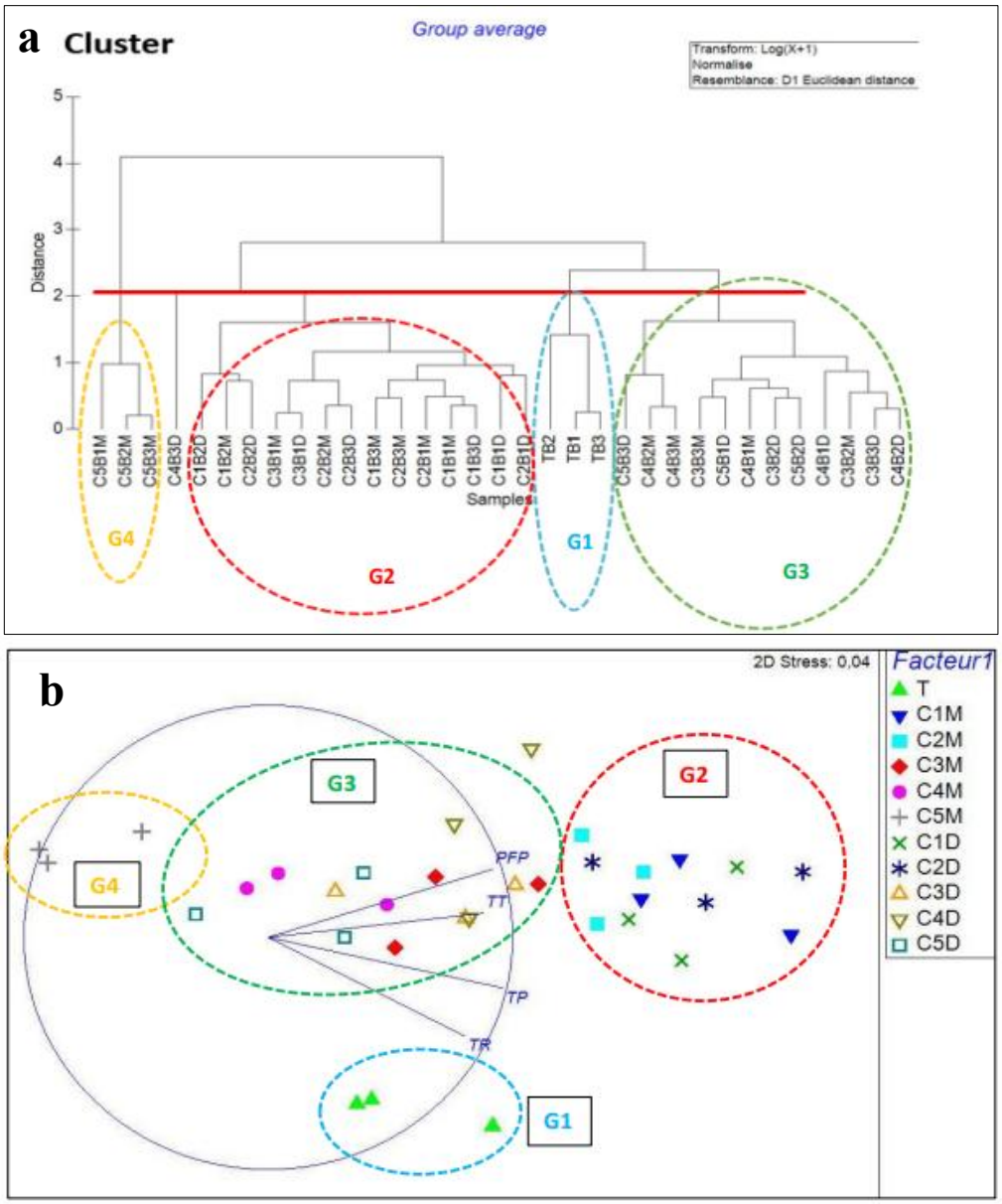

Figure 5. (a) Dendrogram of the hierarchical cluster analysis showing the grouping of treatments according to their effects on radish germination parameters. (b) Score plot of the principal component analysis (PCA) performed on different concentrations of *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D). Abbreviations: Control (T), Concentration 1–4 (C1–C4), Cold extract (M), Hot extract (D), and Cluster (G).

