

Article

Influence of Pelagic *Sargassum* spp. On Soil Amelioration for Seed Germination and Seedling Growth of Corn (*Zea mays*), Scotch Bonnet Pepper (*Capsicum chinense*), and Tomato (*Solanum lycopersicum*)

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Abstract

Pelagic *Sargassum* impacts the Caribbean and West Africa since 2011, disrupting economies and bringing major environmental, social, and health concerns. Avenues explored to valorise this biomass include the production of liquid biofertilisers and biostimulants. There has been less emphasis on the production of compost and mulch, and on their impact on plant growth. Therefore, the effects of compost and mulch prepared from rinsed and unrinsed *Sargassum* on corn, tomato, and pepper were investigated in this study. The elemental composition of soil, compost, mulch, and plant samples was also assessed to investigate the potential transfer of metals and metalloids from the compost and mulch to different parts of the plants (roots, leaves, and fruits). *Sargassum*-derived composts exhibited less effects on seed germination compared to mulch. Significant differences ($p \leq 0.05$) between treatments were observed for seedling growth parameters (height, shoot diameter, and number of leaves). Post-harvest parameters were mixed with the leaf area index and the root-to-shoot ratios varied significantly between treatments but not moisture content. Variations in elemental concentrations were observed between the different parts of the plants and evaluated against established nutritional recommendations and toxicity thresholds. This study provides foundational insights for optimising pelagic *Sargassum*-based compost and mulch preparation to support plant growth.

Keywords: algal blooms; pelagic *Sargassum*; valorisation; compost; mulch; crops; seed germination; seedling growth; elemental composition



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1. Introduction

Brown algae play key roles in ocean carbon fixation, engineering coastal marine ecosystems, and products derived from their biomass are used in several economic sectors. These organisms result from an intricate evolutionary history, harbour different shapes and morphologies, and most of them grow attached to the seafloor, although a few species spend their life floating in the ocean. Among these, *Sargassum natans* and *S. fluitans* are pelagic

species forming the Great Atlantic *Sargassum* Belt that stretches from the Gulf of Mexico to the West Coast of Africa, causing massive blooms and strandings (also referred to as *Sargassum* events) on both sides of the Tropical Atlantic since 2011 [1]. When accumulating near or on the shore, pelagic *Sargassum* brings major ecological disruptions, socio-economic losses in tourism and fisheries, and health concerns that have increasingly been documented in the last ten years [2–4]. Large scale blooms caused by another *Sargassum* species, *S. horneri*, have also been reported in Asia [5].

Brown algal biomass and derived products have many applications that support several industries, including food, animal feed, biofertilisers and biostimulants, biomaterials, and cosmetic formulations [6]. Since 2011, millions of tons of pelagic *Sargassum* accumulate every year along beaches and in coastal waters of the Caribbean and West Africa, and most of it is sent to landfills [7]. Numerous avenues for valorisation have been explored to mitigate the socio-economic and ecological risks presented by *Sargassum* blooms and to turn this nuisance into benefits [8,9]. As *Sargassum* events show no sign of abating, such approaches are important considerations in the context of *Sargassum*-specific adaptation policies [10]. One particular stream of research and valorisation is related to processing pelagic *Sargassum* into liquid extracts for soil amelioration and the improvement of plant growth and productivity. Indeed, several *Sargassum* species have been previously considered for similar applications. The aqueous extract of *S. johnstonii*, as well as granules and powder prepared from this alga, were shown to have great potential to increase the growth, yield, and quality of tomato plants [11,12]. *S. wightii* liquid extract at a low concentration showed a promoting effect on the growth and yield parameters of cluster beans [13]. In addition, tomato plants treated with *S. tenerrimum* extract exhibited improved seed, seedling, and yield parameters [14]. One of the initial studies investigating the biochemical and elemental composition of pelagic *Sargassum* suggested its potential utility as a fertiliser due to its macro and micronutrient profile, particularly its nitrogen-phosphorus-potassium (NPK) ratio [15]. However, this study did not report on arsenic (As), which has been shown since then to be present in high concentrations in pelagic *Sargassum* biomass collected in different parts of the Caribbean [16–20] and most recently in West Africa [21]. In different studies, the digestate resulting from the co-digestion of pelagic *Sargassum* with organic municipal solid waste was suggested as a potential fertiliser [22,23], although the research did not provide evidence based on plant experiment trials. In subsequent work, liquid extracts obtained from pelagic *Sargassum* biomass using different processes were tested. Hydroalcoholic extracts of *Sargassum* collected in Mexico were shown to increase the tolerance of tomato seedlings under salt stress [24]. Moreover, hydrothermal carbonisation and hydrothermal liquefaction processes were used to produce different fractions that were tested on *Arabidopsis thaliana* plants. Aqueous phase products derived from these processes at concentrations greater than 1%, inhibited root growth and lateral root formation, whereas concentrations below 0.1% combined with a nutrient mix provided the potential improvement in leaf and root growth [25]. In a different study, treatments with liquid fractions resulting from the fermentation of pelagic *Sargassum* by *Aspergillus niger* were shown to improve germination parameters and promote the development of tomato seedlings [26]. Finally, significant improvements in the production of bell pepper fruits and of several leafy green crop biomasses were observed in agronomic trials of the newly commercially available *Sargassum*-derived biostimulant Marine Symbiotic® [27].

In parallel to studies investigating the use of liquid extracts derived from pelagic *Sargassum*, other studies have explored the preparation and use of compost and mulch. Two independent reports described the preparation of compost based on mixing different proportions (up to 41.5%) of both washed and unwashed pelagic *Sargassum* combined with food waste and wood chips [28,29]. An assessment of the properties of the different

composts prepared showed that these products complied with the standards outlined by the U.S Composting Council (USCC). In one of these studies, levels of metals and metalloids were monitored in the several composts produced, and concentrations of As (total arsenic, ranging between 4.2 and 7.2 mg/kg) were within the range of safety set by the Environmental Protection Agency and for compost quality (<75 mg/kg, U.S. Composting Council 2002) [28]. Following these, the economic viability of composting *Sargassum* was investigated in the context of southeast Florida. Evaluation of sargassum management strategies and the analysis of sargassum composting strategies and market indicated that *Sargassum* composting could represent an economically viable option to balance some of the costs associated with beach cleaning [30,31]. However, there are currently limited studies describing the impact of adding *Sargassum* compost in soil amendment and on plant growth. For instance, compost prepared from pelagic *Sargassum* collected in Trinidad was mixed with a commercial substrate in different ratios, and these formulations were used to evaluate the performance and quality of hot pepper seedlings [32]. Notably, the *Sargassum*-containing formulations significantly enhanced the sturdiness of the seedlings. In a separate investigation, composts containing 50% to 100% washed and unwashed *Sargassum* harvested in Florida were evaluated to support the growth of radishes [33]. Here, the elemental analysis of the radish plants grown in the presence of different quantities of *Sargassum* compost revealed concentrations of As between 0.49 and 9.94 mg/kg and of cadmium (Cd) between 0.05 and 0.37 mg/kg, which exceeded toxicological limits (0.2 mg/kg for As and 0.05 mg/kg for Cd). These results suggested that *Sargassum* compost may not be recommended for the growth of root vegetables and highlighted the necessity for more research on its effects on different plant species.

