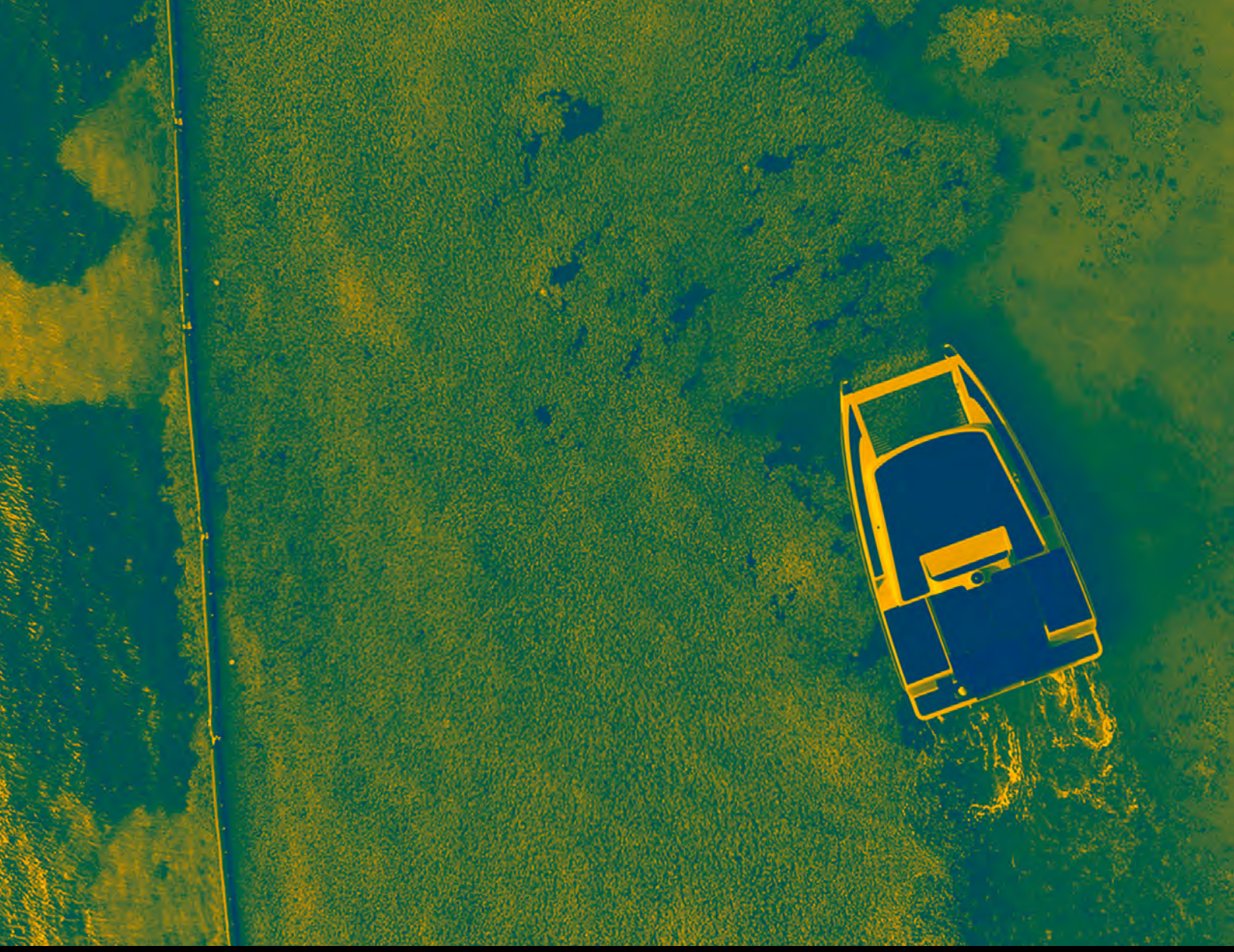

INNOVATIONS FOR SARGASSUM RESILIENCE

IDB | LAB

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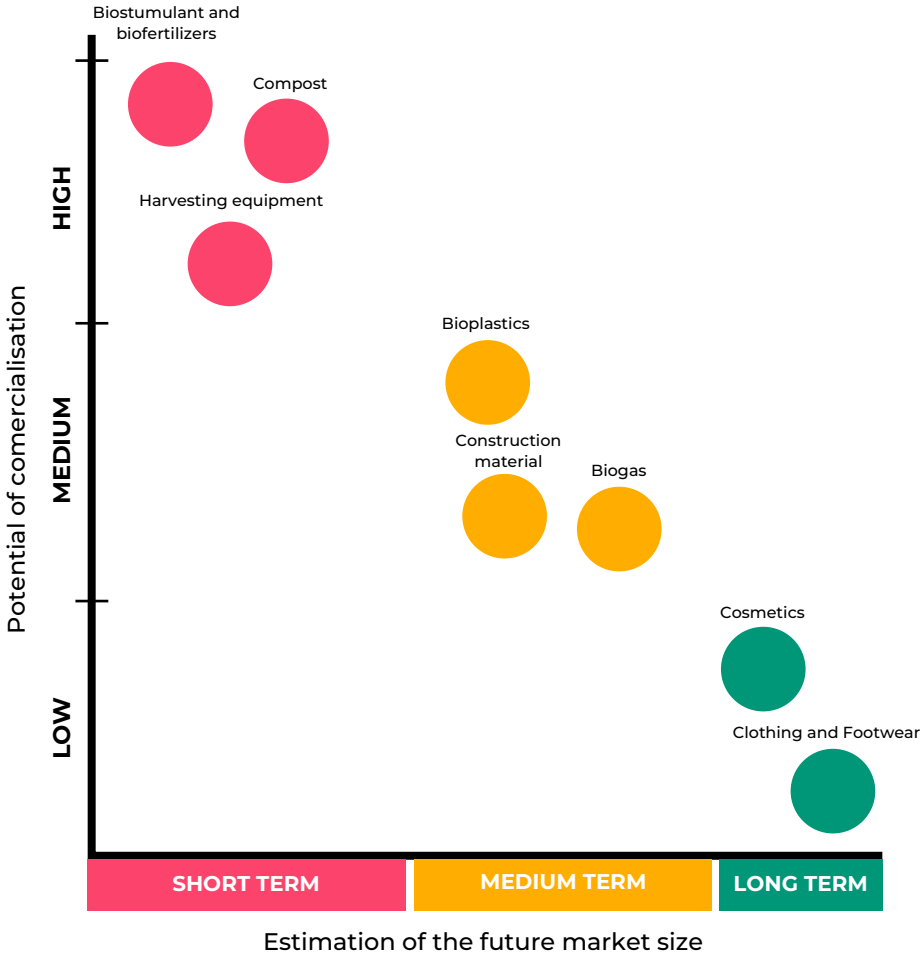
Executive summary

The advent of the sargassum era in 2011, brought significant challenges to socio-economic sectors in the Caribbean and West Africa. Negative impacts from sargassum influxes are still evident, but there has been a thrust to explore the potential of using sargassum as an opportunity. These efforts have catalysed the development of emergent innovation and technological solutions leading to the production of sargassum products and services that have been marketed at regional and international levels. The most comprehensive resource document to date, the "Sargassum Uses Guide", provides an overview of existing and potential uses and a directory of innovators and researchers. While it highlighted the challenges, constraints, and implications for the Caribbean, there was no evaluation of the effectiveness of each solution or a global outlook perspective. Using a multi-method approach, this report provides an updated and comprehensive description of the current sargassum innovation and governance landscape with a proposal of a rapid evaluation feature referred to as the 'Sargometer'. The Sargometer concept is designed to give entrepreneurs an understanding of the major factors that would affect the sustainability and effectiveness of a particular solution. Within this landscape study, case studies featuring outstanding innovators and entrepreneurs and their sargassum related products are highlighted, and efforts were made to include community perspectives regarding the different technological solutions. The document ends with future considerations for the developing sargassum industry.

Based on the findings of this study, technological solutions developed to address sargassum influx events, across the Caribbean and Latin America, predominantly consists of onshore and in-water harvesting machinery as well as various sargassum by-products (e.g., compost, liquid extracts, bioplastics, biogas, construction material, clothing and footwear, and cosmetics). These products are estimated to have varying levels of market potential over the short, medium and long term. Based on our findings, biostimulants and biofertilizers, compost, and harvesting equipment are poised for immediate impact, showing high potential of commercialisation in the short term (Figure A).

Figure A. Estimated market potential and commercialisation timeline for a range of sargassum-based products and services



As it relates to removing and/utilising large quantities of sargassum that inundate shorelines, applications related to harvesting, agriculture, and construction materials show great promise. For solutions that utilise lower volumes of sargassum, the study recommends the adoption of a biorefinery approach to increase the amount of sargassum that is utilised and valorisation opportunities. As the industry develops, it will be essential for governance structures related to sargassum management to evolve accordingly. Currently entrepreneurs are operating within an arbitrary system which has the potential to negatively affect processes along the value chain and the market success of their products. In order to fully take advantage of the mass influxes of sargassum, a quality and regulatory framework with standards and procedures on harvesting, and arsenic levels will be required for certain sargassum-by products to succeed on the international stage. It will also be important to establish policy measures that incentivize and facilitate the development of sustainable sargassum businesses including duty free concessions for importing specialised equipment and free zones to facilitate the acquisition of property. We posit that the appropriate use of technology supported by an enabling environment can catapult even the smallest sargassum enterprise into success on the international stage.

Abbreviations and Acronyms

AD	Anaerobic Digestion
ADEME	Ecological Transition Agency
ASAP	Alleviate Sargassum Action Program
ATVs	All-terrain-vehicles
BNOC	Barbados National Oil Company
CARDI	Caribbean Agricultural Research and Development Institute
CCRAG	Conférence de Coopération Régionale Antilles-Guyane
CHTA	Caribbean Hotel and Tourism Association
CNG	Compressed Natural Gas
COD	Chemical Oxygen Demand
CRFM	Caribbean Regional Fisheries Mechanism
EU	European Union
EEZ	Exclusive Economic Zone
FCDO	Foreign, Commonwealth and Development Office
GASB	Great Atlantic Sargassum Belt
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IDB	Inter-American Development Bank
INTEC	Instituto Tecnológico de Santo Domingo
IOC- IOCARIBE	Intergovernmental Oceanographic Commission Sub-Commission for the Caribbean and Adjacent Regions
KI	Key Informant

LCM	Littoral Collection Module
MIT	Massachusetts Institute of Technology
MMABE	Ministry of Maritime Affairs and Blue Economy
NMMO	N-methylmorpholine-N-oxide
PET	Polyethylene terephthalate
SEMAR	Secretaría de Marina
SOPs	Standard Operating Procedures
SPAW-RAC	Specially Protected Areas and Wildlife- Regional Activity Centre
SSE	Sargassum Seaweed Extracts
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNEP-CEP	United Nations Environment Programme- Caribbean Environment Programme
UNICEF	United Nations International Children's Emergency Fund
UNOPS	United Nations Office for Project Services
USCC	United States Composting Council
UWI-CERMES	University of the West Indies- Centre for Resource Management and Environmental Studies
WCR	Wider Caribbean Region

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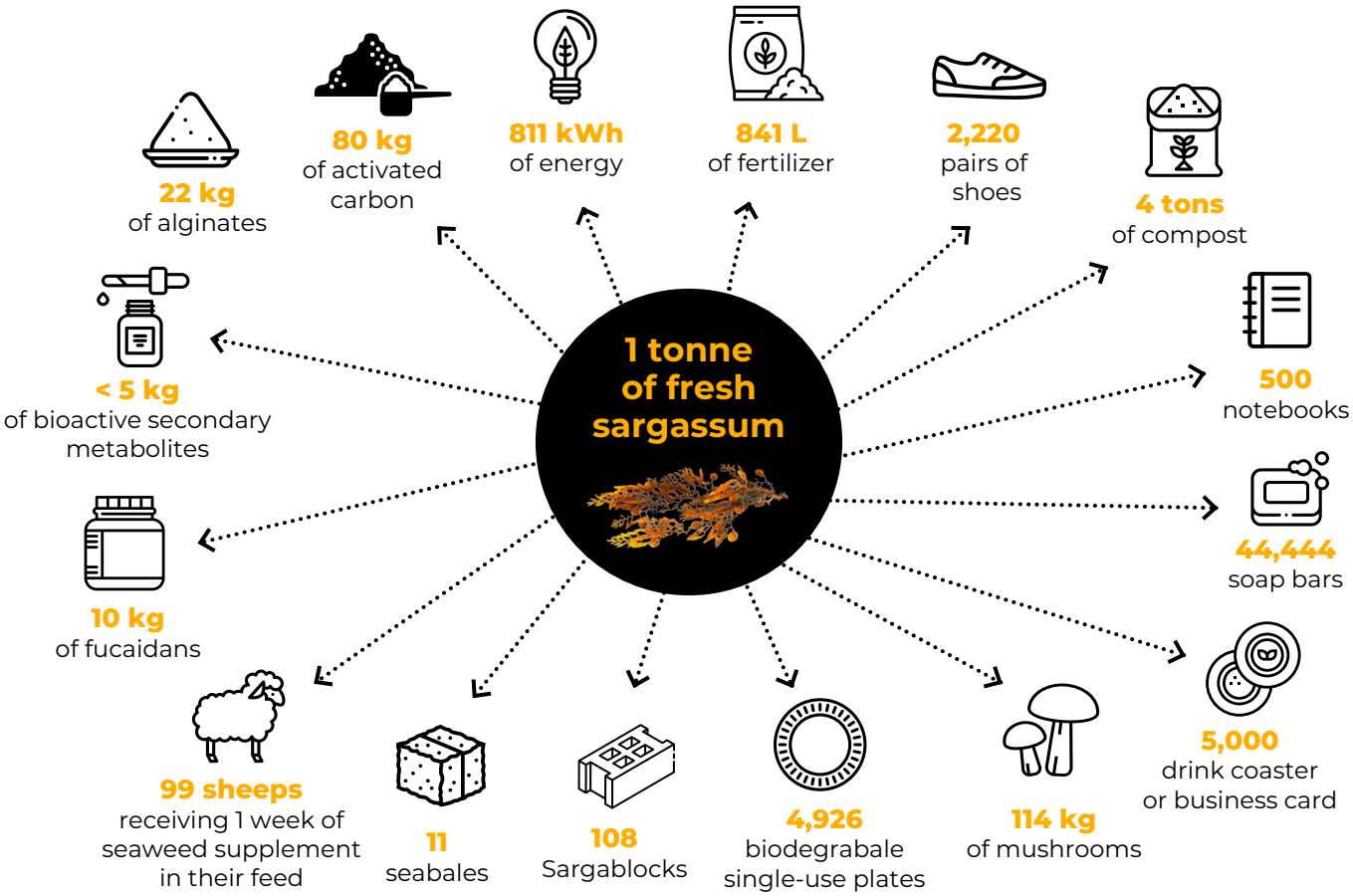
1 Introduction