Effect of Sargassum muticum extracts on radish growth.

Biometric parameters

- Plant size

The radish plants cultivated in the greenhouse were treated with the cold and hot extracts of *S. muticum* (Fig. 6).

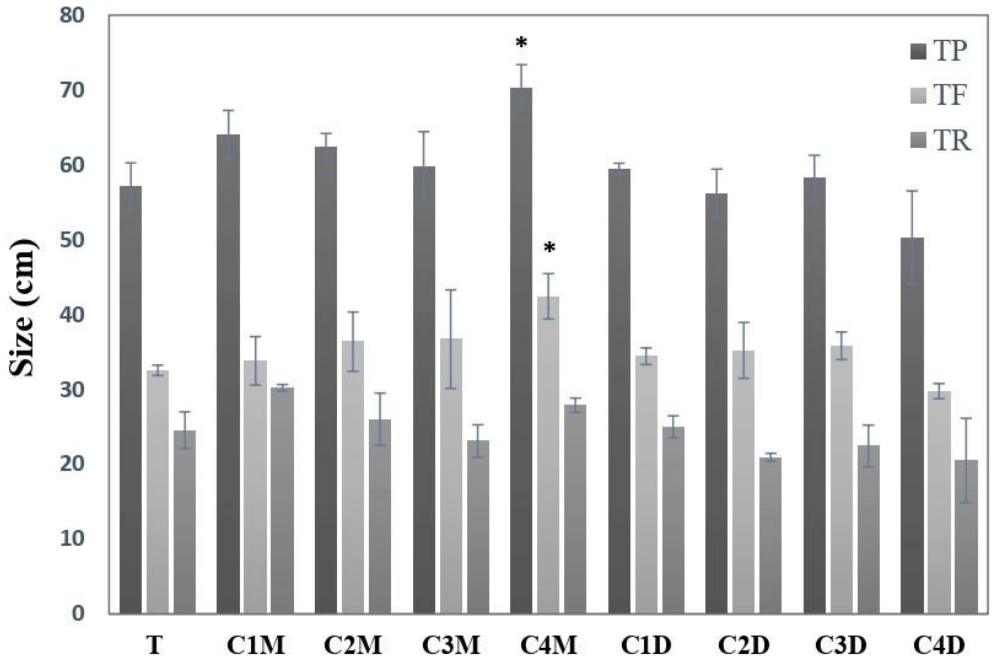

Figure 6. Variation in the size of different parts of *Raphanus sativus* L. plants (total plant height, leaf length, and root length) under different treatments with *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D). Values represent means ± standard deviation (n = 3). * indicates a significant difference compared to the control (T, 0%), according to the Kruskal–Wallis test ($P \leq 0.05$).

The results demonstrated a significant ($p<0.05$) improvement in the growth of radishes. Indeed, plants treated with C4 of the cold extract exhibited a positive effect on plant size, reaching 70.33 cm, compared with control plants measuring 57.11 cm. Similar results were observed for the length of radish leaves, which also showed a significant difference ($p<0.05$), with the C4M concentration promoting leaf elongation to 42.44 cm compared to control plants measuring 32.55 cm. In contrast, this concentration did not show a significant positive effect on root growth when compared to the control**.**

- Fresh weight

Figure 7 shows the results for fresh weight of radish plants, leaves and roots.

