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Assessment of *Sargassum* spp. management strategies in southeast Florida

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ABSTRACT

This study evaluated the economic viability of *Sargassum* management strategies in southeast Florida. Semi-structured interviews were conducted with key informants, beach managers and potential users. To compare the strategies, a cost and market analysis was conducted to assess the value of *Sargassum* compost relative to other compost products available in the market. The findings indicate that composting *Sargassum* is an economically viable option and suggests the potential for recouping some of the costs associated with beach cleaning through the sale of compost. Furthermore, the utilization of *Sargassum* compost could offer a cost-effective alternative as a soil amendment, especially in the face of rising fertilizer costs. However, it is crucial to address concerns regarding compost quality due to contaminants such as plastics and arsenic before implementing a composting operation. This aspect necessitates thorough investigation and remediation to ensure that the resulting compost meets quality standards and is free from potentially harmful contaminants.

1. Introduction

Sargassum spp. (specifically *Sargassum natans* and *S. fluitans)*, and referred in this paper as *Sargassum*, is a genus of brown macroalgae that has been inundating areas not only in the Caribbean but in Central America, North America, and Africa (Langin, 2018; Milledge et al., 2016; LaPointe et al., 2021). These inundations have increased in occurrence and volume since 2011, resulting in overwhelming quantities that are difficult to handle resulting in unmanaged decay and negatively impacting coastal tourism, ecosystems, and human health. In 2018 record-breaking quantities reached the shores of the Caribbean alone, with 20 million tons of beached *Sargassum* measured in June (Wang et al., 2019). In 2021, an estimated 5.1 and 4.6 million tons of *Sargassum* were observed in the tropical Atlantic in January and February respectively, which doubled in March to 10.1 million tons (USFOO Lab, 2021).

There are two known sources of *Sargassum*: the Sargasso Sea in the North Atlantic and a newer source region called the Great Atlantic *Sargassum* Belt (GASB) (Wang et al., 2019). Within the Sargasso Sea and GASB, *Sargassum* persists and proliferates, and portions are transported towards the coastlines where they strand onshore. *Sargassum* inundation events in the Atlantic are thought to be the initiated and influenced by nutrient discharges from the Amazon River, changes in ocean upwelling, higher sea surface temperature, and changes in ocean circulation (Sissini et al., 2017; Sanchez-Rubio et al., 2018; Oviatt et al., 2019; Wang et al., 2019; Johns et al., 2020; Fidai et al., 2020). Studies have shown that these annual blooms are expected to continue into the foreseeable future and will become the "new normal" for areas that are impacted (Wang et al., 2019; Salter et al., 2020; Machado et al., 2022; Trench et al., 2022; Tomenchok et al., 2021). In fact, at the writing of this manuscript record-breaking amounts of *Sargassum* have been quantified in the Atlantic Ocean with predictions for massive influxes for the summer of 2023 (Miller, 2023).

Coastal communities view *Sargassum* as a nuisance and are looking for ways to minimize the impacts from inundations (van Tussenbroek et al., 2017). Once onshore, these large inundations have been a challenge for beach managers. The decomposition of *Sargassum* removes oxygen from the surrounding waters, killing fish and other marine life (Hallegraeff, 2010). Seagrass beds are also known to suffer losses due to *Sargassum* blocking light from the surface (Bartlett and Elmer, 2021). Not only does marine life become affected, but human health is also at risk. When in excessively large quantities and if left unmanaged on shore, *Sargassum* will decompose anaerobically often emitting a foul odor which can also be toxic (Resiere et al., 2018; Dominguez and Loret,

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2019). Additionally, with large inundations of *Sargassum*, plastic waste found in the open ocean and onshore, can get entangled within strandings (Amaral-Zettler et al., 2020). *Sargassum* combined with plastic marine debris has been shown to harbor *Vibrio*, which is a genus of bacteria known to include potentially pathogenic species (Mincer et al., 2023; Theirlynck et al., 2023).

In order to dispose of the large inundations of *Sargassum*, waste managers often haul it to landfills when inundations are excessive. Hauling *Sargassum* to landfills can be viewed as an unnecessary cost, given the possibility of its beneficial uses (van Tussenbroek et al., 2017). Sustainable alternatives, such as composting, may be a viable option. Indeed, the compost itself may be marketable and allow beach managers to recoup some of the *Sargassum* compost production costs (Gajalakshmi and Abbasi, 2008; Kumar, 2011). Even though the large inundations are considered a nuisance, *Sargassum* can viewed as a resource (Milledge and Harvey, 2016; Chávez et al., 2020; Amador-Castro et al., 2021; Trench et al., 2022). In a study conducted by Sembera et al. (2018), food waste and wood chips were mixed with *Sargassum* (unwashed and washed). Even though a usable product was created and met the standards outlined by the U.S Composting Council (USCC) in terms of plant nutrients (nitrogen, phosphorus, and potassium specifically), the proportion of *Sargassum* used in the compost product was small (2%), which limits the amount of *Sargassum* that can be reused. In another study conducted by Walsh and Waliczek (2020), larger proportions (25% or 41.5%) of *Sargassum* were used in a large-scale composting system to assess the quality of the product for utilization in agriculture. The compost produced also met the guidelines outlined by the USCC. In a study by Abdool-Ghany et al. (2023), which evaluated compost ranging from 50% to 100% *Sargassum*, compost produced was capable of sustaining the growth of radishes. However, nutrient levels were not optimal, plus bacteria and arsenic levels occasionally failed regulatory guidelines thereby limiting some beneficial uses. To our knowledge, there has been only one additional study conducted that composted pure *Sargassum* but in the sole context of mangrove restoration (Trench et al., 2022). Data gaps exist in understanding the operations and economic viability of compost production by beach managers or small enterprises, especially when *Sargassum* landings are large, and the availability of additional feedstocks are limited. Research is needed to assess the economic viability of composting pure *Sargassum*, as an alternative for managing large inundations.

This study addresses data gaps by exploring the economic viability of composting *Sargassum*. This study not only evaluates the efficacy of *Sargassum* management strategies but also conducts a comprehensive cost analysis of the *Sargassum* composting operation. Additionally, a market analysis was conducted to compare the value of *Sargassum* compost with other compost products available in the market. Results represent a step towards expanding composting of *Sargassum* to a broader range of communities.

