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ADAPTATION AND SUSTAINABLE MANAGEMENT OF MASSIVE INFLUX OF SARGASSUM IN THE CARIBBEAN*

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Abstract

The massive influx of sargassum is a problem that affects several countries in Africa and the Caribbean. Even though a decade has passed since the first event, an integrated management and adaptation strategy for this phenomenon have not yet implemented in most of these countries, with environmental, economic, and social effects, aggravated by the continuous growth of the quantities that land year after year. This work analyzes the publications since 2011 related to the sargassum invasion in the Caribbean area, the environmental management, and the solutions that allow us to face the current situation in a coordinated and efficient way. The prediction of sargassum streaks continues to be an unsolved problem for most Caribbean countries, which requires an urgent solution. On the other hand, the evaluation of the ecological impact of sargassum invasions on ecosystems has poorly documented, which requires further scientific research in this field. Regarding the management of this phenomenon in sectors such as tourism and fishing, it is necessary to continue systematizing the experience of all these years to establish coordinated strategies and management and adaptation plans that allow minimizing the negative impacts that the massive influx of sargassum causes on both sectors. Lastly, it is necessary to continue making coordination efforts among all the actors that are investigating this topic, to validate the best experiences implemented in all stages of the sargassum management process, including such core issues as the conservation of sargassum and its use as raw material for different applications.

Keywords: adaptation, management, recovery, sargassum, sustainability

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1. Introduction

Annually, in the period between March and August, large quantities of sargassum sail near the coasts of the Caribbean islands. The pelagic species that make up this family of brown macroalgae are *Sargassum fluitans* and *Sargassum natans*. Since 2011, the massive influx of sargassum into the Caribbean Sea has increased. With a greater or lesser magnitude, the phenomenon continues to repeat every year. The inflows occurred in 2015 and 2018 were especially significant (Wang et al., 2019). The severity of the sargassum outbreak varies markedly across the Caribbean region. Some small island countries have had to declare a national emergency in this situation. In other countries, the impact on the tourism sector has been considerable.

The causes of massive sargassum landings are not yet well defined, presumably due to ocean warming due to long-term cycles such as the Southern Atlantic Oscillation and global climate change, to changes in ocean circulation, and due to the effects of climate change and variability (Mendez-Tejeda and Rosado, 2019; Wang et al., 2019). There is a consensus that we need more information on the environmental impact of the massive influx of sargassum, the risk of disasters and the economic costs caused by this phenomenon, and that collaborative action is necessary for the Caribbean before this problem becomes a recurring environmental disaster.

For this reason, it is necessary to take adaptation and sustainable management actions for the massive influx of sargassum in the Caribbean. In this sense, the present work aims to analyze the works published since 2011 related to the sargassum invasion in the Caribbean area, specifically those related to environmental management and solutions that allow us to face the current situation in a coordinated and efficient way.

In recent years, algal lands have increased significantly to Caribbean beaches, hindering the economy of tourism, aquaculture, and regular fisheries (Milledge et al., 2020). Sargassum limes to beaches can be classified, depending on the color of the sargassum, like green, red, or gold. Despite the existence of a large number of seaweeds, the most distinctive landmarks are those of pelagic algae (*Sargassum natans* and *Sargassum fluitans*), which cause golden tides, particularly in the Caribbean and West Africa region (Laffoley et al., 2011).

The amount of pelagic sargassum in the ocean is vast and, therefore, the potential for golden tides as well. The Sargasso Sea is the largest aggregation of algae in the world, with a total biomass of approximately 10 million tons. About 1 million tons of sargassum leaves the Gulf of Mexico, through the Florida Straits, and enters the Sargasso Sea area of the Atlantic Ocean annually. However, the Sargasso Sea and the Gulf of Mexico are not the only sources of the golden tides in the Caribbean. There is a new source identified, the Northern Equatorial Recirculation Region, which has caused approximately 10,000 tons of seaweed to reach the beaches of the Caribbean islands during the 2015 invasion. However, invasions are not limited to the Caribbean. It also occurs on the beaches of the Gulf of Mexico, the Atlantic coast of the United States, and the coast of West Africa.