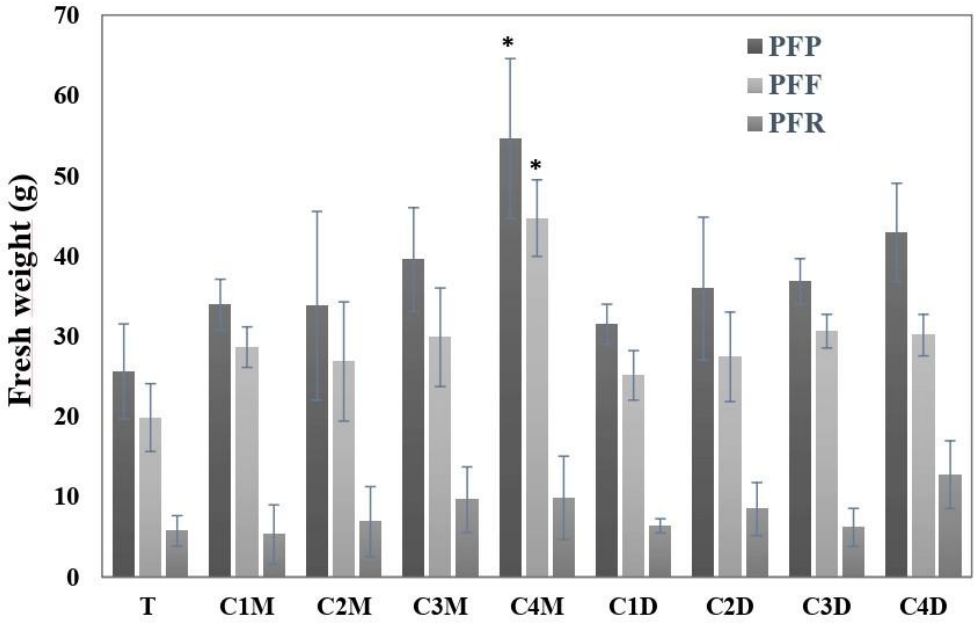

Figure 7. Variation in the fresh weight of different parts of *Raphanus sativus* L. plants (whole plant: PFP; leaves: PFF; roots: PFR) under different treatments with *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D). Values represent means ± standard deviation (n = 3). * indicates a significant difference compared to the control (T, 0%), according to the Kruskal–Wallis test ($P \leq 0.05$)

The results revealed a significant ($p < 0.05$) improvement in the fresh weight of both plants and leaves, measuring 54.61 g and 44.78 g, respectively, compared to the control, which recorded 25.64 g for plants and 19.85 g for leaves. No significant difference was observed in root fresh weight when compared to the control. By contrast, other treatments with both types of extracts did not show a significant difference when compared to the control. Accordingly, the most favourable response was observed in plants treated with the C4M extract prepared by cold extraction**.**

Biochemical parameters of radish

The biochemical parameters measured in this study included total chlorophyll content in the leaves and the concentrations of minerals, including potassium (K^+) and calcium (Ca^{2+}), in the roots**.**

Total chlorophyll in leaves of radish

The results indicated that the total chlorophyll content in the leaves of radish plants treated with the different treatments**,** including both types of extracts (M and D), showed no significant difference ($p > 0.05$). It can therefore be concluded that neither extract type exerted a positive effect on chlorophyll synthesis in radish plants**.**

