

Article

Challenges of Turning the Sargassum Crisis into Gold: Current Constraints and Implications for the Caribbean

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Abstract: Over the last decade, the Caribbean has seen massive, episodic influxes of pelagic sargassum negatively impacting coastal ecosystems, people's livelihoods and climate-sensitive sectors. Addressing this issue solely as a hazard has proven extremely costly and attention is slowly turning towards the potential opportunities for sargassum reuse and valorization. However, turning the 'sargassum crisis into gold' is not easy. In this study we use a multi-method approach to learn from sargassum stakeholders (researchers, entrepreneurs and established businesses) across the Caribbean about the constraints and challenges they are facing. These can be grouped into five broad categories: (1) unpredictable supply of sargassum; (2) issues related with the chemical composition of the seaweed; (3) harvest, transport and storage; (4) governance; and (5) funding. Specific issues and potential solutions associated with each of these categories are reviewed in detail and recommended actions are mapped to five entry points along a generalized value chain to demonstrate how these actions can contribute to the development of sustainable sargassum value chains that promote economic opportunities and could help alleviate impacts of massive influxes. This paper offers guidance to policy makers and funding agencies on existing gaps and challenges that need to be addressed in order to scale-up successful and sustainable solutions to the sargassum crisis.

Keywords: sargassum valorization; holopelagic; environmental hazard; constraints to commercialization; policy; value chains



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1. Introduction

Unprecedented blooming of holopelagic sargassum seaweed (*Sargassum natans* I, *S. natans* VIII and *S. fluitans* III; hereinafter simply referred to collectively as sargassum) has been occurring across the equatorial Atlantic over the last decade. When advected into the Caribbean Sea, these sargassum influxes result in mass strandings of millions of tonnes of the seaweed along windward shorelines across the region [1–3].

Since 2011, these mass influxes of sargassum have disrupted fisheries [4–6], severely impacted the tourism industry [3,7], caused significant damage to critical nearshore ecosystems including seagrass meadows and sandy beaches [3,8], created health problems for coastal populations exposed to rotting sargassum [9–11], and have incurred costs of hundreds of thousands of dollars to governments and the private sector in clean-up and disposal operations [3,12]. Effects are likely everlasting in some areas, where entire coastal ecosystems have been altered.

This new 'sargassum crisis', caused at least in part by a combination of ocean eutrophication and climate change is now being considered the 'new norm' [13,14], to which Caribbean nations must find ways to adapt. The negative impacts on national economies and coastal livelihoods have initiated a rapidly growing interest in utilizing stranded sargassum as a raw material for developing a wide range of potentially valuable products;

thus turning this hazard into an opportunity [3,15,16]. Budding entrepreneurs and research teams across the region are working towards the development of innovative businesses and projects that could potentially derive benefits from using sargassum seaweed, and concurrently help to mitigate damages caused by recurrent strandings (see reviews by [16,17]). Despite the keen interest across the region in developing viable businesses that valorize sargassum, progress has been slow and there are still relatively few examples of sustainable businesses making sargassum-based end products.

This study examines a wide range of research and business initiatives across the Caribbean region, from micro, small and medium sized enterprises (MSMEs) to larger scale ventures, to examine and better understand the nature and scope of constraints currently faced by researchers and entrepreneurs seeking to use sargassum as a raw material. We also discuss the implications of these constraints for further development and expansion of stakeholder ideas and businesses, and offer recommended actions to address current knowledge gaps and constraints. In so doing, we aim to provide guidance of particular relevance to policy makers and funding agencies, on gaps and challenges that need to be addressed in order to move forwards with scaling-up successful and sustainable solutions that will help to defray the current costs of clean-up and disposal, prevent further damage to the coastal marine environments, economies and livelihoods, and to provide adaptive solutions.

2. Materials and Methods

This study employed a multi-method approach that included a combination of primary data gathering through informal face to face and virtual interviews, site visits and remote communication by email, telephone and video conference with sargassum entrepreneurs and researchers across the Caribbean and beyond, and secondary data obtained from desk review. All previously identified stakeholders were approached at first, and a snowball sampling method was employed to recruit more participants for the study, in which key informants provided referrals for other entrepreneurs and innovators exploring sargassum uses. The use of multiple methods and data sources allowed us to obtain information on respondents' perceptions of constraints to realizing their proposed goals in research or business endeavors valorizing sargassum, as well as constraints recorded in the literature. This data collection and review took place between October 2019 and September 2020.

Face to face interviews and site visits were conducted with entrepreneurs and researchers in attendance at the International Sargassum Conference and Sarg'Expo in Guadeloupe (October 2019), as well as those in a number of sargassum industry hubs across the Wider Caribbean, including Guadeloupe, Dominican Republic, Mexico and Barbados. Additional researchers and entrepreneurs in Barbados, Canada, Cayman Islands, Colombia, Ecuador, France, French Antilles (French Guiana, Guadeloupe, Martinique, St. Barts), Germany, Israel, Italy, Jamaica, Japan, Mexico, Netherlands, Norway, Poland, St. Lucia, Trinidad and Tobago, United Kingdom and United States of America were contacted remotely. The desk review of published and grey literature covered relevant scientific literature, newspaper articles, webpages, reports, databases, conference proceedings and presentations.

Stakeholder perceptions and information gleaned through desk study were categorized into several main topics of relevance to researchers and funding agencies interested in addressing gaps in knowledge, and to policy makers and funders concerned with supporting innovation and valorization of sargassum as a means to mitigate the sargassum crisis through adaptation and resilience.

3. Results and Discussion

In this section, we present stakeholder perceptions and evidence documented in the published literature of the key constraints faced in attempting to valorize sargassum, and we discuss the implications of these for the various businesses.

3.1. Respondent Profile and Sargassum Applications

Primary data were collected from interviews with 72 key informants from 24 countries/territories in the Wider Caribbean Region and beyond (Table 1). More information about the sargassum-related products being developed or commercialized by the key informants is given in Table 2.

