THE DEVELOPMENT OF A SAND-SEAWEED SEPARATOR FOR USE IN REDUCING SAND LOSSES WHEN REMOVING LARGE QUANTITIES OF SARGASSUM FROM A BEACH

A Thesis

by

PAUL MULLEN

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Chair of Committee,	Thomas L. Linton
Committee Members,	William E. Rogers
	Jens Figlus
Head of Department,	Kyeong Park

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ABSTRACT

Sargassum landings on the beach can affect tourism activity as large mounds of Sargassum restrict access to the beach and water. As the Sargassum decomposes it produces foul smelling gases which can further reduce the attractiveness of the beach. Research was conducted to evaluate the effectiveness of a device designed to minimize sand content when removing Sargassum from a beach. Currently a State law prevents the removal of Sargassum from beaches in Texas. The basis of the ordinance is to prevent sand that may be contained in the Sargassum from being removed as well, thus contributing to beach erosion. This is the first research attempt to develop a device that minimizes the sand content when removing large quantities of Sargassum from a beach. The Sand-Seaweed Separator device was designed, constructed and tested to determine its efficiency and feasibility of separating sand from Sargassum. To test the device's efficiency, experiments were conducted in which sediment was mixed with Sargassum and put through the separator; the separated sediment and Sargassum were then collected, weighed, and analyzed. In 10 controlled experiments, it was shown that the Sand-Seaweed Separator is 96.8 ± 1.42 % efficient at separating sediment from Sargassum when the mixture is 90% sediment and 10% Sargassum.

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Contributors

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1. INTRODUCTION

Sargassum is a brown seaweed that floats freely in the ocean and never attaches to the ocean floor (Doyle and Franks, 2015). The name Sargassum was derived by Portuguese fishermen because of its similarity to grapes – *salgazo* – specifically the grapelike structures which are gas bladders that serve to keep Sargassum afloat (Frankel, 1990). One of the first documented encounters with Sargassum was by the flotilla of Christopher Columbus when sailing to the New World (Webster et al, 2013; Dickson, 1894).

There are two common species of Sargassum in the Caribbean and the Gulf of Mexico. These are: *Sargassum fluitans* – characterized by short stalks, broad leaves – and *Sargassum natans* – which have long stalks, narrow leaves. Combined they serve as unique and important habitats to over 145 invertebrates species and over 127 species of fish (Edwards, 1970; Laffoley et al., 2011).

The Sargassum found in the Caribbean and the Gulf of Mexico originates in the Sargasso Sea. It is carried by wind and ocean currents such as the Gulf Stream through the Sargassum migratory loop (Webster et al., 2013). Sargassum starts in the Sargasso Sea, is driven south by wind and ocean currents, and is eventually transported towards the Gulf of Mexico (Figure 1). Thereafter, depending on wind and ocean currents, it can make landfall anywhere along the coast of the Gulf of Mexico or be transported back to the Sargasso Sea by the Gulf Stream thus completing the Sargassum Migratory Loop, (Figure 1).

The earliest historic record of Sargassum landings in Galveston dates back to January 1864 (Webster et al., 2013). However, the earliest report of removing Sargassum from Galveston's beaches was not until 1935, where Sargassum was loaded onto barges and dumped offshore, only to get washed ashore again (Webster et al., 2013). Referring to the historic records on Sargassum landings, a cyclical pattern was identified that dates back over 117 years (Webster et al., 2013).

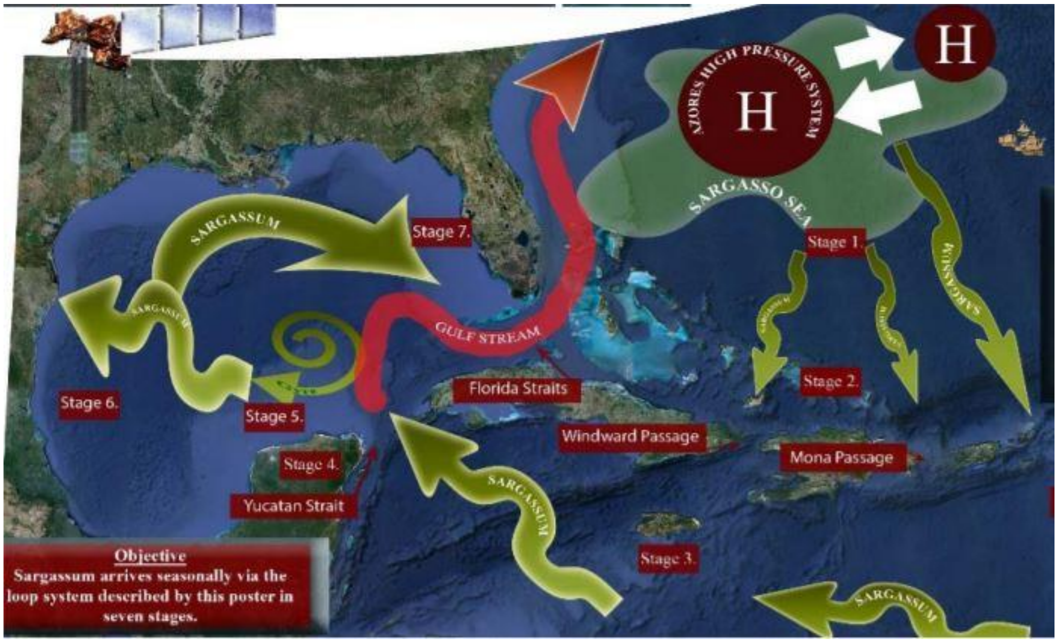

Figure 1 Sargassum Migratory Loop. Adapted from Frazier et al., 2013.

Beach managers along the Texas coast have long had to deal with large periodic landings of Sargassum (Webster et al., 2013). Prior to the development of the Sargassum Early Advisory System (SEAS) forecasting program, Sargassum landings would often come with no warning. Large and unexpected Sargassum landings during the tourist season can severely diminish tourist activity, resulting in adverse economic impact to tourist dependent coastal economies (Webster et al., 2013).

At the same time, Chapter 15.4 (c) of the Texas Administrative Code bans the removal of Sargassum from Texas' beaches (Texas, 2015). As the Sargassum cannot be removed from the beach, beach managers have had to rely on emergency funds to relocate Sargassum landings to less popular areas on the beach (Webster et al., 2013). The raking and relocating of Sargassum on Texas beaches can cost public entities more than $2.91 million per year (Webster et al., 2013).

Current beach cleaning equipment is not efficient for the removal of Sargassum when large landings occur. The aim of this study was to develop a more efficient method of removing Sargassum from the beach reducing concomitant removal of sand. Galveston experiences several meters of shoreline loss per year, therefore, it is vital that the least amount of sand is removed from the beach when removing the Sargassum (Feagin et al., 2005). In order to manage large

Sargassum landings without damaging the beach, a small-scale, Sand-Seaweed Separator was developed. Through its use Sargassum can be removed from the beach, without loss of sand. The Sand-Seaweed Separator was designed to operate on a continuous feed basis to cope with large quantities of Sargassum.

When Sargassum is collected by a front-end loader (Figure 6) different ratios of Sediment-Sargassum mixture are collected due to varying Sargassum deposits and operator inconsistency. Therefore, different ratios of sediment and Sargassum are mixed together during Sargassum collections. Assuming that in a worst-case scenario the front loaders collect a mixture of 90% sediment and 10% Sargassum, the Sand-Seaweed Separator will therefore be designed to operate under such conditions. If the Sand-Seaweed Separator can separate 90:10 sediment to Sargassum ratios, smaller ratios would also be accounted for, as smaller ratios of sediment would separate faster.

This thesis provides an insight into the development of a machine that could be used in reducing sand losses when removing large quantities of Sargassum from a beach, and expands on the following research questions:

1) How much sand will be removed from the beach per tonne of Sargassum by means of the Sand-Seaweed Separator?

