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Application of stranded pelagic sargassum biomass as compost for seedling production in the context of mangrove restoration

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Abstract

The *Sargassum* spp. inundations across the Atlantic and Caribbean that began in 2011 have continued unabated and new uses for the biomass are being continuously explored. Mangroves protect shorelines, store carbon, enhance water quality and promote biodiversity. Their restoration can be hindered by poor soils associated with urbanized coastlines. *Sargassum* spp. application in the form of mulch, compost and plant tonics has yielded positive results in a range of plants. As part of transforming the inundations to benefit communities, *Sargassum* spp. compost (SC) was assessed in mangrove seedling production for restoration. Pure SC was mixed with soil/sand medium, as different treatments, for the production of *Rhizophora mangle* seedlings in 'wet' and 'dry' nurseries. Plants in the 'wet' nursery performed poorly, with 90-100% of plants in 50 and 100% SC, respectively, dying after six weeks. Seedlings in all SC treatments in the 'dry' nursery survived with obvious and statistically significant treatment differences. Height and number of leaves indicated best growth in the 75% SC treatment while the control (0% SC) had poorest growth. Seedling health, greatest in the control, was poorest in 50 and 100% SC. Elemental analysis of SC, seedlings and soil/sand medium indicated that several elements (Na, K, Ca, As, Se) found in high concentrations in the SC, were low in the plants. Overall, low sequestration of elements by mangrove seedlings, and the reported ability of mangrove soils to reduce element mobilization through chelation, indicate potential for use of *Sargassum* spp. in soil amelioration for mangrove restoration without proportional contamination of the ecosystem. We see potential for the use of nuisance *Sargassum* spp. blooms to support mangrove restoration, leading to increased benefits to coastal communities who are being affected by the inundations.

1 Introduction

Large floating mats of pelagic sargassum seaweed, comprised of *Sargassum natans* I*, S. natans* VIII *and S. fluitans* III (Schell et al. 2015), have been inundating shorelines across the Caribbean since 2011 (Wang et al., 2019) and there is evidence that these annual blooms will continue into the foreseeable future; becoming the "new normal" (Wang et al., 2019; Salter et al., 2020 and Machado et al., 2022). Although widely considered a nuisance (van Tussenbroek et al., 2017), many have come to regard the algal biomass as a resource (Milledge and Harvey, 2016; Chávez et al., 2020; Amador-Castro et al., 2021) with a plethora of projects exploring uses, which include soil amelioration (Desrochers et al., 2020). The effectiveness of *Sargassum* spp. in improving plant production (applied as mulch, compost or liquid fertilizer) has been shown for several food crops (CARDI, 2015). However, there is a threat of increasing the salinity of the soil (CARDI, 2015) and although this may be ameliorated by washing the *Sargassum* spp. before and during composting (Eyras et al., 1998), this measure can be too expensive for some communities and also leaches nutrients (CARDI, 2015).

While there are examples of the use of *Sargassum* spp. seaweed for restoration of dunes (Desrochers et al., 2020) and to enhance the actual growth of dune plants (Williams and Feagin, 2010; Thompson et al., 2020), there is no previous research on the use of sargassum seaweed in mangrove restoration or rehabilitation. It is hypothesized that mangroves and other coastal plant species growing in poor soil conditions will benefit from the soil amelioration properties of *Sargassum* spp. (improved texture, water holding capacity and increased nutrients), and is expected to also be able to tolerate increased soil salinity. The production of compost from pelagic *Sargassum* spp. by mixing with other plant material (wood chips and food waste) has been reported (Sembera et al., 2018). However, there is yet no example of composting pure *Sargassum* spp., which would make use of larger quantities of the feedstock, and facilitate an assessment of the effect of the pure compost on coastal plant species like mangroves.

Mangrove ecosystem services are well known and include shoreline protection, water quality improvement, biodiversity support through the provision of a range of habitats and carbon sequestration. Since 2006, over 200 benefits of mangroves have been documented (Lee et al., 2014) and later grouped into regulating, supporting, provisioning and cultural ecosystem services (e.g., Uddin et al., 2013; Webber et al., 2016; Kathiresan, 2012; Mitra, 2018). There has also been increasing global recognition of mangrove importance in carbon sequestration (Alongi, 2012; Sandeman et al., 2018), with mangroves showing high rates of carbon capture and almost permanent storage in the forest sediment as well as living biomass of leaves, stems and roots (Donato et al., 2011; Alongi, 2014).