In a recent investigation, we elucidated the potential utility of compost derived from *Sargassum* in enhancing the growth of seedlings of the red mangrove *Rhizophora mangle* under conditions prevailing in dry nurseries, with implications for mangrove restoration initiatives [34]. An analysis of the height and number of leaves of seedlings grown in the presence of different quantities of *Sargassum*-derived compost (SC) mixed with sand showed that the best growth was observed in the treatment containing 75% SC, while the control condition corresponding to 0% SC showed the poorest growth. However, seedling health was greatest in the control treatment and poorest in 50 and 100% SC [34]. Elemental analysis of the soil/sand medium, SC, and mangrove seedling samples indicated that certain elements (Na, K, Ca, As, and Se), which were present in elevated concentrations in the SC, were found to be significantly less concentrated in the plants, particularly in the leaves. Building on our work on mangrove seedlings and on previous studies on pelagic *Sargassum* compost, we investigated here the effect of compost and mulch prepared from rinsed and unrinsed *Sargassum* biomass on seed germination and the seedling growth of corn, tomato, and pepper. The comparative utility of the washed vs. unwashed *Sargassum* would be of importance to local users, as the process of washing with fresh water can be expensive, time consuming, and may lead to a decrease in the concentration of essential plant nutrients [35]. We also assessed the elemental composition of soil, compost, mulch, and plant samples to investigate the potential transfer of metals and metalloids from the compost and mulch to different parts of the plants (roots, leaves, and fruits). Such knowledge is currently very limited and of importance to decide if compost and mulch derived from pelagic *Sargassum* can be safely applied in an agricultural context and for feed and food production.

2. Materials and Methods

2.1. *Sargassum* Collection and Processing

Fresh *Sargassum* was collected from the swash zone along the Hellshire coastline (17°53'51" N 76°53'40" W), St. Catherine, Jamaica, between 2021 and 2022. The biomass was allowed to drain in perforated crates for 24 h in a cool and dark room. The algae were then separated to consider two conditions, unrinsed and rinsed biomass, before further processing. The rinsed portion was obtained by vigorously washing algae under running fresh water for five minutes to remove surface salt, sand, and debris. For the unrinsed portion, *Sargassum* biomass was cleaned by hand to remove sand and non-*Sargassum* debris.

For the preparation of compost, rinsed and unrinsed biomass were individually combined with sawdust, as described previously [36]. Specifically, eight volumes of *Sargassum* were combined with two volumes of sawdust (8:2 *w/w*, dry weight) and thoroughly blended for ten minutes until the sawdust and algae were completely integrated. The two separate batches were then allowed to compost outdoors in 1.5 m × 1.5 m × 1.5 m tarpaulin lined boxes and decompose for thirty days. The efficiency of the composting process was checked by ensuring that the electric conductivity of each treatment was below 1.9 dS cm⁻¹ using a RCYAGO soil EC and temperature meter [35]. Compost mixtures were then placed in opaque and sealed plastic containers in a cool and dark room to halt any further breakdown until use.

For preparation of mulch, fresh *Sargassum* was collected as indicated above and allowed to drain in perforated crates for four days in a cool and low-light controlled environment. The algae were then separated into two equal batches by weight, and these were treated as described above to obtain rinsed and unrinsed *Sargassum*. Subsequently, both batches were spread to a thickness of 2.54 cm on a tarpaulin lined table under a 50% sunblock knit shade house for seven days. Batches were then sealed in transparent plastic bags and stored in a cool and dry environment until use.

2.2. Plant Experimental Design and Layout

Plant parameters including seed germination, shoot height, photosynthetic capacity, shoot diameter, and plant health were assessed for 40 days using a randomised experimental design for the different treatments tested.

2.2.1. Seed Germination

Three plant species were considered: the monocotyledon *Zea mays* (corn), the dicotyledon *Solanum lycopersicum* (tomato), and *Capsicum chinense* (scotch bonnet pepper). Experiments were conducted over a 21-day period in a gable roof-style glass greenhouse at the Department of Life Sciences Botanical Gardens at the University of the West Indies, Mona campus, Jamaica, during September 2021 and July 2022. Germination experiments were performed in top covered 50-cell seed starter trays and comprised five treatments consisting of different combinations of soil (Lambert LMG-Org commercial soil, Lambert Peat Moss Inc., Rivière-Ouelle, QC, Canada) and *Sargassum*-based compost or mulch: CON, soil only; RC, 1:1 (*w/w*) ratio of soil and rinsed *Sargassum* compost; URC, 1:1 (*w/w*) ratio of soil and unrinsed compost; RM, 1:1 (*w/w*) ratio of soil and rinsed mulch; and URM: 1:1 (*w/w*) ratio of soil and unrinsed mulch.

The seed sowing was performed by hand in starter trays between October and November 2021, at about 1 cm deep. One hundred seeds per crop species were used for each treatment, with two seeds in each cell. The cells were watered with tap water immediately after sowing and every day until the final emergence. All observations on germination parameters were recorded at the time of germination, and monitoring was performed from the first germination until no further germination was observed at two-day intervals.

2.2.2. Seedling Growth

Seedling growth experiments were conducted in a gable roof-style glass greenhouse using a complete randomised block design, with five replications for each plant species and treatment as described above. Treatments as described for the seed germination experiments above (CON, RC, URC, RM, and URM) were conducted in 5 gallon (18.9 L) non-woven grow bags with a 30 cm soil depth. Forty-five-day-old seedlings from the seed germination CON experiment were transplanted into individual treatment bags and allowed to grow for six weeks. All growth parameters were recorded at three-to-four-day intervals. Plant height was measured from the grow bag topsoil surface up to the base of the highest mature leaf for corn and the base of the apical bud for tomato and pepper [37]. Stem girth was measured 1 cm from the base of the stem using a vernier calliper. Counts of the number of mature leaves were conducted according to the time intervals indicated above until the end of the experiment. Final measurements of the plant height, number of leaves, and leaf area index (LAI) were carried out at the end of the 6-week period. Overall plant health was recorded twice a week for each replicate over the time of the experiment. It was ranked and allotted a class according to Table 1.

Table 1. Overall plant health class description.

Code	Rank	Description
0	Dead	Completely dead plant.
1	Worst	Disease-ridden, drooping, heavy senescence, dead leaves, and pests.
2	Bad	Moderate pests, mild flaccidity, moderate leaf-yellowing, or other abnormalities.
3	OK	Fair health, no leaf discolouration, moderately turgid, and minor abnormalities.
4	Good	No abnormalities, turgid plant, no signs of disease, minor scarring, or holes in leaves (<2 mm).
5	Best	Plant in pristine condition.