Galveston's beach is a major attraction to tourists visiting the island. A Sargassum free beach is more attractive than a beach covered with Sargassum. However, if a lot of sand is removed from the beach by means of the Sand-Seaweed Separator, then the Sand-Seaweed Separator could negatively impact the future of Galveston's tourism economy by contributing to beach erosion. In order to determine if the Sand-Seaweed Separator could benefit Galveston, the amount of sand removed from the beach per tonne of Sargassum must be determined.

2) Is there a significant difference in efficiency when separating sediment from fresh Sargassum and old Sargassum?

When large Sargassum landings occur, thousands of tonnes of Sargassum can get washed up on popular tourist beaches. In order to determine the timeframe in which the Sargassum should be removed from the beach, the difference in efficiency when separating fresh Sargassum and old Sargassum (3 days old) must be determined. If the Sand-Seaweed Separator is more efficient at separating sand from fresh Sargassum than old Sargassum, this would indicate that the Sargassum should be collected from the beach sooner rather than later.

3) Is there a significant difference in the amount of organic matter lost during separation between fresh Sargassum and old Sargassum?

Sargassum becomes brittle as it dry's and begins to decompose. Therefore, small bits of old Sargassum are expected to break off in the Sand-Seaweed Separator. In order to remove the greatest amount of Sargassum from the beach, the difference in organic matter lost during separation between fresh and old Sargassum must be determined. If there is a lot of organic matter lost during the separation of sand and old Sargassum, this would indicate that Sargassum bits are breaking off during the separation process and remaining on the beach. Therefore, Sargassum would need to be collected sooner in order to reduce the amount of Sargassum breaking in the Sand-Seaweed Separator.

2. LITERATURE REVIEW

2.1 Tourism

Coastal economies are heavily dependent on tourism. When Sargassum landings occur, this can have negative impacts on the tourism industries (Webster et al., 2013; Semeoshenkova et al., 2015; Williams et al., 2008). Loss of tourism revenue can have a ripple effect on local economies (Snider et al., 2015). In 2014, tourism was worth $29.2 billion in on-shore spending to the Caribbean economy, and contributed to over 80% of the regional GDP (Milledge et al., 2016). Galveston, Texas, is also heavily dependent on tourism, as the tourism industry was the second largest employer in Galveston in 2015, generating $153 million in tax revenue (Tourism Economics, 2015). Tourists are known to avoid resorts affected by large Sargassum landings (Milledge et al., 2016).

Approximately two billion trips are made to American beaches each year as beach recreation is one of the most popular outdoor recreational activities in the United States. (Snider et al., 2015). Beaches have multiple functions. The most common are in the form of coastal protection, natural reservoirs, and human recreation (Sarda et al. 2015). There are five main categories that tourists want in a beach: good water quality, safety, facilities, no litter and excellent scenery (Williams et al., 2016). However, large mounds of Sargassum restrict human access to the beach and water (Williams et al., 2008; Smetacek et al, 2013). As a result, mass Sargassum landings typically reduce the appeal of a beach and impair the economy in coastal communities if not managed correctly.

2.2 Sargassum Landings

Reports of heavy Sargassum landings covering beaches along the Texas coast date back to 1891 (Webster et al., 2013). In recent years there has been massive influx of Sargassum along the western Gulf Coast and islands within the Caribbean (Ramdwar et al., 2016). When these mass Sargassum landings occur, beach managers are often forced to use emergency funds to relocate Sargassum to less popular beaches (Webster et al., 2013). In 2015, the Sargassum influx in Tobago was declared a disaster and $454,000 (USD) were used in the clean-up (Ramdwar et al., 2016). Similarly, the Mexican government spent $5 million on Sargassum clean-up in 2015

(Milledge et al., 2016). Based on the Sargassum clean-up in Mexico, it is estimated that a similar clean-up in the Caribbean would have cost at least $120 million in 2015, as it was estimated that approximately 10,000 tonnes of wet Sargassum washed up on Caribbean beaches daily during the Sargassum inundation (Milledge et al., 2016). Sir Hilary Beckles, the Vice Chancellor of the University of the West Indies described the Sargassum landings in the Caribbean and in the Gulf of Mexico as an “international crisis” and “the greatest single threat” to the Caribbean (Milledge et al., 2016). While there are ecological benefits to Sargassum when it is washed ashore in small quantities, the economic benefits associated with removing mass Sargassum landings may overshadow the ecological benefits of leaving Sargassum on the beach in highly developed areas (Schiro et al., 2016; Williams et al., 2008).

However, Sargassum also has many benefits as it can be compacted, baled, and used as a method to increase erosion resistance in sand dunes, as the Sargassum bales absorb wave energy. Long-term benefits of compacting, and baling Sargassum include dune vegetation growth, increased capture of aeolian sediment transport, and an increase in dune resilience to erosion (Figlus, 2015). Other benefits of Sargassum range across a broad scale of biodiversity as it is rich in a number of elements such as calcium, potassium, sodium and iodine (Laihao et al., 2001). Sargassum is used as food, livestock fodder, medicine, tea, biofuel, fertilizer, as well as in the production of algin and sodium alginate (Doyle and Franks, 2015; Laihao et al., 2001; Wang and Chang, 1994; Kaladharan and Kaliaperumal, 1999).

2.2 Rules & Regulations

2.2.1 Beached Sargassum

Sargassum also has some undesirable side effects related to the tourist industry. When there are large Sargassum landings on beaches this is not only unattractive in appearance but as it begins to decompose; it produces foul smelling gases of decomposition (Williams et al., 2008). One of the gases emitted is hydrogen sulfide. Prolonged exposure to this gas may cause nausea, eye irritation, headaches and loss of sleep (Doyle and Franks, 2015). It has also been reported that exposure to these decomposition “fumes” cause metals to corrode and tarnish as well as damage electronic equipment, such as air-conditioning units and computers (Doyle and Franks, 2015; Hinds et al., 2016).

The Occupational Safety and Health Administration (OSHA) – an agency of the United States Department of Labor – has an 8 hour worker exposure limit for construction and shipyard workers when Hydrogen Sulfide concentration is 10 ppm (UNITED STATES, 2016). Prolonged exposure to Hydrogen Sulfide between 2-5 ppm may cause nausea, headaches or loss of sleep, while Hydrogen Sulfide levels greater than 20 ppm may cause dizziness, poor memory and fatigue (UNITED STATES, 2016). Therefore, decomposing Sargassum could be a health hazard to visiting tourists. A combination of the gas released by the decomposing Sargassum, and its appearance on the beaches could negatively impact the local tourism industry.

The removal of Sargassum from the beach is not permitted in Texas as a State ordinance prevents the removal of Sargassum from Texas beaches. Chapter 15.4 (c) of the Texas Administrative Code prevents the temporary or permanent removal of sand from the beach (Texas, 2015). The basis of this ordinance is to prevent the sand that may be contained in the beached Sargassum from being removed from the beach, thus contributing to coastal erosion. If Sargassum is left on the beach, it can deter tourists and pose a health hazard as it begins to decompose, providing further grounds for its removal.

2.2.2 Offshore Sargassum

Sargassum mats provide important habitat to over 145 invertebrate and 127 species of fish (Edwards, 1970; Laffoley et al., 2011). The Fishery Management Plan for Pelagic Sargassum Habitat of the South Atlantic Region designated Sargassum as an Essential Fish Habitat (EFH) due to the important role that Sargassum mats serve to various marine species. An EFH is considered to be an area of water or surface necessary to fish for spawning, breeding, feeding, and growth to maturity (South Atlantic Fishery Management Council, 2002). The plan was created in November 2002 and approved in 2003. This plan introduced strict regulations regarding the harvesting of Sargassum off the East coast of the United States. The approved Fishery Management Plan for Pelagic Sargassum Habitat of the South Atlantic Region is enforced by The Magnuson–Stevens Fishery Conservation and Management Act, which is the primary law that governs conservation and fisheries management in United States federal waters (Buck et al., 2004). The Magnuson-Stevens Act helps prevent overfishing, rebuild overfished stocks and protects essential fish habitats (Buck et al., 2004). The approved fishery management plan prohibits all harvest and possession of Sargassum from the South Atlantic Exclusive Economic Zone (EEZ);

1. South of the 34 ° North Latitude line.
2. Prohibits all harvest of Sargassum from the South Atlantic EEZ within 100 miles of the North Carolina coast.
3. Limits the harvest of Sargassum to November through June in the South Atlantic EEZ.
4. Limits the annual Total Allowable Catch (TAC) to 5,000 pounds landed wet weight.
5. Requires an official observer on each Sargassum harvesting trip.
6. Harvesters must use specific gear for harvesting Sargassum (South Atlantic Fishery Management Council, 2002).