2. Materials and methods

2.1. Interviews with beach managers and potential compost users

A set of two questionnaires (copies in supplement) were developed for two categories of key informants, beach managers and potential compost users. The questions utilized for each questionnaire were based on input during Technical Awareness Group meetings that were held with stakeholders (with representatives from government agencies, environmental non-profits, commercial enterprises, and academia) (Abdool-Ghany et al., 2022b). In brief, the questionnaire for beach managers asked about beach management and practices (specifically of *Sargassum*), interest and experience in composting *Sargassum*, and costs associated with beach management. The responses from this questionnaire were organized to compare beach management objectives, size of area managed, *Sargassum* management (during peak and off season), and communication of the strategy. The strategies used by the agencies were also ranked by the research team (high, medium, low) in terms of cost effectiveness, environmentally friendliness, manageability, and beach appeal. The questionnaire for potential compost users asked about their interest in *Sargassum* compost products, and for those that produced their own compost, composting techniques used. The responses to this questionnaire were used for a market analysis. Once the questionnaires were developed, a two-person research team used these questionnaires to conduct semi-structured interviews during 2021 and 2022 with each category of key informants.

Beach managers included individuals from local government agencies that handle the maintenance of beaches in southeast Florida. Southeast Florida was chosen because of the range in management approaches and the willingness of stakeholders to share information through a pre-existing stakeholder group. Beach managers interviewed described the implementation of their *Sargassum* management strategies. A total of six beach managers were interviewed, representing four agencies. The first three agencies were represented by one beach manager each. The fourth agency was represented by three beach managers. Composting was the primary management strategy for Agency 1. A detailed cost analysis was conducted of the composting operations for Agency 1. In addition to "no management", two additional management strategies identified from the interviews were compared to the costs associated with composting as defined by Agency 1. Field visits were also conducted for three of the agencies (Agency 1, Agency 2, and Agency 4).

The second category of informants interviewed, consisting of potential compost users, included four organic growers and one local liquid fertilizer business. In addition to the questionnaires, field visits were conducted with the organic growers. For the market analysis (described below), samples of alternative composts produced by three of the four organic growers were also collected for nutrient analysis (nitrogen, phosphorus, and potassium) for comparison with nutrients associated with *Sargassum* compost. Samples were not available from the local business. The responses to these questions provided us with information about the market value of alternatives to *Sargassum* compost.

At the conclusion of each set of interviews, the key informants were asked about drawbacks and limitations associated with composting. These responses were summarized in tabular form.

2.2. Cost and market analysis

For the cost analysis, we focused on Agency 1 since composting was to be the basis for comparison on management strategies. For Agency 1, we created an enterprise budget for composting *Sargassum*, using accepted methods (Wentworth et al., 2002; Zurbrügg et al., 2005; Chen 2016). This budget included all the costs involved in managing the compost pile (i.e., labor, machinery operating and depreciation costs, land rental values, and return on capital). We then compared Agency 1′s total cost to produce *Sargassum* compost to the cost that nearby local governments (Agencies 2 through 4) spent to remove and dispose of the seaweed found on their beaches. This information was then augmented with feedback received from a commercial beach grooming company to refine comparisons to operations by Agency 1.

For the market analysis, we compared two factors: 1) the quality of the compost product for growing plants, as expressed by nutrient measurements (nitrogen, phosphorus, and potassium) plus pH, and 2) the pricing of the compost products on the market. To expand on the description in the introduction, during an earlier study (Abdool-Ghany et al., 2023), we composted *Sargassum* using 6 different recipes (unwashed *Sargassum*, washed *Sargassum, Sargassum* plus grass clippings, *Sargassum* plus mulch, outdoor *Sargassum*, outdoor *Sargassum* plus vegetative waste). We report here the nitrogen, phosphorus, potassium values and pH for these six recipes. Additional details about the prior work with these 6 *Sargassum* recipes is available in Abdool-Ghany et al. (2023).

For comparison, we also report the nitrogen, phosphorus, potassium values and pH of compost products that were gathered from the farms of organic growers that were interviewed for the market analysis. The non-*Sargassum* compost samples provided by organic growers were made from: a) food and mulch, b) compost combined with chicken manure c) potting soil, and d) potting soil and plant biomass. Whereas the process of measuring nitrogen, phosphorus, potassium in our earlier study is described in detail in Abdool-Ghany et al. (2023), the nitrogen, phosphorus, potassium values of the samples collected from the organic growers were sent to a commercial laboratory (A &L Great Lakes Laboratories, Fort Wayne, Indiana) and as detailed in the supplemental text analyzed by standard protocols (Test Methods for Examination of Compost and Composting (TMECC) by the USCC.

As no market currently exists for *Sargassum* compost, we estimated its value by first comparing the nutrients of *Sargassum* compost combinations against compost produced from the alternative organic materials. We then used the price of similar nutrient quality products as described by the organic growers which they either purchased from third party sources or sold to other local growers. Similar comparative market analyses have been employed to place a monetary value on compost and other products that are currently unavailable in the market (Wentworth et al., 2002; Waliczek et al., 2020). Unlike the Waliczek et al. (2020) study which was based on a hypothetical scenario to estimate the price for *Sargassum* compost, based on what consumers said they were willing to pay for it, our study makes a direct price comparison to compost products already in the market. This market comparison allowed us to obtain a range of potential market values for each of the compost recipes based on the market prices supplied by the local growers.

2.3. Statistical analysis

In order to determine the normality of the data, a Shapiro-Wilk test was performed on the *Sargassum* compost treatments and the organic compost samples collected. It was determined that the data was normally distributed, thus parametric tests were used to compare the nitrogen, phosphorus, potassium, and pH values for the *Sargassum* compost treatments and the organic compost samples. Independent t-tests were used to compare the two sets of data. Differences were considered statistically different for p values less than 0.05.