Authors selected the deep detailed review of the research results given in the scientific papers over the world. Besides, authors have made their own research in recent years and those results are included in the analysis as well.

2. Results and disccusion

2.1. Impact of the sargassum inundations on the Caribbean

Sargassum deposits occur naturally and regularly on beaches, albeit in smaller amounts than those that landed between 2011-2019. The organisms they transport can be valuable sources of food for the beach fauna (Mendez-Tejeda and Rosado, 2019). In

principle, beach sargassum is not harmful to human health (Fiermonte, 2015), although there have been some reports of minor skin and eye irritations. The effect on humans of exposure to high concentrations of hydrogen sulfide is concentration-dependent and can be fatal, causing pulmonary, neurological, and cardiovascular damage. Subchronic and chronic exposures can cause conjunctival and upper respiratory tract irritation, headaches and vestibular syndrome, memory loss, and modification of learning skills.

Fig. 1 shows the increase in publications related to the economic, social, and environmental impacts of the massive influx of sargassum in the period 2011-2020. It is clearly seen from the figure that the problem discussed attracts more and more attention of the scientists fro different area of knowledge.

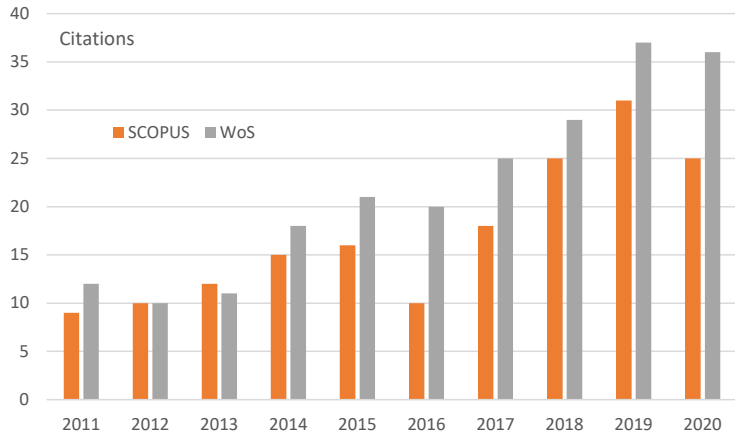

Fig. 1. Publications related to the economic, social, and environmental impacts of the massive influx of sargassum in SCOPUS and Web of Science (WoS)

Large deposits are not beneficial for marine and coastal ecosystems, causing negative impacts on them and essential economic activities in the Greater Caribbean region such as tourism, fishing and marine transport (Rodríguez-Martínez et al., 2020). The massive influx of sargassum to the coasts sometimes has a negative impact (Willoughby, 2018), because when currents and winds bring the algae to shore, the gas-filled vesicles begin to deteriorate from wave action and friction with the seafloor, and the algae sink. Once the sargassum is damaged, it begins to rot, creating an environment in the seawater that is poor in oxygen and with a decrease in pH (van Tussenbroek et al., 2017).

The absence of oxygen is detrimental to living organisms that inhabit the coastal zone, such as coral reefs (Cabanillas-Terán et al., 2019), and the seagrasses that support the biodiversity on which the inhabitants of the coastal communities depend and which serves as an attraction for tourists. The shade that sargassum generates from accumulation is also detrimental to seagrasses (van Tussenbroek et al., 2017) and corals that depend on sunlight for their development and growth, and to turtle nests found in the sand, since, not receiving direct heating from the sun, changes the sex relationship between females and males towards males. The deaths of thousands of fish, seagrasses, and damage to mangroves have been reported, as well as alterations in the trophic dynamics of some species (Cabanillas-Terán et al., 2019). The cause of mortality appears to be the combined effect of high concentrations of ammonium and hydrogen sulfide, along with hypoxic conditions (Cabanillas-Terán et al., 2019).