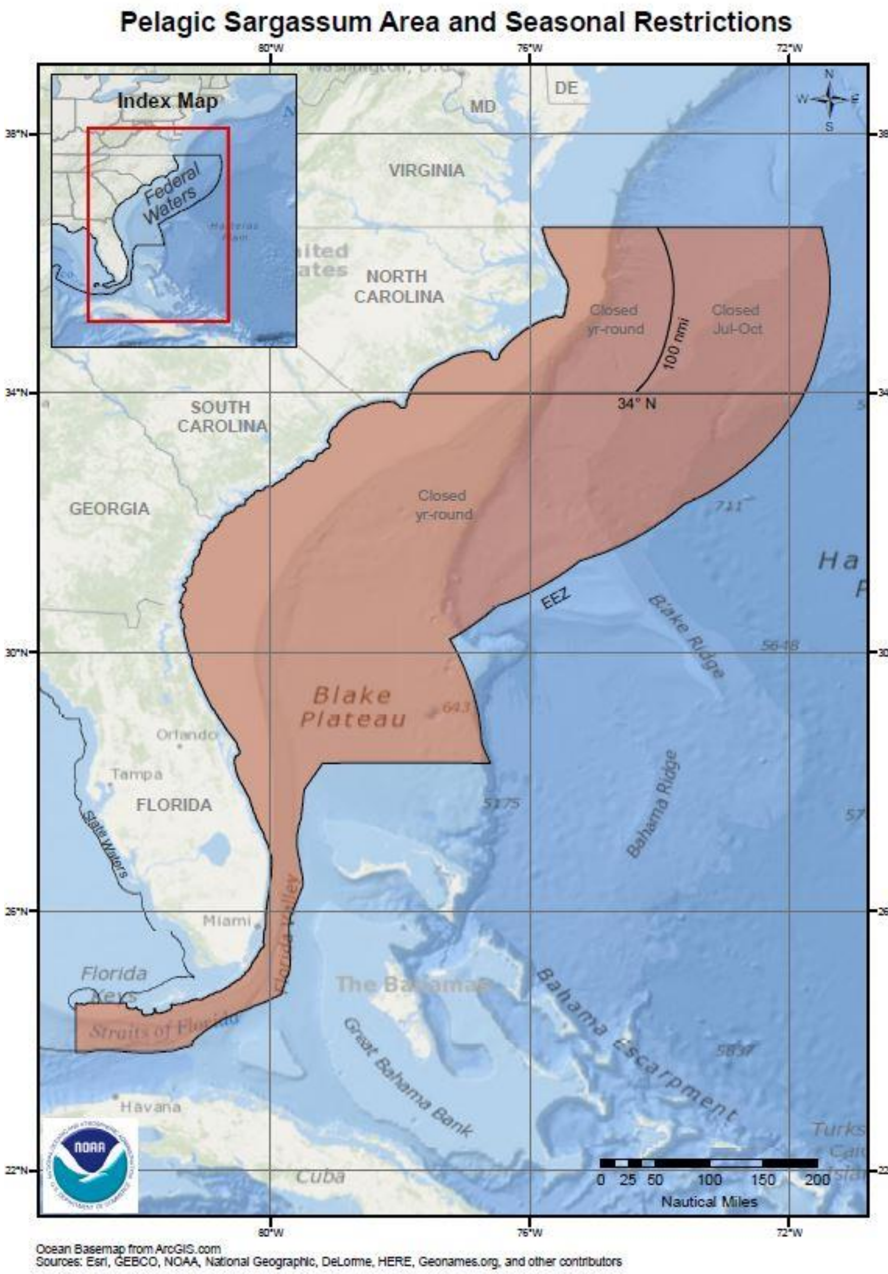

Figure 2 Pelagic Sargassum Essential Fish Habitat Area. Adapted from NOAA (n.d.)

Aqua 10 Corporation, is one company that was put out of business due to the approved fishery management plan. Aqua 10 Corporation developed livestock and plant food supplements from Sargassum. Aqua 10 estimate that they harvested a maximum of 2 tonnes of Sargassum per year (Associated Press, 1999). Ocean Harvest Technology is another company that uses Sargassum in their animal feed products. Due to the restrictions on harvesting Sargassum in the South East Atlantic EEZ companies such as Ocean Harvest Technology are forced to source their

Sargassum elsewhere. However, Sargassum that is washed ashore in the Gulf of Mexico could be collected and separated using the Sand-Seaweed Separator to be used for dune nourishment projects, and/or sold to companies such as Ocean Harvest Technologies to be used in animal feed products. This would not only benefit the local tourism economies by having clean beaches but also create local employment.

2.3 Current Beach Cleaning Methods

There are a wide range of methods used for beach cleaning. Hand raking or manual removal of Sargassum is preferred, because it removes the least amount of beach sediment (Hinds et al., 2016). Research indicates that manual beach cleaning is cheaper than mechanical beach cleaning (Vanhooren et al., 2011). However, when mass Sargassum landings occur, thousands of manual beach cleaners need to be hired to cope with Sargassum landings of such magnitude. In 2015, when large Sargassum landings occurred in Cancun, Mexico, the Mexican government funded a Sargassum removal program for 12 million pesos ($742,574 USD) where workers manually collected and removed Sargassum as seen in Figure 3 (Walten, 2015).

Figure 3 Workers manually collect and remove Sargassum in Cancun, Mexico. Adapted from Partlow, J., Martinez, G., 2015

Mechanical beach rakes such as BeachTech beach cleaners and the Barber SURF RAKE are used globally (Thompson, 2013). Both of these machines work off a similar principle, using a mesh-like conveyor belt to separate sediment from seaweed. Spring tines are attached to a conveyor belt which sweep the seaweed off the beach onto a mesh-like conveyor belt. This conveyor belt shakes the excess sediment off the seaweed. The seaweed is then collected in hopper at the back of the machine with minimal sediment attached, as seen in Figure 4.

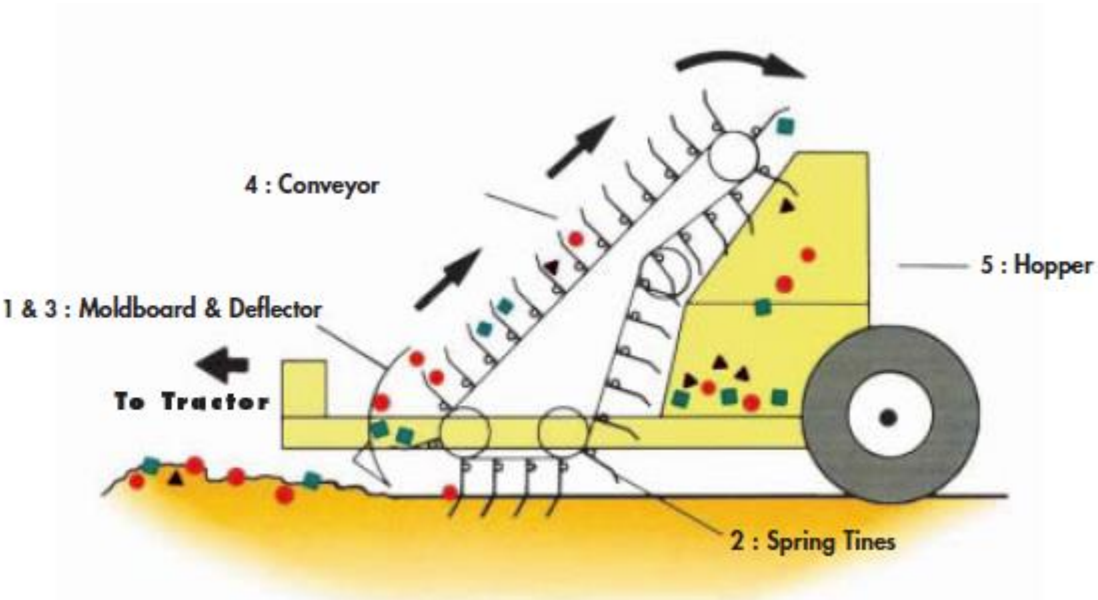

Figure 4 How Barber SURF RAKE works. Adapted from Dorian Drake International Incorporated. (n.d.)