Despite the ecological, economic, cultural and climate regulation value of mangroves, these forests are being destroyed globally at rates of 1 – 2% per year (Giri et al., 2008; Hogart, 2015); such that mangrove cover has declined by 35% over the last two decades due to human activities (Krauss et al., 2008). Mangrove forests have been threatened by mariculture (primarily shrimp farming) (Giri et al., 2008), excessive timber harvest (Kairo et al., 2001), deforestation for development (Valiela et al., 2001), hydrology changes (Turner and Lewis, 1997) and rising sea levels which force mangroves to recede to unsuitable land margins (Webber et al., 2016).

As is the case with many developing countries, Jamaica has lost almost 20% of mangroves in the last decade, due to coastal development and land reclamation as well as extreme weather events (Trench, 2021). Mangrove rehabilitation efforts have had increasing success but in some cases require severe interventions like, sediment replacement and slope reconstruction to restore hydrology as well as replanting of nursery-reared (hardened) seedlings (Nguyen et al., 2016 and Trench, 2021). In some cases the sediments used for mangrove rehabilitation sites is riverine sand, which does not provide high levels of organic matter as is naturally found in mangrove forests (Reef et al., 2010).

Urbanised coastlines (like the shores of Kingston Harbour, Jamaica) provide a good example of mangrove areas that have experienced severe habitat modification and have little chance of restoration being facilitated by natural recruitment of seedlings from adjacent forests. Such shorelines are said to be “propagule limited” (Lewis, 2009) and often require extensive replanting using nursery reared seedlings for restoration efforts to succeed. Furthermore, soil conditions in such areas are often so altered that there is need for sediment replacement or substantial amelioration for the introduced plants to survive. It was hypothesized that nursery propagation and out-planting of seedlings for severely altered urbanised areas may be enhanced by the use of natural soil ameliorants like sargassum seaweed. This would also make use of the algal biomass associated with the pelagic *Sargassum* spp. inundations.

Rhizophora is the most common mangrove genus along Atlantic coasts (Cerón-Souza et al., 2020) and *R. mangle* is the most commonly used and easily propagated mangrove. *R. mangle* usually grows at the seaward edge of the forest, has been shown to be the most productive of the coastal mangrove species and has great ecosystem services due to the sheltered, nursery-habitat (Mandal et al., 2019) created by its prop-roots hanging into adjacent lagoon. In this context, our work aimed to determine whether *R. mangle* seedlings showed enhanced growth and optimal health with the use of pure *Sargassum* spp. compost (SC) under nursery conditions. The use of pure SC would also facilitate identification of contaminants reported to be associated with pelagic *Sargassum* spp. blooms (Chávez et al., 2020; Milledge et al., 2020); in particular arsenic (Davis et al., 2021; Tonon et al., 2022).

2. Materials and Methods

2.1 Compost production

Pure *Sargassum* spp. compost (SC) was produced by storage of fresh un-washed and unsorted *Sargassum* spp. from which all non-sargassum plants and debris had been removed. The sargassum biomass was collected from near shore waters using a surf net at two locations in Jamaica; Hellshire coastline, St Catherine, and Fort Rocky, Palisadoes coastline (Kingston) in the summer months of 2019 and 2020 respectively. Care was taken to ensure that the collected material was free of beach sand. The *Sargassum* spp., which consistently comprised of a mix of *S. fluitans* III, *S. natans* I and *S. natans* VIII (Machado et al., 2022; Schell et al., 2015) in descending order of biomass, was placed in large black plastic bags which were stored unsecured (allowing air through but not rainwater) in an earthen pit for three months. The material was periodically 'turned' to effect mixing. The highest temperature recorded from the composting material during the day was ~36 ^{o}C.

2.2. Propagule establishment

Similar sized *R. mangle* propagules, collected from mangrove forests along the north coast of Jamaica were soaked in fresh water for 24 hours, measured and weighed, and then planted in a soil/sand mixture (in approximately 50:50 ratio) used as potting medium in the mangrove nursery. Mangrove propagules (10 per treatment for wet nursery experiment and 3 per treatment for dry nursery experiment) were planted to the same depth in potting bags containing SC, soil/sand or a mix based on the following five treatments: A- 100% SC; B- 75% SC with 25% soil/sand; C- 50% SC and soil/sand; D- 25% SC and 75% soil/sand; E- 0% SC (a soil/sand only control).

The experiments were conducted at a mangrove nursery located at the Discovery Bay Marine Laboratory, north coast, Jamaica in successive years for wet and dry nursery experiments. The wet nursery experiments were conducted in September 2019 and only maintained for approximately 6 weeks due to death of all plants in selected treatments. The experiment was repeated under 'dry' nursery conditions approximately one year later.