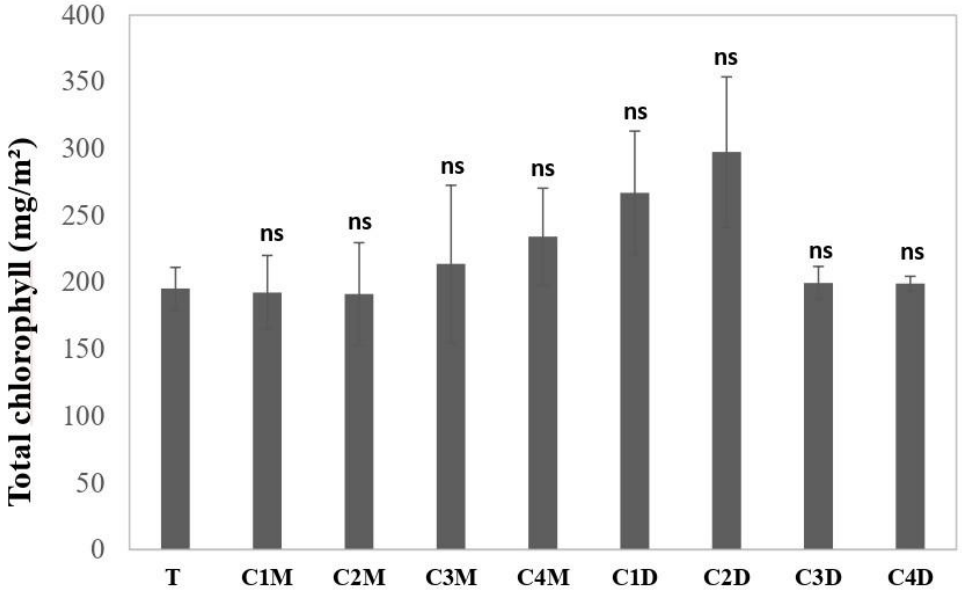

Figure 8. Total chlorophyll content of *Raphanus sativus* L. leaves under different treatments with *Sargassum muticum* extracts. Values represent means ± standard deviation (n = 3). **ns** indicates no significant difference compared to the control (T, 0%), according to the Kruskal–Wallis test (P > 0.05).

Mineral content in the roots of radish

Figure 9 shows the results for the minerals content (calcium and potassium) in the roots of the radish in below.

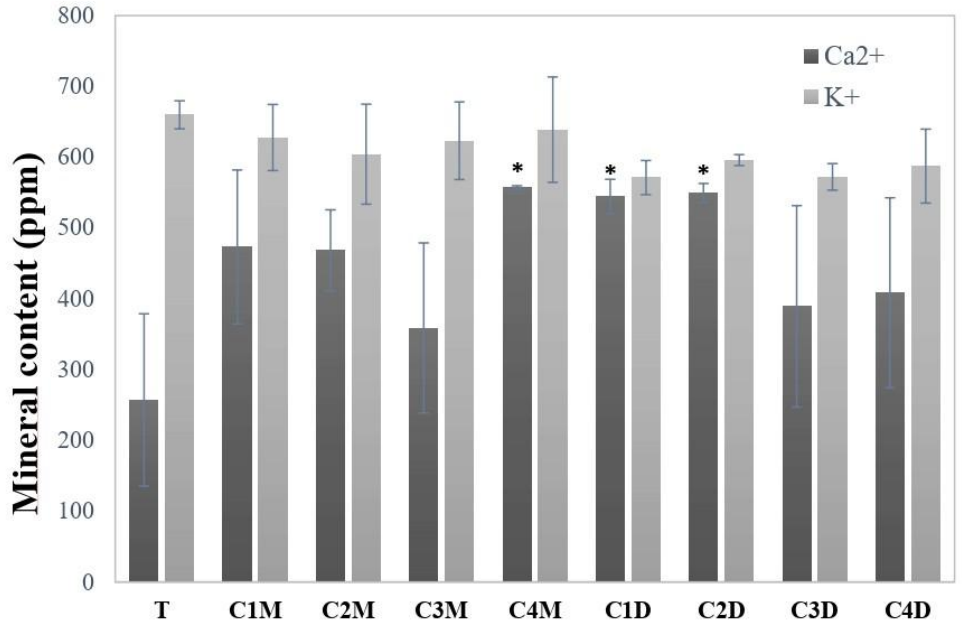

Figure 9. Mineral content of calcium (Ca^{2+}) and potassium (K^{+}) in the roots of *Raphanus sativus* L. under different treatments with *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D). Values represent means ± standard deviation (n = 3). * indicates a significant difference compared to the control (T, 0%), according to the Kruskal–Wallis test (P ≤ 0.05).

The calcium content exhibited a significant difference ($p < 0.05$) between three concentrations (C4M, C1D, C2D) and the control, which had the lowest value of 257.2 ppm. The remaining concentrations showed no significant difference when compared to the control (0%).

No significant difference ($p > 0.05$) was observed for the potassium content of the roots when compared to the other concentrations and the control group. Accordingly**,** the concentrations that increased the calcium content were C4M, C2D, and C1D, with values of 557.4 ppm, 549.7 ppm, and 544.9 ppm, respectively.

Understanding treatment-variable interactions using hierarchical clustering and Spearman correlation analysis

The Spearman test was performed to examine the correlation between different growth parameters, including biometric and biochemical measurements. Figure 10 shows the results of this analysis.