3. Results

3.1. Analysis of management strategies

The agencies that were interviewed differed in beach management objective, size of area managed, management strategies (Fig. 1), and mode of communication with stakeholders (Table 1). Beach management by Agency 1 was driven by the aesthetics of the beach. Agency 1 employs composting as their primary management strategy and provides information about the inundations and their management strategy methods on a website for constituents. Agency 2 was concerned about the bacteria levels and aesthetics of the beach and decided to use deep burial. Information pertaining to their management strategy and why it was chosen is provided on a website. Ecology of the beach area was a major concern for Agency 3. Thus, the strategy that Agency 3 employed when amounts were excessive was pull bar, which minimizes disturbances to the beach. Finally, Agency 4 was concerned about aesthetics of the beach. Since a longer stretch of beach area is managed, there are three strategies used, but the main strategy is cut and turn. Agency 4 also used websites and signage to communicate the extent to of the *Sargassum* inundations.

Studies have shown that integrated *Sargassum* contributes towards fecal indicator bacteria contamination of coastal waters. As such, other management methods were adopted by beach managers. For example, deep burial is utilized in some areas to try to minimize the impact of *Sargassum* decay on the concentration of bacteria in the nearshore water (Abdool-Ghany et al., 2022a). In addition to cut and turn, Agency 4 also utilizes decomposition as a strategy to manage *Sargassum* when the inundations are excessive. With this process, the *Sargassum* is removed from the beach to a staging area and allowed to dry, decompose, and integrate into the underlying sediment. To address the inundations of *Sargassum* on beaches during peak season, the most common management method is to collect it on the beach and haul it away to a landfill, which is usually done by a third-party company. All four agencies use websites as their main form of communication with the public about *Sargassum.* Agencies 3 and 4 are the only ones that use signs posted in various locations along their beaches to inform beachgoers about *Sargassum.*

We compared the management strategies employed by each Agency

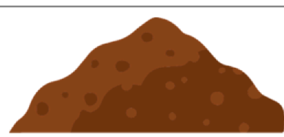
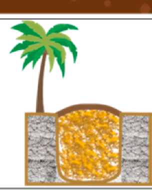
Management Style	Description
 Composting	*Sargassum* is allowed to decompose overtime within a dedicated heap. *Sargassum* moved into various places in the compost facility to separate recent and older strandings to control decomposition. As the *Sargassum* decomposes, it is then moved to other areas of the pile to make room for fresher *Sargassum* that is brought in.
 Deep burial	Process by which a 3-to-4-foot pit is created on the beach and then filled back with *Sargassum*. This pit is then covered with sand and the *Sargassum* decomposes within the pit.
 Integration-Pull Bar	A bar is attached to a tractor and pulled across the top of the beach. The *Sargassum* is tilled into the top layer of the sand but is minimally broken down by mechanical processes. It is a form of integration.
 Integration-Cut and Turn	Similar to the pull bar strategy in that the *Sargassum* is tilled into the sand, but this process involves breaking the *Sargassum* into smaller pieces. It is a form of integration.

Fig. 1. Summary of the management styles that are used in Southeast Florida. There were four strategies that were identified by Agencies that took an active role in managing *Sargassum* inundations.

Table 1
Description of beach management strategies, objectives, size of areas managed, and communication methods for agencies that manage *Sargassum* at beaches in southeast Florida.

Agency	Agency 1	Agency 2	Agency 3	Agency 4
Beach Management Objective	Concerned about the aesthetics of the beach	Concerned about the bacteria levels and aesthetics of the beach	Not concerned about a pristine appearance but about the ecology preservation of the area	Maintaining the aesthetics of the beach as it is important for tourism
Size of area managed	Approximately 6.4 km	Approximately 2.0 km	Approximately 1.4 km	Approximately 27.4 km
***Sargassum* Management During Off-Peak Season**	Composting Seaweed is removed and transported to an off-site compost pile	Deep burial of seaweed 1 to 1.5 m and capped with a layer of sand	Pull bar used to till *Sargassum* into the sand and used to minimize beach disturbance	Cut and turn strategy is used along some beaches
***Sargassum* Management During Peak Season**	Composting	Deep burial in addition to hauling away to a landfill	Pull bar	Relocating *Sargassum* to a staging area that allows for decomposition Haul away to landfill from hotspot areas
Communication Strategy	Provides information to the public via website about the seaweed composting efforts. Includes information about how much is saved, and statement of sustainability	Provides information to the public via website, which offers information on the management style used and detailed explanation as to why it is chosen	Provides information to the public via website as well as public signage along the beach. Website and signs provide information on the ecological importance of *Sargassum*	Provides information to the public via website as well as public signage along the beach. Website provides a Q&A format for information. Signage is simple and briefly explains what *Sargassum* is

across four parameters, beach appeal, environmental friendliness, manageability, and cost effectiveness (Table 2). Most of the Agencies are concerned about keeping and maintaining the beaches pristine in appearance (i.e., white sand without organic debris). For beach appeal, we rated Agencies 1, 2 and 4 as high due to their objective of beach management focused on aesthetics. All three of the Agencies want beaches that meet tourist expectations of white sandy beaches since tourism is an important industry to the local economy.

Table 2
Ratings of high, medium, and low of the viability assessment across the agencies.

Agency	Beach Appeal	Environmentally Friendly	Manageability	Cost Effectiveness
Agency 1	*High* Keeps beach looking pristine	*Medium* Energy expended to keep beaches pristine in appearance to take to composting facility	*Low* Operations in house which requires a high level of coordination	*High* Has own composting operation with all machinery and land
Agency 2	*High* Keeps beach looking pristine	*Low* High energy use to clean beach and using landfill space	*High* Managed by a third party which requires a lower level of coordination	*Low* Outsourcing to third party is costly when there are large inundations. Cost is reliant on the number of truckloads and tipping fees
Agency 3	*Low* Beach not pristine-in appearance with black compost mixed in with white sand	*High* Leaves on the beach and tills in	*Medium* Operations in house, limited activities outsourced to a third party	*High* Has own machinery and maintains beach in house
Agency 4	*High* Keeps beach looking pristine with a staging area that is out of view of beach goers	*Medium* High energy use and space for portion sent to landfill but less energy intensive for portion that is buried	*Medium* Outsourcing of hotspots requires little management but some for sporadic cleaning of remaining beaches	*Medium* Costly for the portion that is removed and deposited into landfills but less for the beaches where *Sargassum* is incorporated into the dunes