2.3. Collection and Processing of Plant Material

At the end of the six weeks, final growth measurements were taken, and the plants were harvested by carefully uprooting them from their receptacles while ensuring that the roots remained intact. Potting bags were gently compressed in alternating circular motions to loosen soil from around the roots. Excess soil mixture was removed from the roots by gently shaking loose particles and placing them under running water until all traces were removed. The roots and plants were then blot dried. Fresh weights of stems and roots were recorded in addition to leaf area (laminae only), root-to-shoot ratio, and total weight per plant (g) [38]. Leaf area was calculated using the fresh weight of a 1 cm² of leaf laminae according to the following formula:

$$\text{Leaf Area (LA)} = ((\text{Sample leaf area})/(\text{Sample leaf weight})) \times \text{Total weight of leaves} \quad (1)$$

After all fresh weights were taken, plants were placed into paper envelopes and placed in a furnace at 50 °C for 72 h [39]. After removal from the oven, samples were allowed to cool for 24 h, and relevant dry weights and ratios were determined.

2.4. Analysis of Other Plant Parameters

2.4.1. Germination Experiment

The imbibition period, i.e., the number of days from sowing to commencement of germination, was recorded for all tested treatments. The rate of emergence (RE) was calculated according to the following formula:

$$RE = ((\text{No. of seedlings emerged 4 days after sowing}) / (\text{No. of seedlings emerged 14 days after sowing})) \times 100 \quad (2)$$

The germination percentage (GP) was calculated by dividing the total number of germinated seeds by the total number of seeds sown in the trays and multiplying by 100. The number of germinating seeds was determined from the first germination to no further germination.

The germination period was calculated as the time difference between the first and final emergence (number of days) recorded.

Seed vigour was calculated by dividing the total number of healthy seedlings by the number of total seedlings and multiplying by 100.

The germination index (GI) was calculated as described in the following formula [40]:

$$GI = \sum (G_t / D_t) \quad (3)$$

where G_t is the number of germinated seeds on day t , and D_t is the time corresponding to G_t in days.

The germination value (GV) was calculated according to the following formula [41]:

$$\text{Germination value (GV)} = (\sum DG_s / N) \times (GP / 10) \quad (4)$$

where GP is the germination percentage at the end of the experiments, DG is the daily germination speed obtained by dividing the cumulative germination percentage by the number of days since sowing, $\sum DG_s$ is the total germination obtained by adding every DGs value obtained from the daily counts, N is the total number of daily counts starting from the first germination, and (10) is a constant.

2.4.2. Seedling Growth Experiment

The parameters described below were evaluated considering five plants per treatment.

The change in shoot height (ΔH) was calculated according to the following formula:

$$\Delta H = H_f - H_i \quad (5)$$

where H_f corresponds to the final height measurement performed on the last day of the experiment, and H_i to the initial height measured during the first day of the experiment [42].

The change in leaf number (ΔL) was calculated as follows:

$$\Delta L = L_f - L_i \quad (6)$$

where L_f corresponds to the final number of leaves counted on the last day of the experiment, and L_i to the initial number of leaves counted on the first day of the experiment.

The change in shoot diameter (ΔSD) was determined using the following formula:

$$\Delta SD = SD_f - SD_i \quad (7)$$

where S_{Df} corresponds to the final shoot diameter measured on the last day of the experiment and S_{Di} to the initial shoot diameter measured on the first day of the experiment.

The percentage moisture content (MC) was calculated as follows:

$$MC = ((FW - DW)/FW) \times 100 \quad (8)$$

where FW corresponds to the fresh weight of the whole plant and DW to the dried weight of the whole plant determined on the last day of the experiment.

The mean root-to-shoot ratio (R:S) was calculated using the following formula:

$$R:S = R_DW / (L_DW + S_DW) \quad (9)$$

where R_DW is the root dry weight, L_DW the leaf dry weight, and S_DW the stem dry weight measured on the last day of the experiment.

2.5. Elemental Analysis of Plant and Soil Materials

Dried plants and soil samples were milled for 30 s at 300 MHz with a Tissue Lyser II (Qiagen, Hilden, Germany) in a 10 mL grinding jar (Qiagen, Hilden, Germany) using a 20 mm stainless steel grinding ball. The samples (~0.2 g) were then digested in a CEM MARS6 microwave digestion system in 20 mL Xpress vessels using concentrated sub-boiled nitric acid at 200 °C for 10 min (CEM standard Xpress procedure for plant material). Following digestion, the samples were diluted with Milli-Q water to form an ~20 mL mother solution, then subsampled to give an ~1000× total dilution. The daughter samples were spiked to give a final concentration of 5 ppb of In and Re to act as internal standards. Standards were made from the Inorganic Ventures Environmental standard (IV-Stock-50) and also spiked to give 5 ppb In and Re. The samples were analysed on an Agilent 8900 Triple Quad inductively coupled plasma mass spectrometer (QQQ-ICP-MS) in standard, helium (He), and oxygen (O₂) modes depending on the element of interest [43].

2.6. Statistical Analysis

Results are presented as mean ± SEM (Standard Error of the Mean). Statistical analyses were carried out using SPSS Statistics Version 22.0. All parameters were analysed by a Levene's test to assess the variation between values, followed by a Kolmogorov–Smirnov and Shapiro–Wilk test to check if the values followed a normal distribution. The significance of differences between treatments at $p \leq 0.05$ was determined by a one-way ANOVA for variation among sample means accompanied by Tukey's post hoc multiple comparison test.

3. Results

3.1. Seed Germination Parameters

Results for seed germination experiments were presented in Table 2. Comparisons could not be tested statistically because each value does not represent a mean of individual replicate seedling values but a single parameter calculated for each treatment.

Table 2. The effects of *Sargassum* treatments on seed germination of corn, tomato, and pepper.

Plant	Treatment	Imbibition Period (Days)	Rate of Emergence (RE)	Germination Percentage (GP, %)	Germination Period (Days)	Seed Vigour (SV)	Germination Index (GI)	Germination Value (GV)
Corn	CON	2	61.54	26	10	84.62	4.67	9.81
	RC	2	85.71	21	4	80.95	4.00	11.53
	URC	4	35.48	31	10	80.65	4.96	13.47
	RM	4	30.77	26	8	76.92	4.17	7.75

Table 2. Cont.