Mechanical beach rakes such as BeachTech beach cleaners and the Barber SURF RAKE are most effective when the Sargassum mounds are less than 1 ft tall. When the Sargassum is over 1 ft tall, these machines are not very efficient, as the clearance between the beach and the machine is too small which results in the beach cleaning machines pushing the Sargassum like a bulldozer, as seen in Figure 5 below. When the Sargassum mounds are over 1 ft tall, these mechanical beach rakes are required to do multiple passes in order to collect all the Sargassum from the beach. Therefore, mechanical beach rakes are not very efficient at removing Sargassum from the beach when Sargassum mounds are over 1 ft tall.

Figure 5 Barber surf rake pushing Sargassum.

When mass Sargassum landings occurred in Galveston, Texas, in 2014 (Figure 6), large front-end loaders such as the Hyundai 740-9 were used for relocating the Sargassum. The height of the Sargassum mounds was estimated to vary between 2 - 4 ft; therefore, mechanical beach rakes were not suitable as the tractors pulling the rakes would get stuck. The front-end loaders were the most efficient method of moving the Sargassum. However, these front-end loaders can collect a lot of sand from the beach while gathering Sargassum which can contribute to beach erosion.

Figure 6 Hyundai 740-9 dumping Sargassum. Adapted from Harvey, R., & Smith, B., 2014.

The Hyundai 740-9 front-end loader and the Barber SURF RAKE 600HD both have a maximum capacity of 2.3 m^3 (Thompson, 2013). The time taken to fill a Barber SURF RAKE 600HD is significantly longer than the time taken to fill a bucket of the front-end loader; therefore, front-end loaders tend to be a lot more efficient at gathering Sargassum when large landings occur.

In the Gulf of Mexico, Sargassum in not considered as an EFH, therefore, Sargassum can be harvested in the Gulf of Mexico. One method of harvesting or preventing the Sargassum from making landfall on beaches is a machine known as “The Sargator” (Figure 7). The Sargator is a small barge that has a device similar to a conveyor belt on the front of the barge that collects Sargassum from the water. The Sargator costs $300,000 and can hold up to 10 tonnes of Sargassum onboard the barge at any one time (Hinds et al., 2016). In order to collect all the

Sargassum before it comes ashore multiple Sargators would be required which may not be the most cost-effective solution.

Figure 7 The Sargator collecting Sargassum. Adapted from Sargator (n.d.)

Another method for preventing Sargassum from making landfall is the Beach Bouncer boom by Elastec (Figure 8). The beach bouncer is designed to deflect Sargassum and other floating trash from beaches. The "Beach Bouncer" costs $6,000 per 100 ft section. Therefore, in coastal communities such as Galveston, Texas, that has 32 miles of beach, it would cost over $10 million to prevent Sargassum and other debris from landing on the beach using the Beach Bouncer. The most popular section of beach in Galveston is adjacent to the seawall which stretches 10 miles. It would cost over $3.1 million to prevent Sargassum landings from beaches adjacent to the seawall using the Beach Bouncer. The Beach Bouncer floats 12" above the surface of the water. As Galveston can experience waves over 6 ft tall, the Beach Bouncer would not be very effective at deflecting the Sargassum from Galveston's beaches as the wave height may render the system useless, since Sargassum floats of the surface of the water. Additionally, the Beach Bouncer is designed to deflect floating debris. Therefore, if a Beach Bouncer was deployed off the coast of Galveston it may protect Galveston from Sargassum landings but may affect neighboring coastal communities East or West of the island. The Beach

Bouncer is a solution to certain coastal communities; however, it does not appear to be the most cost-effective solution for Galveston.

Figure 8 ELASTEC Beach Bouncer. Adapted from ELASTEC (n.d.)

Moreover, Juvenile Kemp's Ridley sea turtles typically live in Sargassum mats in the Gulf of Mexico; therefore, harvesting Sargassum in the Gulf of Mexico would remove an important habitat and risk the injury or death of an endangered species (Musick et al., 1997, Laffoley et al., 2011; Feagin et al., 2010). In order to reduce the risk of killing endangered turtles while harvesting Sargassum, the harvesting should be done onshore.

The considerable shortcomings of the most commonly used devices for preventing Sargassum landings and removing beached Sargassum indicates the need for large scale and more efficient Sargassum removal device.

3. DATA ACQUISITION AND METHODS

3.1 Sand-Seaweed Separator

The Sand-Seaweed Separator used for this project is a small-scale prototype of a machine that can be used to separate sand from Sargassum (Figure 9). As hand raking and mechanical rakes are not efficient when large Sargassum landings occur and front-end loaders can collect a considerable amount of sand in the removal process, the Sand-Seaweed Separator concept is a means to efficiently reduce the amount of sand being taken when removing large quantities of Sargassum from beaches.

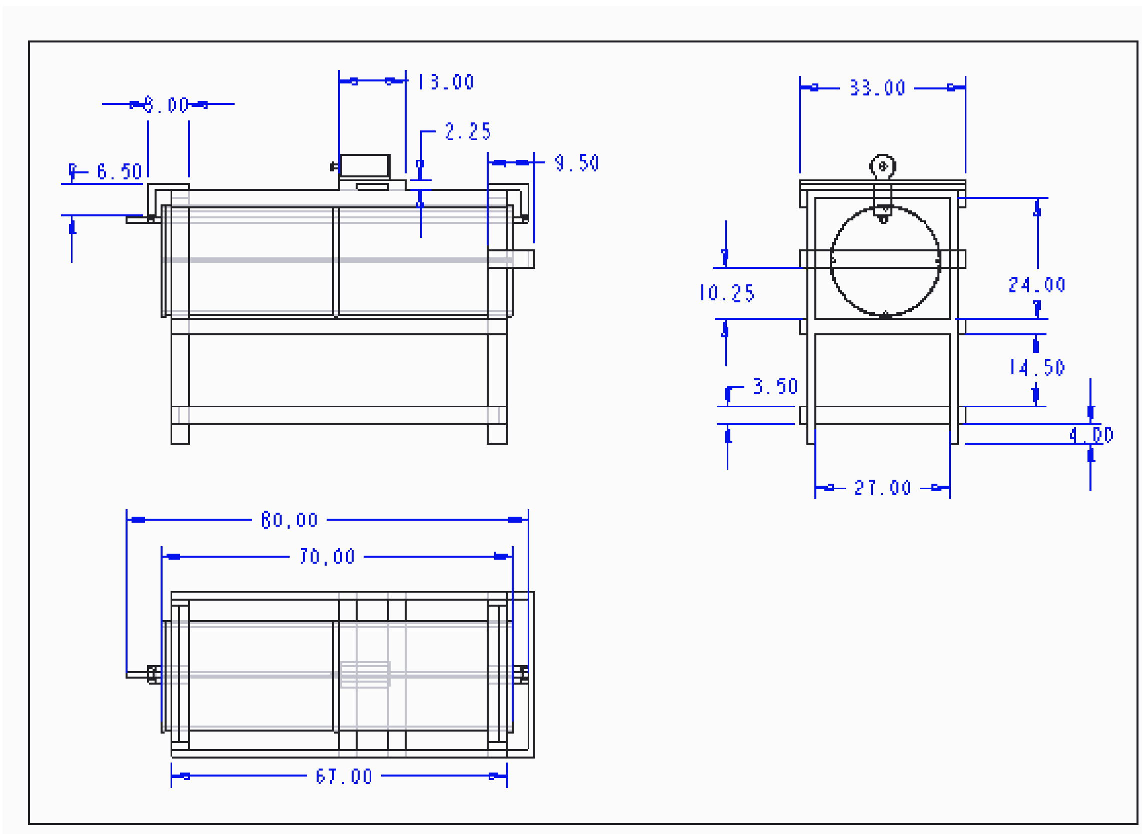

Figure 9 Drawing of Sand-Seaweed Separator, units are in inches.