During 'wet' nursery conditions the plants were exposed to normal seawater (35 psu) or brackish water salinity of 20 psu. The water level in the nursery enclosures was altered on 12 hour cycles and the enclosures in which the plants were kept allowed to completely drain for 12 hours before replacing the water for another 12 hours. Thus diurnal tides were simulated. Water levels were just enough to cover the soil during the 'high tide'. Treatments with different SC and soil/sand ratios were segregated, kept in different enclosures in the 'wet' nursery so as not to have leachate from one treatment influencing another.

For the 'dry' nursery experiment no 'tidal' fluctuations were introduced, however plants were watered from above with a sprinkler type set up twice per day (06:30 and 17:00). Treatments were also segregated, kept far enough apart in the nursery so as not to have the leachate mixing across treatments.

The dry nursery experiment was established in September 2020 and terminated in June 2021 (40 weeks) and plants in all treatments were alive up to the end of the experiment. Seedlings were assessed each week for number of leaves, number of nodes, height above soil level

and health status. Height, nodal distances, leaves and biomass have proved to be useful mangrove seedling parameters (Gab-Alla et al., 2003; Hoppe-Speer et al., 2011). The health index was developed for our assessments to facilitate having an objective indication of seedling condition considering the potential deleterious effects of the *Sargassum* spp. The health index was based on a numeric scale of 0 – 5 as follows:

0 - Dead, no leaves, no green areas on stem, stem withered.
1- Surviving (plant has green colour on stem) but no leaves;
2- Surviving, plant with few withered leaves, pale or yellow with curling, scarring or spotting of leaves;
3- Poor health, possessing few leaves with evidence of thinning, and pale or yellow;
4- Good health, leaves not fully green but succulent (not thin or curled);
5- Best health possible, leaves fully green and succulent.

2.3 Elemental analysis using Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

At the end of the dry nursery experiment *R. mangle* seedlings were removed from the soil, thoroughly washed with fresh water and sun-dried before roots and leaves were separated from the stems and ground separately for elemental analysis. Sun-drying was done over 48 hours at temperatures between 30 and 35 ^{o}C in the day and 20 to 24 ^{o}C at night. Stems were not analysed. Samples of the pure SC and the soil/sand potting medium (n = 3) were also sun-dried for elemental analysis, as indicated for the mangrove seedlings. All samples (~0.2g) were digested in a CEM MARS6 microwave digestion system in 20 ml Xpress vessels using concentrated sub boiled nitric acid at 200 ^{o}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 ~ 1000x total dilution. The daughter samples were spiked to give a final concentration of 5 ppb for 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 final concentrations. The samples were analysed on an Agilent 8900 QQQ-ICP-MS in standard, He and O_2 modes depending on the element of interest.

2.4 Statistical tests

Statistical tests were conducted using SPSS Version 22 to assess if there was significant difference in plant parameters across the different treatments. $P < 0.05$ was accepted as significant for all parameters. The Shapiro-Wilks analysis was used to test normality amongst all the parameters, and due to the assumptions of the data, where normality was achieved (number of leaves and number of nodes) the one-way ANOVA test of variance was conducted. The Kruskal-Wallis analysis was used where normality was not achieved (Height and Health Ranking). Kruskal-Wallis was also used to assess significant differences in element concentration (in ppm) between treatments for roots and shoots, pure SC and soil/sand medium. Principal component analysis was used to group the 25 elements based on concentrations across treatments, pure SC and soil/sand medium.

3. Results

3.1 'Dry' nursery experiment

After 40 weeks, median height ($p < 0.001$), number of leaves ($p = 0.045$) and seedling health ($p < 0.001$) were found to vary significantly between treatments (Supplementary File S1). Height (Fig. 1) indicated best seedling growth occurred in the 75% *Sargassum* spp. compost (SC) treatment while the poorest growth was from the control (0% SC); followed by seedlings in 100% SC.

Number of leaves was similarly greatest for seedlings in 75% SC treatments (Fig. 2) and by the end of the experiment lateral branching was observed only in that treatment. Seedling health index (Fig. 3) was highest in the control and poorest in 100% SC, followed by the 50% SC treatment which also showed poor health (comparable to 100% SC treatment). This was indicated by curling of the leaves and dark spots along with yellowing/loss of colour (Fig. 4). Leaves also appeared thin (loss of succulence). Number of nodes did not vary significantly between treatments ($p = 0.860$).

3.2 'Wet' nursery experiments

All seedling parameters assessed in the wet nursery varied significantly between SC treatments (height, $p < 0.001$; number of leaves, $p < 0.001$; number of nodes, $p < 0.001$; health index, $p < 0.001$) (Supplementary File S2). However, the most noteworthy finding was the rapid demise of the plants under 'wet' nursery conditions. Seedling survival in the 'wet' nursery was especially poor for treatments of 100% and 50% SC. Complete loss of leaves and presumed death of the plants was seen after three weeks (Table 1). One plant of ten subsequently recovered in the 50% treatment but there was no recovery of plants in the 100% treatment after 6 weeks. The control (0 % SC), by contrast showed 90% seedling survival.