Across the globe there has been an increase in Harmful Algae Blooms that cause deleterious consequences for shore-based activities and negatively affect nearshore coastal ecosystems (Kraan 2008; Smetacek and Zingone 2013; van Tussenbroek et al. 2017; Chávez et al. 2020; Joniver et al. 2021;). For countries in the Wider Caribbean Region (WCR) and west Africa, the year 2011 marked the beginning of unprecedented mass proliferations of holopelagic sargassum seaweed (*Sargassum natans* I, *S. natans* VIII and *S. fluitans* III; hereinafter simply referred to collectively as sargassum). Since the first event, recurrent 'blooms' have developed into a vast band (5,500 miles in 2018) of sargassum that is commonly known as the Great Atlantic Sargassum Belt (GASB) (Wang et al. 2019). This broadscale phenomenon has and continue to negatively affect key economic sectors within the WCR (i.e., tourism, fisheries) placing a strain on local and regional resources (Ramlogan, McConney, and Oxenford 2017; Engel 2018; Speede, Cox, and Oxenford 2018; Taylor 2019; Bartlett, Lee, and Myers 2019; Oxenford et al. 2019). To ameliorate some of the economic damage, innovative approaches and entrepreneurial initiatives have emerged to harness potential economic benefits of the abundant biomass (Milledge and Harvey 2016; Chávez et al. 2020; Desrochers et al. 2022).

Like most brown algae, sargassum contains proteins, carbohydrates, lipids, fibre, ash, vitamins, minerals, and secondary metabolites making it potentially viable for many applications (Davis et al. 2020; Milledge et al. 2020; Nielsen et al. 2021). In a 2021 regional assessment Desrochers et al. (2022) identified 15 potential sectors for sargassum application: (1) Animal husbandry, (2) Crop production, (3) Antifouling, (4) Bioenergy, (5) Bioplastics, (6) Bioremediation and purification, (7) Clothing, footwear and accessories, (8) Construction materials, (9) Cosmetics, (10) Electrochemical industry, (11) Environmental restoration, (12) Food and beverages, (13) Lubricants, surfactants and adhesives, (14) Paper products, and (15) Pharmaceutical and biomedical. Efforts to 'scale-up' potential sargassum uses indicate that one metric ton of fresh sargassum can provide a wide range of valuable products (Figure 1).

Figure 1. Relative product yields that could potentially be produced from one metric ton (1000kg) of fresh sargassum. Taken from United Nations Environment Programme - Caribbean Environment Programme (2021)



To date the Sargassum Uses Guide, published in 2022, stands as the most comprehensive resource in the Caribbean region, cataloguing an extensive array of potential applications for sargassum across 15 different sectors. Despite the region's decade-long efforts to manage sargassum, there are few examples of successful sargassum value chains that utilise large quantities of biomass. Biodegradable material, paper products, and cosmetics have been popular small-to-medium-sized ventures while larger industrial enterprises have developed agricultural products, construction blocks and biofuel. Interestingly, based on a global assessment conducted by the (World Bank 2023), applications developed across the WCR differ in their potential to become significant short-, medium- or long-term markets with the majority of efforts falling within short to medium-term markets.

Rendering the abundant masses of sargassum into sustainable economic opportunities that create jobs, address biomass removal, and strengthen the resilience and adaptation of affected countries will likely require a focus on applications that have the potential to establish medium to long-term markets. However, attempts to valorise this abundant bioresource have been met with several hurdles which hinder the development and/or upscaling of many sargassum products and services. Within the WCR, challenges associated with sargassum valorisation can be grouped into five broad categories: (1) unpredictable supply (of sargassum and its different morphotypes); (2) insufficient knowledge of the chemical components including micro-pollutants; (3) harvesting, transport, and storage; (4) governance; and (5) funding (Oxenford et al. 2021; Desrochers et al. 2022).

Valorisation of pelagic sargassum will be integral to the Caribbean region's ability to adapt to the continuing mass influxes. However, key challenges identified by Desrochers et al. (2022) and Oxenford et al. (2021) must be adequately addressed to achieve the full commercial potential. Entrepreneurs will play a crucial role in developing sargassum products and deploying innovative harvesting technologies, creating employment opportunities, and contributing to local economies. Thus, a thorough investigation into the efficacy and sustainability of sargassum enterprises is needed to shed light on their performance and uncover the ongoing challenges and limitations that hinder scalability. This inquiry is crucial to assess the viability of sargassum ventures and devise strategies to overcome challenges.

This Sargassum Landscape Study, commissioned by the Inter-American Development Bank (IDB) Group's Innovation Lab, sets out to identify, record, and assess the technological advancements employed in Central America, Mexico, and the Caribbean for sargassum utilisation, and ascertain their outcomes and efficiency. Over the past decade, the IDB Group's Innovation Lab has played an active and financial role in conducting several pilot projects to address the sargassum crisis in Latin America and the Caribbean. It is anticipated that this study will contribute to IDB's continued efforts and provide valuable information that policy makers and funding institutions can use to make informed decisions on the level and type of support to extend to valorisation initiatives.

2 Methods

A multi-method approach (Figure 2) comprising both primary and secondary data collection was employed to support the development of the Landscape Study.

2.1 Desktop Review

A thorough desktop review was conducted to gather existing data and information related to technological advancements employed in Central America, Mexico, and the Caribbean for sargassum utilisation. This included the identification of technological advancements already implemented or under development. For instance, sargassum harvesting methods, processing and conversion technologies, sargassum applications in agriculture, biogas, cosmetics, plastics, and building materials. The desktop review also supported a situational analysis of existing governance arrangements and gave insight into the enabling environment for sustainable sargassum initiatives. Data and information were collected from peer-reviewed journal articles, technical reports, conference proceedings, newspaper articles, webpages, and grey literature.

2.2 Key Informant Interviews

Primary data collection involved key informant (KI) interviews with founders of sargassum-based businesses, sargassum researchers/experts and representatives of sargassum management authorities in Central America, Mexico and the Caribbean. Leveraging the expertise of these KIs was crucial for obtaining first-hand insights into the current products and services and associated processes, challenges, and achievements. The KIs were engaged through established professional networks, as well as online platforms such as SARGNET and the Sargassum Podcast. These platforms serve as communities for sargassum experts worldwide, including those focusing on technological advancements related to sargassum.

Additionally, the Phyconomy Seaweed Database served as a valuable resource in identifying sargassum-based businesses, featuring more than 1200 entries on seaweed industries, 55 of which specifically utilise sargassum.

A total of 34 sargassum businesses presumed to be operational in Central America, Mexico and the Caribbean were identified and contacted (refer to Annex 1). Out of the 34 businesses contacted via email, 13 replied. Likewise, 35 sargassum researchers/experts (refer to Annex 2) and 6 sargassum government officials were contacted, resulting in 5 responses from the researchers/experts and 2 responses from the government officials. The overall response rate was 26.7%.

Google Meet was used to facilitate the virtual interviews. Semi-structured interviews were conducted as they facilitated a predetermined list of interview questions but still gave the consultant the scope to ask further and more in-depth questions. The questioning route took into consideration not only the state-of-the-art initiatives based on existing publications, but also ongoing research within the scope of the study.

2.3 Site Visits

Four in-country coordinators (all knowledgeable in the sargassum field) from Mexico, the Dominican Republic, Puerto Rico and Jamaica were engaged to conduct site visits to sargassum facilities or plants. Their tasks were to document processes, challenges encountered, and observed outcomes. The in-country coordinators identified sargassum businesses in the respective countries that were operational and organised guided tours or discussions with plant personnel or experts. They documented operations, technology, and processes involved in sargassum utilisation.

A site visit protocol was developed, and the in-country coordinators were briefed on the approach and specific information to be collected (in accordance with the objectives of the study) during the visits. Photographs and videos were included (once permitted). Guided by the consultant, the coordinators developed comprehensive reports which were used in the development of the case studies.

2.4 Surveys

Surveys were conducted with members of affected communities in Mexico, the Dominican Republic and Puerto Rico to gauge community perspectives and assess the impact of technological solutions. Following the crafting of the survey questions, the Kobo Toolbox platform was used to create digital forms, administer, store and analyse survey data. The in-country coordinators aided in the identification of target communities and conducted surveys with affected communities, all while ensuring cultural sensitivity. Efforts were undertaken to involve at least 50 community members from Mexico, the Dominican Republic, and Puerto Rico in the survey. However, only 29 individuals participated, resulting in a response rate of 58%.

2.5 Structure and Prepare the Report

All data gathered were compiled and organised according to themes and analysed. Solutions were evaluated for their effectiveness and sustainability and challenges, limitations, lessons learned and case studies were developed. Metrics to assess the efficiency of the sargassum solution were developed based on a set of criteria and in accordance with the objectives of the study.

Figure 2. **Multi-method approach**

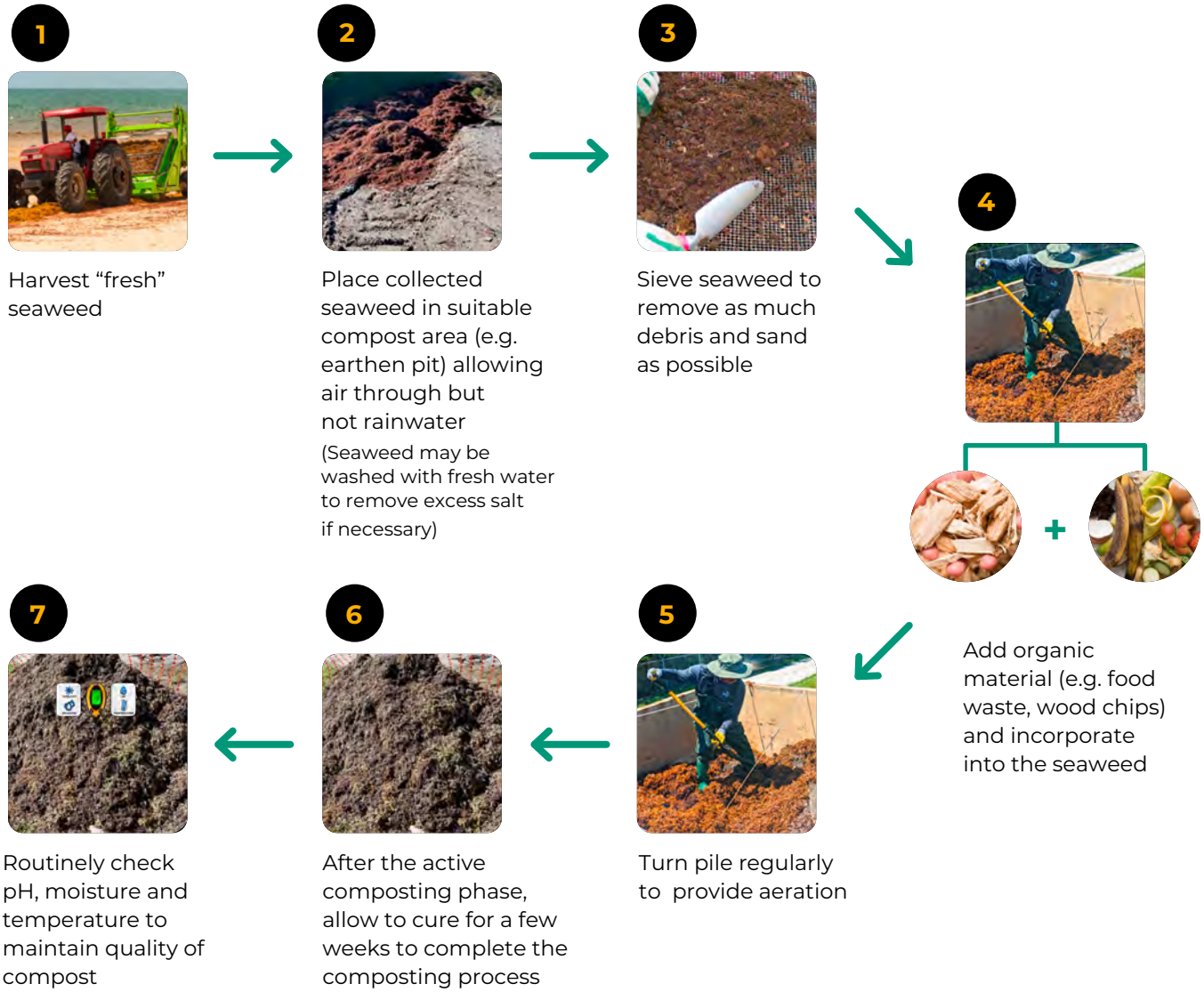
3 Identification of Technological Solutions Implemented in Central America, Mexico and the Caribbean

Despite the comprehensive scope outlined in the Sargassum Uses Guide, it's important to recognize that not all of these applications have been implemented on a commercial scale in Caribbean territories. In this section we explore the practical and feasible solutions that to our knowledge and investigations have gained traction in the Caribbean region. These range from traditional uses like compost, biostimulants and biofertilizers to applications such as bioplastics, biogas, and even construction materials. Additionally, we delve into its potential applications in clothing and footwear, cosmetics, and the development of on-shore and in-water harvesting equipment. With its rich nutrient content and versatile properties, sargassum presents a multitude of opportunities for sustainable innovation across various industries. Throughout our exploration, we highlight research studies and specific examples of sargassum utilisation within the Caribbean region, showcasing how local initiatives are leveraging this abundant resource to address environmental challenges and drive economic development. At the end of each section, we summarise the key pros and cons for each application.