The damage caused to seagrasses contributes to beach erosion since they stabilize the sediments that help prevent erosion.

Animals such as turtles, dolphins, and others stay trapped in the sargassum mass cannot escape nor breathe and die. In turtle nesting areas, newly hatched baby turtles are prevented from reaching the sea and also die, while turtles that come to nest cannot go out onto the sand to do so. After the sargassum influx events, green algae proliferate near the beach and will deposit in the sand (Willoughby, 2018). There is insufficient knowledge about the ecological impact of sargassum invasions on ecosystems in general, an impact that needs to be assessed for which biodiversity indicators are required (UNEP, 2018).

On the other hand, the ecological importance of sargassum must be taken into account since it serves as breeding habitat for a large number of invertebrate and fish species that are linked to this ecosystem and a refuge for migratory species. More than 127 species of fish and 145 species of invertebrates associated with the presence of pelagic sargassum are reported in the bibliography (Laffoley et al., 2011). Some of these species are endemic to Caribbean ecosystems, such as sargassum crab, sargassum shrimp, sargassum needlefish or pipe, sargassum anemones, sargassum slug, sargassum snail, juvenile swordfish, tilefish, drift (Nomeidae) and sea turtles. The latter ones are considered the most threatened since sargassum represents the ideal refuge for sea turtle hatchlings who find in sargassum a complex structural habitat that protects them against predators, poaching, coastal development, and casual capture in fisheries (UNEP, 2018).

Finally, it is necessary to consider the impact of the sargassum that falls on the seabed. Deepwater ecosystems, limited by their inability to use primary production as a carbon source, depend on other sources to support life. Large-scale sedimentation of sargassum has been shown to form an essential trophic link between surface and benthic production and should be considered more in the future as a regular contribution of carbon to the seabed in the North Atlantic.

Sargassum stranded along the shoreline causes fouling on the beach and significantly reduces its attractiveness. The several meters of height that accumulate on the beach during golden tides limits swimming and access to boat moorings near the coasts and ports.

It also causes the cancellation of reservations and the closing of rooms near the beach (Fiermonte, 2015). As it floats close to shore, sargassum can pick up small plants and animals that stick and grow on the leaves of the algae. The included insects can bite people. Nevertheless, the biggest complaint in tourist places is the very unpleasant smell of decomposing sargassum, with a large number of flies that it attracts. If the golden tide events continue to occur without a satisfactory response to these events, tourism may decrease significantly.

Sargassum causes problems in the fishing sector since it brings a loss of fishing days due to the impossibility of transiting through the accumulations of sargassum near the coast. In some cases, fishers are unable to row through the floating banks of sargassum, and in others, there is the possibility that the motorboats could damage the transmission by entangling the sargassum in the propellers.

There are conflicting reports on the impact on fisheries of some species, such as flying fish and dorado. Fishing with nets is also affected since sargassum becomes entangled in them. It decreases the total catch and the size of the fish caught, changes the composition of the catches and the type of fish in the catch (Willoughby, 2018). Fishing and aquaculture can also be severely affected by the mortality of fish and other marine species, resulting in reduced and disturbing fish catches.

2.2. Handling and management of sargassum invasions

The massive influx of sargassum to the coasts of the Caribbean countries requires establishing management and integrated management actions, which allow different countries to reduce environmental, economic, and social impacts. Management and management programs must take into account the monitoring and forecast of the arrival of

sargassum in territorial waters in order to organize the harvest of the algae, its preparation and storage, and its possible use or final destination safely for man and the environment.

Several tools permit to monitor and forecast the arrival of sargassum, and some of them have been integrated into joint projects. In this sense, the SPAW protocol, from the Caribbean Environmental Program (PAC), between the University of South Florida (USF) and the Texas A&MG (TAMUG), together with other partners, develops a prediction system from the sargassum arrivals. On the other hand, there is some progress in the project TAMUG, aimed at achieving higher specificity on the beaches where the landfalls will occur as part of the short-term predictions of the sargassum landings (UNEP, 2018).