The growth parameters (height, number of leaves, number of nodes) and health rank assessed in the surviving 'wet' nursery plants showed a similar pattern across treatments. Number of leaves, number of nodes and health were greatest in the control (0% SC) while the 50 and 100% SC treatments showed lowest values (Fig. 5). Height was again similar with 50% and 100% SC treatments showing poorest growth while plants in 75% SC treatment showed greatest values (similar to the control and the 25% SC treatment).

3.3 Elemental analysis

Elemental analysis of seedlings after the dry nursery experiments indicated 25 elements (Table 2). Six elements (Na, Mg, K, Ca, As, Se), found in high concentrations in the SC had minimal concentrations in the plants (roots or leaves) (Supplementary Fig. S1). Most of the elements (Be, Al, V, Cr, Ni, Co, Mn, Fe, Ag, Ba, Pb, Th, U) had high concentrations in the soil/sand medium compared to the SC, however these were still low in the plants (Supplementary File S.3). Most elements (19 of 25) displayed a general pattern of greater mean concentrations in the roots than in the leaves while only four (Mg, Ca, Mn and Ti) were higher in the leaves.

Elements of interest, As and Na, had greatest mean concentrations in the pure SC (202.43 ppm and 50,676.21 ppm, respectively), however concentrations of these were much lower in the *R. mangle* seedlings (Table 2). Arsenic (As) concentrations in the *R. mangle* seedlings were

less than 4% of concentrations in the SC for all except roots grown in 100% SC (which had 11.9% of As concentration in the SC). For Na, mean concentration in the *R. mangle* seedlings grown in 100% SC were all lower than 17.7% of the SC concentration, except for roots in 100% SC which had mean Na concentrations of 21.5% of the SC concentration.

Principal Component Analysis (PCA) indicated four groups (Fig. 6). PCA also confirmed the groupings by the inclusion of elements found high in the pure SC (Mg, Na, K, Ca, As, Se) in one cluster group. Ni which was high in the soil/sand medium, low in SC and with varied concentrations across *R. mangle* roots and leaves was identified by the PCA as an outlier.

4. Discussion

Since the *Sargassum* spp. influx across the Caribbean began in 2011, these algae have been assessed for efficacy in crop production with indication of success, in particular improved crop productivity as well as resistance against pests and harsh environmental conditions (CARDI, 2015; Desrochers et al., 2020). Mohanty et al. (2013) and Walsh (2019) used *Sargassum* spp. in compost form and examined the production of this for agriculture and horticulture applications. Liquid *Sargassum* spp. extract has also been used in foliar application to achieve significant growth (Miranda et al., 2021). Pelagic *Sargassum* spp. have been shown to be rich in macro and micronutrients (Davis et al., 2021; Machado et al., 2022; Tonon et al., 2022) and so the production of commercial fertiliser from *Sargassum* spp. is well established (Desrochers et al., 2020). Interestingly, the use of *Sargassum* spp. for mangrove restoration has not been previously explored. This is particularly relevant as we seek to achieve successful mangrove rehabilitation in urbanised areas which have less than ideal sediment conditions, and we saw the need to explore the utility of sargassum for this application.

4.1 Impact of Sargassum spp. compost (SC) on mangrove seedlings under different nursery conditions

The wet nursery results clearly demonstrated that use of high concentrations of SC (100%) combined with waterlogged conditions result in very poor outcomes, quickly affecting plant survival. Rotting of the roots was observed concomitantly with the presence of a strong smell of hydrogen sulphide (H_2S) gas. Rotting *Sargassum* spp. has been reported to produce H_2S gas which has resulted in decline in natural mangrove and seagrass habitats (Oxenford et al., 2021). The finding of survival in the 50% SC being similarly poor to that of the 100% SC treatment is difficult to explain. The height of plants in 50% SC was also as low as the 100%, while 75% compost in the wet nursery yielded the greatest heights. The value of the 'wet' nursery experiments however, was to demonstrate the deleterious effect of SC in water-logged soils and a similar propensity for H_2S production as was observed with rotting of fresh *Sargassum* spp. in coastal areas.