Table 1. Summary of key informant stakeholders from whom information was gathered.

| Stakeholder Group | Barbados | Canada | Cayman Islands | Dominican Republic | Ecuador/Germany | France | French Antilles | Israel | Italy | Jamaica | Japan | Mexico | Norway | Netherlands | Poland | St. Lucia | Trinidad & Tobago | UK | USA | TOTAL |
|------------------------------------|----------|--------|----------------|--------------------|-----------------|--------|-----------------|--------|-------|---------|-------|--------|--------|-------------|--------|-----------|-------------------|----|-----|-------|
| NGO/community group | 1 | | 1 | | | | 3 | | | | | | | | | | | | 1 | 6 |
| Private sector business/consortium | 5 | 1 | | 3 | 1 | 4 | 11 | 1 | 1 | 1 | | 14 | 1 | 1 | 1 | 1 | | | 1 | 47 |
| Researcher/research group | 4 | | | 2 | | | 3 | | | 1 | 1 | 5 | | | | | 2 | 1 | | 19 |
| TOTAL | 10 | 1 | 1 | 5 | 1 | 4 | 17 | 1 | 1 | 2 | 1 | 19 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 72 |

Table 2. Summary of stakeholders shown by country, category and sargassum-related product, from whom information was obtained on current constraints and challenges being experienced in attempting to valorize sargassum.

| Location | Stakeholder Category | Sargassum-Related Product |
|----------------------------------|---------------------------|---|
| Barbados | Private sector business | Biostimulants/fertilizer supplement, biogas, construction material, cosmetics, environmental restoration, construction material, environmental restoration |
| | NGO/community group | Environmental restoration |
| | Researcher/research group | Crop production (fertilizer supplement, mulch), biogas, bioethanol, alginate extracts, bioremediation, membranes, bioplastic, biofuel, bacteria biocatalysts |
| Canada | Private sector business | Water quality management, bubble curtains |
| Dominican Republic | Private sector business | Floating barriers, harvester boats, transportation, processing (compost, mulch, bioplastic), collection and transport of organic waste for biogas, carbon sequestration |
| | Researcher/research group | Activated carbon, biogas |
| Dominican Republic/French Guiana | Private sector business | Activated carbon |
| Ecuador/Germany | Private sector business | Biogas |
| France | Private sector business | Biogas and crop production (digestate), bioplastics |
| | Private sector consortium | Bioenergy, bioplastic, compost and soil amendments |
| | Researcher/research group | Activated carbon, biochar, electrochemical industry |
| French Antilles: Guadeloupe | Government research group | Multiple across most uses |
| | Private sector business | Bioenergy, activated carbon, biochar, harvesting, compost, air quality monitoring |
| | NGO/Community group | Public awareness, community clean-ups, monitoring |
| | Association | Compost |
| French Antilles: Martinique | Researcher/research group | Agricultural use (crop production and animal use) |
| | Private sector business | Paper, bioasphalt, coastal management, floating booms, compost |

Table 2. Cont.

| Location | Stakeholder Category | Sargassum-Related Product |
|--------------------------------|---------------------------|--|
| French Antilles: St. Barts | Private sector business | Bioenergy, paper |
| French Antilles: French Guiana | Association | Sargassum impacts to fisheries |
| Israel | Private sector business | Biogas and crop production (digestate) |
| Italy | Private sector business | Harvesting |
| Jamaica | Private sector business | Supplementary animal feed |
| | Researcher/research group | Pharmaceutical, biomedical, alginates, secondary metabolites |
| Japan | Researcher/research group | Arsenic content in algae |
| Netherlands | Private sector business | Biogas, bioenergy, digestate |
| St. Lucia | Private sector business | Biostimulants |
| Mexico | Private sector business | Bioplastics, pellets for combustion, paper and cardboard, fertilizer supplement, compost, mulch, cosmetics, construction blocks, shoes, floating barriers, biogas, activated carbon, alginates, harvester boats, beach clean-up, fucoidans |
| | Private sector consortium | Sargassum boat, floating barriers, active member of the Puerto Morelos Protocol on sargassum management |
| | Researcher/research group | Animal feed, crop production (mushroom substrate), purification and bioremediation, biofilters, eco-toxicology of sargassum leachates, biodiversity, sargassum physiology |
| Mexico /Norway | Private sector business | Primary processing and harvesting |
| Poland | Private sector business | Bio-based tableware and packaging |
| Trinidad and Tobago | Researcher/research group | Bioplastics, purification and bioremediation, biofilters/membranes, bioelicitors, nanopesticides, biostimulants, bioremediation, phyto-nutraceuticals |
| UK | Researcher/research group | Biofuels |
| UKOTs: Cayman Islands | Private business/NGO | Compost |
| USA | NGO | Carbon sequestration, carbon neutral energy |
| | Private sector business | Beach clean-up |

It is clear from the variety of stakeholders interviewed (Tables 1 and 2) and the reviewed literature, that Caribbean sargassum influxes have motivated research and innovation for using sargassum in multiple ways, including in agriculture, food and beverages, clothing and accessories, bioenergy, bioplastics, paper, pharmaceuticals, cosmetics, construction materials as well as for bioremediation and purification (see [16] for review of uses).

3.2. Overview of Constraints

Despite the many potential opportunities for valorizing sargassum in the Caribbean, stakeholders explained that exploring these opportunities has been met with a number of constraints that continue to challenge start-up businesses, and present barriers for the expansion and scaling-up of existing sargassum-based ventures.

Five key areas of concern emerged: (1) the uncertainty surrounding supply; (2) insufficient knowledge of the chemical components including micro-pollutants and their variability; (3) challenges with harvesting, transport and storage; (4) governance is lacking or there is an uncertain regulatory environment; and (5) significant funding constraints for research and development, and for supporting innovation. Each of these constraints and associated challenges are considered in more detail in the following sections and summarized in Table 3.

Table 3. Descriptive summary of five key constraints and associated challenges faced by researchers and entrepreneurs developing commercially viable sargassum-based products in the Caribbean.