The Sand-Seaweed Separator was designed to operate on a continuous feed basis to cope with large quantities of Sargassum. The separator consists of a large perforated cylindrical drum with a pipe going through the center that sprays water on the sediment-seaweed mixture as it rotates (Figure 10). As the mixture passes through the separator, water is sprayed inside the separator to assist in removing the sediment from the seaweed. As sediment particles are typically finer than the Sargassum, the sediment passes through the separators screen as Sargassum exits the separator. The separator is inclined at a small angle, this allows for gravity to move the seaweed through the separator (Figure 11).

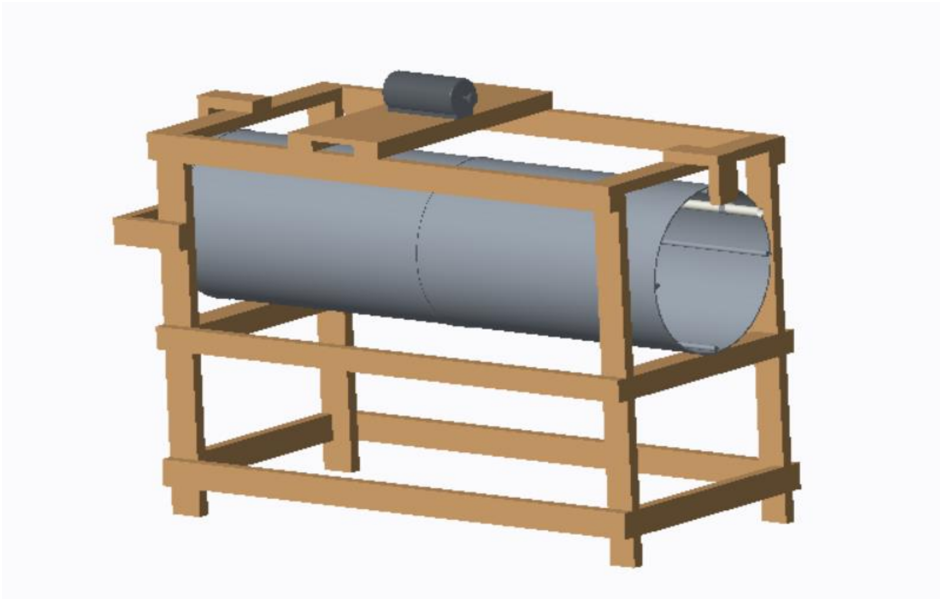

Figure 10 CAD design of the Sand-Seaweed Separator.

There are multiple variables on the Sand-Seaweed Separator such as drum size, mesh size, length, wash water volume and many more. However, only two variables were controlled in this experiment, namely the angle of incline and the revolutions per minute (RPM) of the drum. The optimum settings were determined by means of trial and error: when the angle of incline was too big, the Sargassum tumbled out the opposite end of the separator; when the angle of incline was too small, some of the Sargassum came back out of the separator at the point of entry. The optimum angle for the separator was seven degrees and the optimum speed was 18 RPM. Due to the constraints of this project a commercial grade pump was chosen for a maximum flowrate with best cost-benefit ratio. The pump used in the Sand-Seaweed Separator pumped water at a rate of 18 gallons per minute. This experiment was undertaken in a controlled environment using non-turbid waters. However, practical field experiments indicated that similar results would be expected when the water pump was suspended above the seafloor. In order to ensure that the water used contained minimal sediment, the water pump was placed approximately 75 ft out from the shoreline. The pump was anchored and suspended approximately 2 ft above the seafloor to avoid pumping sediment into the separator.

As previously mentioned, when Sargassum is collected by a front-end loader (Figure 6) different ratios of Sediment to Sargassum mixture are collected due to varying Sargassum deposits and/or operator inconsistency. Therefore, every front-end loader bucket full of Sargassum contains a certain amount of sediment from the beach. For the purpose of this experiment, large operator error is assumed; therefore, a ratio of 90% sediment and 10% Sargassum was used for the mixture in the experiment. In this experiment separate was defined as, to divide into constituent or distinct elements. Therefore, it was assumed that if the Sand-Seaweed Separator could separate, 90% sediment and 10% Sargassum, smaller ratios would also be accounted for, as smaller ratios of sediment would separate faster.

Figure 11 Sand-Seaweed Separator on the beach.

3.2 Data Acquisition Methodology

Sediment and fresh Sargassum were collected from the beach. In order to remove any sediment from the Sargassum, the Sargassum was put through the sand-seaweed separator three times to ensure that only minimal sediment was attached to the Sargassum. A 1 kg sample of Sargassum was collected and placed in a bucket. A sub-sample of the Sargassum was also collected. Similarly, 9 kg of sediment was collected and put in the same bucket; a sub-sample of sediment was also collected. The sediment and Sargassum were mixed together in the bucket. The mixture was then dumped into the Sand-Seaweed Separator. After all the Sargassum had gone through the separator, the water pump and separator were powered off. The sediment and Sargassum separated was allowed to drain for five minutes before being collected and weighed. After the samples were weighed, sub-samples of the sediment and Sargassum were collected. The sub-samples were then analyzed for sediment and bulk organic matter content using a classic loss on ignition procedure, following standard methods (Heiri, 2001). To find organic matter content, the samples were put in an oven overnight to determine the dry weight of the samples. After the oven drying, the organic matter was combusted to ash and carbon dioxide at a temperature of 550 °C in a furnace. The weight loss in the samples should be proportional to the amount of organic carbon contained in the sample (Heiri, 2001). By weighing the samples after they passed through the furnace the organic matter content could then be determined. Figure 12 illustrates the various different stages of the separation process.

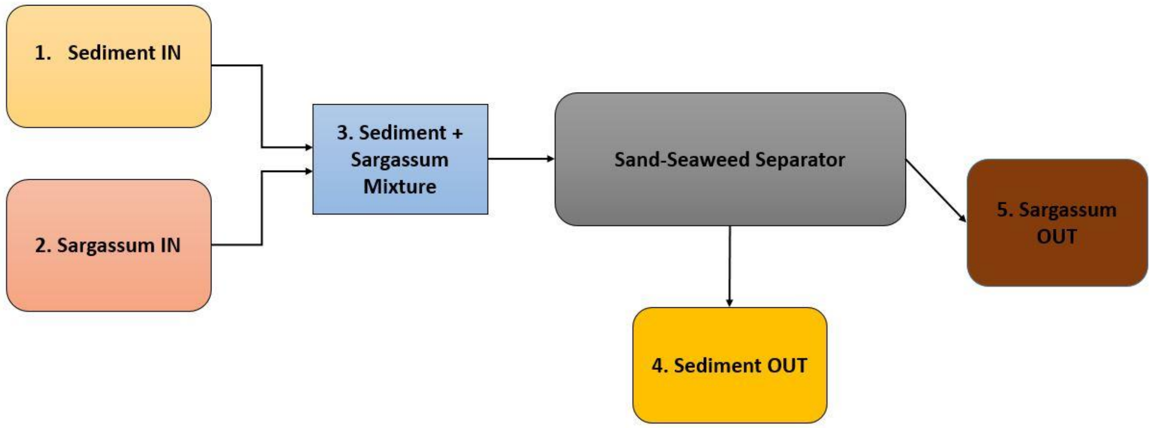

Figure 12 Different stages of the separation process.