3.1 Compost

Sanders et al. (2011) define composting as the natural process of converting organic matter into a useful, waste-free product. Figure 3 illustrates the typical process for producing seaweed compost. Composting has regarded a cost-effective, straightforward, and practical approach for utilising seaweed biomass (Desrochers et al. 2022). It was not unexpected that given the surges in sargassum reaching Caribbean coastlines, composting became a widely adopted agricultural practice initially used to mitigate the associated adverse effects. However, as more studies emerged on applications of sargassum in agriculture, views on its efficacy have been mixed.

Figure 3. Overview of general process for converting seaweed to compost



Among the concerns raised was the abundance of sodium and inorganic arsenic in naturally occurring sargassum (CARDI, 2015; Desrochers et al., 2022). However, research conducted at Texas State University revealed that incorporating sargassum into compost piles did not result in any adverse effects despite its elevated salinity levels. The pH, soluble salt content, carbon-to-nitrogen ratio, and heavy metal content of all samples, regardless of washing, fell within the optimal and desirable ranges for compost typically utilised in the horticultural industry according to the U.S. Composting Council (USCC) standards (Sembera et al. 2018).

In the study washed and unwashed sargassum (4% each) were each mixed with cafeteria food waste and local wood chips (48%) to create a total of nearly ≈25 yard^3 of stabilised compost valued at US$900 on the local market (Sembera et al. 2018). According to the study, prewashing seaweed did not appear to be necessary in creating a quality compost. Although the study did not evaluate effects on plant growth, the carbon:nitrogen ratios of the samples were between 13.40 and 13.50 which according to the authors should increase plant-nutrient availability when applied to soil. Arsenic levels ranged from 4.2-7.2 ppm which were well within the EPA standards for compost. Despite these encouraging outcomes, it is important to highlight that only a small percentage of sargassum biomass was utilised in making the final product.

Walsh and Waliczek (2020) conducted similar studies utilising unwashed sargassum but incorporated a larger amount of biomass into the final product. Additionally, the inclusion of fish waste reportedly improved the quality of the sargassum compost. In the study, equal parts of sargassum and wood chips (41.5%), 4% fish waste and 13% food waste had the best results in terms of organic matter content and overall nutrient levels.

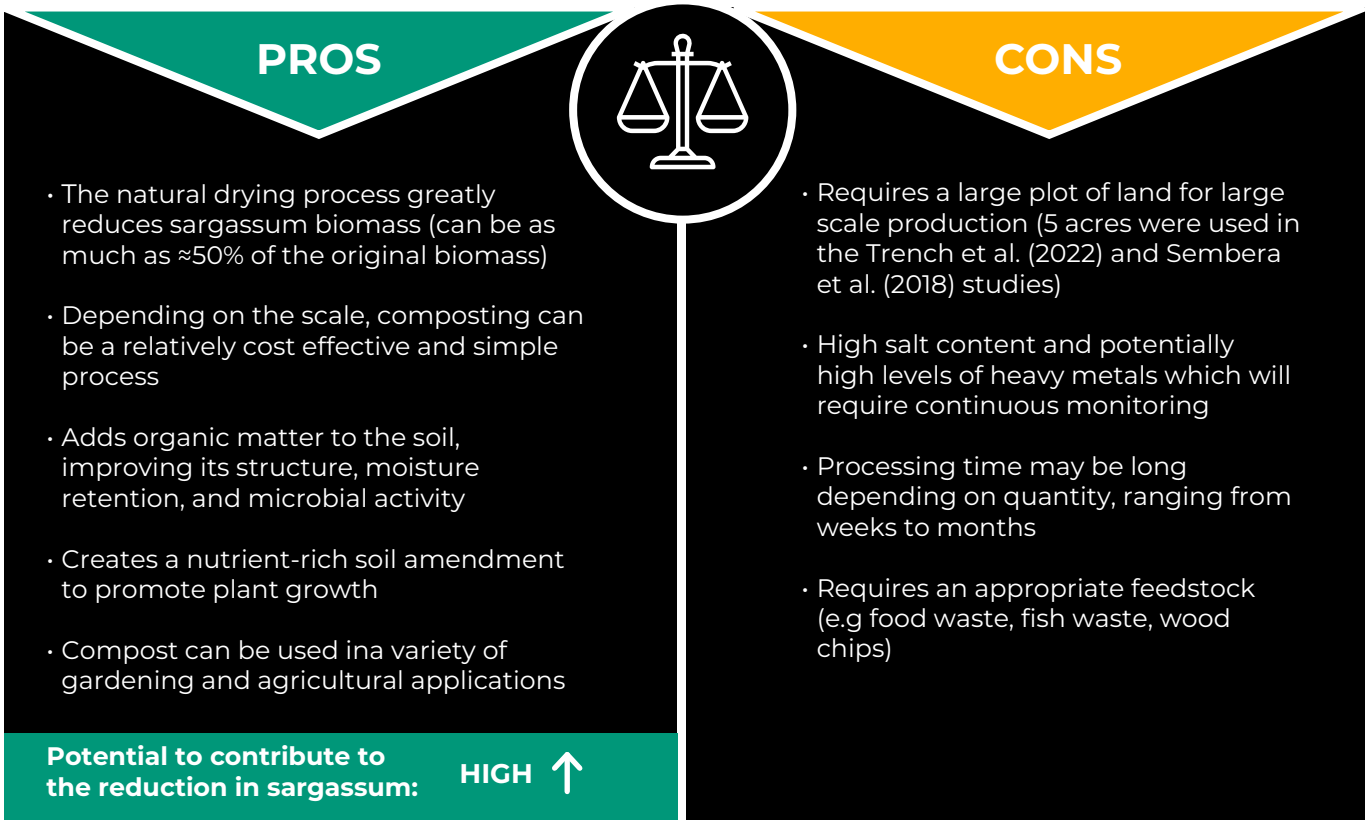
Positive results were also documented in Jamaica, this time as it relates to mangrove restoration. In a study by Trench et al. (2022), a compost was created mixing unwashed and unsorted sargassum with a sand/soil medium (approximately 50:50 ratio). According to the study, best *R. mangle* seedling growth (indicated by height and number of leaves) occurred with a mix of 75% sargassum compost with 25% soil/sand mix. Notably, poorest outcomes were observed with 100% sargassum compost, showing that pure sargassum compost is deleterious to plant health and growth. An interesting finding was that the concentration of several elements (sodium, potassium, calcium, arsenic, and selenium) naturally found in high concentrations in the sargassum compost, were low in the plants (Trench et al. 2022). Other authors have reported that mangrove plants, especially *Rhizophora spp*., can regulate heavy metal uptake (Alongi et al., 2004; MacFarlane and Burchett, 2002; MacFarlane et al., 2007). These findings are quite encouraging for addressing the dual challenges of sargassum accumulation and mangrove degradation.

Research shows that with appropriate proportions, and mixed with other material there is potential to use sargassum as a compost. However, it should be cautioned that utilising large quantities of sargassum may also increase the heavy metal content of the final product. Therefore, implementing methods to mitigate heavy metal content along with frequent testing are necessary to ensure safety (read more about heavy metals in Section 3.3). Consideration should also be given to the amount of sand present in unwashed biomass which could decrease the moisture-holding capacity within the compost. Harvesting at sea may minimise the sand collected. However, in some instances, higher amounts of sand in compost may be seen as beneficial in circumstances where soils need better drainage (Walsh and Waliczek, 2020). Consistent sampling is necessary to ensure the product meets the requisite industry standards and is suitable to market.

Over the years, a few companies in the Caribbean have introduced compost made from sargassum seaweed to the market, utilising various quantities of sargassum in the final products (e.g. AlgeaNova, BlueGreen, Grogenics, Sway, and Holdex Environment). In Martinique, Holdex Environnement, has commercialised sargassum compost, containing up to 10% sargassum (Desrochers et al. 2022). The company has been co-composting sargassum with green and agricultural waste and in 2018, processed more than 3,000t (CCRAG, 2018). AlgeaNova in Dominican Republic, has also been producing a sargassum-based compost, made with 60% sargassum and 40% *Leucaena leucocephala* (also known as river tamarind) (Desrochers et al. 2022). Read more about AlgeaNova in Section 6.9.

Work continues in the Caribbean to find suitable ways to utilise sargassum biomass as a compost. The Caribbean Regional Fisheries Mechanism (CRFM) launched a multiyear project working with Plant and Food Research from New Zealand. The project aims to develop liquid fertilizers and an organic compost from processed sargassum, for eventual incorporation into farmer and grower practices in the Caribbean (CRFM, 2023). An interesting initiative in Dominica, the Alleviate Sargassum Action Program (ASAP) was launched in 2021 which uses vermicomposting to create sargassum compost. It blends the sargassum with earthworms and other organic materials like shredded cardboard, grass cuttings, and animal manure to generate compost (Global Issues, 2022).

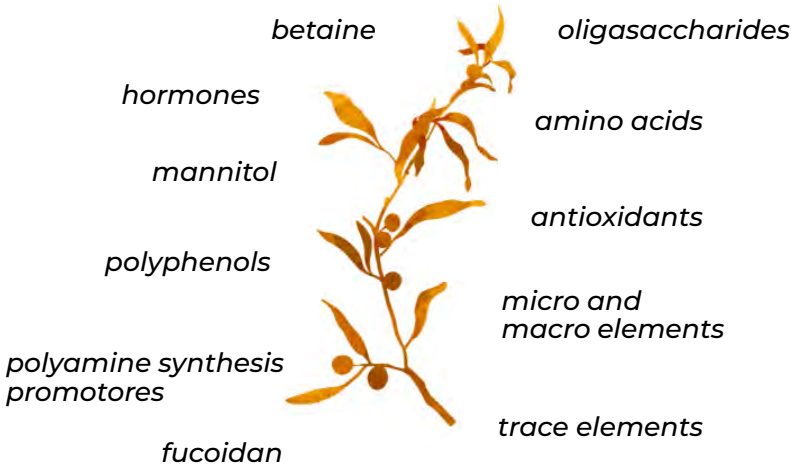
Figure 4. **Pros and cons of developing sargassum-based compost**



3.2 Liquid extracts (biostimulants and fertilizers)

Liquid extracts have emerged as the most commonly used seaweed product worldwide, often marketed as biofertilizers or biostimulants (CARDI, 2015). Compared to other types of algae, brown seaweeds (e.g. *Sargassum spp.*, and *Ascophyllum spp.)* have a higher presence of natural phytohormones, and micro and macro-nutrients contents which are beneficial for plant growth and development (Mahmoud et al., 2019) (Figure 5). Sargassum is rich in essential minerals, including potassium, though it has low nitrogen and phosphorous contents (López-Miranda et al., 2021).

Figure 5. **Key components of pelagic sargassum (Adapted from Dianco, n.d.)**



Different extraction methods with various modifications are used to obtain these valuable compounds from sargassum such as solvent extraction, steam distillation, and supercritical fluid extraction (Kumar et al. 2012). A simplified solvent extraction process is presented in Figure 6 below.

Figure 6. Overview of the typical solvent extraction process for seaweed

Companies like Sarga Agriscience, a brand of Carbonwave in Puerto Rico, developed their own proprietary sargassum liquid extraction process. Sarga Agriscience has innovated "a gentle, cold, non-chemical extraction process which leaves cellulose behind" (Carbonwave, 2023). Experimental tests conducted with the barley plant revealed a notable increase in yield by 12.5%. Additionally, they provided insights into the potential economic gains, reporting that for a treatment cost of US$15, they observed an additional US$200 increase in barley yield per hectare (Carbonwave, 2023).

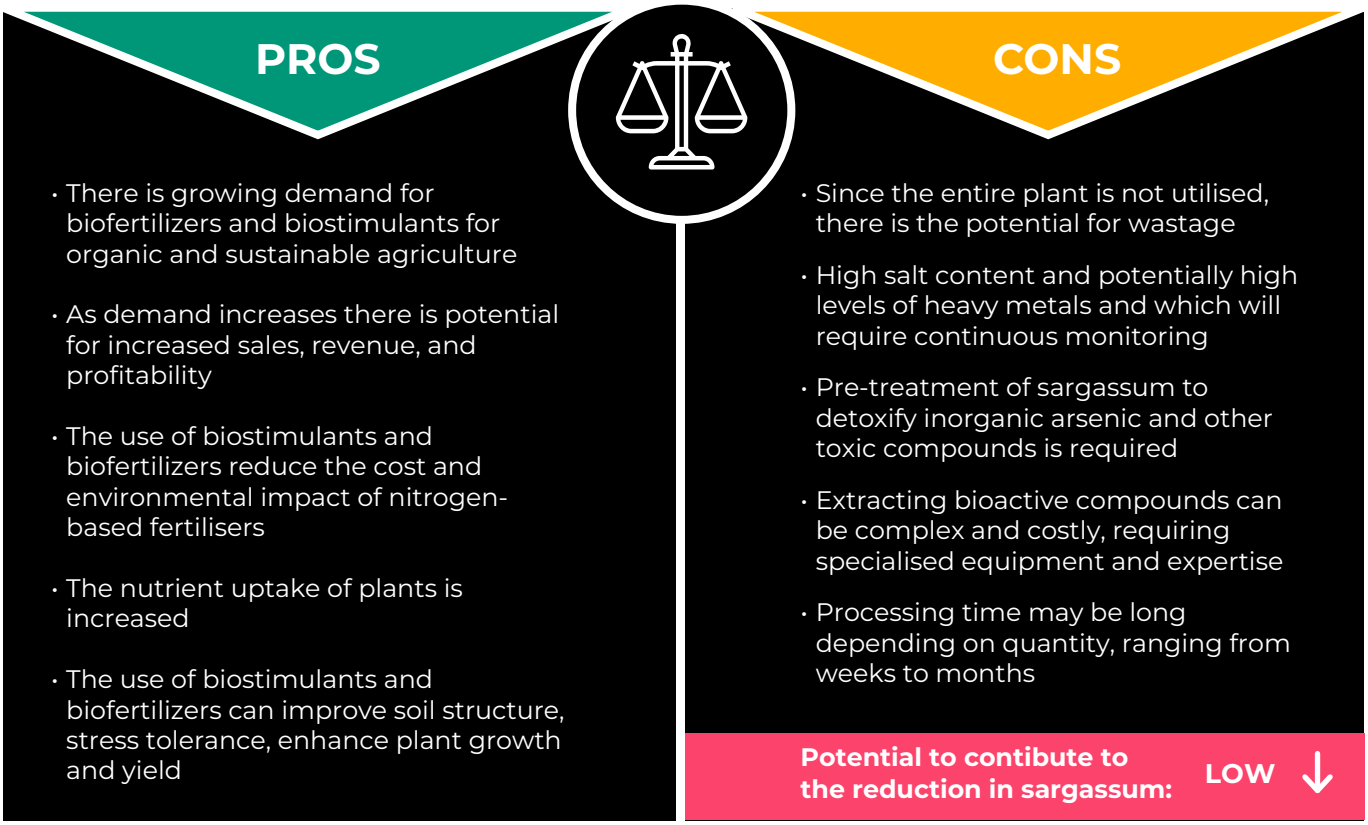
Many investigators have proved the stimulatory effects of sargassum seaweed extracts (SSE) on seed germination (Kumari et al., 2011; Fatimah et al., 2018), early seedlings growth and vigour (Sariñana-Aldaco et al., 2022; Jayasinghe et al. 2016), and improving seedling establishment in a wide variety of vegetable crops (Sutharsan et al., 2014; Kumar et al. 2012). SSE have also shown positive results as inducers of tolerance to biotic and abiotic stress (Sariñana-Aldaco, 2022). A study conducted in Mexico by Sariñana-Aldaco (2022) showed that the application of extract of sargassum modulated different physiological, metabolic, and molecular processes in tomato seedlings, with possible synergistic effects that increased tolerance to salinity. In the study 1.5% hydroalcoholic SSE was used at a ratio of 1g of seaweed and 20mL of 50% ethanol.