| Constraint | Challenge | Description |
|----------------------|--|--|
| Unpredictable supply | Lack of accurate forecasts | <ul style="list-style-type: none"> • Significant uncertainty regarding the drivers of sargassum blooms; • Limited optical satellite coverage in the cloud-covered sargassum source regions, especially in the eastern Equatorial Atlantic, constrains detection of sargassum in places that could ultimately deliver sargassum to the Caribbean. This creates difficulties for accurate ‘seeding’ of predictive transport models that use ocean current forecasting to predict sargassum arrivals; • The relatively high optical noise (e.g., sun glint, Sahara dust, atmospheric moisture) in satellite images covering the Equatorial Atlantic, and the difficulties associated with confirming the presence of sargassum in remote ocean areas to validate interpretation of satellite images again presents uncertainty for accurately ‘seeding’ predictive transport models, especially for forecast models over more than 3 months; • Lack of validation of regional wind-induced slippage added in the predictive transport models versus actual movement of sargassum mats in situ, creates large uncertainties in predictions; • Uncertainty in the accuracy of global open ocean current models over long-distance paths through this complex and dynamic ocean region; • Difficulty in transitioning predictions from open ocean models to coastal environments with complex local currents and winds constrains the accuracy of forecasting the locations of sargassum stranding events; • High costs of precision satellite imagery and radar that could help in observing movements of sargassum nearshore and thus local predictions of strandings; • The sparsity of information on the growth and senescence/sinking of sargassum as it travels through different environments constrains prediction model accuracy since these will influence whether the biomass of sargassum changes significantly between tracked start and end points. |
| | Insufficient monitoring | <ul style="list-style-type: none"> • The lack of consistent national and site-level monitoring of sargassum strandings, especially the quantity (as volume or weight) and the location, constrains the ability to provide ballpark figures of availability of sargassum as a raw material; • Insufficient monitoring data constrains ability to predict what could be expected in the future, based on past occurrences; • Precludes the use of stranding data to validate predictive models/forecasts. |
| | Variability in species mix and quality | <ul style="list-style-type: none"> • The relative abundance of the three most commonly recognized species morphotypes that comprise the stranded sargassum vary unpredictably by month and year; • Non-sargassum species (e.g., seagrasses, benthic algae) are commonly mixed in with stranding sargassum and the relative amounts are variable by location and over time; • Quality of sargassum as a raw material can be highly variable as a result of the age and condition of the algae, whether or not it has previously stranded, whether it contains marine debris (e.g., plastics) and other flotsam (e.g., driftwood) or other marine organisms. |

Table 3. Cont.

| Constraint | Challenge | Description |
|------------------------------|---------------------------|--|
| Chemical composition | Limited chemical analyses | <ul style="list-style-type: none"> • Insufficient and non-standard chemical analyses of sargassum across the region means there is still considerable uncertainty in the chemical composition of sargassum; • High cost, limited testing facilities in the region, and difficulty accessing results of chemical analyses, especially those funded privately. |
| | Variable composition | <ul style="list-style-type: none"> • High variability in reported concentrations of many components; • Spatial and temporal differences in the concentration of many components; • Differences among sargassum species and forms in their chemical composition. |
| | Micro-pollutants | <ul style="list-style-type: none"> • Rapid biosorption of heavy metals and other micropollutants by sargassum as it travels across the ocean from the source regions to the Caribbean means that it may contain dangerous levels of these pollutants; • Concentrations of micropollutants is variable over space and time and has frequently exceeded safe limits for various uses in the testing so far conducted; • Uncertainty of levels of micropollutants after the different processing of sargassum. |
| | High levels of minerals | <ul style="list-style-type: none"> • High levels of salt (NaCl) and other minerals (e.g., iodine) are typically found in sargassum. |
| | High ash content | <ul style="list-style-type: none"> • High content of unusable ash (inert biomass) relative to other components. |
| Harvest, transport & storage | Labor and equipment costs | <ul style="list-style-type: none"> • Harvesting sargassum is labor-intensive and in many situations requires highly specialized equipment, that many remain idle for months in between influx events; • Specialized equipment is still under development and/or has limited availability and is generally very costly; • Limited access to, or use of, available knowledge is still resulting in the purchase of equipment and implementation of harvesting methods that are not well suited to local contexts; • Transfer, sorting and transport of heavy wet sargassum from collection sites to storage or use sites is expensive. |
| | Damage to environment | <ul style="list-style-type: none"> • Inadequate sharing of lessons learned with regards to appropriate harvest/collection/storage methods and equipment, leading to environmental damage. |
| | Lack of storage protocols | <ul style="list-style-type: none"> • Insufficient knowledge on appropriate methods for long-term storage of sargassum for different uses; • Large area or specialized equipment is required for drying sargassum. |

Table 3. Cont.

| Constraint | Challenge | Description |
|-------------------|--|--|
| Governance | Lack of policy and management guidance | <ul style="list-style-type: none"> • The mass influxes of sargassum are a relatively new phenomenon and are characterized by great uncertainty; • No prior policy or governance framework specific to sargassum; • Governments have been slow to respond and even to date very few have implemented sargassum management plans. |
| | Lack of harmonized standards | <ul style="list-style-type: none"> • There is a lack of protocols and few if any local or regional standards specific to sargassum to support safe harvesting, storage and product processing and use. |
| | Uncertain access to harvest | <ul style="list-style-type: none"> • No regional policy with regards to access and harvesting of sargassum as a shared or transboundary resource; • With the exception of Mexico and the USA, there are no national guidelines regarding sargassum harvesting or management of access conflicts. |
| Funding & support | Mobilization of funds | <ul style="list-style-type: none"> • Funding to explore valorization of sargassum has been slow to mobilize and difficult to access, especially for MSMEs; • Very limited availability of funds to support new ventures; • Limited capacity and access to collateral among potential entrepreneurs to access funds. |
| | Viewed as a hazard | <ul style="list-style-type: none"> • Sargassum is generally still viewed as a hazard rather than as a potential opportunity, such that funding has been focused on clean up and mitigation, not on developing beneficial uses. |
| | Inadequate infrastructure | <ul style="list-style-type: none"> • A general lack of industrial infrastructure in many countries to support industrial scale uses. |
| | Inadequate institutional arrangements | <ul style="list-style-type: none"> • Limited institutional support for innovators; • Governments are generally not adaptive enough to support new, high risk ventures. |

3.3. Unpredictable Supply

3.3.1. Challenges

Since the first sargassum influx events of 2011, there has been high inter-annual and seasonal variability in the amount of sargassum arriving and stranding along shorelines [2,4,17,18], with volumes of beached sargassum ranging between nothing to tens of thousands of cubic meters per km of shoreline per month in the Mexican Caribbean [2]. There is still an incomplete understanding of the drivers conducive to sargassum blooms [1,18–20] and major uncertainty and variability surrounding the timing, quantity and location of sargassum influx events. Forecasting sargassum influxes into the Caribbean is complicated by the somewhat unpredictable ‘release’ of sargassum from its ‘new’ consolidation (source) region across the equatorial Atlantic, exacerbated by the complex and variable mobility of oceanic pelagic sargassum ‘mats’ as they travel vast distances (thousands of kilometers) from their source to their stranding locations along Caribbean coastlines. These oceanic pelagic mats likely take different routes in different months (depending on the highly variable and complex surface currents and winds transporting them), and possibly coming from different source sub-regions within the equatorial Atlantic [1,21–23].

Despite ongoing important advances in sargassum detection, monitoring and prediction addressing these uncertainties (e.g., [2,13,18–21,24–31]), significant technical challenges and knowledge gaps remain. These continue to inhibit accurate forecasting of sargassum influx events in real time, especially over hours (which is necessary for automated harvest solutions) and over time frames greater than three months to allow advanced planning for high abundance sargassum seasons or years. These forecasting challenges are detailed in Table 3.