The interest in prediction studies of the massive influx of sargassum to the coasts is evident in the increase in this topic's publications in the last ten years (Fig. 2).

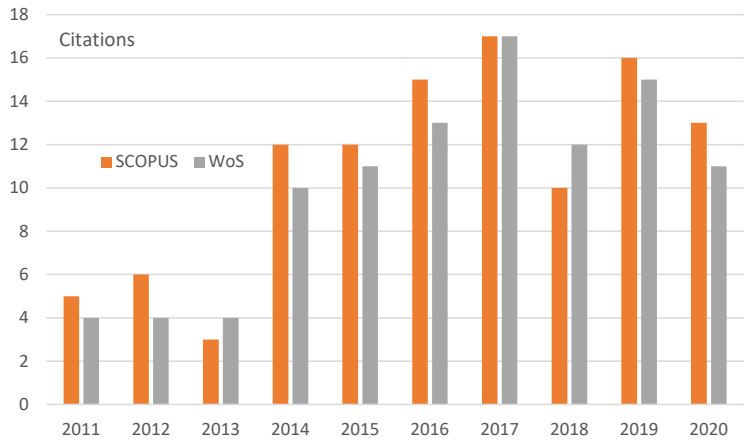

Fig. 2. Publications related to predicting the massive influx of sargassum to the coasts in SCOPUS and Web of Science (WoS)

The sargassum harvest was initially carried out upon reaching the beaches or coasts. Today it is a question of carrying it out at sea to lessen the impacts caused by its arrival in coastal systems. The cleaning of the beaches must be done without excess, as it can affect the life of the birds, the nesting of sea turtles, and the vegetation of the dunes. There are some cases in which beach cleaning is mechanical using specialized machinery. This procedure contributes to the erosion of beaches. This type of equipment can also damage dunes.

Manual extraction of sargassum on beaches is carried out by raking and transporting with wheelbarrows, bags, or dragging with tarps. Manual cleaning is very flexible and can be performed in a wide variety of locations, but it requires a lot of work and time. In this way, beach cleaning also has a social component. Where manual cleaning is not practical, as in the case of large volumes of sargassum, it is carried out with mechanical equipment. To minimize the impact of mechanical cleaning is preferable to use machines with large soft tires than tracked vehicles.

Several investigations are related to harvesting methods at sea, due to their lesser impact on coastal ecosystems. The process has two stages, the placement of containment barriers and the subsequent harvesting with boats. A direct method of removing sargassum from the sea is through the use of boats. Other options are harvesting on high seas and the use of skimmer, a machine generally used for the collection of oil during the occurrence of spills into the sea (Milledge and Harvey, 2016).

The seasonal nature of sargassum tides requires a method to preserve it and to be able to provide a continuous supply to its various possible applications. Two methods used to

preserve large volumes of organic material are drying and silage. Sun-drying is the primary method for drying algae (Valderrama et al., 2013), but it depends on the climate and the volume of sargassum. Sun-drying in tropical places can take 2-3 days in sunny areas, but it could take up to seven days in rainy periods (Valderrama et al., 2013). Despite these limitations, solar methods are the least expensive drying option. Solar drying can cause considerable denaturation of organic compounds in algae. On the other hand, lyophilization tends to cause less damage to organic materials but is more expensive than conventional or solar drying. Freeze-drying has been used for algae but is considered too expensive for large-scale drying of sargassum, and its use is mainly limited to research and some high-value products obtained from seaweed.