SSE are used in a variety of ways including foliar application, soil drenches as well as seed treatments usually applied during the early stages of plant growth (CARDI, 2015; Mahmoud et al. 2019). Ali et al. (2021) suggest that foliar sprays of less than or equal to 0.05% v/v of the extract have been reported to be optimal for crop growth and result in more effective control of disease and higher yields. It should be noted that the method of application, times of application and the rate of application differ according to the plant variety and growth stages. According to Mahmoud et al. (2019) the most significant stimulatory effects occur during the early stages of plant growth. Chilli, tomato, red radish, soybean and chickpea are some of the crops that have been extensively studied with SSE (Noli et al. 2021; Fatimah et al. 2018; Adderly et al. 2023).

As it relates to the heavy metal content in SSE, the extracts typically result in lower heavy metal content because the extraction process isolates the useful compounds, leaving behind much of the plant material where heavy metals may accumulate. This selective extraction helps to reduce the concentration of heavy metals in the final product. Companies producing biofertilizers and biostimulants from SSE such as Red Diamond Compost Algas Organics are said to yield very low concentrations of heavy metals including arsenic, cadmium, mercury, and lead. Desrochers et al. (2020) explains that digestate, the nutrient-rich solid residue from anaerobic digestion commonly used in agriculture, is likely to contain high levels of heavy metals such as arsenic and cadmium. The authors highlight that digestate with high levels of heavy metals poses disposal challenges and is unsuitable as fertilizer.

Over the years several companies have been exploring sargassum-based fertilizers and biostimulants in the Caribbean such as Algas Organics, Red Diamond Compost, Salgax Biotecnología Marina Aplicada, Sargasso Organics, C-Combinator, Alquimar and Dianco de México (Desrochers et al., 2022). Algas Organics based in St. Lucia has been dubbed a pioneer in the development of sargassum-based plant-tonics in the Caribbean. Now a large scale enterprise, the company continues to penetrate international markets. Currently Algas processes over 1,000,000 pounds of sargassum seaweed annually and currently exports to 10 countries (Algas Organics, 2023). The products are sold at various sizes from 1 gallon (US$46.64) to 275 gallons (US$9,597.50). Dianco de México has also managed to sustain large-scale production, manufacturing 10,000 tons of biofertilizers and biostimulants monthly (1 ton in 5 minutes). The Mexican-based company prides itself on its “zero” waste process, which involves extracting 100% of nutrients from sargassum with very low concentrations of salts and heavy metals. Impressively, the company returns 95% of the collected sand back to the beaches (Dianco, n.d.). Read more about Dianco de Mexico in Section 6.12.

Figure 7. **Pros and cons of developing sargassum-based biofertilizers and biostimulants**



3.3 Heavy metal extraction

Despite the potential uses in agriculture identified, there are also high hurdles which have hindered the advancement of many businesses. Chief among these hurdles is the high content of heavy metals, notably inorganic arsenic. Sargassum has been on the radar of scientists due to its high capacity to absorb toxic inorganic arsenic from the environment which can be harmful to humans and the environment. Studies across the Caribbean have found that inorganic arsenic concentrations exceed allowed levels for some agricultural products and animal feed with implications for human health (e.g. Rodríguez-Martínez et al. 2020; Devault et al., 2022; Alleyne et al. 2023).

The findings have prompted many small businesses producing agricultural products, especially compost, to suspend operations, unless they implemented methods to ensure that the heavy metal content remained within permissible levels for commercial agricultural products. The allowable levels for heavy metals in fertilizers and biostimulants can vary depending on regulatory standards, intended use, and specific regional regulations (Figure 8). Notably, there are no regional safety standards for sargassum-based products.

Figure 8. Examples of maximum arsenic and cadmium levels permitted in fertilizers by different countries and agencies (ppm)

Country	Arsenic	Cadmiu
New Zealand	75 ppm	280 ppm in phosphorus fertilizers
USA-California (California department of food and agriculture)	2 ppm for each percent available phosphate	4 ppm for each percent available phosphate
Canada (Canadian Food Inspection Agency 2018)	75 ppm product (based on 4400kg/ha/yr application rate of product)	20 ppm product (based on 4400kg/ha/yr application rate of product)

Source: https://www.cavehill.uwi.edu/cermes/research-projects/sargassum/docs/desrochers_et_al_2020sargassum_uses_guide_advance.aspx

On a positive note a few businesses, including Grogenics which produces compost, have reportedly devised patented processes to mitigate the heavy metal content, enabling them to sustain operations. Owing to their patents, the exact methodologies employed by these companies are not disclosed. However, Grogenics has provided some insights, revealing that they effectively neutralised the heavy metal content through a process known as Microbial Bioremediation (Grogenics, 2023). This technique involves the use of microbes to immobilise or transform heavy metals into less harmful forms. Read more about Grogenics in Section 6.5.

Although there are numerous publications within the region which examine the heavy metal content of sargassum, there is a notable scarcity of research on methods to treat sargassum to lower the concentration of the heavy metals to acceptable levels. Indeed, studies (e.g. Wang et al., 2021; Yamashita, 2014) beyond the Caribbean have explored heavy metal removal in other sargassum species, particularly those used for consumption (e.g *Sargassum fusiforme)*. Processing methods involving hot water, citric acid, and fermentation, are considered effective in drastically reducing the inorganic arsenic content, however, the levels of organic acids and amino acids are also significantly altered (Wang et al., 2021). Therefore, in the case of Caribbean sargassum, and its applications in agriculture, it is crucial to employ extraction methods that also preserve the integrity of the valuable compounds within the seaweed.

On the other hand, sargassum's inherent biosorption properties make it a potentially valuable tool for environmental remediation to address pollution. According to Desrochers et al. (2020), sargassum is capable of removing a variety of contaminants (e.g. high nutrient loads, heavy metals, dyes, phenols) and can therefore be used to treat polluted sites and wastewater effluents. In the Caribbean there has been quite a bit of research on the conversion of sargassum to activated carbon for bioremediation purposes, particularly in Mexico, Guadeloupe, Martinique, Dominican Republic and Trinidad. Desrochers et al. (2020) alluded to a range of applications including purifying air and other gases, controlling odours, bioremediation of contaminated soils and coastal waters, and in water filtration systems. With ongoing research and development, it is possible to enhance the efficiency and scalability of this approach. However, the variability in sargassum composition, the need for efficient harvesting and processing methods, and the disposal of contaminated biomass will have to be considered.

3.4 Bioplastics

The Caribbean region accumulates over 320,000 tons of uncollected plastic waste annually (World Bank, 2023). Furthermore, based on beach clean-ups and surface water surveys, the region is considered to have higher levels of plastic pollution than other marine ecosystems (World Bank, 2023). This has been attributed to inadequate or non-existent systems for collection, recycling, and disposal of urban and industrial waste (Aranda et al. 2022). Bioplastics present an advanced sustainable alternative due to their biodegradability by soil microorganisms and reduced adverse environmental impacts. Depending on the type of bioplastic used, there are several options for the end of the product's life cycle. Some of these include recycling, composting, incineration, anaerobic digestion (AD) or feedstock recovery (Desrochers et al., 2022).

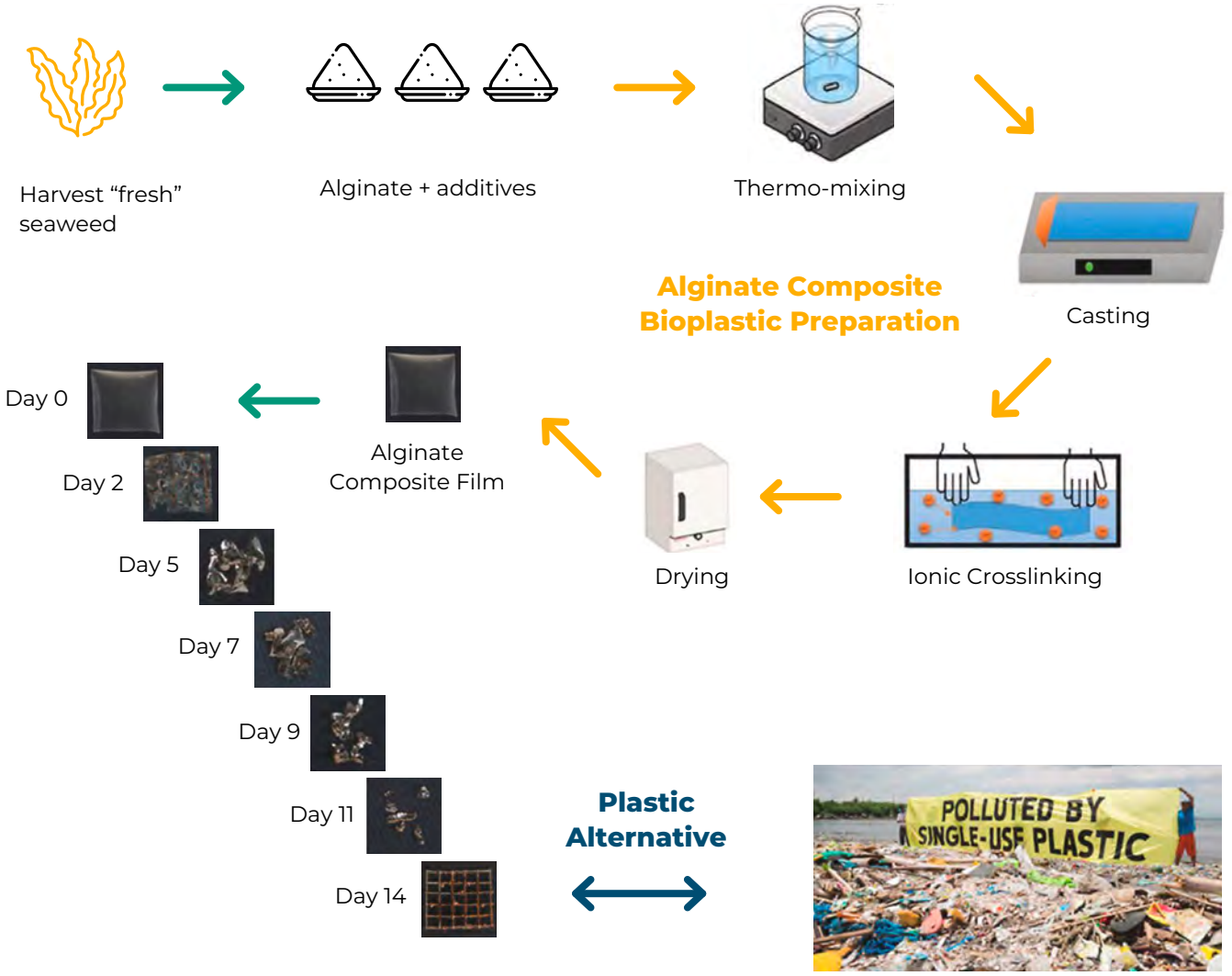
The use of seaweed and seaweed extracts in synthesising biodegradable bioplastics is gaining popularity. Commercial brown seaweeds such as *Laminaria, Eclklonia,* and *Macrocystis*, and to a lesser extent sargassum, contain valuable polysaccharides, including agar, alginate, and carrageenan (Mohammed et al. 2020). Research has shown that these polysaccharides are potential bioplastic precursors and can be utilised in the manufacturing of biopolymetric films and biodegradable packaging materials. Some applications include food containers and packages, plastic bottles and cups, plastic dishes and bags (Farghali, et al. 2023; Mohammed et al. 2023).

Among these polysaccharides, sodium alginate is quite abundant, comprising up to 40% of its dry weight depending on the source (Mohammed et al. 2020). Although sargassum typically yields lower percentages (usually <19%) of these valuable polysaccharides compared to other commercial brown seaweeds, certain extraction methods can enhance the yields of alginate extracts (Mohammed et al., 2020). For instance, by using a Box-Behnken Response Surface Design combined with multistage extraction, Mohammed et al. (2020) obtained a yield as high as 28% after 2 stages and a purity of 92% for purified alginate samples. Mixing with other species or reinforcement materials can also improve their characteristics and properties (Mohammed et al. 2023).