Plant	Treatment	Imbibition Period (Days)	Rate of Emergence (RE)	Germination Percentage (GP, %)	Germination Period (Days)	Seed Vigour (SV)	Germination Index (GI)	Germination Value (GV)
Tomato	URM	6	0.00	2	0	−300.00	0.67	0.22
	CON	4	57.14	49	8	91.84	11.08	30.67
	RC	2	50.55	91	10	95.60	19.58	129.36
	URC	2	82.35	68	12	94.12	15.36	67.02
	RM	4	3.53	85	8	95.29	16.00	49.38
	URM	4	12.50	64	10	93.75	6.57	37.24
Pepper	CON	6	0.00	85	4	92.94	9.33	91.34
	RC	4	15.66	83	8	95.18	10.17	91.62
	URC	4	6.98	86	10	95.35	7.64	76.41
	RM	4	1.27	79	8	94.94	6.83	77.29
	URM	6	0.00	90	6	93.33	11.17	77.05

Values recorded for the shortest imbibition periods depended on plants and conditions: 2 days for corn (CON and RC) and tomato (RC and URC), and 4 days for pepper (RC, URC, and RM). Similar trends were observed for the longest imbibition periods: 4 days for tomato (CON, RM, and URM); 6 days for corn (URM) and pepper (CON and URM). The higher rate of emergence for corn and pepper was observed during the RC treatment (85.71 and 15.66, respectively) and for tomato under the URC condition (82.35). The lowest values for this parameter were monitored under the URM condition for corn (0.00), URM and CON for pepper (0.00), and RM for tomato (3.53). The maximum germination percentage (GP) for corn was observed in the URC treatment (31%), for tomato in RC (91%), and for pepper in URM (90%). The minimum GP observed for tomato was in CON (49%), for pepper in RM (79%), and for corn in URM (2%). This latter result indicated that URM treatment has a very detrimental effect on the germination of corn seed, and this was reflected in the other parameters investigated for this plant. *Sargassum* treatments reduced the germination period in two species, i.e., corn and tomato in the RC (4 days) and RM treatment (8 days), respectively, whereas the CON treatment presented the lowest value for pepper (4 days). The URC treatment showed an extended germination period for tomato (12 days) and pepper seedlings (10 days); for corn seedlings, the URC and the CON treatments showed the same value (10 days). The maximum seed vigour was found in RC for tomato (95.60), in URC for pepper (95.35), and in CON for corn (84.62); minimum values for this parameter were observed in CON for both tomato and pepper (91.84 and 92.94, respectively) and in URM for corn (−300.00). The RC treatment provided the highest germination index (GI) and germination value (GV) for tomato (19.58 and 129.36, respectively). For corn, the highest values for these parameters were determined under URC treatment (4.96 and 13.47, respectively). For pepper, a higher GI (10.17) was calculated under URM conditions and a higher GV (91.62) in RC. The lowest GI and GV values were calculated for the URM treatment for corn (0.67 and 0.22, respectively); for tomato, the lowest GI value was observed for URM (6.57), and the lowest GV value for CON (30.67). For pepper, the GI and GV values were the lowest for RM (6.83) and URC treatment (76.41), respectively.

3.2. Seedling Growth Parameters

A statistical analysis of seedling growth parameters indicated that differences in height, shoot diameter, and the number of leaves were significantly different between treatments ($p < 0.001$) (Supplementary File S1).

3.2.1. Plant Shoot Height

The maximum change in shoot height was observed in URM for corn (59.96 cm), RC for pepper (28.56 cm), and URC for tomato (60.52 cm) (Figure 1). The minimum change in shoot height was found in CON for corn (34.93 cm), URC for pepper (18.90 cm), and RM for tomato (46.88 cm). URM treatment led to the highest mean shoot height for corn (77 cm), RC treatment for pepper (38.70), and, for tomato, it was observed after the URC treatment (69.06 cm) (Figures S1, S2, and S3, respectively). The shortest shoot heights were observed in CON for corn (55.60 cm), in URC for pepper (29.50 cm), and in RM for tomato (54.50 cm).

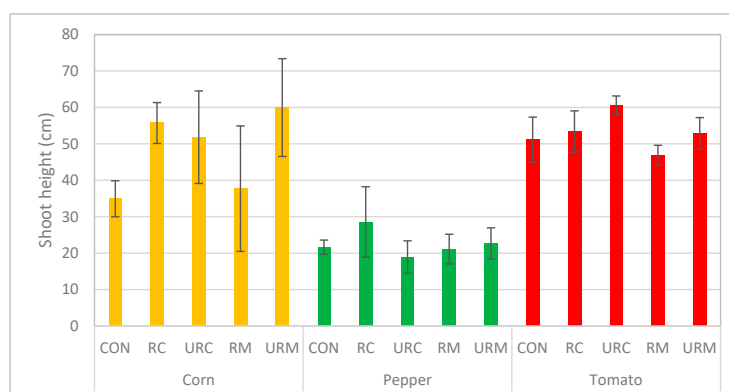


Figure 1. Changes in the shoot height of corn, pepper, and tomato plants after 6 weeks of *Sargassum* treatments.

3.2.2. Number of Leaves

The maximum change in the quantity of leaves was found in pepper grown under the URM condition (27.60) and under the CON condition for tomato (227.60) (Figure 2). The changes in the number of leaves were the same for CON, RC, and RM for corn (1.40). For the latter, an increase in the number of leaves was observed during the first weeks of the experiment for all the conditions tested, then these numbers decreased to levels equal to those measured at the start of the experiment (Figure S4). The minimum change in the quantity of leaves was observed under the URC condition for corn (0.80) and RC for both pepper (15.80) and tomato (170.80). After six weeks of experiments, the RC condition showed a higher abundance of leaves for corn (4.70). For the pepper plants, it was under the URM treatment (33.80) and in CON for tomato (239) (Figures S5 and S6, respectively). The lowest quantity of leaves was found after URC treatment for corn (3.80) and RC for pepper (22.4) and tomato plants (181.2).

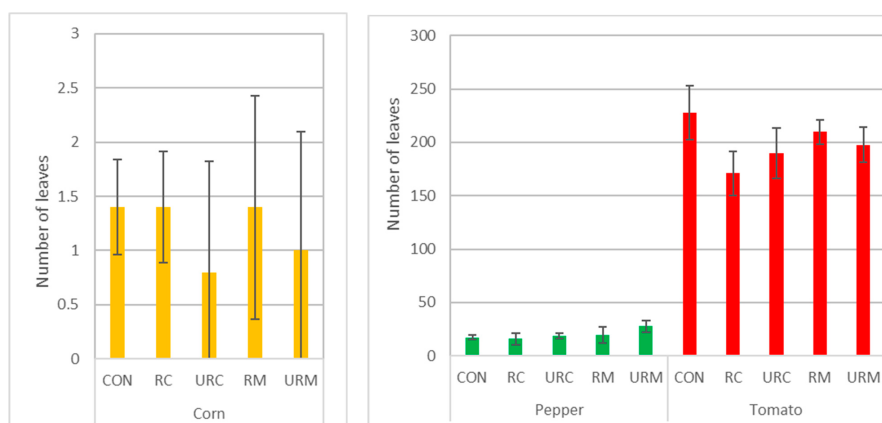


Figure 2. Changes in the number of leaves of corn plants (left panel), and of pepper and tomato plants (right panel) after 6 weeks of *Sargassum* treatments.