Agency 3 viewed the *Sargassum* onshore as being beneficial and a natural occurrence. We ranked it as high in the environmentally friendly category. The beach manager from Agency 3 mentioned that the beach is a “Functioning ecosystem and there are plants there.” So, education for Agency 3 is the best tool other than removing the *Sargassum* on the beach. In order for the patrons of the beach to see it as such Agency 3, “Provides more education when necessary.” Agency 3 will, “Up the ability to answer phones calls and provide education on *Sargassum*” when there are large influxes, since this agency does not remove any of the *Sargassum*. Until there is a more environmentally friendly solution, Agency 3 decided it was, “Not going to remove it [*Sargassum*]." Even if it will be removed, it won’t be every day.” Agency 2, on the other hand, prioritizes maintaining the beach in pristine appearance, but acknowledged that this prioritization is not the most cost-effective or environmentally friendly. They would rather, “Turn a waste into resource,” which in turn is more environmentally friendly than taking the *Sargassum* to a landfill. Agency 1 also desired to keep the beaches clean and pristine appearance but composted the *Sargassum* that makes its way onshore. When compost produced by Agency 1 is ready to be used by the city, additional mechanical processes are used to remove large plastic debris that is entrained. The compost that was created by Agency 1 was used as fill in medians across the city. Agency 1 noted that the plants in these public spaces that had *Sargassum* compost as soil amendment “grew so fast.”

We rated Agency 2′s strategy on manageability as being high. Outsourcing beach cleaning was very costly, but it also offered a manageable solution, as the agency did not have to be concerned with coordinating the logistics. Agency 1 was rated as low for manageability since composting operations were managed internally and all operations were conducted in-house, which required the Agency to undertake coordination and logistical activities. Although the manageability was ranked low for Agency 1, the manager from the agency was happy with the process. The manager explained that the Agency, “Can’t help but win with this one.” Agency 4 uses a combination of in-house beach cleaning and outsourcing for removal, “From what is called hotspots” along the beaches.

The fact that the beach managers have different procedures to address *Sargassum* influxes provides us with an opportunity to make comparisons of the strategies in terms of their cost-effectiveness. We compared the strategies of the other Agencies to Agency 1, which used composting. Agency 1 cleaned the coastline every day and the collected *Sargassum* was hauled away to a local park. The local park is located approximately 8 km from the beach. The *Sargassum* composting operation by Agency 1 was run in-house using their own equipment and employees. While the Agencies were concerned about maintaining their beaches in pristine appearance, they also had to meet budgetary constraints. A local waste management official from one of the agencies pointed out that they had, "Desire to deal with this in a cost-effective way." Cleaning the beach by hauling *Sargassum* to a landfill was the costliest strategy. The representative from this agency described it as, "Take $445,000 put it in a dump, throw a little gasoline in there and light a match." For two of four managers, the costs associated with outsourcing during heavy seasons was voiced as a concern. Composting and cleaning the beaches in house is much more cost effective, as implemented by Agency 1 and Agency 3.

3.2. Cost and market analysis

There are three primary costs associated with running a *Sargassum* compost operation (Fig. 2). The first is the cost of beach cleaning. The second cost is associated with hauling of the *Sargassum* to an allocated site. The cost for beach cleaning and hauling by Agency1 was estimated at $308,800 per year. Finally, the third cost was associated with composting., which includes the maintenance of the pile as well. We estimated that Agency 1 spends US $78,100 per year to operate its *Sargassum* compost pile (Fig. 3). These costs include $53,800 for the bulldozer, $10,600 for the shaker, $13,000 in personnel costs, and $700 for land (See Blare et al., 2023 for details). If Agency 1 did not have a composting operation, they could dispose of the *Sargassum* in a landfill. Before Agency 1 started composting *Sargassum* in 2010, they spent $200, 000 annually on disposal costs, which included the landfill tipping fees and transportation costs to take the *Sargassum* to the landfill, the practice utilized by Agency 2 during peak *Sargassum* season. When indexed to inflation, according to the U.S. Consumer Price Index, the $200,000 costs for Agency 1 to dispose *Sargassum* in a landfill would be valued at $260,000 in 2022. However, many of these costs have likely increased at a faster rate than inflation. The actual cost to Agency 1 if it were to revert to this former strategy of landfill disposal would likely be larger than $260,000 for tipping fees and hauling. Prior to Agency 1 establishing its own composting operation, the costs in any given year varied depending on the amount of *Sargassum* onshore and the truckloads used to haul it to a landfill. Since composting is now conducted in-house at Agency 1, the costs are more stable given that they no longer pay tipping fees and the hauling to the compost facility is completed with existing in-house equipment. The costs used in the comparison of management styles assume fixed mobilization costs. Also, the costs are based on the amount of *Sargassum* that makes landfall and the size of the beach.

For a better comparison to determine which practice (landfilling, composting, or integrating) is most cost effective, we compared the actual cost that Agency 1 incurred to implement the composting strategy to what it would have had to spent to take the *Sargassum* to the landfill or integrate it into the beach. Agency 2 which implemented the landfill management strategy spent around $300,000 to dispose of 2676 m^3 (3500 yd^3) of *Sargassum* in 2020, which is $112 per m^3 ($86 per yd^3). Considering that Agency 1 collected 3609 m^3 (4721 yd^3) off its beaches in 2019, the Agency potentially would have spent nearly $406,000 to dispose of the *Sargassum* in 2020, which is more than 5 times the cost to operate the composting facility ($78,100 per year) and higher than the $260,000 low end landfilling cost described above. Agency 3 which implemented the integration strategy spent $210,000 in 2020 to rake and integrate the *Sargassum* on its beach. Considering that Agency 1′s beach is 4.6 times longer than Agency's 3 beach, we would expect that Agency 1 to have spent at least that amount to clean and integrate the *Sargassum* into its beaches in 2020.

By investing in the composting facility, we estimate that Agency 1 saved around $328,000 that would have been spent to dispose of the *Sargassum*. Agency 1 also used the compost it produced as fill to meet its landscaping needs in its parks and roadways. The manager of Agency 1 estimated that purchasing this fill would have cost between $2000 and $3000. The value of this fill maybe even more, as Agency 3 budgeted approximately $5000 in 2022 to purchase soil for landscaping projects. Thus, we estimate that Agency 1 saved nearly $330,000 by composting the *Sargassum* in 2021 rather than disposing of it.