In the Caribbean, researchers across the region have been investigating the use of sargassum as a source of extracts to produce bioplastics, with promising findings (Mohammed et al 2023; 2020). Although published studies are limited, they suggest that sargassum holds promise as a feedstock, particularly to produce bioplastic film. Such films could find applications in food packaging and preservation, demonstrating the potential of sargassum in the bioplastics industry.

Efficient alginate extraction methods are crucial for maintaining the integrity and purity of alginate, and successful production of bioplastics. In a study emerging from Trinidad, Mohammed et al. (2023) successfully extracted sodium alginate from *Sargassum natans* harvested in Trinidad using a six-step process (Figure 9). These generally included: initial pre-treatment with formaldehyde, acid treatment with sulphuric acid, alkali extraction, bleaching, precipitation, and drying. This process resulted in the creation of alginate composite films which could be used as food packaging. The findings revealed that the material possessed comparable properties to those of synthetic and bio-based plastic alternatives, including good degradation under 14 days. According to Mohammed et al. (2023), the techno-economic analysis conducted on alginate bioplastics suggests high economic feasibility, with a potential cost of US$4.56 per kg. Given that the seaweed bioplastic industry is relatively new in the Caribbean region, more studies should be geared towards technical feasibility and market analyses.

Figure 9. Overview of the bioplastic formulation to form alginate composite films

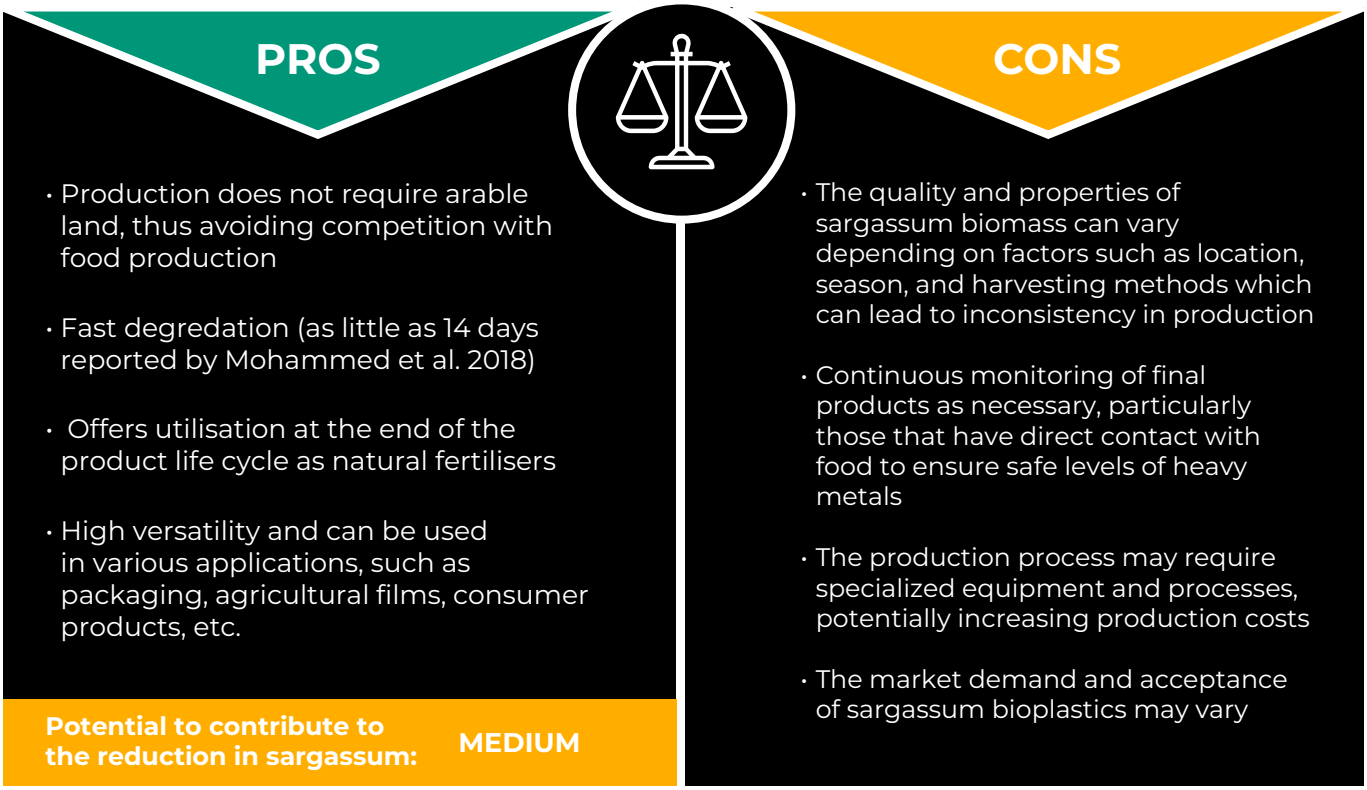


Source: https://www.sciencedirect.com/science/article/pii/S0268005X22007123

A few companies across the Caribbean are pioneering research and development efforts to explore the feasibility of transforming sargassum into bioplastics. Some of these include Albaplas, BioPlaster Research, AlgeaNova, EcoMyco, Carbonwave and Thalasso Ocean. Bioplaster based in Mexico has been a beacon of innovation. Their process transforms 1 ton of sargassum to an impressive 5 tons of bioplastic used in a diverse array of products. From water-soluble plastic films to yarn for woven fabric, their bioplastic serves as a sustainable alternative to traditional materials, catering to various industries and consumer needs (Bioplaster, n.d.). Other products include hydrogels for agriculture, solid foam for packaging and insulation and thermoplastic pellets (read more about Bioplaster in Section 6.3). AlgeaNova's innovations focus on the creation of fully compostable plates, crafted from a blend of 50% sargassum and 50% cassava, which degrades within 30 days (Desrochers et al. 2022).

As companies continue to explore commercialisation of sargassum-based bioplastics, Desrochers et al. (2022) emphasise the importance of adherence to local regulations and conducting biodegradability tests. They also underscore the necessity of ensuring access to adequate facilities for the proper disposal or recycling of materials to avoid further environmental impact.

Figure 10. **Pros and cons of developing sargassum-based bioplastics**



3.5 Biogas

Sargassum, just like other brown seaweeds or macroalgae, has a high moisture content (80–90%), high carbohydrate content (40–60% dry weight) and have cell walls that contain very little lignin and low levels of cellulose (Thompson et al., 2020; Desrochers at al., 2022). Several authors have acknowledged that this specific makeup enables microbial conversion of organic matter to biogas, a sustainable energy source mainly made up of methane and carbon dioxide (Thompson et al., 2020; Desrochers et al. 2022; Milledge et al. (2019). Despite the potential, this application must overcome a number of hurdles before it can compete in the fuel market.

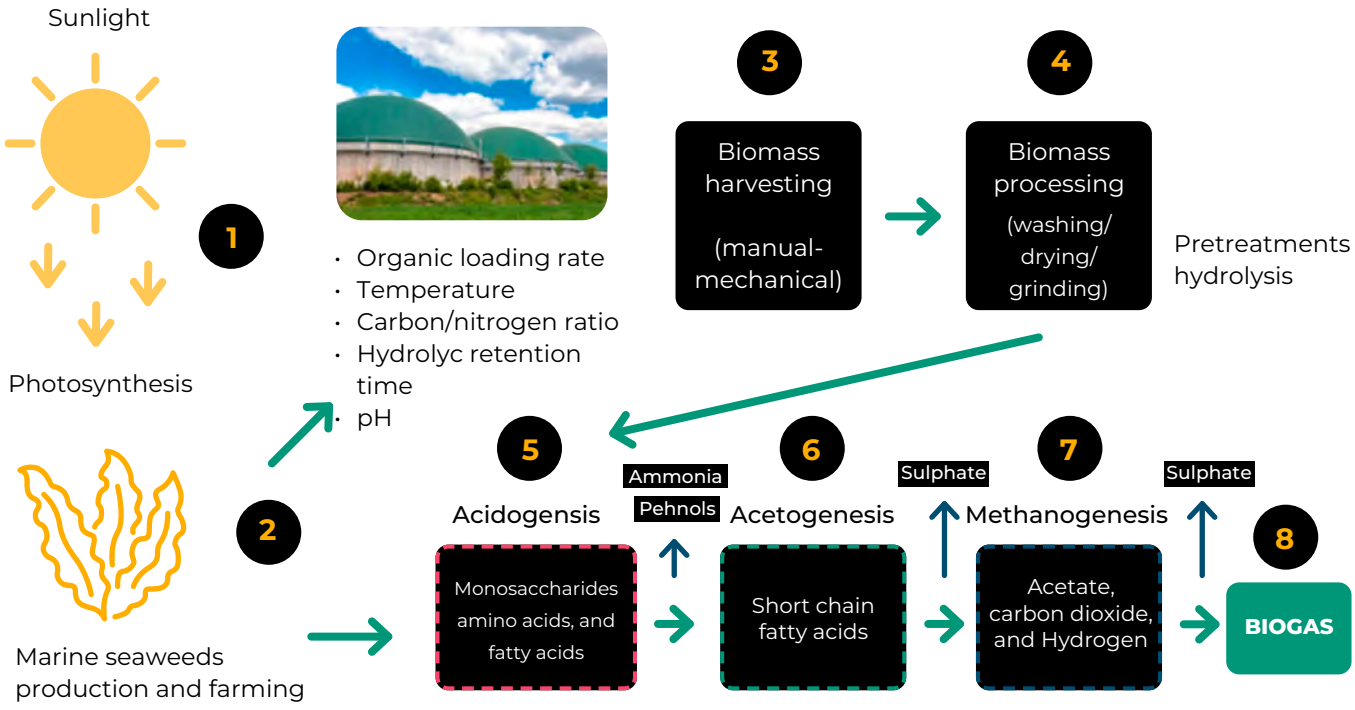
Factors such as the salt content, the structural complexity of polysaccharides, the presence of sulphur and polyphenols, and a low carbon to nitrogen ratio are all elements that lower the overall methane yield (Thompson et al., 2020). For instance, in an experimental study using sargassum from Barbados, Thompson et al. (2020) found that the methane content was 29.29% of the theoretical methane potential. More drastic results were reported by Milledge et al. (2020) who reported zero methanation of sargassum sampled in the Turks and Caicos. Both studies attributed the previously mentioned factors as limitations that reduced methane production.

To overcome the limitations and enhance quality and marketability, hydrothermal pre-treatment and co-digestion with various substrates are recommended (Thompson et al. 2021; Amador-Castro et al., 2021; Al-lami and Herjevik 2023). Published studies highlight wheat straw, waste cooking oil, wastewater sludge, municipal solid wastes, animal manure, food waste and waste paper as viable co-substrates for brown macroalgae (Desrochers at al., 2022; Thompson et al. 2021). Orozco-González (2022) suggests that a combination of metal nanoparticles, different co-substrates, and ingenious feedstock pre-treatments has good potential to attain the best yields.

According to Thompson et al. (2021), Anaerobic digestion (AD) is largely the process of choice for biomass with high water content, such as seaweed, to achieve the recommended optimal carbon/nitrogen ratio of 20-30:1. According to Milledge et al. (2019), AD is a relatively simple and versatile procedure from an infrastructure/engineering perspective. It converts biomass in an oxygen-free environment into biogas, a mixture of methane (60–70%) and carbon dioxide (30–40%) (Zhao et al., 2022). Additionally, AD has the capacity to utilise all the organic carbon material of algae rather than one specific component.

Zhao et al. (2022) explains that AD occurs in a series of biological processes which include: hydrolysis, acidogenesis, acetogenesis and methanogenesis dioxide. Hydrolysis initiates the process by breaking down complex organic compounds into simpler molecules, while acidogenesis and acetogenesis involve the fermentation of these molecules into volatile fatty acids and acetic acid, respectively. Finally, methanogenesis completes the process by converting these intermediates into methane and carbon dioxide (Zhao et al., 2022). Figure 11 summarises the general AD process for seaweeds.

Figure 11. General process of anaerobic digestion of seaweed biomass



Source: https://link.springer.com/article/10.1007/s10311-022-01520-y

In terms of practical applications, biogas serves as a more environmentally friendly option for cooking gas, heating, and generating electricity. Although biogas is commonly utilised for cooking and lighting in households, (usually small-scale), there are also opportunities to use biogas in motorcycles and certain car engines (Papacz, 2011).

While anaerobic digestion of sargassum holds promise for biogas production, it is essential to address potential environmental concerns such as unintentional methane emissions which can offset its environmental benefits. It is therefore crucial to implement strategies to minimise methane emissions and ensure the overall sustainability of the process.