3.2.3. Plant Shoot Diameter

The maximum change in shoot diameter was monitored in the RC for corn (3.71 cm), URM for pepper (0.434 cm), and RM for tomato (0.58 cm) (Figure 3). The minimum variations in this parameter were observed after RM treatment for corn (1.3 cm) and pepper (0.32 cm) and RC for tomato (0.53 cm). The maximum shoot diameter was observed in the RC for corn (6.80 cm), URM for pepper (0.65 cm), and CON and RM for tomato (0.79 cm) (Figures S7, S8, and S9, respectively). The minimum shoot diameter was found in the RM for corn (4.70 cm) and URC for pepper (0.55 cm) and tomato (0.76 cm).

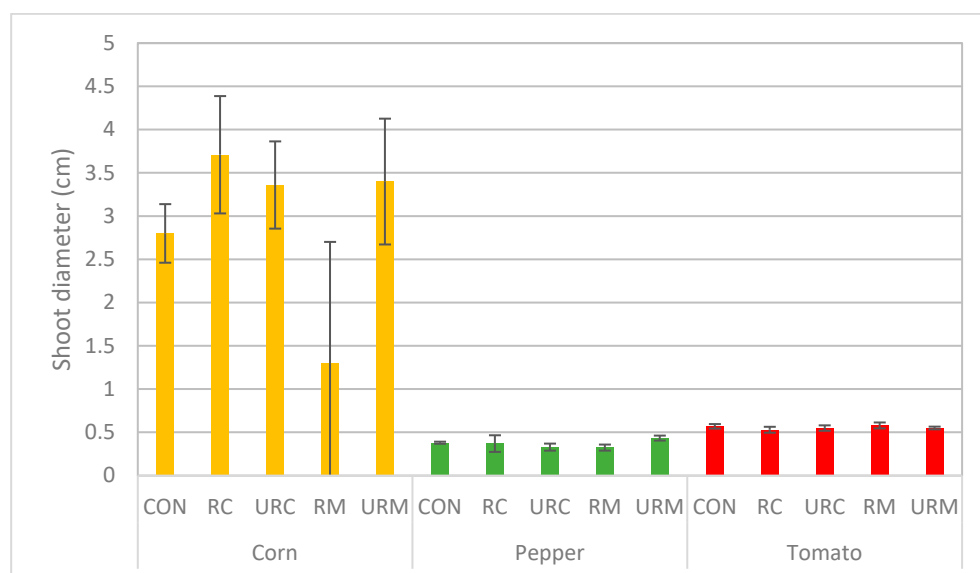


Figure 3. Changes in the shoot diameter of corn, pepper, and tomato plants after 6 weeks of *Sargassum* treatments.

3.3. Description of Plant Health

The overall plant health class description for corn, pepper, and tomato plants after *Sargassum* treatments is presented Table 3. Most of the pepper and tomato plants ranked 4 and 5, while for corn plants the distribution of the ranks was more stretched towards the lower ranks of 2 and 3. For corn, only one seedling was ranked at 5 (URC condition), while most of them were ranked 3–4 across the treatments. The highest number of plants ranked 4 was observed for the RC (32) and CON (26) conditions. For pepper, most of the seedlings ranked 4–5 across all treatments, with plants ranked 5 being more frequent under the RC (24) and CON (16) conditions compared to the other treatments. For tomato, the number of plants ranked 5 was higher than for pepper and could be found in all the conditions tested, in particular after the CON (27), RC (24), and URM (22) treatments.

Table 3. Distribution of health class ranks for corn, pepper, and tomato seedlings after *Sargassum* treatments.

Treatment	Health Rank	Number of Plants		
		Corn	Pepper	Tomato
CON	0	0	0	0
	1	1	0	0
	2	7	0	0
	3	21	6	7
	4	26	43	31
	5	0	16	27

Table 3. Cont.

Treatment	Health Rank	Number of Plants		
		Corn	Pepper	Tomato
RC	0	0	2	0
	1	0	5	0
	2	3	2	4
	3	20	3	5
	4	32	29	32
	5	0	24	24
URC	0	0	0	0
	1	2	0	0
	2	17	2	1
	3	24	7	2
	4	11	56	51
	5	1	0	11
RM	0	2	0	0
	1	5	0	0
	2	8	4	2
	3	21	7	2
	4	19	51	47
	5	0	3	14
URM	0	0	0	0
	1	0	0	0
	2	19	0	0
	3	17	5	5
	4	19	53	38
	5	0	7	22

3.4. Analysis of Plant Post-Harvest Parameters

Three parameters were investigated: leaf area index (LAI), moisture content (MC), and root-to-shoot ratio (R:S). Statistical analysis for these parameters provided mixed results: leaf area index and root-to-shoot ratios showed significant differences between treatments ($p < 0.001$), while it was not the case for the moisture content ($p = 0.524$), with large standard deviations attributable to variable but low sample numbers (Supplementary File S1).

The highest LAI values, expressed in cm^2 , were observed in the RM for both corn and pepper (512.10 and 3901.65, respectively) and RC for tomato (8475.79) (Figure 4). Minimum LAI values were obtained under the CON treatment for both corn and pepper (163.20 and 1930.77, respectively) and in URM for tomato (5459.85).

The effects of *Sargassum* treatments on the MC of corn, pepper, and tomato are presented in Figure 5. The highest contents were observed for these three plants under the URC condition, and values were as follows: 73.71% for corn, 77.40% for pepper, and 76.2% for tomato. The lowest values for this parameter were calculated in the CON condition for corn (62.61%) and after RC treatment for both pepper and tomato (58.34% and 69.65%, respectively).

Values of R:S for corn, pepper, and tomato are presented in Figure 6. The highest R:S was determined after CON and URM treatments for corn (0.14), CON for pepper (0.34), and URC for tomato (0.23). The lowest values were calculated under the URC and RC conditions for corn (0.10), RC for pepper (0.15), and CON for tomato.

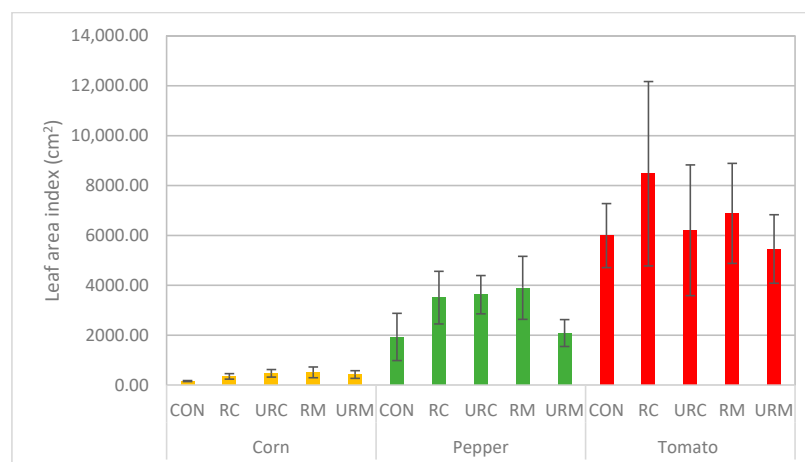


Figure 4. Changes in the leaf area index (LAI) of corn, pepper, and tomato plants after 6 weeks of *Sargassum* treatments.