Samples that were used for the market analysis were collected from six *Sargassum* compost samples we created as part of a prior study

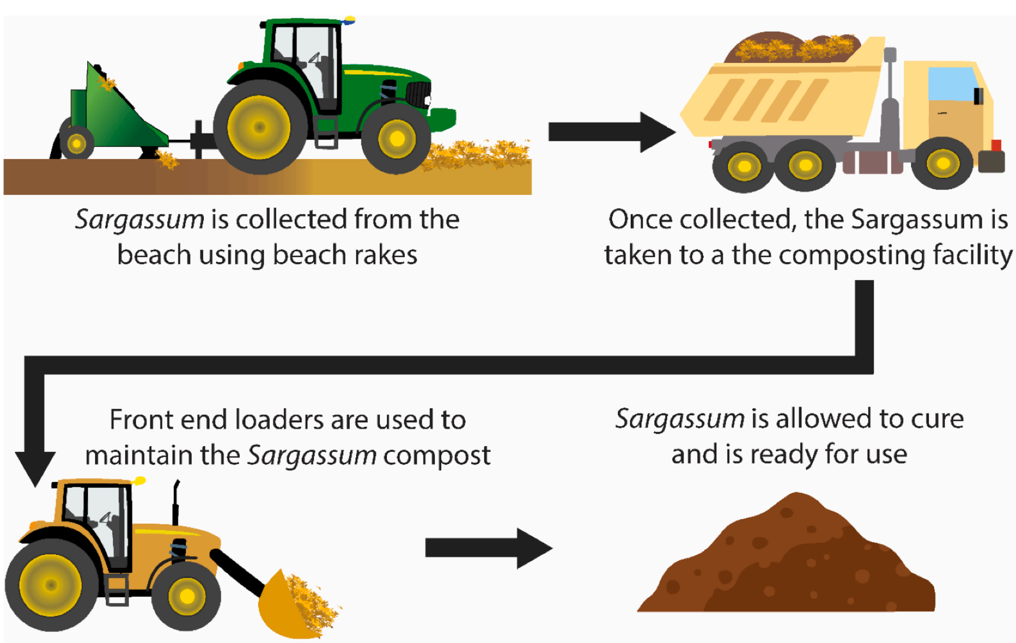


Fig. 2. Processes that are associated with a *Sargassum* composting operation. There are three main costs that are considered when starting a composting operation. The first cost is associated with beach cleaning, the second cost is associated with hauling, and finally the last cost is for composting, and all associated maintainance operations.

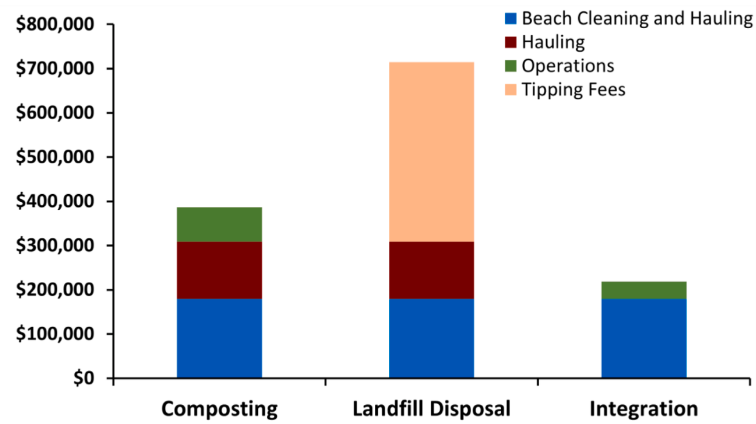


Fig. 3. Graph depicting the costs associated with three management strategies. The costs for composting and landfill disposal corresponded to those computed from information provided by Agency 1. The added operational cost for integration (cut and turn) was calculated using information provided by a commercial beach cleaning agency.

(Abdool-Ghany et al., 2023) and another 3 were collected from the organic growers we interviewed. As mentioned above, samples were analyzed for nitrogen, phosphorus, potassium, and pH. For the six *Sargassum* compost treatments that we created, composted, and tested, the nitrogen values ranged from 0.75 to 1.26% by weight (Table 3). Phosphorus values ranged from 0.043- 0.15% by weight. Treatments with grass clippings and vegetative waste tended to have higher phosphorus values. Potassium ranged from 0.06 to 0.39% by weight. The treatment with 100% unwashed *Sargassum* as well as mulch in the small-scale experiments had higher potassium values, with values of 0.39 and 0.38% by weight. The pH ranged from 8.91 to 9.77. Lower pH levels were measured in 100% *Sargassum* compost from the large-scale experiments compared to those created using the tumbler composters.

For the four compost samples provided by the organic growers (Table 3), nitrogen ranged from 0.64 to 1.10% by weight, phosphorus ranged from 0.05 to 0.15% by weight, and potassium ranged from 0.14 to 0.51% by weight. Finally, the pH ranged from 7.84 to 8.31. There were some similarities when comparing the *Sargassum* compost to the organic compost collected from the organic growers. The nitrogen values for the compost in the large-scale 100% unwashed *Sargassum* treatment had a value of 1.10% and in the small-scale 100% unwashed *Sargassum* treatment had a value of 0.99%. This is very close to the values that were measured for the compost combined with chicken manure, potting soil, and the potting soil mixed with plant biomass compost, which had a value of 0.96%, 1.10%, and 1.03% by weight, respectively. Phosphorus and potassium values for all the *Sargassum* compost treatments were also similar to that of the organic compost.

In the *Sargassum* compost treatments, the treatment with 57% *Sargassum* and 43% vegetative waste had a phosphorus value of 0.15% by weight. The organic compost made from cut with chicken manure had a phosphorus value of 0.15% by weight. Compost combined with chicken manure also had the highest potassium value of 0.51% by weight, while all other compost samples, both *Sargassum* and organic composts, were similar. This study found that the *Sargassum* compost treatments were not statically different than the organic compost products collected for all three nutrients values of nitrogen ($p = 0.662$), phosphorus ($p = 0.744$), and potassium ($p = 0.704$). These results are consistent with those of Nava-Jiménez et al. (2022), who found that nutrients in *Sargassum* were a valuable natural resource and an alternative soil for the cultivation of ornamental plants, as it contains essential elements necessary for plant growth and development. In terms of the pH, *Sargassum* composts were more basic compared to the compost provided by the organic growers. The compost made of food and mulch exhibited the lowest pH of 7.84, while the highest pH was detected in the 100% washed *Sargassum* with a value of 9.77. Overall, the pH values from the *Sargassum* compost treatment and the organic compost samples collected were significantly different (p=<0.001). Abdool-Ghany et al. (2023) measured the carbon to nitrogen ratios for the *Sargassum* compost samples (Table 3). The carbon to nitrogen ratios were 20.9, 30.8, 31.0, 33.6, 20.8, and 31.90 for the 100% unwashed *Sargassum*, 100% washed *Sargassum*, 80% *Sargassum* and 20% grass clipping, 92% *Sargassum* and 8% mulch, 100% unwashed *Sargassum*, and 57% *Sargassum* and 43% vegetative waste, respectively.