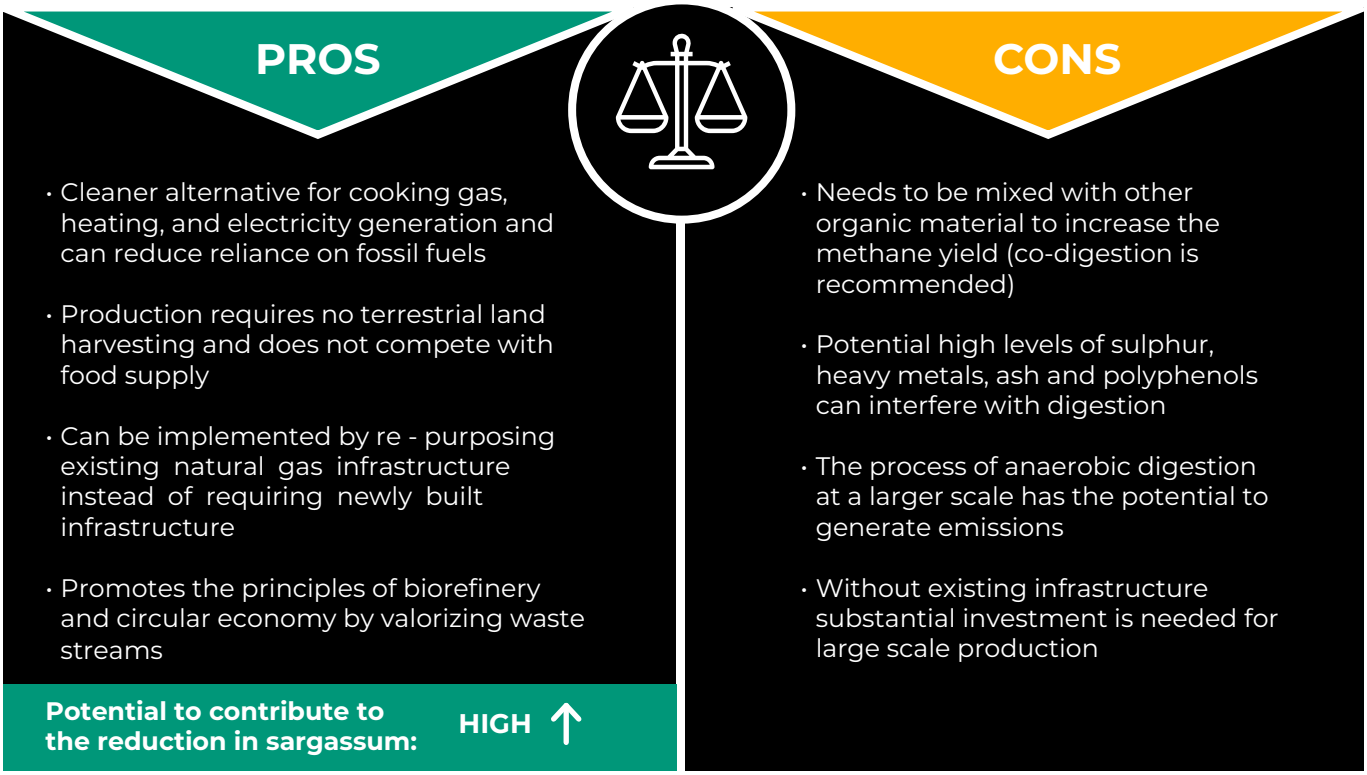
Although there are no companies in the Caribbean that have commercialised biofuel production using sargassum, companies such as EnergYAlgae, Rum and Sargassum and Nopalimex are exploring this potential application. Pioneering studies have also been initiated by Thompson et al. (2021) who assessed the viability of hydrothermal pre-treatment and AD techniques in generating biogas from sargassum and raw food waste as source materials. Findings from the study suggested that an annual feed input of 15,750t of hydrothermally pre-treated sargassum/raw food waste (mass ratio of 25:75) can yield 0.69GWh of electricity, 1.0GWh of heat and 15,750t solid–liquid digestate. Other studies conducted in the region also show the high potential for exploiting sargassum as an energy source (e.g. López-Sosa, 2020; Ávalos-Betancourt et al., 2021; Azcorra-May et al., 2021; Al-lami and Herjevik 2023).

Nopalimex, a Mexican company with a history of developing biodigesters, is planning to establish a new facility to process up to 150t/day of sargassum and produce 20,000m^3/day of biogas, enough fuel to power 500 cars (Galeana, 2023). Additionally, the plant would also generate 60,000L/day of biofertilizers. The initial cost of the plant is estimated at US$133,890.30. In 2019, experimental tests yielded promising outcomes for biogas production, with methane levels ranging from 58% to 65% (Galeana, 2023).

Barbados has also been exploring the applications of biogas within the transport sector. Rum and Sargassum Inc. based in Barbados represents a visionary enterprise and has gained much attention in recent years for its novel approach utilising rum distillery wastewater, Blackbelly sheep manure, and sargassum seaweed, to produce fuel for the local transport sector. The company successfully demonstrated the feasibility of converting gasoline-consuming internal combustion engine (ICE) vehicles to Compressed Natural Gas (CNG) vehicles (Henry et al. 2021). According to the study, the conversion process is not only environmentally sustainable but also economically viable. The estimated cost for this conversion is approximately US$500 USD, making it a cost-effective solution for transitioning to a more sustainable transportation option. This figure encompasses expenses related to acquiring the CNG Kit and the refuelling cylinder necessary for the conversion process. According to Henry et al. (2021) there is increasing evidence of the successful implementation of biomethane to fuel CNG - converted vehicles and thousands of these vehicles already exist in the wider Caribbean region (read more about Rum and Sargassum in Section 6.2).

Thompson et al. (2021) argue that AD facilities/plants present a cost-effective alternative to thermal waste treatment technologies and offer scalability to meet energy demands. They estimate the capital cost for deploying a large, centralised digester processing 30,000 tonnes per annum to be around USD 4 million. Further market analyses are required to guarantee its sustainability within the Caribbean region, coupled with the investigation of storage methods for sargassum to meet the feedstock demand.

Figure 12. **Pros and cons of developing biogas from sargassum**

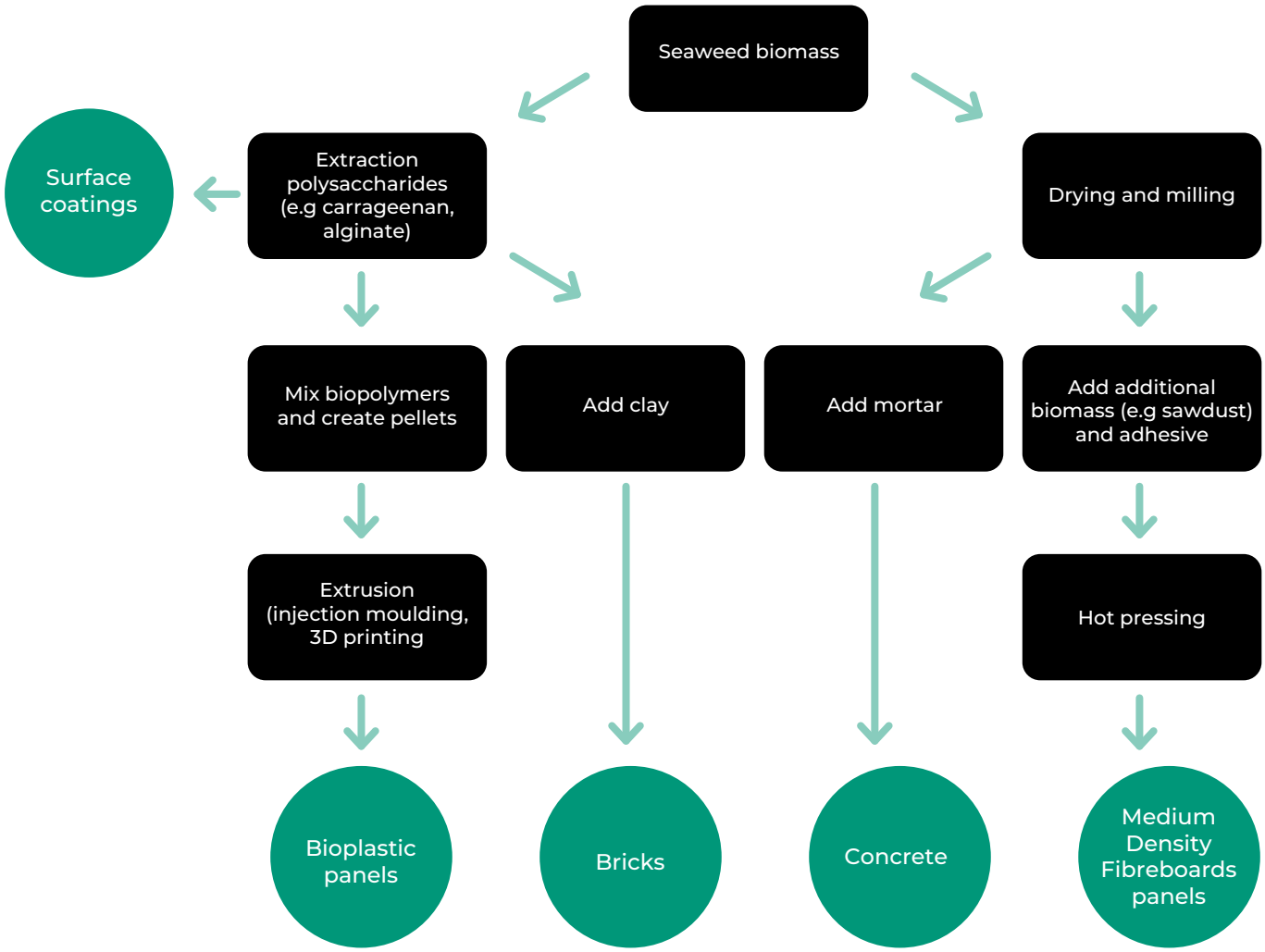


3.6 Construction Material

In certain regions where access to conventional building materials is limited, seaweed has historically been utilised in vernacular architecture (Widera, 2014). Today, as many countries face challenges related to deforestation, there is a growing interest in identifying affordable alternatives to wood. Several studies have asserted that seaweed offers some notable advantages in this regard: it possesses fire-resistance and insulation properties, helps reduce carbon dioxide emissions, has a lifespan of over 150 years, and can also be visually appealing (Widera, 2014; Praveena and Muthadhi, 2016; López-Sosa et al. 2021; Affan et al., 2023). Furthermore, this application has the advantage of using the whole plant with minimal pre-treatment depending on the application. Desrochers et al. (2022) highlight a diverse range of construction materials that can be produced using seaweed, such as resins, foam boards, plastic sheeting, particleboards, slabs, bricks, bio-asphalt, and even furniture. Figure 13 shows examples of processing flows for seaweed derived construction material.

Despite the scarcity of published studies on utilising sargassum biomass in civil construction, the composition of sargassum, abundant in cellulose and other polysaccharides, suggests its potential applications in the sector. Rossignolo et al. (2022) propose that fibres derived from sargassum can serve as reinforcement for composites. These authors, along with Thompson et al. (2020) suggest that the by-products resulting from sargassum processing, like ash produced from burning for energy generation, hold potential for utilisation as a mineral addition in cementitious composites.

Figure 13. **Examples of processing flows for seaweed derived construction material**



Source: https://documents1.worldbank.org/curated/en/099081423104548226/pdf/P175786073c14c01609fe409c202ddf12d0.pdf

In the Mexican Caribbean, López-Sosa et al. (2021) investigated the potential of sargassum as a bioconstruction material. Their research revealed that due to its high organic content, sargassum has low thermal conductivity, making it suitable for use as a thermal insulation material in residential buildings or for energy storage systems in larger structures. Moreover, simulation results conducted by the researchers suggested that a house constructed with cement bricks and sargassum would offer better thermal insulation compared to one constructed with just conventional bricks. This aligns with similar findings from studies conducted by Affan et al. (2023) and Praveena and Muthadhi (2016), which highlight the heat insulation and heat capacity properties of seaweed. These findings present an interesting alternative for the Caribbean region, where temperatures can be high and could potentially reduce the amount of energy needed to cool buildings during hot weather.

While the prospect of using seaweed for construction blocks holds promise for sustainable building practices, consumer confidence hinges on the assurance of quality, durability, and safety, especially as it relates to housing. In a study conducted by Ramasubramani et al. (2016) brown seaweed was used as an additive to concrete, and the durability was tested. The study showed that an 8% addition of the seaweed to concrete showed an increase in strength properties. However, when the seaweed content was increased to 10%, there was

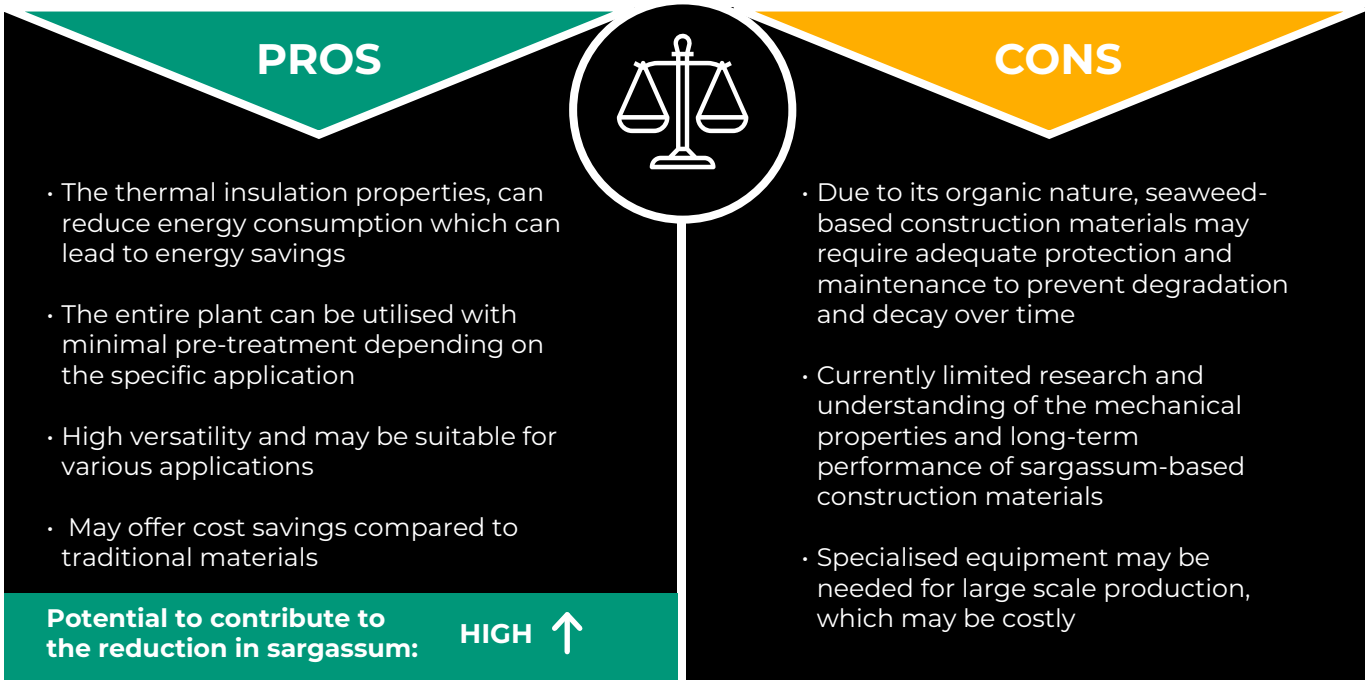
a decrease in these properties. This suggests that there may be an optimal percentage of seaweed content that maximises the beneficial effects on concrete strength, beyond which further addition may have diminishing returns on performance. The potential of rotting in high humidity environments should also be considered (World Bank, 2023). More simulation studies will be needed to ensure long term durability of seaweed construction blocks. Apart from studies on the structural integrity of the blocks, it will also be crucial to quantify their GHG advantages compared to conventional materials. Such studies would provide insights into the overall carbon footprint of sargassum-based construction and help inform sustainable building practices.