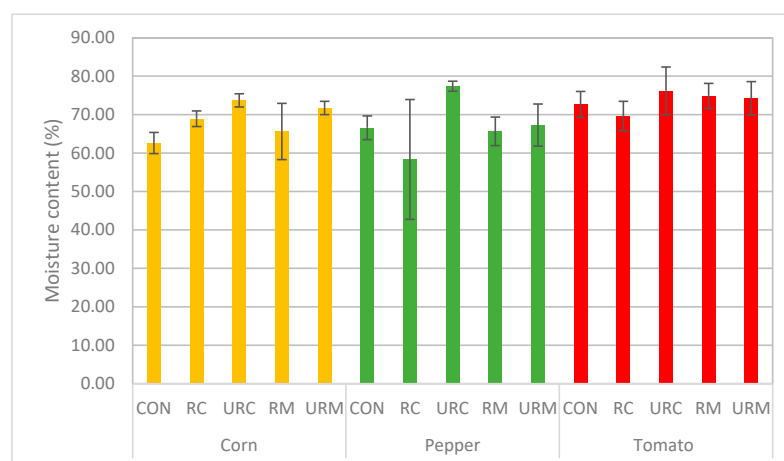


Figure 5. Changes in the moisture content (MC) of corn, pepper, and tomato plants after 6 weeks of *Sargassum* treatments.

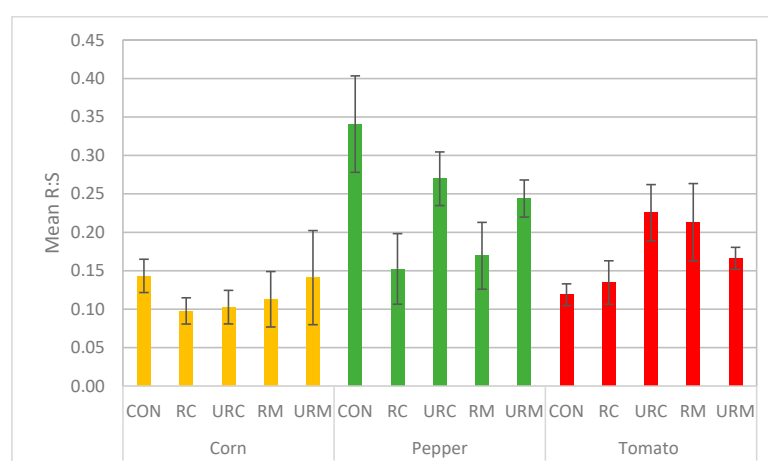


Figure 6. Changes in the root-to-shoot ratio (R:S) of corn, pepper, and tomato plants after 6 weeks of *Sargassum* treatments.

3.5. Elemental Analysis of Mulch, Compost, and Plant (Tomato and Pepper) Materials

No corn samples were considered for this analysis, as the grow bags were unable to adequately support corn plants, and these did not survive to fruiting. Twenty-six elements were considered initially: Na, Mg, P, K, Ca, Cr, Mn, Fe, Cu, Zn, As, Mo, Cd, Ba, Pb, Co, V, Ni,

higher Na contents were determined in Roots RC and Roots RM samples compared to Roots CON. Tomato leaves also accumulated Na after growing in the presence of *Sargassum* compost or mulch when compared to the control condition. Mg was present in tomato roots, leaves, and fruits, with higher contents determined in the leaves under all conditions tested (15,000–20,000 µg/g) compared to the roots (5000–7000 µg/g) and fruits (1500–2000 µg/g). For pepper plants, the Mg content was much higher in the leaves (15,000–23,000 µg/g) compared to root and fruit samples (2500–3500 µg/g) after the different treatments. Variations in Ca contents showed trends similar to what was observed for Mg for both plants and all treatments, although the contents in tomato fruits (700–900 µg/g) were lower than observed for pepper fruits (1000–2000 µg/g).

An assessment of the partitioning of K in tomato samples did not show clear trends between the different parts of the plants. The URC and URM treatments favoured the accumulation of K in roots and leaves when compared to the control conditions, as well as in fruits only for the URM conditions. In pepper, leaves and fruits accumulated higher amounts of K (44,000–70,000 µg/g) compared to roots (29,000–38,000 µg/g) under all the conditions tested, but no clear differences between the different conditions tested were observed. A higher content of P was found in tomato fruits (4000–5000 µg/g) compared to leaves and roots (1600–3500 µg/g), and a similar trend was observed when comparing between pepper samples. Compost and mulch treatments did not trigger any clear changes in this element when compared with the control condition for all the plant samples tested. The content of Mn in leaves was higher compared to root and fruit samples by at least a factor of 10 between the leaves and fruits for both tomato and pepper and under the different treatments tested (Tables S1 and S2). A similar trend was observed for Fe, although its content was more homogeneous between roots and leaves compared with Mn, and the differences were less marked compared to the content in fruits. Individual contents of Zn and Cu were at the same level when comparing the different parts of the same crop under the conditions tested.

Regarding As, the highest concentrations were observed for both crops in their roots after URC and URM treatments, with higher values determined for tomato (208.22 and 120.56 µg/g) compared to pepper (67.79 and 84.84 µg/g). Interestingly, the As content was much lower in the roots obtained from plants grown in presence of compost and mulch prepared with rinsed *Sargassum*. In leaves, the content of As was at least 10 times lower compared to roots, and higher values were determined in URC and URM samples compared to RC and URC, respectively, as described for roots. Finally, the analysis of fruit samples showed that As concentrations were below 1 µg/g for both crops under all conditions tested. Other toxic elements important to consider were Cd and Pb. Cd concentrations ranged between 0 and 2 µg/g, with Pb being in a similar range (0–4 µg/g) (Tables S1 and S2). As described for As, the contents of these two elements were lower in the fruits compared to the other parts of the corresponding plants wherever the *Sargassum* treatments were considered.