A further issue with variability and uncertainty in supply is the relative abundance of the three most commonly recognized species morphotypes (*Sargassum fluitans III*, *S. natans I* and *S. natans VIII*), which show broad-scale spatial and temporal differences in the Caribbean [23,32]. As reported by García-Sánchez et al. [23] the relative proportions of the different morphotypes stranding along Mexican Caribbean shorelines have changed over time, since the first inundations there in 2015, and continue to show inter-annual as well as monthly variations. Moreover, a marked change has been recorded in the predominant form from an initial dominance of *S. fluitans III* and *S. natans VIII*, to a current dominance of *S. fluitans III* and *S. natans I*. Similar observations have been made across other Caribbean locations (Mona Webber, pers. obs., Jamaica; Hazel Oxenford, pers. obs., Barbados).

Beached sargassum can also be mixed with debris (plastics) and other beach wrack, especially seagrasses in many locations, and the relative amounts change with season and sea conditions.

3.3.2. Implications

Not knowing when, how much or where sargassum will occur is one of the most frequently recurring challenges highlighted by the majority of business entrepreneurs, and continues to hinder investment in developing uses for sargassum, and in scaling-up existing micro, small and medium enterprises (MSMEs) into larger commercial ventures. The highly variable sargassum supply and lack of long-term reliable forecasts of sargassum influx events, exacerbated by the absence of monitoring at the national or site-specific level has several important implications for valorizing sargassum. Furthermore, there is a general lack of knowledge among business entrepreneurs about the existing forecast products, and/or the data provided is difficult to interpret. Nonetheless, not having a continuous and stable amount of primary material to develop a business is a problem for attracting investments and scaling-up. Not knowing the approximate volumes of sargassum arriving at any given location over time makes it very difficult to determine appropriate potential uses for sargassum and the size of business to develop. It also constrains the ability of potential investors to perform comprehensive cost projections and analysis to assess the economic feasibility and sustainability of proposed ventures. Since businesses generally

need a reliable supply of raw material to support sustainable production, the uncertainty of a steady supply means that primary processing and storage becomes an important factor in ensuring reliable stock, which presents further challenges (see Section 3.5).

The variability in relative abundance of sargassum forms is, as yet, poorly understood and has implications for valorizing sargassum since different forms appear to have different properties [22,33,34] and are therefore differently suitable for certain applications, such as extraction of specific chemicals for use in pharmaceuticals and cosmetics (e.g., polysaccharides: alginate, fucoidan; and secondary metabolites: flavonoids, sterols, carotenoids).

3.4. Chemical Composition

3.4.1. Challenges

A number of constraints specific to the chemical composition of Caribbean pelagic sargassum were raised by entrepreneurs and are apparent from the literature. These are considered here and summarized in Table 3.

There are still significant knowledge gaps in the chemical composition of Caribbean pelagic sargassum and how this varies spatially and temporally. In general, there has been a relatively low level of sampling and testing in most places [16,22,35]. As Rodríguez-Martínez et al. [22] point out, most studies reporting on the compositional analysis of pelagic sargassum in the Caribbean have small sample sizes (even a single sample), a mixture of species and morphotypes, a narrow geographic scope (only one or a few local sites), and sample collection over a limited time period (in some cases a single day). Most analyses have also been restricted in the number of chemical components examined. This is, in part, because of the complexity and cost of analyses and scarcity of funding and laboratories with this capacity in the region. This is particularly so for arsenic speciation, which requires complex laboratory analyses to identify the different forms (organic vs. inorganic), but is important because some differ markedly in their toxicity, and in their relative abundance under different conditions [36]. There is also insufficient knowledge of how arsenic and other micro-pollutants behave under different sargassum processing methods, or how it behaves when released into the environment in a sargassum-based product or waste product [36].

Even with the relatively small number of studies and samples tested to date, there is high variability in the reported concentrations or relative proportions of most components (see [16,34,36,37]). This may, in part, be a consequence of different analytical and sample preparation methods being used by different studies. Nonetheless, there is strong evidence that it also reflects real differences in the chemical composition between sargassum species, and/or over space and time. For example, it is well known that seaweed chemical composition, in general, varies not only with biotic factors (e.g., species, stage of life cycle, age), but also with abiotic factors (e.g., pH, salinity, water motion, temperature, light availability, mineral content of seawater, and environmental pollutants) [38].

In the case of sargassum, understanding and predicting the compositional variability is further complicated by the fact that pelagic sargassum is mobile, travelling vast distances (many thousands of kilometers) from its source in the equatorial Atlantic to its different stranding locations along Caribbean coastlines, likely taking different routes over time, and possibly coming from different source sub-regions within the equatorial Atlantic and coming into contact with differing environmental conditions [21]. As such, different 'batches' of sargassum are likely to differ in their chemical composition and their micro-pollutant load in particular, thus requiring continued testing of sargassum arriving along Caribbean shorelines.

These observations are supported by the most extensive published study to date, which has found that the concentration of 28 elements in pelagic sargassum arriving along Mexico's Caribbean coastline sampled at eight widely spaced sites over a period of 11 months, showed considerable variation not only among species and morphotypes, but also among locations, and over time, although there was no apparent seasonal pattern [22].

It was suggested that much of the reported variation in element concentration was likely dependent on the route travelled by the floating sargassum and whether or not it passed through contaminated areas, given that sargassum (like other brown seaweeds) has excellent biosorption properties, although highlighting that this former hypothesis required further investigation.

Another example of this variability in chemical composition over space and time is the difference in the relative proportions (ratios) of inorganic carbon, nitrogen and phosphorous (C:N, C:P and N:P) reported for pelagic sargassum in different seasons and from different locations in the North Atlantic, and the observed long-term change in these ratios over the last three decades [14,39]. These authors reported higher C:N ratios in the 1980s compared to pelagic sargassum sampled in the 2010s, and lower C:P and N:P ratios in the 1980s compared with 2010s, suggesting that this reflected changing ocean conditions.

Of particular concern, even with the limited sampling to date, are the high levels of certain toxic metalloids, heavy metals and other potential toxins (e.g., pesticides) that have been reported in pelagic sargassum samples tested across the Caribbean to date. For example, many (but not all) of the limited samples have been found to contain concentrations of total arsenic exceeding most countries' permitted concentrations for certain agricultural and nutritional uses [22,33,34,36,40–43]. Similarly, concentrations of copper, molybdenum and manganese have been found to exceed safe limits in 5 to 22 percent of samples in Mexico [22]. In contrast, a large number of samples collected in the French West Indies over July–August 2018 and March–April 2019 showed that 8 elements (cadmium, chromium, cobalt, copper, nickel, lead, mercury and zinc) were found only in low concentrations on average, and were within current safety standards [37]. Chlordecone, a pesticide originally used on banana plantations, has been found in sargassum samples in areas of known high contamination off coastal areas of Martinique and Guadeloupe [40,42,43], although not in areas considered free of contamination, where fishing is permitted [37].