In the Caribbean, particularly in Mexico, a few companies have successfully commercialised sargassum blocks for construction purposes. One notable company is the BlueGreen company, which introduced the first bricks made of sargassum, aptly named "Sargablocks." Already the company has sold 20 Sargablock homes and donated another 15 to low-income families in Quintana Roo, Mexico (G.R.O.W. and S.E.E., 2023). Each block comprises approximately 40% sargassum (Desrochers et al., 2022). The company can reportedly create 2000 blocks per day and the blocks only require 4 hours of sunbaking. The blocks are also quite economical ranging from USD 0.42 to 0.51 per block (Desrochers et al., 2022). Studies carried out by the Secretariat of Ecology and Environment of Quintana Roo state, Mexico, found that the resistance of the bricks is 75–110 kg/cm^2, while its durability can be up to 120 years, regardless of the region or climate type where they are used (Desrochers et al., 2022). Read more about BlueGreen in Section 6.10.

Another notable application for the construction industry is "Sargacreto," developed by Grupo Dakatso S.A. de C.V. in Mexico. Their process involves dehydrating the sargassum and then incorporating it into concrete at a concentration of 60% (Miranda et al. 2021). Reports suggest that Sargacreto can be utilised in various construction elements such as sidewalks, blocks, joists, and vaults. However, an evaluation of the properties and characteristics of blocks made from Sargacreto was not published (Miranda et al. 2021).

Cardboard paper, while not typically used as the primary material for structural elements in construction, can still be considered a construction material and has potential applications in various contexts within the construction industry. Kee Farms, based in Jamaica, has developed a cardboard paper prototype using sargassum. They utilise approximately 40 pounds of sargassum to produce a 5-10 feet long sheet of cardboard paper, with around 30 tonnes of sargassum collected each season. According to Key Farms, the process of creating cardboard paper from sargassum is relatively straightforward and takes about 4-5 days to complete depending on the quantity of sargassum collected. It begins with washing and fermenting fresh sargassum, followed by testing for heavy metals and the addition of coconut and bamboo. The materials are then combined and placed on a flat surface, excess water is squeezed out, and the mixture undergoes a printing process using rollers before being left to dry. The resulting product is a sustainable packaging paper that has garnered interest from food chains and printeries alike. Kee Farms is currently in the phase of testing the product, and once successful, will look to begin product marketing.

Figure 14. **Pros and cons of developing sargassum-based construction material**



3.7 Clothing and Footwear

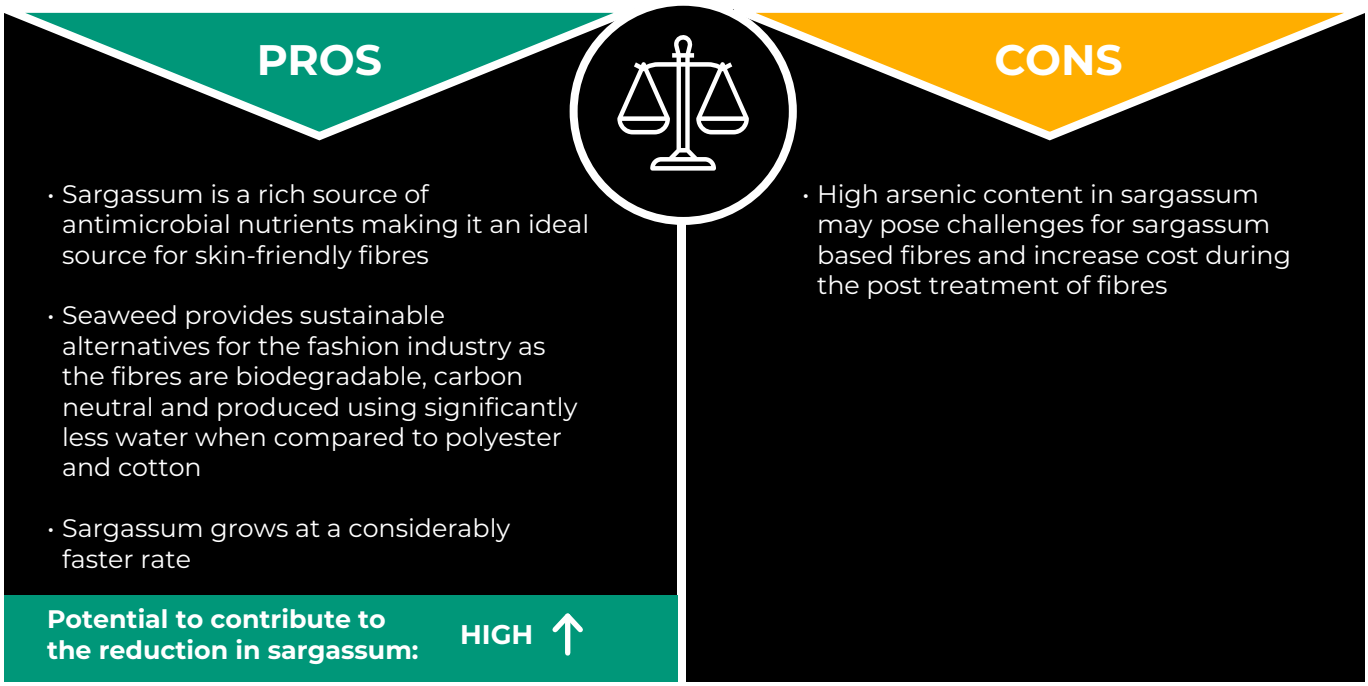
Companies across the United States, Europe, the United Kingdom, and Asia are using algae cellulosic fibres to produce clothing, footwear, yoga mats and backpacks (Algaeing 2021; Bloom 2024; Fabric Link 2024; Keel Labs 2024; Oliver Charles 2024). Cellulosic fibres made from seaweed are typically mixed with other fibres (i.e., eucalyptus and beech wood) and use methods that save both energy and resources (Zhang et al. 2018). While companies are likely to have different Standard Operating Procedures (SOPs), the process of converting seaweed into fibres usually involve 4 main steps: (1) dissolution of pulp fibres (e.g., wood pulp) into liquid pulp via the N-methylmorpholine-N-oxide (NMMO) dissolution method; (2) grind seaweed and combine with liquid pulp; (3) force the seaweed and liquid pulp mixture through tiny holes called spinnerets to create long thin fibres; and (4) washing and post treatment of fibres (Zhang et al. 2018; Oliver Charles 2024). Resulting fibres are biodegradable, carbon neutral and produced using significantly less water when compared to polyester and cotton (Oliver Charles 2024).

Within the Caribbean, the Mexican company 'Renovare Ocean' is the only company, to date, producing footwear from beached sargassum on an industrial scale (Renovare 2022; Desrochers et al. 2022; AIM2Flourish 2024). In an interview with AIM2Florish, CEO Mario Daniel López explained how the arrival of sargassum sparked his innovation to incorporate the abundant bioresource into his already patented footwear made from PET (polyethylene terephthalate) bottles. In the absence of any governmental financial support, Renovare won the Premio Latinoamerica Verde (~US$20,000); this allowed the company to increase their impact and advance their production to the next level (AIM2Flourish 2024). Now holding the patent for creating the material needed to make shoe soles from sargassum, Renovare Ocean has found a way to produce ecological footwear, create job opportunities and address the removal of sargassum biomass from beaches. Within their process, beached sargassum is collected, washed (to remove sand that inhibits the polymer transformation process), sun dried and grinded before it is integrated into the polymer that makes the shoe sole. To increase

the durability of the sole, an inert layer of sargassum may also be incorporated and various chemical elements are added to the sole to stop the sargassum decomposition process (AIM2Flourish 2024). With an estimated monthly production rate of 20,000 pairs or Renovare Ocean shoes, this technological innovation removes approximately 2 tonnes of beached sargassum and provide over 100 jobs (includes persons who remove sargassum from beaches and persons working in the shoe factory) (AIM2Flourish 2024).

On a smaller scale, a 2020 start-up company 'Dadli Yellow' sets out to use sargassum and other natural fibres to create unique eco-friendly textiles (Antigua and Barbuda Science Innovation Park n.d.). This technological solution to address sargassum influxes was formed during the Dadlihack 3.0 Business Competition in Antigua and Barbuda. Dadlihack 3.0 is part of the United Nations Office for Project Services (UNOPS) Global Innovation Challenge that provides funding to support innovative ideas. As a winner of the 2020 Dadlihack 3.0, Dadli Yellow received US$5000 and aims to develop a Caribbean-based micro industry from the manufacturing of marine-inspired textiles (Antigua and Barbuda Science Innovation Park n.d.).

Figure 15. Pros and cons of developing sargassum-based clothing and footwear



3.8 Cosmetics

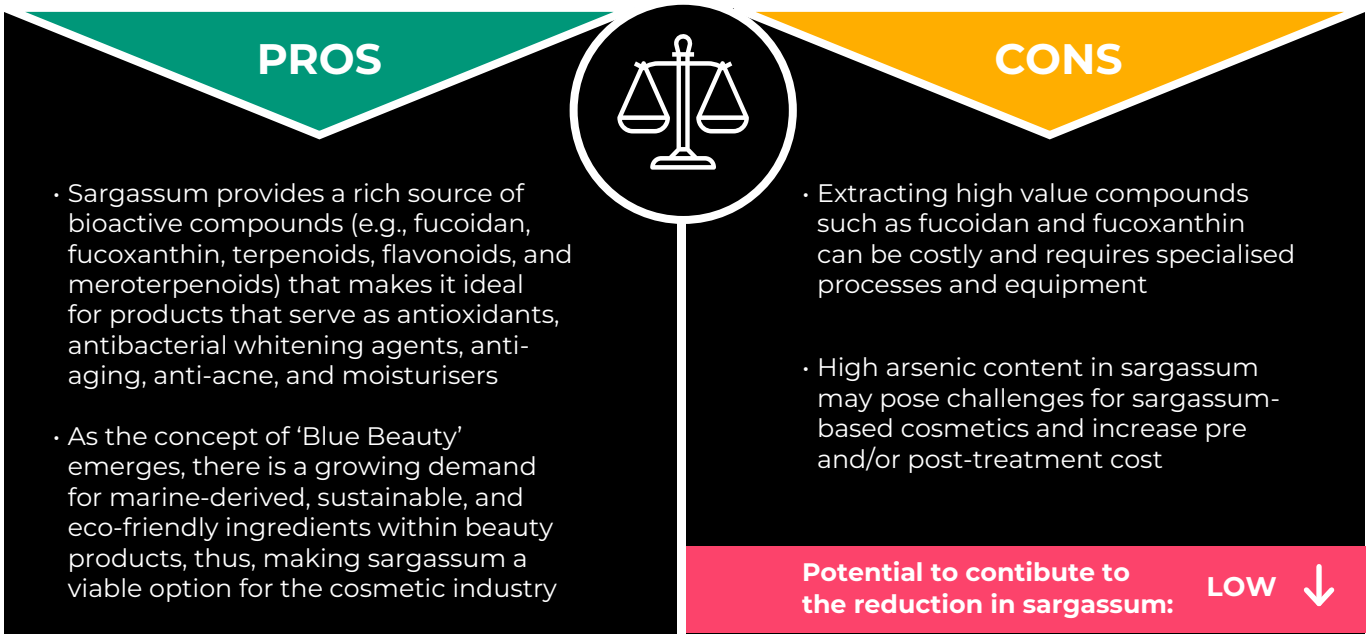
The increasing demand for sustainable, organic, and natural products within the cosmetics industry has resulted in the production of a line of algal-based products given the natural and revitalising properties of seaweeds (López-Hortas et al. 2021; Pagels et al. 2022). Seaweeds provide a rich source of bioactive compounds (e.g., fucoidan, fucoxanthin, terpenoids, flavonoids, and meroterpenoids) that make them ideal for products that serve as antioxidants, antibacterial whitening agents, anti-aging, anti-acne, and moisturisers (Jesumani et al. 2019; Morais et al. 2021; Lee et al. 2022). However, despite the proven potential of seaweed extracts in cosmetics, there has been very little development with the use of sargassum in cosmetic products within the WCR to date.

The 2022 Sargassum Uses Guide previously identified two companies, 'Salgax Biotecnología Marina Aplicada' (based in Mexico) and 'Oasis Laboratory' (based in Barbados) that were

exploring the use of sargassum for beauty products. However, both companies have since ceased operations. According to our research, there is currently only one company 'Spargassum' that uses sargassum to produce spa products (e.g., massage oils, soaps, hair oils). Spargassum co-founders Gennike Mayers and Donnalisa Phillips used the reoccurring mass inundations as an opportunity to incorporate the raw material into a line of cosmetics previously developed by Ms. Donnalisa Phillips. Initially, both co-founders experimented with sargassum in their homes on a very small scale. However, after securing funding (US$10,000) from the Inter-American Development Bank through the Tobago's Blue Economy Ideas Competition, they were able to conduct lab tests (for arsenic and other elements) and experiment with formulations, taking their kitchen-based idea to the next level. Within their process, fresh sargassum is collected at sea, washed thoroughly with rainwater, sun dried and grinded before it is incorporated into soaps and massage oils. As of August 2023, Spargassum products are officially on the market and the company is currently seeking further funding from the Foreign, Commonwealth and Development Office (FCDO) open grants to develop more products and scale up operations (read more about Spargassum in Section 6.6).

To date, the potential application of sargassum within the Caribbean cosmetics industry remains largely 'untapped'. While there are over 20 well established Caribbean owned cosmetic companies none of them currently provide algal/seaweed-based products (The Karibbean Kollective 2024). However, with several labs (e.g., Tecnologico de Monterrey, School of Engineering and Sciences and Instituto Tecnológico de Santo Domingo) successfully extracting alginate from sargassum there is potential for Caribbean cosmetic products to use alginate from sargassum as a thickening and gelling agent and/or to provide intense hydration in facial products.