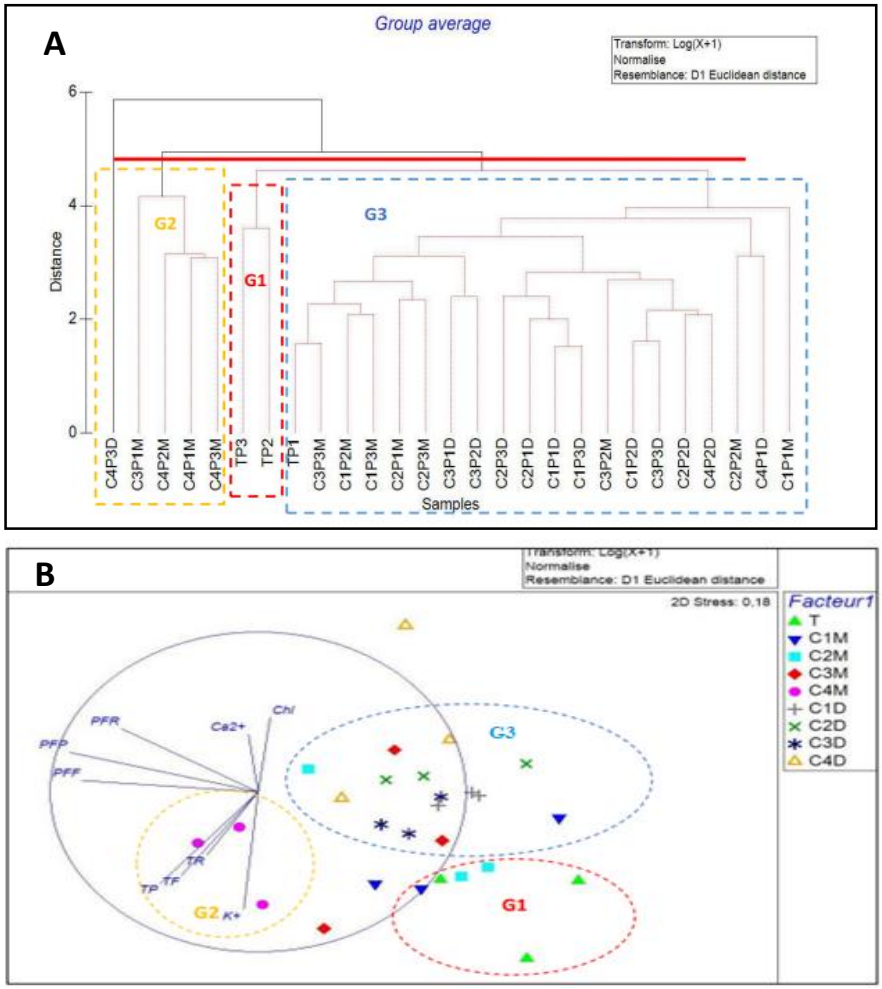

Figure 10. (A) Dendrogram of the hierarchical cluster analysis illustrating the grouping of treatments based on biometric and biochemical parameters of radish plants. (B) Score plot of the principal component analysis (PCA) showing the relationships between treatments and measured variables following application of *Sargassum muticum* extracts obtained by cold maceration (M) and hot extraction (D). Abbreviations: Control (T), Concentrations 1–4 (C1–C4), Cold extract (M), Hot extract (D), and Cluster (G)

The clustering analysis and Spearman correlation test of the entire data show that the different treatments are generally classified into three groups according to their effects on the growth parameters of radish plants. G1: the control group treated with distilled water, clearly distinct from the other treatments. G2: a group consisting of the C4M concentration of the extract prepared by maceration, which resulted in optimal growth performance, specifically in terms of plant size and fresh weight of radish plants when compared to the control. G3: a group encompassing the remaining concentrations of the two types of extracts, which exhibited a growth pattern similar to the control.

Discussion

Seaweed extracts are widely considered for their exceptional content of nutrients, vitamins, phytohormones, and secondary metabolites, making them a valuable and distinctive source of plant nourishment [34–36]**.** This has been associated with increased growth and crop yield [36,37].

Seed germination is one of the most crucial early stages in plant growth, typically defined as the emergence of the radicle from the surrounding tissues [38,39]. Acceleration of seed germination is characterized by an increase in germination speed associated with a reduction in mean germination time. Seed germination may be enhanced through faster germination, resulting in a shorter mean germination time.