Adding to the constraints of valorization is the fact that, like other seaweeds, pelagic sargassum examined in the Caribbean typically has a high concentration of saline elements (e.g., Na, K, Ca, Mg and Cl) and other minerals such as iodine (see [22,33,41]), as well as a high percentage of ash [33,44].

3.4.2. Implications

Insufficient testing and lack of standard analytical methods, together with the unpredictable spatial and temporal variability in the precise chemical composition of sargassum, means that there is still considerable uncertainty with regard to the viability of many potentially valuable uses, particularly in agriculture, food and pharmaceutical industries, where there is a potential for entering the food chain and/or coming into direct body contact.

Variations in the concentrations of certain compounds can be problematic, since components such as sulfur, salt, insoluble fibers and low carbon to nitrogen ratios (C:N), can inhibit the growth of methanogenic bacteria. This could mean that anaerobic digestion rates and methane (biogas) yield would be inconsistent [45]. Changes in the C:N ratio could also impact the adequacy of sargassum as a (complementary) fertilizer.

Of particular concern are the biosorbed micropollutants which are potentially highly problematic for uses that enter the food chain, and/or the environment. As López-Contreras et al. [46] point out, the organic, chemical and bacteriological substances contained by pelagic sargassum could become a source of contamination during storage and repurposing processes, or even in the products made from the sargassum. Findings of Devault et al. [36] support this position, particularly as it pertains to arsenic, stating that reported levels in sargassum “could well give cause for concern across all potential applications, in particular for human and animal use. Similarly, there are concerns for the widespread applications or disposal of this [sargassum] biomass due to environmental impacts in the case of storage, landfill or composting”. Further, Milledge et al. [33] and Thompson et al. [45] point out that undesirable levels of heavy metals, particularly arsenic,

are likely to remain in the digestate after the process of anaerobic digestion to produce biomethane, thus restricting its typical use in agriculture.

The potentially high levels of certain elements and contaminants will hinder the development of several potential uses and will require continued testing of the raw material at all stages of the production process and the end product to ensure public and environmental safety. This will likely be very costly and could result in unpredictable failures to meet safety standards. There are currently no specific standards or requirements established for sargassum-based (or algae-based) products in the Caribbean. High arsenic has already led France's Food Safety Agency to recommend exclusion of any food/feed using *Sargassum* spp. from the Caribbean [9].

As Devault et al. [36] note, edible seaweeds are generally cultivated or harvested from the wild as attached, benthic species, whereas the collection of beach cast or floating sargassum raises numerous concerns including the uncertain quality and safety for use in food or any other use that has the potential to enter the food chain or come into direct body contact, lack of traceability, unknown history of growth and potential contamination.

High salt content presents a challenge for several potential applications. These include agricultural uses, since high salt content could result in long-term damage to the soil through salinization, and to animals requiring more water and becoming dehydrated or even the potential development of ailments such as kidney stones [47]. Attempts at applying solely seaweed in the raw or composted form have resulted in soil salinization in some cases and prompted authorities in Martinique and the Caribbean Agricultural Research and Development Institute (CARDI) to recommend against direct spreading of sargassum in agriculture [48]. High salt is also a problem for the renewable energy sector since it can inhibit the production of biomethane and ethanol, and can also be a problem for the bioremediation of metals (see [16] for review). Removing excess salt is not only costly and time consuming, but also requires large amounts of fresh water which is unsustainable across water-scarce countries of the Caribbean [48]. High concentrations of certain micro and macro nutrients (e.g., iodine) can also be toxic for humans, animals and plants.

Although the high ash content of sargassum is beneficial for agricultural uses (e.g., complementary fertilizers or animal feed), it could be problematic for production of bioenergy, particularly for direct combustion and gasification, since high ash content will reduce the gross calorific value (also referred to as 'higher heating value' [HHV]) resulting in a lower energy yield than is typical for most terrestrial plant biomass [15,49].

3.5. Harvesting, Transport and Storage

3.5.1. Challenges

Sargassum arrives 'free of charge', but from lessons learnt over the last decade, a large labor force and/or specialized machinery and equipment are required for effective large-scale shoreline or in-water collection, and to minimize environmental damage. Transferring sargassum from boat harvesters and from onshore mechanized rakes and stockpiles to other means of transport also requires grabs, conveyors or other customized solutions, all of which can be very costly. At certain places, booms (barriers) are used to keep either tourist or public beaches clean from the seaweed; these booms need to be specially designed to efficiently retain sargassum, with firm anchorage to the seafloor, and in addition require regular cleaning usually by special harvesting boats, elevating costs. Furthermore, the methods and equipment need to be customized across a wide range of physical conditions found at different sites, such as the prevailing winds and sea conditions, water depth, nearshore habitats, environmental sensitivity, shoreline type (rocky, sandy, cliff, artificial), beach slope and width, and site access, among others.

After or during collection, and depending on the end use, sargassum may need sorting to provide a suitable raw material for further processing or to prevent damage to the environment. A system for scaring off or removing associated fauna, such as sea turtle hatchlings, from sargassum collected off-shore should be established to protect fauna that seeks refuge in the mats. Separating sand from sargassum collected on the beach is very

important to prevent beach erosion. Depending on the destination of sargassum, removing other beach wrack (e.g., seagrasses, other seaweeds), marine debris (e.g., plastics) and flotsam (e.g., driftwood) from sargassum harvested either at sea or from the beach may be necessary. Separating fresh sargassum from partially decayed or dried sargassum is also an issue for uses that require high quality fresh seaweed, and would likely require at-sea collection.

Some of these challenges have been addressed by repurposing existing machinery and equipment through modifications, or by the development of new purpose-built equipment that has significantly increased efficiency and decreased environmental impacts of sargassum collection and cleaning. However, although important lessons were learned early on, largely through trial and error, and innovative designs were developed, they were not widely shared [50]. Although there are significant ongoing efforts to gather information, assess sargassum collection methods [51], and develop informative materials and best practice guides, that recognize the importance of methods customized to local conditions (e.g., [52–55]), there are still problems with accessing the information, and limited availability of customized equipment.