The positive response of red mangrove seedlings to 75% SC treatment in the dry nursery was best indicated by changes in seedling height. The gradual change in median height from maximum in the 75% SC along the decreasing treatment percentages (50%, followed by 25% and then the control) indicated the positive effect of *Sargassum* spp. on *R. mangle* seedling growth. Growth in pure SC (100% treatment) was low, being marginally higher than the control, and was accompanied by poorest health, showing that pure SC is deleterious to plant health and growth. There were indications of high concentrations of growth inhibiting substances or other constituents that have deleterious effects on growth and health of the plants in the undiluted compost. Several authors have reported occurrence of heavy metals and substances like

phenols (sometimes in high concentrations) from *Sargassum* spp. (Milledge and Harvey, 2015; Milledge et al., 2020). Arsenic in particular has been measured from fresh and dried *Sargassum* spp. at concentrations above the accepted EPA values and with a dominance of the highly toxic inorganic form (Davis et al., 2021; Milledge et al., 2020; Tonon et al., 2022). The inhibitory effects from use of the 100% SC treatment would support the recommendation that the SC be mixed with other plant material (Milledge et al., 2020) or used in lower concentrations with soil mixes. Use of 25 to 50% *Sargassum* spp. in compost trials by Walsh (2019) achieved good plant growth and low arsenic levels (4.2-7.2 ppm in the plants) which are within the EPA standards for such activity (Desrochers et al., 2020).

The experiment facilitated assessment of the growth (and health) parameters normally used to assess seedlings within a mangrove nursery or after out-planting (Trench 2021). The effect of *Sargassum* spp. on number of leaves was not as clear as seen for plant height in the dry nursery experiments. Leaf production and retention was however noticeably best in the 75% SC treatment while the 50% treatment was the poorest. We do not currently have any clear explanation for the observed responses in 50% SC. Mangroves, especially the *Rhizophora* spp., have been reported to show necrosis and leaf loss (as well as low leaf production) in response to increasing and above-normal salinity (Aslam et al., 2011) as well as to other chemical stressors (Proffit and Develin, 1998). Other effects, like leaf thickening (succulence), have also been reported for *Rhizophora* spp. grown in high salt conditions (Parida and Jha, 2010). While the leaf damage observed in our experiment was expected, the occurrence of thinning of the leaves (reduced thickness or loss of succulence) in especially the 100% treatment as well as in the 50% SC, would suggest that the plants were not responding to salt stress (Parida and Jha, 2010). The responses may be due to the effect of other (chemical) stressors. Heavy metals and other toxins, (e.g. insecticides like chlordecone), which are sequestered by *Sargassum* spp. after prolonged periods in the environment (Devault et al., 2020) could be toxic to the plants in high compost concentrations. Hence the need for elemental analysis of the plants, compost and soil used as potting medium.

4.2 Partitioning of elements between soil/sand medium, *Sargassum* spp. compost and mangrove seedlings

Our findings of high elemental concentrations associated with the soil/sand support the idea that mangrove sediments may act as an efficient metal trap (Silva et al., 1990; Saher and Asmat, 2017). These authors also indicated that mangrove sediments can be the main reservoir for heavy metals when compared to the living biomass; the later accounting for less than 1% of what was retained in the sediments. Others have reported that mangrove plants, especially *Rhizophora* spp., due to ion exchange at the roots, can actually regulate heavy metal uptake (Alongi et al., 2004; MacFarlane and Burchett, 2002; MacFarlane et al., 2007. The combined effect may account for the low elemental concentrations we observed in the plants.

It was our expectation that seedling roots would have greater elemental concentrations than leaves based on direct contact with source, and our results did indicate that generally mangrove seedling roots had higher concentrations of elements than the leaves. Mangroves are reported to be resistant to heavy metals (Machado and Lacerda, 2004) and tolerance, in especially *R. mangle,* has been suggested by Walsh et al. (1979) to be due to formation of non-toxic sulfides in the root or at the root surface. The plants may also employ detoxification at the tissue level and ion-exclusion at the roots which is part of the same salt-exclusion mechanism (Scholander et al., 1962), or a combination of these factors. Metal exclusion is therefore strongly suggested but also detoxification at the tissue level due to high tissue residues without

proportional effect on the plant (Walsh et al., 1979). This was also seen in our experiments where for some elements in high concentrations in the soil/sand potting medium and with high root uptake in the control treatment, low concentrations were found in the leaves and there was no obvious compromise to plant health. Furthermore, we observed that the only elements found to be higher in leaves than roots tended to be those naturally associated with plant leaves (e.g. Mg, Ca, Mn).