As water was sprayed on the sediment-Sargassum mixture during the separation process, the moisture content of the sediment and Sargassum was expected to increase. Therefore, the mass of the sediment and Sargassum was expected to increase as the moisture content of the sample increased. In order to determine how much the moisture content varied during the separation process, the moisture content of the sediment and Sargassum samples were analyzed before and after the separation process.

Each sample collected contained a certain percentage of air, water, and solid matter in the form of organic and inorganic matter (Figure 13). In order to determine the efficiency of the Sand-Seaweed Separator the moisture content and organic matter content of each sample were analyzed. By calculating the percentage of moisture in each sub-sample, the amount of moisture in each sample could be calculated. By subtracting the mass of the moisture from the total mass of the sediment, the mass of the dry sediment could be calculated.

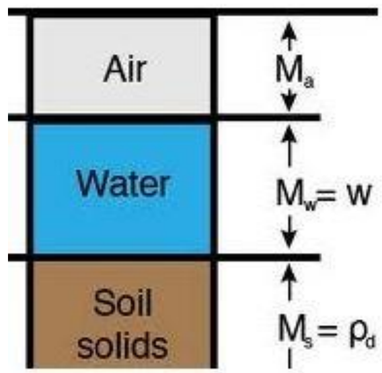

Figure 13 Moisture & Organic Matter in Sample. Adapted from Fredlund D. G., Rahardjo H., 1993.

Small pieces of Sargassum may have broken off and fallen through the screen of the separator. In order to calculate how much Sargassum fell through the screen, the organic matter of the sediment was calculated both before and after the experiment. By comparing the organic matter content after the separation process to the organic matter content before the separation process, the amount of Sargassum that fell through the screen could be calculated. Similarly, in order to calculate how much sediment was not separated from the Sargassum, the organic matter content of the Sargassum before and after separation was compared.

As Sargassum begins to decompose it becomes very brittle, therefore, the process was repeated again three days later with Sargassum that was originally collected three days prior to see how the results may vary as a function of Sargassum decomposition time.

3.3 Data Analysis

To calculate the water content of the samples, the samples were put in an oven at 100 °C overnight. When the samples were removed from the oven the water content was calculated using equations 1-3 below.

Equation 1 was used to calculate the mass of the water.

$$M_W = M_{PWS} - M_{PDS} \tag{1}$$

Where M_w is the mass of the water, M_{PWS} is the mass of the porcelain dish plus the mass of wet sediment, and M_{PDS} is the mass of the porcelain dish plus the mass of the dry sediment.

Equation 2 was used to calculate the mass of the dry sediment.

$$M_D = M_{PDS} - M_P \tag{2}$$

Where M_D is the mass of the dry sediment, M_{PDS} is the mass of the porcelain dish plus the mass of the dry sediment, and M_P is the mass of the dry porcelain dish.

Equation 3 was used to calculate the water content of the sediment.

$$WC = \frac{M_{PWS} - M_{PDS}}{M_{PDS} - M_P} x\ 100 \tag{3}$$

To calculate the organic matter, equations 4-6 were used. To calculate the mass of the ashed sediment the 50 g samples were put in a furnace at 550 °C for five hours. The mass of the ashed sediment was determined by weighing the sample after cooling.

To calculate the mass of the ashed sediment, equation 4 was used:

$$M_A = M_{PA} - M_P \tag{4}$$

Where M_A is the mass of the ashed sediment, M_{PA} is the mass of porcelain dish plus the mass of the ashed sediment, and M_P is the mass of the dry porcelain dish.

To calculate the mass of organic matter, equation 5 was used:

$$M_O = M_D - M_A \quad (5)$$

Where M_O is the mass of the organic matter, M_D is the mass of the dry sediment, and M_A is the mass of the ashed sediment.

To calculate the organic matter content, equation 6 was used:

$$OM = \frac{M_O}{M_D}\ x\ 100 \quad (6)$$

By comparing the organic matter content in the samples before and after separation the amount of sediment separated by the separator could be determined. To determine the efficiency of the separator equation 7 was used:

$$Separation\ Efficiency = \frac{sediment\ out}{Total\ sediment\ in}\ \mathrm{x}\ 100 \quad (7)$$

After calculating the separation efficiency, the amount of sediment removed from the beach by means of the Sand-Seaweed separator was calculated.

4. RESULTS

This section presents the results collected from separating sediment from fresh Sargassum and old Sargassum in Table 1 and Table 2 below. Fresh Sargassum is defined in this experiment as Sargassum that was collected from the beach within one day of being washed ashore. Old Sargassum is defined in this experiment as Sargassum that is three days older than the fresh Sargassum. The Sediment Sample IN (1) and Sargassum Sample IN (2) represent the mass of the sediment and Sargassum prior to being mixed together, before the separation process. The Sediment Sample OUT (4) and Sargassum Sample OUT (5) represent the mass of the sediment and Sargassum after going through the separation process. As water was sprayed on the mixture during the separation process, the moisture content of the samples were calculated before and after separation in order to determine how much moisture was added to each sample. The moisture content in Table 1 and Table 2 is first represented as a percentage of the sample, then the mass of moisture in the sample is represented in kilograms. By subtracting the mass of moisture in the sample from the mass of the sample, the mass of the sample without any moisture is given in kilograms. Similarly, in order to determine if each sample gained or lost organic matter, the organic matter content of the Sediment Sample IN (1) and Sargassum Sample IN (2) was analyzed and compared to Sediment Sample OUT (4) and Sargassum Sample OUT (5). The organic matter content in Table 1 and Table 2 is first represented as a percentage of the sample, then the mass of the organic matter in the sample in kilograms and then, the mass of the sample without any organic matter is represented. The Sediment In, in the bottom row of section 1 and 2 represent the mass of sediment without moisture or organic matter that was in each sample prior to separation. The Sediment Out, in the bottom row of section 4 and 5 represent the mass of sediment without moisture or organic matter that remained in each sample after the separation process.

The mean moisture content of the sediment prior to being mixed with fresh Sargassum and put through the separator was 18.56% ± 0.82. After the sediment was separated from the fresh Sargassum and allowed to drain it had a mean moisture content of 21.55% ± 0.72. The mean moisture content of fresh Sargassum increased during the separation process from 86.27% ± 1.55 to 87.69% ± 2.25. Similarly, the moisture content of the sediment used with the old

Sargassum increased from 19.63% ± 1.25 to 21.41% ± 0.83. The moisture content of the old Sargassum decreased as it went through the separator from 90.71% ± 0.77 to 89.05% ± 2.07.