Another issue of relevance to entrepreneurs is the storage of sargassum. Relying on a raw material with a highly variable availability, will require stockpiling and preservation of sargassum to ensure a constant supply for industry in times of low sargassum influx. A further challenge is that effective preservation methods for extending storage time of sargassum for different uses are still being explored.

3.5.2. Implications

The requirement for a large labor force and/or specialized collection equipment that is very costly to purchase and maintain (e.g., purchase price ranges from around USD 100,000 for mechanized rakes; up to USD one million for specialized barges; and USD several hundred per meter for retention booms which then cost USD several hundred per meter per year to maintain [4]) means that sargassum as a raw material is likely to be expensive. Furthermore, in many cases, demand for the innovative customized collection and transport equipment has outstripped production, making it difficult to access. As a consequence, there are still cases where unsuitable, but readily available heavy machinery is still being deployed and significant environmental and aesthetic damage is ongoing, especially through the compaction and removal of large amounts of beach sand [51,56]. This has been exacerbated in other cases by limited knowledge sharing, resulting in ignorance and even the purchase of unsuitable machinery. The fact that fresh sargassum is wet, heavy and salty also adds to the cost of transport and maintenance of equipment.

In cases where sargassum needs sorting/separating this is not only tedious but requires significant manpower or specialized separation equipment to automate the process. This too can add considerably to the cost of obtaining good quality raw material.

Storage of sargassum may require significant physical space for initial drying or if ensilage is used. Furthermore, inappropriate storage (or disposal) of harvested sargassum can lead to several challenges including environmental and human health issues. For example, leachates (potentially containing high levels of nutrients and toxins) can pollute natural water bodies [8,36,43]. Furthermore, if sargassum remains wet, it will begin anaerobic decomposition, releasing toxic hydrogen sulfide and ammonia gases which not only have a very unpleasant odor but also present a significant health hazard for handlers and nearby communities [9,57].

3.6. Governance

3.6.1. Challenges

There are significant governance challenges with the harvest and use of sargassum, as summarized in Table 3. A significant challenge is that mass sargassum influxes are a relatively new phenomenon and that there are many uncertainties, including: supply; chemical and species composition; appropriate collection, transport and storage methods

and equipment; feasibility of a myriad of potential uses; the market demand for end products; and knowledge gaps regarding environmental impacts and product safety.

The unexpected and unprecedented influxes of sargassum initiated in 2011 meant initially that there was a complete lack of applicable guiding policy or governance framework to manage this new phenomenon [58]. Furthermore, the great uncertainty with whether or not this would be a recurring phenomenon discouraged the development of an appropriate governance mechanism for several years. The initial focus was on treating sargassum as a non-recurring hazard or disaster, and removing it from critical coastlines as rapidly as possible. There was, and still is, relatively little attention paid to the potential opportunities for valorizing sargassum.

As such, sargassum-specific management strategies had to be developed from scratch. Several countries in the Caribbean region have now established or are in the process of setting up Sargassum Taskforces or National Committees comprising a mix of government and private sector agencies to provide support and coordination in addressing the multi-sectoral issues of sargassum influxes. However, in many cases, the ability of these Taskforces/Committees to function has been limited by insufficient funding and access to the most recent knowledge generated by the dynamic research environment that currently characterizes this new phenomenon. Some countries have begun, or are at advanced stages, of drafting sargassum management plans/strategies. However, most, if not all, still need to be approved by cabinet or other competent authorities and assigned resources to support implementation, and regulations to support the management plans and valorization of sargassum are lagging behind [59].

3.6.2. Implications

The lack of well-developed governance arrangements or specific focus on supporting valorization of sargassum in most countries continues to constrain the development of uses for sargassum, particularly large-scale commercial enterprises. This is further complicated by uncertainty and the transboundary nature of the mobile sargassum. For example, UNEP-CEP [60] point out that the potential commoditization of sargassum raises issues around ownership and extraction rights to the 'resource'. Currently, there is no regional policy that speaks to the harvesting of sargassum as a shared resource, which is a significant hindrance for the development of any large-scale, mobile, offshore harvesting enterprise. The lack of local harvest regulations including access permits, increases the uncertainties and potential conflicts faced by businesses using sargassum as a raw material.

The lack of protocols and standards for sargassum harvesting, waste and end products has implications for environmental and human health and further adds to the uncertainties faced by businesses attempting to valorize sargassum [36].

The lack of standards, and listing of sargassum species among allowable ingredients for imported products is also likely to constrain new products (e.g., cosmetics) from entering primary international markets such as China, and thus prevent investment by international manufacturers [36].

3.7. Funding and Support for Innovation

3.7.1. Challenges

A number of important constraints have been raised by stakeholders around the issue of funding and innovation support (Table 3). Given that sargassum influx events were totally unexpected back in 2011, and their recurrence was uncertain, it is not surprising that funding for research and development was initially unavailable and thereafter relatively slow to mobilize.

Although substantial funding has now been mobilized to support many initiatives across the Caribbean region, this has generally been in support of developing effective mitigation activities; improving monitoring and prediction; strengthening networking and information sharing among stakeholders including raising public awareness and education.

Inadequate funding and support has been made available to entrepreneurs looking to valorize sargassum. A confounding issue is that loans and donor funding are typically very difficult to access. Furthermore, government budgets are generally not adaptive enough to support new ventures especially those with high uncertainty.

A further constraint is that most economies in the region (particularly the insular Caribbean) depend on marine (e.g., fisheries) and coastal (e.g., tourism) resources and thus lack industrial infrastructure that could support large scale industrial ventures that have the potential to help solve the enormous cost of clean-up efforts currently sustained by governments (e.g., the Mexican Government has spent USD millions to tens of millions per year in sargassum clean-up [4]) and the private sector (e.g., hoteliers in the Mexican Caribbean have spent in excess of USD quarter of a million per year on wages of sargassum beach cleaners [4]).

3.7.2. Implications

The current difficulties in accessing funding to support the development and commercialization of sargassum businesses, and the lack of a supporting environment to encourage entrepreneurship and new ventures is a significant constraint to the growth of a Caribbean sargassum industry.

The funding constraints continue to hold back and limit MSMEs in particular, from developing commercially viable uses for sargassum and/or scaling up their businesses. Young entrepreneurs especially, often lack the collateral needed as security deposit for repayment of loans. Furthermore, loans to develop businesses based on an unpredictable supply of raw material that would be considered high risk, further complicates access to funds.

Many Caribbean entrepreneurs lack the capacity and support needed to navigate through the often daunting and time-consuming process of applying for donor funding and in fulfilling stringent reporting requirements.