4. Discussion

This study seeks to explore the efficacy of exploiting Caribbean *Sargassum* inundations as a new resource for sustainable agricultural development. So far, few studies have documented the impact of *Sargassum*-derived compost and mulch on plant growth. When considering parameters associated with the seed germination of corn, pepper, and tomato, it appeared that RC and URC treatments were less impactful than RM and URM conditions. *Sargassum*-based compost may be more advantageous compared to mulch when sowing the seeds of these plants to avoid impairing germination and to produce healthier seedlings. In particular, results obtained for RC samples indicated an accelerated rate of emergence,

germination period, and imbibition period when compared to the control. In contrast, the URM displayed a deceleration in the rate of emergence and imbibition period in comparison with the control. These observations could be attributed to the negative physiological effects of salt stress on the germination of corn, tomato, and pepper. RC and URC samples showed lower concentrations of Na compared to RM and URM, and the three tested plants have been previously shown to be NaCl sensitive [44–46]. Results for plant shoot height, shoot diameter, and leaf area index showed that the utilisation of RC and URC tended to increase the primary growth of all plants when compared to the control condition. This is in line with previous results obtained after applying mulch derived from the species *Sargassum wightii*. Such treatment was shown to positively impact the growth of okra and cowpea plants [47], as well as increase the height of the saplings, the number of seeds in a panicle, and the grain weight of paddy [48]. The combination of increased shoot height, stem diameter, and leaf area index observed in our study is reminiscent of the results of previous work showing the use of pelagic *Sargassum* in the formulation with commercial soil to be effective for the commercial production of hot pepper seedlings [32]. In this study, it was found that pepper seedlings produced in the presence of 50% commercial substrate and 50% pelagic *Sargassum* compost had essentially the same dry and fresh root weights, number of leaves, and leaf areas of those sown in 100% commercial soil substrate. The combination of increased shoot height and stem diameter also alludes to an overall higher sturdiness quotient (SQ), which is indicative of seedlings being less likely to have unfavourable responses to stressors during transplanting [32]. In addition, under the conditions tested, our analysis of overall plant health revealed that most of the pepper and tomato seedlings ranked 3 (OK)–4 (Good)–5 (Best), while for corn plants the distribution of the ranks was more stretched towards lower rank 2 (Bad)–3–4. To complete the analysis of plant growth parameters, the moisture content and the root-to-shoot ratio were investigated. Very limited differences were observed in the moisture content for the three crops under the different conditions, with values obtained after treatments with *Sargassum*-derived compost and mulch close to those determined under the control condition. This suggested that the presence of *Sargassum* products did not impact the amount of water present in the whole plants. In contrast, differences were observed when comparing the root-to-shoot ratio between the control and *Sargassum* treatments, in particular for pepper and tomato. For pepper, the presence of *Sargassum* in the formulations tended to decrease the values of R:S, suggesting that higher stem and leaf biomasses were produced and/or less root biomass occurred under these conditions. In contrast, *Sargassum* treatment tended to increase R:S values for tomato, suggesting that both types of plants may differently manage the presence of *Sargassum* regarding primary production and the allocation of resources.

The analysis of elemental composition, which focused on tomato and pepper plants, revealed both notable similarities and differences concerning their metal and metalloid contents. The sodium content in mulch treatments was almost twice as high as in the compost treatments, with a limited difference between the rinsed and unrinsed conditions. All Na present in these treatments originated solely from the *Sargassum* biomass, as no Na was detected in the commercial soil used. Our data suggest that rinsing the seaweed biomass before processing may be less important than opting for compost or mulch. Based on the results presented for the plant growth parameters, the former may seem like a better option, although mulch preparation requires shorter time and less work throughout the production process. Interestingly, no Na was found in the different pepper samples, in contrast with tomato leaves and roots under all the *Sargassum* conditions tested. It is also worth mentioning that no Na was found in tomato fruits. These observations suggest that both pepper and tomato may handle the presence of NaCl differently.

To the best of our knowledge, only one study has reported details of the elemental composition of vegetables grown in the presence of *Sargassum* compost [33]. Interestingly, concentrations of elements in radishes grown in the presence of different quantities of *Sargassum* compost were compared with guidelines provided by the Agricultural Analytical Services Lab (AASL) at Penn State College of Agricultural Sciences [49] and the Codex Alimentarius Commission (CAC) [50] for nutritional and toxicological considerations, respectively. We followed a similar approach for analysing the concentrations of elements determined in the fruits of tomato and pepper under different *Sargassum* treatments (Table 5). The results indicated that both tomato and pepper fruits met the nutritional recommendation for P, K, Fe, and Zn; however, levels for Ca, Mg, Mn, and Cu were below the recommended thresholds. This finding contrasts with results obtained for radishes, for which conditions were met for Ca, Mn, and Cu but did not satisfy the requirements for Zn.

Table 5. Comparison of concentrations of selected elements determined in tomato and pepper fruits collected after growth under different types of *Sargassum* treatments with AASL guidelines used for nutritional purposes (considered as minimal values) and CAC guidelines used for toxicological considerations (considered as maximum values). Values are expressed in $\mu\text{g/g}$ (ppm).

Tomato							
Elemental parameters	AASL	CAC	Control	Rinsed compost	Unrinsed compost	Rinsed mulch	Unrinsed mulch
P	3000	-	4804.26 $\pm$ 175.71	3964.58 $\pm$ 293.67	4163.13 $\pm$ 302.15	4772.41 $\pm$ 231.83	4705.52 $\pm$ 400.76
K	23,000	-	45,817.8 $\pm$ 1508.95	45,386.75 $\pm$ 1900.01	46,494.77 $\pm$ 606.71	48,090.75 $\pm$ 2088.81	52,679.35 $\pm$ 3496.67
Ca	10,000	-	801.84 $\pm$ 101.47	740.45 $\pm$ 56.59	723.05 $\pm$ 81	677.93 $\pm$ 77.54	854.1 $\pm$ 116.51
Mg	5500	-	1820.8 $\pm$ 91.49	1680.86 $\pm$ 90.63	1769.91 $\pm$ 48.86	1820.46 $\pm$ 61.47	2080.94 $\pm$ 60.95
Mn	30	-	9.55 $\pm$ 0.2	9.69 $\pm$ 1.24	9.23 $\pm$ 1.31	8.87 $\pm$ 0.33	8.05 $\pm$ 1.52
Fe	40	-	52.13 $\pm$ 12.35	81.52 $\pm$ 39.18	70.39 $\pm$ 23.38	125.41 $\pm$ 50.76	72.24 $\pm$ 8.88
Cu	10	-	4.69 $\pm$ 0.75	6.25 $\pm$ 1.59	6.81 $\pm$ 0.34	5.75 $\pm$ 0.17	4.51 $\pm$ 0.72
Zn	25	-	32.22 $\pm$ 1.45	27.96 $\pm$ 1.97	31.48 $\pm$ 3.09	35.62 $\pm$ 1.73	33.7 $\pm$ 1.84
As	-	0.2	0.55 $\pm$ 0.12	0.74 $\pm$ 0.13	0.97 $\pm$ 0.15	0.8 $\pm$ 0.08	0.72 $\pm$ 0.08
Cd	-	0.05	0.09 $\pm$ 0.03	0.18 $\pm$ 0.06	0.21 $\pm$ 0.05	0.12 $\pm$ 0.03	0.14 $\pm$ 0.03
Pb	-	0.1	0.04 $\pm$ 0.03	0.08 $\pm$ 0.06	0.08 $\pm$ 0.03	0.07 $\pm$ 0.05	0.05 $\pm$ 0.05