Considering that Agency 1 collected 3609 m^3 (4721 yd^3) of *Sargassum* in 2020 and that from our composting testing we found that freshly collected *Sargassum* contains 90% water, we estimate that the agency would have produced 361 m^3 (472 yd^3) of compost. Compared to the value of the composts produced and used by growers in south Florida

Table 3
Nitrogen-Phosphorus-Potassium and pH values of the compost with data provided for compost produced within the small- and large-scale experiments by the researchers and from compost provided by organic growers.

	Sample Treatment	Nitrogen% by weight	Phosphorus% by weight	Potassium% by weight	pH	Price (per m^3)
Small-Scale (Tumbler Composters)	100% Unwashed *Sargassum*	0.991	0.052	0.391	9.67	–
	100% Washed *Sargassum*	0.754	0.043	0.238	9.77	–
	80% *Sargassum* and 20% Grass Clipping	1.102	0.121	0.183	8.91	–
	92% *Sargassum* and 8% Mulch	0.748	0.060	0.381	9.63	–
Large-Scale (Compost Piles)	100% Unwashed *Sargassum*	1.097	0.054	0.061	9.26	–
	57% *Sargassum* and 43% Vegetative Waste	1.263	0.152	0.108	9.17	–
Organic Compost	Food and Mulch	0.640	0.090	0.140	7.84	$1060
	Compost combined with Chicken Manure	0.960	0.150	0.510	8.09	$52
	Potting Soil	1.100	0.050	0.180	8.11	$160
	Potting Soil Mixed with Plant Biomass	1.030	0.070	0.230	8.31	–

that have a similar nutrient composition ($1060 per m^3), we estimate that *Sargassum* compost produced by Agency 1 to be worth as much as $377,600. If Agency 1 were able to sell its compost at this rate, it would be able to recoup nearly all the costs to clean the beach estimated to be $308,800 and to operate the compost pile, which costs $78,100. It would only cost the Agency 1 a net $9300 to clean the beach and operate the pile. Considering the market value of the compost, operating the compost pile would also be more cost effective than incorporating the *Sargassum* into the beach, as practiced by Agency 3.

This analysis would indicate yearly cost savings of $299,500 for Agency 1 for composting and selling the *Sargassum* compost rather than incorporating it into the beach. Considering that the equipment to operate the compost facility is valued at $310,000 and land valued at $100,000, the total investment cost to operate the compost facility to would be $410,000 (Blare et al., 2023). With such a large cost savings, the return on the investment would be 73%. Using a discount rate of 5%, based on the Federal Funds rate in the Spring of 2023, the payback period on the investment would be just 1.45 years.

Results from the interviews also emphasized limitations associated with composting. Contaminants were a concern for beach managers, and a concern for potential users of *Sargassum* compost. Since entrainment of plastics is a drawback of the *Sargassum* compost produced by Agency 1, buyers are unlikely to value this compost as much as that made by local growers which does not contain visible entrained plastics (Table 4). From the interview conducted with the local business owner, he noted that "It's [*Sargassum*] filled with plastics" as it makes its way on shore. Even if the *Sargassum* compost from Agency 1 were valued at half the price of the high-quality compost produced by local growers, it would still be worth $188,800, more than double the cost to manage the compost pile. Also, during the interview process, land space for composting was voiced as a concern by two of the four beach managers interviewed.

One compost operator mentioned that *Sargassum* compost is undervalued in the commercial market because of its lower nitrogen-phosphorus-potassium (NPK) values. This compost operator states that measurements of NPK values do not consider all the additional benefits provided by compost. She explained that compost, "Doesn't have to have a high NPK value. What matters is what the plant needs." The microorganisms found in compost are essential to soil health and, thus, plant vigor. She explained that "Seaweed is known to be an amazing fertilizer for plants." This is also supported with the liquid fertilizer that is produced with the local business owner. The local business owner mentioned that the compost product "Can be used on just about anything" given the nutrient content. As growers and gardeners begin to realize this additional value of *Sargassum*, they would likely be willing to pay for it, providing an economic boom for agencies that compost it.

Overall, the results from the cost and market analysis suggest that the economics favor composting *Sargassum* over disposal in a landfill. The value generated from composting could possibly be used to offset the cost of grooming the beach. Perceptions by potential users of the *Sargassum* compost vary, some in favor and others recognizing limitations.

Table 4
Advantages and Limitations of *Sargassum* Compost as Identified by the Key Informants.

Advantages	Limitations
• Reuse of a material that would otherwise be landfilled • Provides an alternative to integration to preserve sand quality especially when inundations are excessive • Provides a substrate that can support plant growth • Nutrient value similar to product used by organic growers • Selling of compost can recoup costs associated with operation	• Land space for composting operation • Contaminants such as heavy metals, mainly arsenic, and large debris made of plastics • During peak season, the cost that is associated with outsourcing the *Sargassum* management • Permitting limitations from government agencies

4. Discussion

4.1. Observations of management strategies

Collectively, Agencies 1, 2, and 4 were concerned about the aesthetics of the beach and wanted to make sure it looked pristine, whereas Agency 3 was more concerned about ecological preservation. Agency 4 managed the largest beach areas, while Agency 3 managed the smallest. The five main *Sargassum* management practices included composting (Agency 1), deep burial (Agency 2), pull bar (Agency 3), cut and turn (Agency 4), and hauling away to landfill when in excess (Agency 2 and 4). When comparing managing a composting operation (Agency 1) to disposing *Sargassum* in a landfill (Agency 2), composting this material is more a cost-effective alternative used to remove the *Sargassum* and thus promoting a beach with white sand. However, operating a compost facility requires greater management and coordination than outsourcing beach cleanup through landfilling. It also requires the capital to invest in creating the facility, purchasing the equipment and access to land. While integrating the *Sargassum* into the beach sand (Agencies 3 and 4) proved to be a cost-effective alternative to manage *Sargassum* influxes, the result can leave the beaches looking less like the idealized white sand beaches expected by many tourists. If beach appearance is not a concern, the strategy of integrating the *Sargassum* may be the best alternative, especially when inundations are small. Nonetheless, the sale of compost may help offset the costs of cleaning the beach and provide an important fertilizer and soil amendment.