It is unfortunate that the region is typically characterized by cumbersome bureaucratic procedures for setting up, operating and growing a business [61]. These present enormous hurdles, particularly for MSMEs. This is often exacerbated by burdensome taxes and the poor state of infrastructure and lack of effective institutional frameworks.

4. Recommendations and Conclusions

Overcoming the current challenges to build sustainable sargassum industries that create jobs, build capacity, and address biomass removal will be critical in helping the region adapt to the on-going sargassum influxes. This will also be important in helping to improve resilience of Caribbean States to climate change, natural disasters, and crises of socio-economic nature through diversification of their industries.

Addressing the key constraints and their associated challenges and turning the currently perceived hazard into a benefit will require multiple actions, many of which have policy implications, and are outlined in the narrative that follows. Before presenting these priority actions it is important to place them within a broader systematic framework for categorizing interventions to sargassum influxes as outlined in the updated sargassum white paper [60] under the 'Adaptation' subcategory referred to as 'Harvest and reuse as commodity.' This emphasizes the importance of promoting valorization not only as an economic opportunity but as a means of alleviating influx impacts. An important first step is to determine the feasibility of sargassum valorization, and this requires more attention to potential value chains and the appropriate entry points for addressing current challenges.

To date, very few publications promote the concept of sustainable sargassum value chains in the Caribbean e.g., [46,60]. López-Contreras et al. [46] present a sustainable harvesting and valorization chain for sargassum in the Dutch Caribbean comprising four stages: sargassum harvesting, storage/transport, processing/conversion and products/applications. A three-phase implementation plan is presented to address the nineteen knowledge gaps identified and the entry points along the chain for intervention [46]. The

UNEP-CEP white paper [60] outlines a sargassum value chain with six stages. Here we offer a slightly simplified sargassum value chain with five stages (Figure 1). We recognize however, that the sequence of the stages and the number of steps within a stage will vary, especially with respect to ‘transportation’ since transportation (by land or sea) may be required multiple times along the chain. Furthermore, cross cutting activities such as research and development, quality control, environmental and social safeguards, and mitigation of impacts are of course integral to all stages of the value chain. Nonetheless, this generalized sargassum value chain provides a good frame for mapping the priority actions related to each stage and thus identifying appropriate entry points for interventions as outlined in the narrative that follows.



Figure 1. Example of a generic sargassum value chain.

4.1. Promoting Sustainable Sargassum Value Chains

4.1.1. Harvest

Sargassum harvest is the first stage in the value chain and has several key constraints. One of these is the unpredictable supply of sargassum with the associated challenges and knowledge gaps being accurate forecasts, monitoring, and variability in species composition and quality (Table 3). Recommended actions for this entry point in the chain are:

- Improve precision of sargassum influx forecasts through improved ocean transport models that mimic sargassum movement and account for changes in biomass (e.g., through growth and mortality, natural subduction in Langmuir cells or during storms), and use of remote sensing technology (e.g., drones, satellite imagery, fixed cameras) and citizen science to improve the ease and geographical scale of monitoring sargassum strandings to validate forecasts;
- Expand the lead-time of forecasts (beyond a few months) by using wider satellite coverage of the Equatorial Atlantic;
- Integrate ocean and coastal models that aid in the timely prediction of sargassum stranding locations and quantities;
- Develop easily accessible internet-based platforms to share locations and predictions of sargassum influxes;
- Conduct hazard exposure and vulnerability mapping exercises to systematically address the spatial complexity and variation of hazard impacts from sargassum in order to optimize response planning and harvesting operations;
- Develop a simple rapid assessment methodology to monitor the relative composition of pelagic sargassum forms (species and morphotypes) and quality over space and time.

Another key constraint at this stage in the chain is the high costs associated with harvesting, as well as several important knowledge gaps. Suggested actions to address these are:

- Consider ways of reducing the costs of acquiring and operating specialized sargassum harvesting and sorting equipment (e.g., local manufacturing, duty-free importation or other subsidies);
- Improve access to knowledge and communication networks to share lessons learnt and promote best practices for on-shore and in-water collection methods that suit the local context;
- When employing booms for the purpose of avoiding strandings or concentration of sargassum biomass, use the designs that have proven to work in similar conditions, and collect the retained sargassum frequently (at least once a day);

- Develop protocols and standards for harvesting of sargassum that ensure work-place safety and minimal damage to the environment;
- Where in-water harvesting is the preferred method, studies are needed to inform best practices to avoid biodiversity loss (e.g., distance from shore, options for avoidance or release of associated fauna).

4.1.2. Storage

The intermittent supply of sargassum will require storage solutions to ensure an uninterrupted supply to industry and prevent a break in the value chain during periods of low or no sargassum influxes. Again, there are several constraints and knowledge gaps that could be addressed at this entry point by the actions outlined here:

- Determine the best storage methods (e.g., dried, ground, ensilage, pellets) for different uses of sargassum;
- Develop protocols and standards for safe storage of sargassum to prevent release of leachates or toxic gases to the environment;
- Consider storage locations that best suit the local context and minimize costs;
- Promote unrestricted access to stored sargassum by regulating providers, based on transparent protocols/rules/regulations, to avoid a monopoly and price gouging;
- If demand is high, consider the potential for sargassum mariculture as an alternative to storage.

4.1.3. Transport

Reduction of the high transportation costs for sargassum by land or sea is critical for development of viable value chains and could be addressed by:

- Reducing transport distances as much as possible;
- Promoting innovation in the development of low-cost transportation solutions that also reduce the carbon footprint of operations, maintain the quality of the raw material, and contribute to local livelihoods;
- Considering the potential for at-sea processing facilities to support offshore harvesting operations;
- Develop protocols and standards for safe, efficient methods of transportation.

4.1.4. Processing and Packaging

This stage of the value chain is the most complex and is likely to include multiple steps. Addressing the knowledge gaps regarding the compositional analysis of sargassum is vitally important before considering specific actions related to the processing and packaging of sargassum end-products. The following priority actions are therefore recommended:

- Promote uses that do not enter the food chain in the short to medium term, until the uncertainty regarding toxicity and the lack of standards related to sargassum-based products have been addressed;
- Develop local capacity (laboratories, trained staff) across the region to quickly and efficiently conduct compositional analyses of sargassum using standardized analytical methods, and reduce cost of testing (through subsidies if necessary);
- Undertake more extensive (over space and time) sampling and compositional analyses of sargassum (including separation of different sargassum species and morphotypes) to improve understanding of the variation in chemical composition and its local suitability for certain potential sargassum-based products;
- Increase testing to determine concentrations of potentially harmful components such as heavy metals including arsenic in both its organic and inorganic forms (speciation analysis), pesticides and other pollutants which are readily picked-up by sargassum as it travels, and to determine whether these are transferred/bioaccumulated to crops, soil, animals and into the food chain when sargassum is used in agriculture;

- Develop safety standards and introduce required testing for sargassum end-products for direct contact, consumption, and agricultural uses, as well as appropriate storage and disposal methods;
- Promote or require mixing of sargassum with other materials when considered necessary for efficient production and/or safe end-products;
- Promote transparency and sharing of compositional analysis results (e.g., introduce mandatory standardized labelling of compositional profile if end-product is to enter the food chain or direct body contact).