Pepper							
Elemental parameters	AASL	CAC	Control	Rinsed compost	Unrinsed compost	Rinsed mulch	Unrinsed mulch
P	3000	-	3805.86 $\pm$ 86.19	4652.24 $\pm$ 264.92	4379.28 $\pm$ 111.84	4465.28 $\pm$ 354.47	4257.17 $\pm$ 333.29
K	25,000	-	49,882.08 $\pm$ 3335.62	51,819.74 $\pm$ 1580.51	44,895.51 $\pm$ 1729.13	44,018.21 $\pm$ 543.79	51,596.17 $\pm$ 3545.29
Ca	6000	-	1276.19 $\pm$ 153.58	1697.73 $\pm$ 88.49	1283.19 $\pm$ 89.45	2027.75 $\pm$ 427.29	1193.73 $\pm$ 193.65
Mg	3000	-	2640.77 $\pm$ 138.95	3443.12 $\pm$ 143.82	2637.79 $\pm$ 156.6	2699.53 $\pm$ 244.3	2806.92 $\pm$ 63.08
Mn	30	-	22.99 $\pm$ 0.49	29.71 $\pm$ 1.59	16.23 $\pm$ 1.2	11.09 $\pm$ 5.86	18.05 $\pm$ 2.87
Fe	30	-	65.92 $\pm$ 9.75	69.53 $\pm$ 6.85	70.18 $\pm$ 6.7	57.58 $\pm$ 33.14	59.4 $\pm$ 7.71
Cu	5	-	4.54 $\pm$ 0.84	6.03 $\pm$ 0.52	6.54 $\pm$ 1.04	6.18 $\pm$ 3.1	4.3 $\pm$ 0.98
Zn	25	-	24.62 $\pm$ 0.95	30.28 $\pm$ 3.27	25.29 $\pm$ 1.75	40.03 $\pm$ 14.2	24.76 $\pm$ 1.67
As	-	0.2	0.37 $\pm$ 0.19	0.57 $\pm$ 0.06	0.39 $\pm$ 0.29	0 $\pm$ 0	0.77 $\pm$ 0.1
Cd	-	0.05	0.14 $\pm$ 0.03	0.3 $\pm$ 0.06	0.24 $\pm$ 0.04	0.2 $\pm$ 0.1	0.15 $\pm$ 0.05
Pb	-	0.1	0.02 $\pm$ 0.02	0.01 $\pm$ 0.01	0.04 $\pm$ 0	0.06 $\pm$ 0.03	0.01 $\pm$ 0.01

Concerning toxic elements, the total content of As in the different formulations examined in our study was below 40 $\mu\text{g/g}$ and, in particular, less than 15 $\mu\text{g/g}$ in the rinsed and unrinsed compost. Rinsing *Sargassum* biomass did not contribute to the decrease in the content of As. It is possible that applying such a treatment for 5 min was too short to have an impact, as a previous study has shown that 20 min of washing and soaking of *Hizikia fusiforme* (*Sargassum fusiforme*) in tap water could reduce total As by 30 to 60% [51]. A content of 15 $\mu\text{g/g}$ of As is below most of the maximum levels of total As allowed in products for agricultural application listed in regulations applied by several countries [52]. When monitoring the As content in plant samples, the highest values were measured in the roots of plants grown in the presence of *Sargassum* compost and mulch (up to 208 $\mu\text{g/g}$ in

tomato roots URC samples). The roots are in direct contact with the compost and mulch and therefore have the potential to assimilate As in a much larger quantity compared to other parts of the plants. All the values determined for tomato and pepper fruits were below 1 µg/g. However, almost all of them were above the maximum value recommended by CAC (0.2 µg/g) (Table 5). These values were lower than most of the values measured in radishes grown in presence of *Sargassum* compost [33]. This suggests that fruiting crops such as tomato and pepper may absorb less As in the eaten parts than root vegetables such as radishes. The contents of Cd in tomato and pepper fruits were also above the maximum limit recommended by CAC, while values for Pb were below.

5. Conclusions

Our foundational study showed that *Sargassum*-derived mulch and compost impact seed germination, seedling growth, post-harvest parameters, and elemental concentrations in different parts of the plants. These results should be considered as a step forward towards improving the preparation of *Sargassum*-derived products in the context of soil amelioration and testing them to grow varied plants for food, feed, ornament, and to restore ecosystems, in comparison with commercially available media. Such experiments should include the analysis of plant germination, growth, and reproductive yield, as well as the determination of elemental composition in media and plant samples to understand the fate of toxic elements present in *Sargassum* biomass such as As, Cd, and Pb. Valorisation of pelagic *Sargassum* can be seen on a large industrial scale but also on a more limited and local scale. For the latter, communities should be able to implement simple biomass processing methods, such as preparations of compost and mulch, as long as these methods are shown to be safe for the plants, people, and the environment. It could also be recommended that *Sargassum*-derived compost and mulch be mixed with other organic soil ameliorants, as preliminary experiments in communities indicated that selected crops grown in a mix of *Sargassum* and grass compost performed as well as plants grown in pure *Sargassum* compost. By adopting these methods, communities, often among the most adversely affected by *Sargassum* influxes, could reap direct benefits while contributing to sustainable environmental management.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/phycology5030044/s1>. Figure S1: daily changes in the shoot height of corn plants during 6 weeks of *Sargassum* treatments; Figure S2: daily changes in the shoot height of pepper plants during 6 weeks of *Sargassum* treatments; Figure S3: daily changes in the shoot height of tomato plants during 6 weeks of *Sargassum* treatments; Figure S4: daily changes in the number of leaves of corn plants during 6 weeks of *Sargassum* treatments; Figure S5: daily changes in the number of leaves of pepper plants during 6 weeks of *Sargassum* treatments; Figure S6: daily changes in the number of leaves of tomato plants during 6 weeks of *Sargassum* treatments; Figure S7: daily changes in the shoot diameter of corn plants during 6 weeks of *Sargassum* treatments; Figure S8: daily changes in the shoot diameter of pepper plants during 6 weeks of *Sargassum* treatments; Figure S9: daily changes in the shoot diameter of tomato plants during 6 weeks of *Sargassum* treatments; Table S1: Concentrations of elements determined by ICP-MS in compost and plant materials grown under several compost treatments. Results are expressed as µg/g (ppm) of biomass DW; Table S2: Concentrations of elements determined by ICP-MS in mulch and plant materials grown under several mulch treatments. Results are expressed as µg/g (ppm) of biomass DW. Supplementary File S1: Statistical analysis of results obtained for plant growth parameters. Supplementary File S2: Statistical analysis of results obtained for the elemental analysis of mulch, compost and plant (tomato and pepper) materials.

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