An alternative method of preservation is silage. Typically, silage conditions are achieved from spontaneous anaerobic fermentation with lactic acid bacteria naturally occurring in lactic acid-producing biomass or from inoculation. Leaching and demineralization are inherent characteristics of silage that can be beneficial for subsequent processes, such as anaerobic digestion, pyrolysis, and gasification. Despite its widespread use in land agriculture, little research has been done on how to preserve marine algae biomass year-round to meet ongoing demand (Milledge and Harvey, 2016). However, silage can cause changes in biomass composition and the degradation of some organic compounds, making it not an adequate conservation method for the production of high value-added compounds.

One of the key recommendations of the Caribbean Sea Commission to address the threat of the massive arrival of sargassum to the coasts is to support research on its commercial uses. The sargassum might be used for different purposes: fertilizers, animal feed, biopolymers, biofuels/biogas obtaining activated carbon and biochar, and to be able to manage it sustainably (Fiermonte, 2015; Francoeur et al., 2019; Laffoley et al., 2011; Li et al., 2017). However, it is necessary to take into account some safety issues due to the bio-absorbent properties of sargassum that might have high levels of heavy metals and metalloids such as arsenic (Milledge and Harvey, 2016; Rodríguez-Martínez et al., 2020). Therefore, market research and chemical analysis are necessary before developing any product. The sustained growth of scientific articles that study various alternatives for the use and commercialization of sargassum (Fig. 3) shows the search for a sustainable solution to this environmental problem.

Among the advantages of using sargassum for the production of biofertilizers, the following can be mentioned: mitigating the ecological damage that macroalgae blooms can cause to eutrophication of coastal ecosystems; recycle the N and P that drains into the sea from the land agricultural from the application of synthetic fertilizers, making it possible to reduce their use; take advantage of micronutrients and substances with potential to benefit the crops and soils present in these macroalgae; increase the natural capacities of the soil and crops for carbon sequestration, while reducing the burning of fossil fuels for the production of synthetic fertilizers; obtaining economic benefits with the use of raw material of low value or without commercial value today. Macroalgae are also used to prepare compost. Regarding this use, there is one aspect that needs attention, which is the salinity of the final product.

Regarding the potentialities of use in animal feed, it is essential to note that sargassum is rich in minerals, carbohydrates (beta-carotene), vitamins and contains a moderate amount of protein. However, applications of sargassum algae associated with agriculture, animal feed, and any other that involves contact or consumption for living organisms, will depend on the content of heavy metals in algae and other toxic compounds. Sargassum is known to be a bio-remediating agent. Several studies have demonstrated the presence in sargassum of heavy metals, rare-earths and metalloids with high values (Rodríguez-Martínez et al., 2020; Tejada-Tejada et al., 2019), among which stands out arsenic, as it is a carcinogen compound.

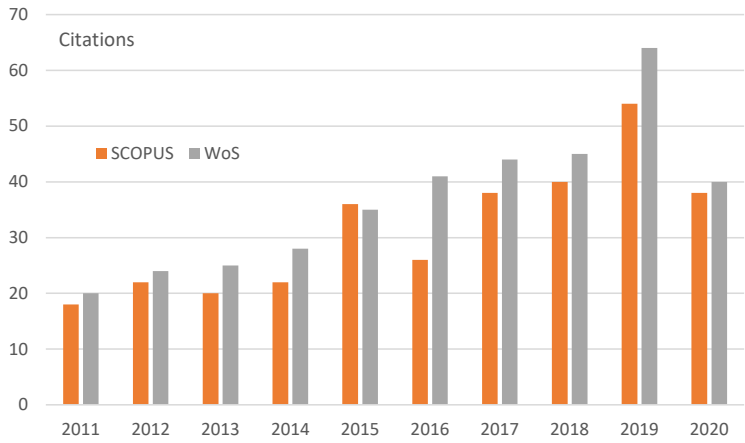

Fig. 3. Publications related to the uses and commercialization of sargassum and its products in SCOPUS and Web of Science (WoS)

The biochar has been produced experimentally from brown algae, including Sargassum spp. (Milledge and Heaven, 2014). Likewise, the obtaining of activated carbon from sargassum is reported, by basic or acid activation, with potential applications as a catalyst (Li et al., 2017), adsorbent for the decontamination of waters containing microcontaminants (Francoeur et al., 2019) or heavy metals (Alvarez et al., 2019), or in electrochemistry.