The present study demonstrated that the two types of S. muticum extracts had no effect on the germination rate of radish seeds, whereas low concentrations (C1M, C2M, C1D, and C2D) at 10% and 20% showed a significant effect on the growth performance of germinated radish seedlings in terms of fresh weight, seedling length, and stem length. This observation is associated with the inherently high germination rates recorded across all treatments, including the control. Furthermore, radish seeds are known for their high and rapid germination capacity [28].

The effect of algae extracts on the fresh weight of plants appears to be linked to biostimulant compounds such as macro- and micronutrients**,** oligosaccharides, phlorotannins, and phytohormones (cytokinins and auxins). Several studies have reported similar findings [35,40]**.** By contrast, high concentrations (C3 and C4) for both extracts showed an inhibitory effect on seedling growth, particularly on root development. This response may be associated with elevated levels of growth regulators, including phytohormones (cytokinins and auxins) [41]**,** as well as nutrients such as minerals, vitamins, amino acids, soluble sugars, and other water-soluble metabolites present in both extracts [42].

In addition, this negative effect may be linked to increased osmolarity of the external seed environment**,** associated with high concentrations of ions and molecules, which can limit water uptake by the seeds and embryo during the initial phase of germination [43]**.** Moreover, most plants, including radish, are sensitive to salinity during germination and early development [44]. Several studies have reported that algal extracts promote seed germination at low concentrations and exert inhibitory effects at high concentrations [45, 46]**.** Moreover, the findings of the present study are consistent with research conducted by Dhir [47], Latique *et al.* [48], and Baltrusch *et al.* [49], which highlighted the enhancement provided by *Ascophyllum nodosum*, *Sargassum vulgare*, and *Sargassum muticum* extracts on the germination of fenugreek, bean, and watercress seeds, respectively. In addition**,** Baroud *et al.* [29] demonstrated that extracts of the brown alga *Fucus spiralis*, at various concentrations, improved the germination rate of tomato seeds, together with increased stem and root length, as well as seedling biomass.

Regarding the growth test, a significant improvement was observed in the final size of radish plants and leaves when compared to the control group. The most effective concentration was C4M (7%), resulting in a plant size of 70.33 cm and a leaf length of 42.44 cm. Moreover, this concentration led to a significant increase in plant and leaf fresh weight, along with an increase in calcium content at the root level**.** Similar results were reported by Silva *et al.* [50], who demonstrated the positive effect of *S. muticum* extract on lettuce plants. Moreover, it is well documented that seaweed extracts stimulate various aspects of plant development [51–54]**.** These studies provide evidence of the positive effects of seaweed extracts on plant growth, including enhanced germination, increased root and shoot growth, improved nutrient uptake, and overall plant vigour.

Various studies have demonstrated that *Sargassum* spp. hot and cold extracts contain a diverse range of metabolites such as fucoidans, proteins, lipids, pigments, minerals, and phenolic compounds [55–62]**.**

A possible explanation for these results is the positive relationship between the composition of *S. muticum* and the growth and development of radish plants. Accordingly, the presence of various metabolites and growth-promoting phytohormones in macroalgae is well documented [47,55–57]. At present, the debate continues on the mechanisms of action of these metabolites and phytohormones derived from algal extracts that enhance plant growth. There is a need for further investigation**.**

Conclusion

Our results indicated that the application of eco-friendly *S. muticum* extracts exerted a positive effect on both germination and growth parameters. These extracts were non-phytotoxic in assays with *R. sativus* L.

(radish) and significantly increased the growth performance of germinated radish seedlings at low concentrations (10% and 20%) for both methods. In addition**,** plant growth was enhanced and calcium content in the roots increased when a high concentration (7%) was applied using the cold extraction method under greenhouse conditions. Further studies are needed to understand the mechanisms in such growth stimulation and to assess the effect of these extracts on other plant species in order to develop eco-friendly and low-cost biostimulant products**.**

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Competing interests

The authors declare that they have no competing interests of a financial or personal nature, which could have influenced the design, conduct, analysis or interpretation of this scientific study.

Authors' contributions

All authors listed have made a substantial contribution to the work, and approved it for publication.

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Data availability

The data presented in this study are contained within the article.

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