Other actions that are recommended for promoting greater diversity and efficiencies in the processing and packaging stage are:

- Encourage the development of ‘sargassum industrial parks’ to support streamlined production processes and increase opportunities for co-development of multiple sargassum-based products;
- Encourage innovators/business entrepreneurs/researchers to form alliances to pool resources and share costs;
- Find suitable sargassum substitutes for use in production when sargassum supply is exhausted to avoid business shut downs and disruption of the value chain.
- Foster creativity through innovation hubs, hackathons and pitch competitions to encourage the development of cutting edge products and institutional support for innovators.

4.1.5. Distribution and Marketing

The distribution and marketing of sargassum-based products is the final step in the valorization process that promotes economic opportunities. This is probably the least developed of the steps at present, given the relatively small number of businesses that have commercialized sargassum in the region to date [16]. A few recommendations follow:

- Promote resilient distribution plans to handle market changes, including supply disruptions and demand increases;
- Consider the integration of emerging technologies including blockchain for efficient supply chain management;
- Promote niche marketing to environmentally conscious consumers willing to pay extra for sustainable items, especially those that result in amelioration of an environmental hazard.
- Consider government subsidies (e.g., tax relief) when purchasing sargassum-based products that utilize significant sargassum biomass and thereby reduce environmental damage and clean-up costs.
- Consider the establishment of country-level sargassum entrepreneur associations to pool resources for marketing at regional and international levels;
- Sargassum related products and services should be branded as blue growth initiatives to promote successful uptake given the growing attention towards the emerging blue economy in the region.

4.2. Policy Implications

Regional policies and statements that support the valorization and commercialization of sargassum include: the 2018 United Nations Environment Programme-Caribbean Environment Programme (UNEP-CEP) white paper ‘Sargassum Outbreak in the Caribbean: Challenges, Opportunities and Regional Situation’ [12]; the 2021 updated white paper ‘Turning the crisis into an opportunity’ [60]; and the 2019 ‘Final Declaration of the International Conference on Sargassum in Guadeloupe ‘Caribbean Programme for Sargassum’ (<https://pressroom.oecs.org/final-declaration-of-the-international-conference-on-sargassum-a-commitment-to-cooperation-in-the-caribbean>, accessed on 12 May 2021).

Management and regulation to support commercialization of sargassum is particularly difficult at this relatively early and uncertain stage of development. However, a number of supporting policy actions are suggested to promote the development of sargassum industries:

- Develop a regional policy on access and harvesting of sargassum as a shared or transboundary resource;
- Regulate national harvesting permission/licenses to promote sustainable harvest;
- Consider how sargassum fits into existing natural resource ownership and rights legislation and policy in their countries/territories and pursue updates as needed [60];
- Create national policy frameworks for the development of MSMEs to encourage sustainable sargassum businesses;
- Build the capacity of small- and medium-scale entrepreneurs in the areas of business development, accessing grant funding, marketing, financial and human resources management;
- Create the enabling environment for affected stakeholders (fisherfolk and coastal community residents) to pursue sargassum uses as an alternative livelihood;
- Promote synergies between the tourism and sargassum industries to support sustainable development of valorization initiatives that can alleviate the sargassum hazard for tourism;
- Provide incentives for businesses that contribute to governments' cost recovery arrangements for cleaning beaches of sargassum;
- Consider the introduction of a 'sargassum tax' through tourism or other initiatives (such as the one in Quintana Roo, USD 1 per day per visiting tourist), to help fund sargassum innovation;
- Use opportunities for sargassum innovations to be considered as blue growth initiatives which can be integrated into blue economy strategic frameworks and road maps. This can support economic diversification and resilience to reduce economic vulnerability and reliance on a small number of sectors;
- Increase the number of public-private partnerships in the domain of applied research and product development. This would allow spreading the risk of investment while maximizing innovation;
- Consider blended finance models to encourage private sector involvement in sargassum exploitation;
- Consider the establishment of country-level institutional arrangements that include research consortia to champion the development of valorization initiatives and explore funding opportunities to support successful implementation.

The pathway to developing a sustainable financing mechanism for research and development to support sargassum enterprises will require substantial investments of time and money, and collaborative approaches between public and private sectors. Although many barriers exist, there are some enablers at the science-policy interface that may support advancements in the near future.

Investment into commercializing products and seed funding for marketing needs to be enhanced to build sustainable sargassum industries that create jobs, build adaptive capacity, and address biomass removal. Addressing current constraints and providing strong support for entrepreneurs seeking to valorize sargassum is an opportunity that could diversify local industries, and offer solutions for a sustainable and equitable blue recovery to the COVID-19 crisis in the region.

4.3. Conclusions

The priority actions outlined above cannot be implemented in isolation, they must be executed in tandem with ongoing efforts to improve communication of new knowledge. To date many initiatives including conferences, symposia, fora, discussion groups, webinars, podcasts and exhibitions dedicated to sargassum, formal networks, and knowledge hubs are sharing information, improving access to documentation and allowing exchange of ideas and questions. Examples include: SPAW-RAC basecamp, SargNet Listserv and Slack Workspace, Guadeloupe Sarg'Expo, the Sargassum Information Hub (<https://sargassumhub.org>, accessed on 15 May 2021), and The Sargassum Podcast (<https://marinefrontiers.org/sargassum>, accessed on 20 May 2021).

This paper presents the constraints and challenges for a more detailed consideration of specific issues and potential solutions. The evidence suggests that although efforts to explore opportunities in the Caribbean are well underway, sargassum influxes will remain more of a hazard than a benefit, unless current constraints are adequately addressed [61]. It is recommended that the solutions and actions proposed are integrated into a regional strategy and action plan that promotes valorization as an economic opportunity and as a means of alleviating influx impacts.

We anticipate that this paper will offer guidance to policy makers and funding agencies, on existing gaps and challenges that need to be addressed in order to scale-up successful and sustainable solutions to the sargassum crisis by ‘turning it to gold’.

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