Regarding the potentialities of sargassum as an energy source, the first thing is to identify whether or not energy is required as an initial drying step (Milledge and Harvey, 2016). The methods of obtaining energy that require dry macroalgae are conventional gasification, direct combustion, transesterification to biodiesel and pyrolysis. For their part, the methods that allow the use of wet macroalgae are anaerobic digestion, fermentation to bioethanol, or biobutanol and hydrothermal treatments or wet roasting. Of these methods, direct combustion is the primary method by which energy is produced from dry biomass, but for macroalgae, this procedure has not been sufficiently explored. However, the high energy required to dry the algae, the relatively low thermal values, and the high ash and sulfur content can cause fouling and corrosion in the boilers, and unacceptable emissions could prevent direct combustion as an economical method of exploiting the algae (Milledge and Heaven, 2014).

On the other hand, both gasification and anaerobic digestion have been suggested as promising methods to exploit bioenergy from biomass. Anaerobic digestion has been shown to produce more net energy than supercritical gasification, the latter requiring a more significant input of energy and a negative return on energy investment (Milledge and Heaven, 2014). There is considerable conjecture about the reasons for relatively low practical methane yields compared to theoretical values (Milledge and Heaven, 2014), and more research is needed to find the cause of low methane yields, and how to overcome them.

Another sargassum application is for obtaining less polluting bioplastics than traditional polymers. Algae can serve as one of the alternatives for the production of natural polysaccharides as raw material for high-quality biodegradable bioplastics. There are some challenges to make bioplastics with sargassum, such as ensuring a uniform composition and avoiding contamination with microelements. Nanocomposite films have been obtained from Sargassum natans, demonstrating that the new biopolymer films could be applied for food packaging and preservation.

2.3. Perspectives in research, management and regional collaboration

Based on the academic, technical, business and local experiences, and taking into account the proposals of the national, regional and international meetings related to the topic of sargassum in the Caribbean, we suggest some perspectives for research, management, and collaboration to mitigate the impacts of the sargassum invasions and turn the current problem into an opportunity for sustainable development for the affected countries. In this effort, an important role will correspond to scientific research, which must integrate research centers and universities in the area. The main topics to be addressed, taking into account previous publications (UNEP, 2018) and the opinion of these authors are:

- The development of models and tools to make long-term forecasts (from months to years) of sargassum blooms, taking into account their causes and annual fluctuations in previous years.
- Detailed exploration of the physiology of the different Sargassum species and a better understanding of the origin of each one.
- The development and monitoring of indicators of the biodiversity of the pelagic habitats of sargassum and of the coastal areas where it reaches (corals, beaches, wetlands) to understand the ecological role and impacts of changes in the distribution and abundance of sargassum, the environmental conditions that drive these changes and the environmental impacts.
- Systematic monitoring of the content of heavy metals and other contaminants present in sargassum, as well as the development of more sensitive, quick, and simple analysis techniques, in order to determine the possible uses of sargassum, respecting the laws established in each country or region.
- In-depth regional assessment of the socio-economic impacts and challenges imposed by the massive influx of sargassum to better understand the effective and sustainable management of sargassum.
- The exploration of other possible applications of sargassum, mainly those related to high added value products for the chemical and pharmaceutical industries.
- The development, implementation, and improvement of integrated management models for the management of sargassum limestone, which take into account the particularities of each affected area, guarantee the reduction of environmental, economic and social impacts, and convert the arrival of sargassum into an opportunity for sustainable development.
- The search for technological and financial means for the harvest of sargassum in the sea as a priority, using adequate means of containment (barriers) and collection, which do not affect the mobility of species of marine and coastal ecosystems, nor fishing activities and maritime transport.
- The development of an inclusive sargassum mining that takes into account not only the areas of tourist interest but all the affected territories. Evaluate it as an opportunity for all the communities involved and as a way to create temporary jobs.
- The establishment of sargassum preservation procedures that guarantee the stability of supply for future uses, taking into account the seasonal nature of the sargassum lime.
- The development of productive activities from sargassum and its combination with other local biomass sources, which guarantees an economic benefit to the communities.
- The training and formation of the human resources necessary to assume the new challenges in the management and sustainable management of the sargassum limes.
- Achieving these objectives will require the support of the authorities at all levels and regional integration through (UNEP, 2018).