4.2. Economic viability of Sargassum management strategies

The cost analysis conducted in the current study indicates that composting operations are economically viable. The added cost of a composting operation is small relative to the cost associated with cleaning the beach. The compost product produced has the potential to make up for the cost of the composting and the beach cleaning operation. The cost analysis was based primarily upon Agency 1′s cost estimates, which is 6.4 km in length. For composting, the total cost of beach cleaning and composting operation was estimated at $386,900. Dividing this cost by 6.4 km of beach length provides a cost of $60,450 per km per year. This cost is much less than the estimate for *Sargassum* cleanup costs along the Mexican Caribbean coast. Estimated costs for Mexican and Caribbean coasts ranged from $0.3 million to $1.1 million per kilometer (Rodríguez-Martínez et al., 2023).

The likely reason for these differences in estimated costs is the vast differences in the amount of *Sargassum* stranded. Agency 1 of the current study documented 3608 m^3 of stranded *Sargassum* during 2019 which results in a quantity of 564 m^3 per km. Rodríguez-Martínez et al. (2023) report a quantity of stranded *Sargassum* between 10,015 and 40,932 m^3 per km, amounts which are between an order to two orders of magnitude greater than that observed by Agency 1 in southeast Florida. In other words, the Mexican Caribbean coasts are experiencing volumes of *Sargassum* between 10 and 100 times more than observed in southeast Florida, driving costs for management to much higher levels. We believe that the observations in the Mexican Caribbean coasts represent a strong possibility of future impacts more globally, thus emphasizing the need for more efficient and cost-effective options for the management of *Sargassum*.

4.3. Valuation of Sargassum compost

Sargassum valorization has been explored and challenges and opportunities have been identified (Robledo et al., 2021). One study conducted by Waliczek et al. (2020) examined participants' willingness to buy *Sargassum* compost. They found that there is a potential for specialty seaweed-incorporated compost in the retail market. Participants were willing to pay \$35/m^3 (\$4.00/ft^3) to \$44/m^3 (\$5.00/ft$^{3)}$) for seaweed-incorporated compost. In the current study the price of comparable compost products is estimated at between \$160 to \$1060/m^3, again suggesting the potential economic viability of producing compost from *Sargassum*.

However, given uncertainty in production cost estimates coupled with concerns about permitting, waste management operators are unsure if the sales of this compost at the estimated prices would cover their expenses. Thus, they would be unwilling to take the risk of investing in more expensive *Sargassum* composting facilities if they are not guaranteed a return on their investment or a reduction in overall costs. In addition, in highly urbanized areas, like in Southeast Florida, there may not be affordable land, especially with rapidly increasing land prices, to run a large-scale composting facility or at least land close to the beach to minimize the hauling distance of heavy, wet *Sargassum* (Qiu, 2022).

4.4. Policies surrounding Sargassum in southeast Florida

For agencies evaluating the production of *Sargassum* compost as a management strategy, they will likely have to work with policymakers to ensure that they have permission to conduct such activities. Currently under Florida Administrative Code (FAC), chapter 62–709, *Sargassum* can be composted under the Source-Separated Organics Processing Facility (SOPF) registration program. In 2010 it was determined that the *Sargassum* that washes onshore was "yard trash" (FDEP, 2010). This status was determined in part by the composting operation established by Agency 1. This has allowed Agency 1 to compost *Sargassum* under the registration program. Since the amount of *Sargassum* has increased over the last decade and the issue is now impacting more municipalities across Florida, the Florida Department of Environmental Protection (FDEP) is proposing to update Chapter 62–709, FAC to officially list *Sargassum* with its own definition and with limited end uses.

4.5. Differences in expectations of compost quality

The experience of these agencies in Southeast Florida in managing their *Sargassum* influxes provides lessons learned for other areas affected by *Sargassum* and other seaweed influxes as well as the general management of organic materials. *Sargassum* compost, as recognized by the FDEP, may require its own definitions and permitting given the unique circumstances surrounding its influx and composition. What a local government agency believes is composting and what organic growers consider compost can differ. Organic growers follow stringent composting guidelines as required by the state such as reaching a certain temperature for a given time period. Commercial composting operations are required to maintain a temperature of at least 131°F for at least 15 days (FDEP, 2010). Compost made from fecal waste or manure requires strict temperature requirements. Whereas *Sargassum* is not a fecal waste, so a strict temperature requirement may not be necessary. This strict temperature requirement is needed for manure in order to ensure that pathogens are inactivated from the source material. From our previous study (Abdool-Ghany et al., 2023), this temperature guideline was not achieved for the outdoor piles created. However, bacteria concentrations were within recommended limits for compost made outdoors.

4.6. Contaminants in Sargassum compost

To have usable compost that can be sold, it must be free of contaminants, such as plastic debris and arsenic. One major concern brought to our attention by one of the organic growers was microplastics in addition to macro or large plastic debris pieces. Microplastics are less than 5 mm in size and come from debris that is entangled with the *Sargassum* (Carpenter and Smith, 1972). More than 5 trillion plastic particles are floating in the sea (Eriksen et al., 2014) and have become a common concern in the marine environment. Microplastics that are in the ocean can stick to many different species of macroalgae, especially *Sargassum* (Seng et al., 2020), which then makes its way onshore. Once onshore the *Sargassum* can pick up additional microplastics from activities on the beach (e.g., plastic bags from beach goers and plastic toys left behind). These entangled plastics are difficult to remove; thus, can end up in the final compost product. Compost products are known to have a large number of microplastics that can affect soil chemistry (Yu et al., 2022). Degrading plastics can become more poisonous as they can attract and bind to other man-made chemical pollutants (Kolluru et al., al., n.d). The quality of compost produced might not be what is expected and can limit its market potential.