Table 1 Results from Fresh Sargassum

Fresh Sargassum	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	**Mean**
1. Sediment Sample IN (kg)	9.2900	8.9900	9.1000	9.0200	8.9700	9.0740
1. Moisture content (%)	19.0565	18.1552	18.5787	19.5957	17.4488	18.5670
Moisture in Sample (kg)	1.7703	1.6322	1.6907	1.7675	1.5652	1.6852
Sediment - Moisture (kg)	7.5197	7.3578	7.4093	7.2525	7.4048	7.3888
1. Organic Matter Content (%)	0.5002	0.4079	0.5039	0.4689	0.5269	0.4815
Organic Matter in Sample (kg)	0.0376	0.0300	0.0373	0.0340	0.0390	0.0356
Sediment - Organic Matter (kg)	7.4820	7.3278	7.3720	7.2185	7.3658	7.3532
1. Sediment In (kg)	7.4820	7.3278	7.3720	7.2185	7.3658	7.3532
2. Sargassum Sample IN (kg)	1.0600	1.0600	1.1000	1.0900	1.2600	1.1140
2. Moisture Content (%)	87.6086	84.8920	85.4093	85.1672	88.2733	86.2701
Moisture in Sample (kg)	0.9287	0.8999	0.9395	0.9283	1.1122	0.9617
Sargassum - Moisture (kg)	0.1313	0.1601	0.1605	0.1617	0.1478	0.1523
2. Organic Matter Content (%)	61.0167	52.1261	53.1112	53.3282	66.0225	57.1209
Organic Matter in Sample (kg)	0.0801	0.0835	0.0852	0.0862	0.0976	0.0865
Sargassum - Organic Matter (kg)	0.0512	0.0767	0.0753	0.0755	0.0502	0.0658
2. Sediment In (kg)	0.0512	0.0767	0.0753	0.0755	0.0502	0.0658
4. Sediment Sample OUT (kg)	9.4300	9.1400	9.2000	9.1100	9.0800	9.1920
4. Moisture Content (%)	21.2683	22.7947	21.0220	21.1798	21.4947	21.5519
Moisture in Sample (kg)	2.0056	2.0834	1.9340	1.9295	1.9517	1.9809
Sediment - Moisture (kg)	7.4244	7.0566	7.2660	7.1805	7.1283	7.2111
4. Organic Matter Content (%)	0.4807	0.4937	0.2555	0.4676	0.2533	0.3901
Organic Matter in Sample (kg)	0.0357	0.0348	0.0186	0.0336	0.0181	0.0281
Sediment - Organic Matter (kg)	7.3887	7.0217	7.2474	7.1469	7.1102	7.1830
4. Sediment Out (kg)	7.3887	7.0217	7.2474	7.1469	7.1102	7.1830
5. Sargassum Sample OUT (kg)	1.1200	1.1700	1.2300	1.2100	1.4200	1.2300
5. Moisture Content (%)	84.9656	86.1746	87.3928	90.1466	89.7872	87.6934
Moisture in Sample (kg)	0.9516	1.0082	1.0749	1.0908	1.2750	1.0801
Sargassum - Moisture (kg)	0.1684	0.1618	0.1551	0.1192	0.1450	0.1499
5. Organic Matter Content (%)	54.2974	50.4526	57.7357	65.1384	63.0810	58.1410
Organic Matter in Sample (kg)	0.0914	0.0816	0.0895	0.0777	0.0915	0.0863
Sargassum - Organic Matter (kg)	0.0770	0.0801	0.0655	0.0416	0.0535	0.0635
5. Sediment Out (kg)	0.0770	0.0801	0.0655	0.0416	0.0535	0.0635

Table 2 Results from Old Sargassum

Old Sargassum	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	**Mean**
1. Sediment Sample IN (kg)	8.9900	9.0900	9.1600	9.1300	9.1000	9.0940
1. Moisture content (%)	18.7587	20.4650	17.9862	21.0296	19.9179	19.6315
Moisture in Sample (kg)	1.6864	1.8603	1.6475	1.9200	1.8125	1.7854
Sediment - Moisture (kg)	7.3036	7.2297	7.5125	7.2100	7.2875	7.3086
1. Organic Matter Content (%)	0.3236	0.4029	0.3257	0.3482	0.3173	0.3435
Organic Matter in Sample (kg)	0.0236	0.0291	0.0245	0.0251	0.0231	0.0251
Sediment - Organic Matter (kg)	7.2800	7.2006	7.4880	7.1849	7.2643	7.2836
1. Sediment In (kg)	7.2800	7.2006	7.4880	7.1849	7.2643	7.2836
2. Sargassum Sample IN (kg)	1.0500	1.1000	1.0900	1.0600	1.0500	1.0700
2. Moisture Content (%)	91.4768	89.7041	90.8852	90.1528	91.3527	90.7143
Moisture in Sample (kg)	0.9605	0.9867	0.9906	0.9556	0.9592	0.9705
Sargassum - Moisture (kg)	0.0895	0.1133	0.0994	0.1044	0.0908	0.0995
2. Organic Matter Content (%)	76.2396	63.3162	71.3384	62.9895	79.2268	70.6221
Organic Matter in Sample (kg)	0.0682	0.0717	0.0709	0.0657	0.0719	0.0697
Sargassum - Organic Matter (kg)	0.0213	0.0415	0.0285	0.0386	0.0189	0.0298
2. Sediment In (kg)	0.0213	0.0415	0.0285	0.0386	0.0189	0.0298
4. Sediment Sample OUT (kg)	8.6900	9.1900	9.0400	9.0800	9.0100	9.0020
4. Moisture Content (%)	22.3637	22.0289	21.5314	20.4775	20.6498	21.4102
Moisture in Sample (kg)	1.9434	2.0245	1.9464	1.8594	1.8605	1.9268
Sediment - Moisture (kg)	6.7466	7.1655	7.0936	7.2206	7.1495	7.0752
4. Organic Matter Content (%)	0.2825	0.2560	0.2212	0.1567	0.2506	0.2334
Organic Matter in Sample (kg)	0.0191	0.0183	0.0157	0.0113	0.0179	0.0165
Sediment - Organic Matter (kg)	6.7275	7.1472	7.0779	7.2093	7.1315	7.0587
4. Sediment Out (kg)	6.7275	7.1472	7.0779	7.2093	7.1315	7.0587
5. Sargassum Sample OUT (kg)	1.0000	1.1200	1.1400	1.1200	1.0900	1.0940
5. Moisture Content (%)	89.6914	88.3021	85.8213	90.4608	91.0012	89.0554
Moisture in Sample (kg)	0.8969	0.9890	0.9784	1.0132	0.9919	0.9739
Sargassum - Moisture (kg)	0.1031	0.1310	0.1616	0.1068	0.0981	0.1201
5. Organic Matter Content (%)	66.8038	68.1271	71.6654	67.6439	69.6379	68.7756
Organic Matter in Sample (kg)	0.0689	0.0893	0.1158	0.0723	0.0683	0.0829
Sargassum - Organic Matter (kg)	0.0342	0.0418	0.0458	0.0346	0.0298	0.0372
5. Sediment Out (kg)	0.0342	0.0418	0.0458	0.0346	0.0298	0.0372

4.1 Efficiency of Sand-Seaweed Separator

The separator efficiency for a 90:10 mixture of sediment to fresh Sargassum was calculated to be 96.8% ± 1.42. Similarly, the separator efficiency for a 90:10 mixture of sediment to Old Sargassum was calculated to be 96.5% ± 3.25. The sediment separated by the Sand-Seaweed Separator is presented in Table 3 and Table 4.

Table 3 Efficiency of Sand-Seaweed Separator with Fresh Sargassum

Fresh Sargassum							
Trial	**Total Sediment In (kg)**	**Total Sediment Out (kg)**	**Sediment Lost (kg)**		**Separated Sediment (%)**	**Unseparated Sediment (%)**	**Sediment lost (%)**
1	7.5332	7.4657	0.0676		98.0814	1.0216	0.8970
2	7.4045	7.1019	0.3026		94.8305	1.0824	4.0871
3	7.4472	7.3129	0.1343		97.3165	0.8800	1.8034
4	7.2939	7.1885	0.1054		97.9850	0.5698	1.4452
5	7.4160	7.1638	0.2523		95.8764	0.7220	3.4016
			Average		96.8180	0.8552	2.3269

The average amount of sediment that was not separated from the fresh Sargassum was 0.8552% ± 0.21. The average amount of sediment lost during the separation process of the fresh Sargassum was 2.3269% ± 1.36. There are two main sources of where the sediment was lost; some sediment missed the collection tray that was located beneath the perforated cylindrical drum, and a small amount of sediment was not accounted for, as not all sediment could be removed from the collection tray.