Of the elements found to be high in pure SC (and low in plants), Na and As were deemed of concern because of their abundance in naturally occurring *Sargassum* spp., and their potential to cause poor outcomes and plant damage. While sodium and magnesium are common seawater elements (Ceron-Sousa et al., 2021), sodium was important to consider because salt stress can be very damaging even to coastal plants. According to Aslam et al. (2011), no toxic substance restricts plant growth more than excess salt. Mangrove seedlings have shown leaf damage in persistent hypersalinity (Krauss et al., 2008), condition under which stunting and poor growth (sometimes leading to death) of mangroves has also been observed (Barreto, 2008; Drexler and Ewel, 2001). Arsenic is another element of concern because of its toxicity, potential to cause environmental contamination (Rodríguez-Martínez et al., 2020), and the fact that it has been consistently reported in high concentrations in pelagic *Sargassum* spp. associated with the blooms (Davis et al., 2021; Desrochers et al., 2020).

4.2.1 Sodium contamination

Mangrove plants are said to be facultative halophytes meaning they do not need to grow in saline soils and are found in areas with both high and fluctuating salinities (Parida and Jha, 2010). They employ various mechanisms to tolerate saline environments, including exclusion of salt at the roots, excretion of salts (usually by the leaves) and some tolerance of relatively high salt concentration in the tissues (Hogart, 2015). *Rhizophora* spp. have concentric layers of hypodermal and endodermal cells (called a double-endodermis) in the roots that act as a barrier (Aslam et al., 2011). This genus is also known to move salt into older leaves which are then shed (Hoppe-Speer et al., 2011). Despite these mechanisms, *Rhizophora* is not able to survive in hypersaline soils and prefers the margins of the forest where a range from normal seawater (35 psu) to hyposaline and tidal flushing are experienced (Hoppe-Speer et al., 2011). The natural mangrove environment, however, is dynamic and species therefore tend to be tolerant to a range of conditions even for a short time. In less than ideal situations, these species may exhibit slower growth or appear less 'healthy' rather than be eliminated (Krauss et al., 2008). In the case of hypersalinity or high sodium, mangroves may also expend a lot of energy to remove salt, using large amounts of "photosynthetic energy" (Medina, 1999) and so exhibit slower growth.

4.2.2 Arsenic contamination

Holopelagic *Sargassum* spp., like many brown seaweeds, contain concerning concentrations of arsenic (Rodríguez-Martínez et al., 2020). In our experiments the poor health of the seedlings in 100% SC treatment was thought to be due to increased levels of contaminants like arsenic. The indicators of poor health which included spotting (brown) and curling as well as yellowing of the leaves were very evident in the 100% *Sargassum* spp. compost plants. However, while elemental analysis indicated greatest mean As concentration (202.43 ppm) in the pure SC, the only plant tissue with concentrations greater than 20% (24.1 ppm) was roots of seedlings grown in the 100% pure SC treatment.

This indicates the lack of uptake and sequestration by the *R. mangle* seedlings and the possible utility of *Sargassum* spp. in nursery propagation of this plant. Furthermore, application on a wider scale (out-planting) may have positive outcomes.

5. Application

Collecting and drying or composting of *Sargassum* spp. in tropical coastal communities with high insolation (and low rainfall) is a relatively low cost activity that produces material with potential for several applications. In this context, composting has the greatest potential for soil amelioration as both the properties (texture and water holding capacity) as well as nutrient content of the soil or sand is enhanced (Adugna, 2016; Pan et al., 2012). Desrochers et al. (2020) have indicated that using seaweed as compost in coastal areas is one of the simplest, cheapest and most practical methods of making use of the large algal biomass. In line with this, our experiments show that in appropriate proportions, pure SC does enhance mangrove seedling growth with height, and to a lesser extent leaf production, being good indicators.

While potentially toxic elements found naturally in or sequestered by *Sargassum* spp. remain a concern, for mangroves there is evidence that especially *R. mangle* has developed strategies to minimize uptake. These attributes of mangroves have actually been proposed for application to mitigate metal pollution in coastal areas (Machado and Lacerda, 2004). There is therefore potential for use of the algal biomass in nuisance pelagic *Sargassum* spp. blooms to support mangrove rehabilitation under conditions where the application is in relatively dry areas (e.g. along the urbanised shorelines like Kingston Harbour, Jamaica) and under controlled applications where the ameliorant can be contained in the immediate planting area. This could ensure better success of rehabilitation efforts in such areas as well as make use of the algal biomass; leading to the benefit of impoverished coastal communities who are ultimately most affected by *Sargassum* spp. inundations and mangrove loss.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

CT: investigation, formal analysis, visualization, writing - review & editing; SLT: investigation, formal analysis, writing - review & editing; DT: investigation, formal analysis, writing - review & editing; GM: investigation, formal analysis, writing - review & editing; PF: investigation, formal analysis, writing - review & editing; HS: formal analysis, writing - review & editing; CBM: formal analysis, writing - review & editing; DW: formal analysis, writing - review & editing; TT: conceptualization, funding acquisition, investigation, formal analysis, visualization, writing - review & editing. MW: conceptualization, funding acquisition, investigation, formal analysis, visualization, writing - review & editing.