Another contaminant that is of concern is arsenic, which can be found in elevated concentrations in *Sargassum* (Devault et al., 2020; Whyte and Englar, 1983; Nielsen et al., 2021; Davis et al., 2021; Devault et al., 2020; Milledge et al., 2020). This can pose a limitation for composting of *Sargassum*. Inorganic arsenic has been found to be the predominant form of arsenic in *Sargassum*, with levels ranging from 24 to 172 mg/kg dry weight. Although some reduction in arsenic levels has been observed in decaying *Sargassum*, levels remain elevated. In addition, arsenic levels in *Sargassum* compost from Abdool-Ghany et al. (2023) were within the range of 6.64- 26.5 mg/kg and did not meet regulatory guidelines outlined by the FDEP Soil Cleanup Target Levels (SCTLs) for residential use (2.1 mg/kg) and occasionally exceeded SCTLs for commercial and industrial uses (12 mg/kg) (Abdool-Ghany et al., 2023). .

Johnson and Engel (2022) explored whether the use of *Sargassum*-enriched fertilizer increased heavy metal concentrations in vegetables after harvest. Laboratory analysis revealed higher levels of arsenic (and cadmium) in vegetables (Bok choy, zucchini, spinach) grown in *Sargassum*-enriched soil compared to vegetables grown in plain potting soil. Similar results were seen in Abdool-Ghany et al. (2023), which detected arsenic, cadmium, and lead in radish bioassays. The levels that were detected were above what is regulated by the Food and Agriculture Organizations of the United Nations (FAO) & World Health Organization (WHO) (FAO and WHO, 2019). Due to the elevated levels of arsenic, the use of *Sargassum* is not recommended for crops intended for human consumption. Further work is required to fully determine the risk to health and agriculture, and to investigate processes of arsenic contamination and decontamination of *Sargassum*.

4.7. Alternative composting processes

There is interest in adding other waste streams to *Sargassum* to create a richer product with higher nitrogen, phosphorus, and potassium quantities. One promising opportunity is vermicomposting of *Sargassum* and food waste. Vermicomposting uses worms to convert organic waste into a soil amendment. Issues of contaminants such as microplastics and other toxic metals have the potential to be taken care of during this process if the *Sargassum* and other waste streams are pre-composted. Pre-composting is used in vermicomposting and allows for the material to be broken down before starting the vermicomposting process (Castillo-González et al., 2019). He et al. (2016) found that when using a combined vermicomposting process with sewage sludge and additives (soil, straw, fly ash and sawdust), the heavy metal concentrations were lowered compared to the control without the additive. In a study by Patón et al. (2022), pre-composting, or allowing the material to decompose partially, can increase the rate at which the worms can process the material. In addition, there are other studies that produced a rich product by combining various seaweed types and cow manure as feedstocks for vermicomposting (Ananthavalli et al., 2019a, 2019b). However, more research is needed to understand the cost-effectiveness of this method.

Additional markets are growing for *Sargassum* derived fertilizers like liquid fertilizers. Much of the fertilizers made from seaweed are liquid fertilizers. Further analysis would be needed to understand the economic viability of creating these fertilizers. These fertilizers have a much higher value than compost. For instance, 8 oz of an organic blend of 7 species of seaweed can cost $14 from online retailers (Amazon, 2022).

Sargassum compost is likely to become more attractive because of increasing fertilizer costs, especially for inorganic fertilizers. With recent geopolitical instability and supply chain challenges associated with inorganic fertilizers, growers, nursery operators, landscapers, and even homeowners are finding it difficult to source affordable fertilizers. The price of fertilizer increased by 30% in first quarter of 2022, after jumping 80% the year before. There is little expectation that fertilizer prices will fall in the near term (Baffes and Koh, 2022). Because of these soaring prices, growers throughout the world are exploring alternatives to inorganic fertilizers, which have been the primary plant nutrient source for commercial growers since the 1950s. Many are exploring organic compost, including seaweed, as an option to lower costs while ensuring that crops receive the proper nutrients (Merrigan, 2022). Due to the challenges sourcing inorganic fertilizers and growing consumer demand for organic foods, the market for organic fertilizers is expected to increase 6.3% annually for the next decade (FMI 2022). This market reality is likely to make *Sargassum* composting, and composting of all organic material in general, a more financially attractive alternative. Based on all this evidence, this study suggests that waste managers should not overlook composting in their strategic planning when evaluating options to manage *Sargassum* inundations.

5. Limitations

Limitations of this study are that the analysis corresponds to one point in time and for the current permitting conditions. The jurisdictions and regulations for beach management vary between coastal communities. Some communities may not have regulations in place. Others may enforce regulations through a permitting process. With the recognition of potential health concerns associated with *Sargassum*, regulatory agencies are starting to develop regulations to address these concerns and as such, the feasibility of converting *Sargassum* into a sellable compost may change as permitting requirements change. Additional limitations are associated with the cost numbers. Actual costs for managing *Sargassum* at beaches includes space available for potential staging of *Sargassum* to reduce volume and weight, width of beach to be groomed, and specific hauling distances. All of these factors will influence costs which will impact the economic viability of *Sargassum* composting operations. With stricter permitting requirements the costs for composting *Sargassum* will likely increase potentially reducing the viability of this potential reuse option.

6. Conclusions

In conclusion, this study presents valuable insights into the management of *Sargassum* in southeast Florida and offers a novel approach through the economic assessment of *Sargassum* composting. The research generates new information regarding the economic viability of composting *Sargassum* for beach managers, potentially offsetting cleaning costs through compost sales. It also highlights the cost-effective alternative it presents for users facing rising fertilizer expenses. Moreover, the study underscores the importance of addressing concerns related to compost quality, specifically the presence of contaminants such as plastics and arsenic, before implementing *Sargassum* composting operations. By shedding light on these key aspects, this research contributes to the development of sustainable *Sargassum* management strategies tailored to the unique coastal environment of southeast Florida, while also providing valuable insights for other regions faced with similar challenges.

CRediT authorship contribution statement

Afeefa A. Abdool-Ghany: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Trent Blare:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Helena M. Solo-Gabriele:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interestsor personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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