Table 4 Efficiency of Sand-Seaweed Separator with Old Sargassum

Old Sargassum						
Trial	**Total Sediment In (kg)**	**Total Sediment Out (kg)**	**Sediment Lost (kg)**	**Separated Sediment (%)**	**Unseparated Sediment (%)**	**Sediment lost (%)**
1	7.3012	6.7618	0.5395	92.1427	0.4687	7.3886
2	7.2421	7.1890	0.0532	98.6889	0.5766	0.7345
3	7.5165	7.1237	0.3928	94.1648	0.6093	5.2258
4	7.2235	7.2439	-0.0204	99.8035	0.4786	-0.2821
5	7.2832	7.1613	0.1219	97.9175	0.4089	1.6736
			Average	96.5435	0.5084	2.9481

The average amount of sediment that was not separated from the old Sargassum was 0.5084% ± 0.08. The average amount of sediment lost during the separation process of the old Sargassum was 2.9481% ± 2.95. In Trial 4 of the old Sargassum, there was more sediment collected than sediment inputted. This could be due to a small amount of sediment remaining on the collection tray after trial 3.

After calculating the efficiency at which fresh Sargassum and Old Sargassum (3 days old) was separated by the Sand-Seaweed Separator, the results were compared using a T-test. A T-test is a statistical method that is used to see if two sets of data differ significantly. The p-value in a T-test indicates the probability of getting a value of the test statistic that is at least as extreme as the one representing the sample data, assuming that the null hypothesis is true. The significance level (α) was set at 0.05, therefore a p-value greater than 0.05 would accept the null hypothesis and a p-value of less than 0.05 would reject the null hypothesis.

The T-test used to determine if there was a significant difference in the efficiency of the Sand-Seaweed Separator when separating sediment from fresh Sargassum and old Sargassum resulted in $p = 0.8667$. As $0.8667 > 0.05$, this indicates that there was no significant difference in the efficiency of the Sand-Seaweed Separator, when separating sediment from fresh Sargassum and old Sargassum. Therefore, when the next Sargassum landings occur, beach managers can leave the Sargassum on the beach for at least three days and experience no significant difference in efficiency, when using a Sand-Seaweed Separator to separate sediment from Sargassum.

Another T-test was used to determine if there was a significant difference in the amount of organic matter lost during the separation process between fresh Sargassum and old Sargassum. In this test $p = 0.015$ which is less than 0.05 therefore, there was a significant difference in the amount of organic matter lost in the separation process between fresh Sargassum and old Sargassum. This indicates that a lot more pieces of old Sargassum broke off and fell through the mesh of the screen than the fresh Sargassum. For beach managers this would indicate that it is more important to clean the most popular beaches first in order to have the least amount of Sargassum remaining on the beach as the longer the Sargassum remains on the beach the more likely it is to break into pieces during separation.

Considering that a ratio of 90% sediment and 10% Sargassum is expected to be the worst-case scenario in regards to the ratio collected by the front-end loaders. The amount of sediment removed from the beach per tonne of 90% sediment and 10% Sargassum is 8.55 kg ± 2.1.

5. DISCUSSION AND CONCLUSION

Sargassum has a multitude of benefits, however, leaving accumulations of Sargassum on beaches can smother turtle nests (Laffoley et al., 2011). Large Sargassum landings can cover turtle nesting sites, preventing hatchling turtles from reaching the ocean. Turtles can also die by getting trapped in the large quantities of Sargassum near the shore (Feagin et al., 2010).

Unless the current State Ordinance preventing the removal of Sargassum from the beach is modified to allow the removal by means of the Sand-Seaweed Separator, this cyclical pattern of Sargassum landings will continue to create problems for Galveston's tourism. Tourists have been known to avoid resorts affected by large Sargassum landings, therefore, the removal of Sargassum from the beach could not only increase the tourism revenue in Galveston by having a clean beach, but the Sargassum removed could then be used to create local employment (Milledge et al., 2016). Considering the wide range of benefits that can result from the removal and use of Sargassum washing up on Galveston's beaches, these inevitable Sargassum landings could prove to be beneficial to Galveston's economy rather than a hindrance.

5.1 Cost of Sediment Removed by Sand-Seaweed Separator

There have been numerous beach nourishment projects in Galveston. Between 2015 and 2017, $47 million has been spent to date on beach nourishment of Galveston beaches. The most recent beach nourishment project consisted of pumping 1 million cubic yards of sand onto the beach. The project cost $19.5 million, which equates to $19.50 per cubic yard of sand for this particular project. In December 2014, another beach nourishment project took place in Galveston in front of Dellanera RV Park. This project consisted of depositing 120,000 cubic yards of sand to restore the beach. The Dellanera project cost $4.8 million, which equates to $40 per cubic yard of sand (Rice, 2014). Therefore, the average cost per cubic yard of sand pumped onto Galveston beaches was calculated to be $29.75.

The Sand-Seaweed Separator is 96.8% ± 1.42 efficient with Fresh Sargassum and 96.5% ± 3.25 efficient with Old Sargassum when the mixture of sediment to Sargassum is 90:10. This implies that if 1 tonne of sediment-Sargassum mixture at a ratio of 90:10 was separated using the Sand-Seaweed Separator, a total of 8.55 kg ± 2.1 of sediment would be removed from the beach if the Sargassum was fresh and 5.08 kg ± 0.8 if the Sargassum was three days old. Considering that the sand on Galveston's beaches is valued at approximately $29.75 per cubic yard, the maximum dollar amount of sediment removed from the beach per tonne of 90:10 sediment to Sargassum mixture is $0.27. Therefore, this is a competitive and cost-effective method of maintaining the beauty of Galveston's beaches, an essential goal given the importance of tourism to coastal economies.

5.2 Scalability of Sand-Seaweed Separator

The Sand-Seaweed Separator used in this project was a small-scale prototype. A full-size model would be four times the size of the Sand-Seaweed Separator used in this project. It would have a drum size of 8 ft diameter and 24 ft in length. The Doppstadt SM-620 (Figure 14) is a mobile trommel screen that is similar in size to a full-size Sand-Seaweed Separator. The Doppstadt SM-620 costs approximately $350,000 and consumes 3-4 US Gallons of diesel fuel per hour. Additional modifications to the trommel screen, trommel frame and motor would need to be done to the Doppstadt SM-620 in order to get a similar efficiency to the Sand-Seaweed Separator used for this project. A full-size Sand-Seaweed Separator could process approximately 76.8 tonnes of 90:10 sediment to Sargassum mixture per hour. Approximately 50,000 tonnes of Sargassum washed ashore in Galveston in 2014 (Hill et al., 2015). In a worst-case scenario, sediment and Sargassum would be mixed at a ratio of 90% sediment and 10% Sargassum, then it would take one full size Sand-Seaweed Separator 271.27 days to remove all the Sargassum from the beach. However, if a 10% sediment and 90% Sargassum mixture was separated using a full-size Sand-Seaweed Separator it would take approximately 30.14 days to remove all the Sargassum from the beach.

Figure 14 Doppstadt SM-620 trommel screen. Adapted from Blue Group (n.d.)

5.3 Conclusion

These preliminary tests of the Sand-Seaweed Separator indicate that it is an effective means of removing Sargassum from the beach without taking sand as well. Further research needs to be conducted relating to most efficient angle of incline, drum configuration and speed of rotation. These are needed to determine optimum efficiency of the separator.

While further work is needed to assess the potential scalability of this device, the findings of this research indicates that a Sand-Seaweed Separator could benefit coastal communities that experience large Sargassum landings. The Sand-Seaweed Separator could benefit coastal communities by efficiently removing the Sargassum, thus removing the undesirable side effects that accompany large Sargassum landings. A maximum of 10.65 kg of sediment would be removed from the beach per tonne of 90:10 sediment to Sargassum mixture which is the equivalent to $0.27 of sediment in Galveston, Texas. Considering that the Galveston Island Park Board of Trustees spend $3 million annually on beach maintenance, the Sand-Seaweed Separator could prove to be the most cost-effective method of removing large quantities of Sargassum from the beaches of Galveston. (De Schaun, 2015).

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