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Legend of Figures

Fig. 1. Median seedling height (bar), 25-75% range (box) and non-outlier range (whisker) for red mangrove seedlings in each treatment indicating the % sargassum compost (SC).

Fig. 2. Median number of leaves (bar), 25-75% range (box) and non-outlier range (whisker) for red mangrove seedlings in each treatment indicating the % sargassum compost (SC).

Fig. 3. Median health rank (bar), 25-75% range (box) and non-outlier range (whisker) for red mangrove seedlings in each treatment indicating the % sargassum compost (SC).

Fig. 4. *R. mangle* seedlings showing leaf damage after growth in 100% SC (A) and seedlings in 75% SC showing lateral branching (B). The lateral branching was observed at the end of the experiment.

Fig. 5. Change in seedling parameters; number of leaves, number of nodes, height and health (means with ± 95% CI) across SC treatment in the 'wet' nursery averaged for all weeks.

Fig. 6. Principal Component analysis (PCA) showing grouping of elements according to concentrations in ppm.

Supporting materials

S1. Supplementary File S1 (Excel File). Statistical tests and boxplots for dry nursery plant parameters.

S2. Supplementary File S2 (Excel File). Statistical tests and boxplots for wet nursery plant parameters.

S3. Supplementary File S3 (Excel File). Raw data and boxplots for all elements in plants, soil/sand and SC.

311 Fig. S1. Boxplots of six elements found high in SC and low in the mangrove plants.

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Table 1. Mangrove seedling survival in 'wet' nursery conditions showing death of the plants (0% survival) by week 3 in 100% SC. Experiment terminated after week 6 when one treatment had death of all plants.

	Number of mangrove seedlings remaining alive in each treatment per week						
SC Treatments	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**% survival**
0% SC (Control)	10	10	9	9	9	9	90
25% SC	10	10	9	7	6	6	60
50% SC	10	10	0	0	1	1	10
75% SC	5	5	5	3	3	3	60
100% SC	10	10	0	0	0	0	0

452 Table 2. Element concentration (mean with S.E.) in parts-per-million (ppm) for plant sections in all SC treatments, pure SC and soil/sand
453 potting mix.

Element	Leaves in 0% SC	Leaves in 25% SC	Leaves in 50% SC	Leaves in 75% SC	Leaves in 100% SC	Roots in 0% SC	Roots in 25% SC	Roots in 50% SC	Roots in 75% SC	Roots in 100% SC	Soil/ Sand	Pure SC
Be	0.01±.01	0.000±.000	0.008±.006	0.004±.002	0.003±.003	0.05±.014	0.025±.004	0.025±.01	0.013±.012	0.002±.002	0.20±.01	0.01±.003
Na	1560.78 ±64.27	2267.14 ±43.04	2966.58 ±44.07	2444.78 ±146.84	4726.84 ±80.28	6430.93 ±144.24	7247.74 ±150.194	8979.04 ±135.05	8087.39 ±205.03	10893.02 ±224.90	830.95 ±67.48	50676.21 ±525.80
Mg	4537.53 ±293.23	3911.61 ±56.70	4618.84 ±111.47	4107.99 ±86.21	5903.27 ±59.42	2512.29 ±180.17	2101.96 ±7.59	2105.24 ±89.43	2145.72 ±21.60	3036.78 ±68.12	9172.54 ±730.24	20767.5 ±623.27
Al	57.55 ±10.24	26.26 ±1.99	63.74 ±5.82	58.84 ±13.51	44.83 ±2.92	2344.14 ±371.06	1157.15 ±43.12	560.85 ±101.34	315.01 ±50.73	111.99 ±4.43	11496.95 ±500.80	160.21 ±10.69
K	9648.36 ±321.71	5212.63 ±179.92	6346.68 ±155.64	4924.16 ±118.76	5747.46 ±129.90	7812.36 ±861.39	4625.87 ±7.44	4727.49 ±363.06	4851.39 ±196.54	3094.17 ±12.65	1041.63 ±39.98	76863.61 ±1621.92
Ca	26119.82 ±1137.61	26104.25 ±512.98	29395.10 ±585.52	27501.35 ±640.01	30795.27 ±554.75	12325.62 ±340.93	14735.22 ±247.82	15985.00 ±1076.33	17131.54 ±408.91	22251.60 ±328.42	90140.80 ±8746.77	143919.47 ±6981.48
V	0.23±.06	0.08±.01	0.34±.07	0.1±.05	0.13±.01	11.61±2.46	7.19±.31	6.01±.77	3.65±.41	2.99±.08	56.01±2.27	7.21±.73