- Integration of efforts to measure essential ocean variables, such as those developed by the Intergovernmental Commission (IOC and IOCARIBE), and to develop and use best practices selected by the IODE of the IOC.
- The development of an early detection alert system on a regional scale, which includes understanding the historical patterns of algae abundance, ocean circulation, winds, temperature, and nutrients to compare them with current conditions.
- The implementation of a monitoring protocol based on ships (observation and reporting of sargassum rafts in the open sea by the maritime fleet, including commercial vessels) in the Atlantic Ocean.
- The improvement of global collaboration, coordination, and research at the global, regional, and national levels, both in the execution of projects of diverse natures, as well as the creation of cooperation networks such as SargNet, based at Florida International University.
- The development and implementation of the regional plan for sargassum, which includes the development of an early warning system, a communication strategy, an emergency response plan, and an investigation agenda.
- Holding regional meetings to share experiences and best practices for dealing with and minimizing sargassum landings, which includes national and regional strategic partnerships with affected parties.
- The incentive for countries to reduce ocean pollution from agriculture, changes in land use, and pollution from sources, which is responsible for the excessive growth of algae, with an increase in awareness of the link of climate change.

Sponsor collaborative research on possible uses of sargassum and share knowledge on how to use it for farmers, ranchers, and industrialists, as well as domestically (for example, composting in gardening).

3. Concluding remarks

- The massive influxes of pelagic sargassum to the coasts of the Caribbean have affected the coastal ecosystems. The presence of sargassum has caused negative impacts on the economy, society, and the environment. The most affected economic sectors are tourism, fishing, and maritime transport.
- Socially, coastal populations, tourism, and fishing workers have seen their incomes affected, and some inhabitants have shown a decrease in their quality of life, especially in places where adequate management has not been carried out.
- Environmentally, the loss of species, damage to beaches, wetlands, and the seabed are among the main effects. This environmental situation demands that the Caribbean countries put in place integrated management plans that allow establishing adaptation programs and turning sargassum invasions into an opportunity for sustainable development, taking into account the conditions of each locality.
- Management programs will include monitoring and forecasting the arrival of sargassum in order to organize the harvest of the algae, its preparation, and storage, as well as the possible use with prospects of economic benefit, or final destination safely for the man and the environment.
- Among the applications of sargassum, of economic and social interest, are the use in agriculture as fertilizers and animal feed; biopolymer production; biomass for power generation, which includes the production of biofuels and biogas; obtaining activated carbon and biochar, and other high value-added products for the pharmaceutical, hygiene, and beauty products industries. However, the uncertain availability of sargassum and its bio-absorbent properties, which leads to the

presence of heavy metals and metalloids such as arsenic, limit the production and marketing of the mentioned products.

- The stable production of sargassum products requires the development of the mining industry to ensure collection in all affected areas, and not just tourist areas, and the development of adequate technologies for the conservation of sargassum, which allow its use throughout over a more extended period, or all year. Regarding energy-related applications, the combined use with other biomass sources will be evaluated in order to guarantee a sustainable process.

Lastly, efforts should be made based on academic, technical, business and local experiences, together with the decisions of regional and international organizations related to the topic of sargassum in the Caribbean area, to enforce the strategies and plans of research, management, and collaboration to mitigate the impacts of sargassum streaks and turn the current problem into an opportunity for sustainable development in affected countries.

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