Cr	1.35±.20	0.73±.19	0.63±.08	0.35±.10	0.27±.02	27.33±2.47	18.53±1.22	9.72±1.40	9.04±1.74	7.90±.06	22.68±4.40	0.99±.14
Mn	75.83 ±4.16	92.67 ±3.06	140.22 ±4.65	168.29 ±6.80	113.99 ±2.98	59.72 ±20.11	85.36 ±4.83	51.63 ±5.46	40.37 ±3.40	29.95 ±.72	393.70 ±12.55	32.08 ±1.07
Fe	65.50 ±14.24	38.09 ±11.22	79.11 ±13.67	47.49 ±10.27	33.62 ±1.43	2619.25 ±804.21	1158.37 ±47.85	686.82 ±130.58	439.19±58.79	161.75±1.02	17077.63 ±522.80	114.98 ±6.28
Co	0.08±.01	0.08±.01	0.19±.01	0.19±.01	0.17±.01	1.23±.30	1.00±.05	1.34±.24	1.17±.16	1.68±.07	8.39±.24	1.47±.06
Ni	4.80±1.99	1.03±.07	1.54±.37	0.77±.15	1.15±.38	7.93±.79	5.18±.85	2.47±.31	2.38±.64	5.33±.99	13.31±.71	4.52±.14
Cu	21.67 ±2.51	11.54 ±.54	11.06 ±1.41	7.67 ±1.96	7.83 ±1.31	53.46 ±1.29	135.30 ±76.39	44.01 ±9.11	57.79 ±7.98	46.79 ±6.01	42.76 ±2.05	5.59 ±.22
Zn	11.32 ±1.46	7.42±.46	8.44±.64	7.49 ±1.10	8.60 ±.45	47.83 ±1.59	78.05 ±34.06	44.48 ±10.26	37.28±5.91	37.47±1.05	72.44±.95	14.07±.46
As	0.44±.04	0.63±.03	1.14±.04	0.99±.07	1.11±.02	1.89±.01	5.72±.47	14.85 ±2.65	10.00 ±1.52	24.11 ±.95	27.09 ±2.38	202.43 ±2.13
Se	0.17±.004	0.11±.01	0.09±.02	0.06±.01	0.04±.01	0.19±.03	0.22±.02	0.19±.04	0.11±.01	0.16±.02	0.68±.06	1.29±.03
Mo	0.39±.04	0.26±.002	0.25±.01	0.16±.02	0.10±.01	0.90±.09	0.80±.05	0.57±.06	0.48±.04	0.55±.04	0.70±.15	0.33±.03

Ag	0.004 ±.001	0.002±.001	0.004 ±.001	0.003±.00	0.003 ±.001	0.02±.002	0.02±.006	0.01±.002	0.01±.002	0.01±.001	0.05±.002	0.02±.002
Cd	0.01±.002	0.01±.001	0.02±.002	0.02±.003	0.02±.002	0.40±.01	0.47±.03	0.65±.16	0.31±.05	0.58±.02	1.02±.20	0.64±.01
Sb	0.01±.003	0.01±.003	0.01±.00	0.004 ±.001	0.003±.00	0.03±.002	0.04±.004	0.03±.01	0.04±.01	0.07±.006	0.03±.004	0.08±.003
Ba	44.86 ±1.61	21.35 ±.48	14.02 ±.25	8.29 ±.11	3.08 ±.002	51.17 ±9.78	17.26 ±.44	12.26 ±.92	7.24 ±.91	3.51 ±.11	148.91 ±14.53	38.98 ±.48
Ti	0.02±.002	0.02±.00	0.02±.002	0.02±.00	0.02±.002	0.01±.001	0.01±.00	0.01±.001	0.01±.001	0.01±.001	0.04±.00	0.03±.004
Pb	0.76±.15	0.31±.03	0.41±.07	0.28±.09	0.29±.04	2.23±.06	4.45±2.09	2.10±.45	2.68±.39	2.66±.15	8.87±.64	0.34±.03
Th	0.01±.001	0.003±.00	0.005±.00	0.01±.001	0.004±.00	0.09±.01	0.05±.002	0.02±.01	0.02±.003	0.01±.00	0.86±.03	0.02±.001
U	0.01±.002	0.01±.001	0.01±.001	0.02±.004	0.01±.001	0.30±.002	0.24±.01	0.27±.03	0.20±.03	0.28±.01	1.75±.13	1.22±.08

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