Figure 16. Pros and cons of developing sargassum-based cosmetics



3.9 On shore and in-water harvesting

Overcoming the current challenges associated with sargassum undoubtedly requires large scale valorisation and by extension the harvesting of that sargassum. However, harvesting was identified as one of the major challenges of sargassum valorisation (Oxenford et al. 2021).

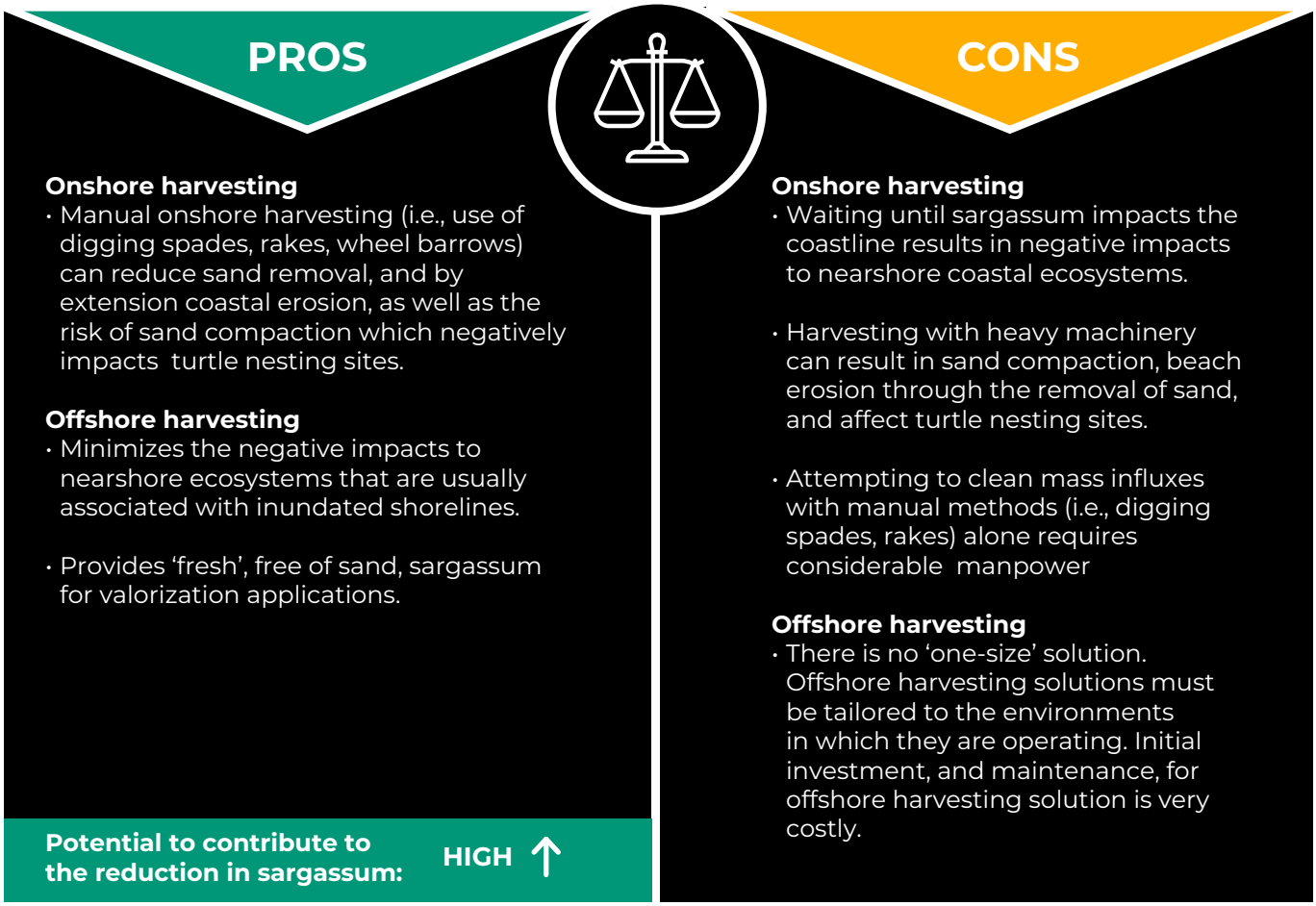
To date, there has been significant variability in the methods used to collect/harvest sargassum (United Nations Environment Programme - Caribbean Environment Programme et al. 2021). Collection/harvest methods largely fall into 5 categories, offshore barriers (e.g., floating booms with meshed skirted fabrics), mechanised offshore collection (e.g., harvesting barges, suction pumps), manual onshore collection (e.g., rakes, shovels, forks, wheelbarrows), mechanised onshore collection (e.g., tractors, long arm excavators, machine surface beach rakes) and collection assistance equipment (e.g., beach groomers, dump trucks) (Chereau 2019).

Across the Eastern Caribbean (e.g., St. Lucia, Dominica, Grenada, and St. Vincent and the Grenadines) harvesting efforts predominantly consist of manual and mechanised onshore collection methods (Sargassum Information Hub n.d.). While there have been some attempts, with varying success, to use offshore barriers in Bequia, stakeholders ultimately resorted back to onshore collection methods (Sargassum Information Hub n.d.). Barbados, like much of the Eastern Caribbean, has also relied largely on manual labour and heavy onshore equipment to clear sargassum from affected beaches; however, there have also been attempts with mechanised offshore collection and offshore barriers. In 2020, the Ministry of Maritime Affairs and Blue Economy (MMABE) was able to purchase a seaweed harvester (the aquamarine aquatic weed harvester) to assist with collection. However, the harvester has not been utilised since its preliminary test that took place off the east coast of the island. Mechanised offshore harvesting efforts made by Barbados, although commendable, demonstrated the importance of having tailor made harvesting solutions. Although the purchased seaweed harvester is capable of successfully removing aquatic weeds and floating debris from water reservoirs, ports, rivers, and lakes (Aquamarine Inc 2024) it was not ideal for harvesting sargassum within the turbulent Atlantic Ocean waters found on the east coast of the island. Similarly, efforts to implement offshore barriers off the southeast coast of the island were unsuccessful (Sargassum Information Hub n.d.). Although attempts at offshore collection in Eastern Caribbean countries and Barbados were done to no avail, there is still potential for future success as St. Lucia, St. Vincent and the Grenadines and Barbados are expected to receive offshore equipment (e.g., floating boom barriers, aquatic conveyors, work boats) through “The Project for Improving National Sargassum Management Capacities in the Caribbean” funded by the Government of Japan (Sargassum Information Hub n.d.; UNDP 2024).

Within the Spanish speaking Caribbean (Mexico and the Dominican Republic) there have been notable efforts at mechanised offshore collection. In Mexico, the Secretaría de Marina (SEMAR) frequently harvests sargassum that is maintained at sea with the use of offshore barriers. Harvesting vessels developed by SEMAR are capable of harvesting ~20 tons of sargassum per day (Sargassum Information Hub n.d.). In addition to SEMAR, several private companies have developed offshore barriers (e.g., GOIMAR, Dakatso, Ocean Solutions México, Manufacturas Industriales DP, Sargazo Solutions, DESMI) and conduct mechanised offshore collection (e.g., Preyco, Tecno Productos GAB, GOIMAR, Dakatso, DESMI, Thalasso) (Sargassum Information

Hub n.d.). In the Dominican Republic, AlgeaNova has developed a suite of innovative systems including barriers, harvesting barges and cleaning vessels that efficiently capture and remove sargassum before it reaches the shorelines (Sargassum Information Hub n.d.). With their aim to revolutionise the process of offshore harvesting, AlgeaNova has developed barges that are capable of collecting ~200 tons (a 10-fold increase when compared to other harvesting models) of sargassum per day (AlgeaNova 2024). Moreover, AlgeaNova offshore barriers are adapted to the place and conditions of implementation and carry 3-times more anchorage than other models (AlgeaNova 2024). On a smaller and more affordable scale, Sargassum Ocean Sequestration of Carbon (SOS Carbon) has developed an innovative harvesting technology called the Littoral Collection Module (LCM) that is adaptable to fishing vessels (SOS Carbon 2022; Sargassum Information Hub n.d.). The LCM is ideal for harvesting sargassum in bays and relatively calm offshore and nearshore environments and is capable of collecting ~ 70 tons of sargassum per day using one vessel (read more about SOS Carbon in Section 6). Beyond serving as benchmarks for the rest of the region, the suite of harvesting solutions observed in Mexico and the Dominican Republic reflect the adaptability and scalability needed to provide large volumes of fresh sargassum for the valorisation of sargassum.

Figure 17. Pros and cons of onshore and in-water harvesting



4 Community Perspectives

Sargassum influxes have emerged as a pressing issue for coastal communities in regions such as Mexico, the Dominican Republic, and Puerto Rico. The impact of these influxes extends beyond mere inconvenience, affecting various facets of daily life, economic activities, and environmental health. In response to this challenge, numerous technological solutions have been implemented, aimed at mitigating the effects of sargassum on affected communities. To assess the efficacy of these solutions and understand community perspectives, a survey was administered to residents from neighbourhoods surrounding sargassum businesses.

4.1 Respondents' profile

Efforts were undertaken to involve at least 50 community members from Mexico, the Dominican Republic, and Puerto Rico in the survey. However, only 29 individuals were willing to participate, leading to a relatively small sample size. Notably, just over half of the participants (51.7%) were aged 56 or above, reflecting the presence of long-standing community members who have witnessed the evolution of sargassum-related challenges over time. Additionally, more than a quarter (27.6%) had resided in their communities for 16-25 years, indicating a deep-rooted connection to the local environment. In terms of employment, over half of the respondents (51.7%) were employed within the community, predominantly in tourism, service, and sales sectors.

4.2 Sargassum impacts

All survey participants unanimously reported being negatively affected by sargassum influxes, highlighting a range of adverse consequences. Among these were the inability to engage in leisure activities due to the presence of sargassum on beaches, resulting in a loss of beach access for both residents and tourists alike. The accumulation of sargassum also emitted

offensive odours, creating an unpleasant environment for coastal communities. Furthermore, instances of flooding occurred when vast amounts of sargassum obstructed waterways, exacerbating existing drainage issues and posing a risk to nearby properties.

Additionally, the health-related repercussions of sargassum influxes were a concern among respondents. Respondents experienced skin rashes, nausea, respiratory ailments, and headaches, indicating a range of adverse health effects associated with exposure to sargassum. These findings underscore the multifaceted impacts of sargassum on community well-being, highlighting the urgent need for effective mitigation and management strategies to address the various challenges posed by sargassum influxes.

4.3 Awareness of technological solutions

There was a notable lack of awareness of sargassum businesses present within their communities, with only 24.1% of respondents indicating awareness. These individuals were knowledgeable about businesses who developed machinery designed for harvesting sargassum both onshore and in-water, products derived from sargassum, and technologies for processing sargassum. Their awareness primarily stemmed from direct interactions with representatives of sargassum businesses, informal communication channels, such as word of mouth, and online platforms like social media. Notably, there was an expression of interest (72.4%) in the establishment of sargassum-related enterprises, underscoring the community's eagerness to explore innovative solutions. The majority of respondents expressed a preference for sargassum harvesters and the development of sargassum-derived products such as compost, fertilizer, construction material, bioenergy, and pharmaceuticals.

4.4 Perception on sargassum innovations

When those participants who were aware of community-based sargassum businesses were asked to rate the effectiveness of existing technological solutions, respondents provided a moderately positive rating, with a mean score of 3.6 out of 5. They acknowledged the utility of these solutions in removing sargassum from beaches, creating employment opportunities, and enhancing the overall tourist experience. However, several challenges and drawbacks associated with current solutions were identified, including a lack of government support, insufficient resources for sustainable actions, limited public awareness, inadvertent entrapment of marine species in sargassum harvesters and barriers, and wastage of unprocessed sargassum.

In light of the identified challenges, respondents offered valuable suggestions for enhancing sargassum management strategies. These included advocating for greater sargassum removal efforts and the installation of barriers to intercept sargassum before it reaches shorelines. Additionally, calls were made for improved collaboration among relevant stakeholders to reduce fragmentation of responses, the formation of dedicated sargassum working groups, and the development of comprehensive management plans focused on sustainability and research. Respondents also emphasised the importance of community involvement in addressing the sargassum issue effectively and wanted more initiatives or opportunities for residents. Moreover, participants suggested exploring innovative solutions such as developing treatment plants for processing unusable sargassum, thereby turning a perceived waste material into a valuable resource.

4.5 Community engagement

Despite the acknowledgment of the importance of community involvement, the survey highlighted a disparity in the level of engagement in sargassum-related activities among community members. Just one person was employed in sargassum businesses within their community. This respondent serves as an Environmental Coordinator in a company specialising in processing sargassum. Similarly, just one person indicated employment in a sargassum business outside of the community, holding a position within a National Cabinet of Sargassum. The presence of a member of the National Cabinet of Sargassum among the respondents signifies the opportunity for broader collaboration and coordination at the national level.

While direct employment in sargassum-related businesses was limited, the survey revealed that some community members were actively involved in various activities related to sargassum management. These activities included beach cleanups, educational initiatives, coordination of sargassum management activities, and providing funding and capacity building to sargassum-related projects. Such grassroots efforts demonstrate the commitment of community members to addressing the sargassum issue through collective action and collaboration. Community engagement plays a crucial role in addressing complex environmental challenges and can foster a sense of ownership and responsibility towards sargassum management.

The survey also highlighted challenges related to information dissemination and awareness within impacted communities. Participants indicated receiving infrequent updates about developments related to the sargassum business in their community, suggesting a need for improved communication channels and outreach efforts. Enhancing community awareness and engagement through regular updates and information sharing could foster greater participation and support for sargassum management initiatives.

While technological solutions hold promise in mitigating the impact of sargassum influxes, community involvement is paramount for their effective implementation. By understanding community perspectives and leveraging local knowledge, it becomes possible to develop more effective, inclusive, and sustainable strategies for managing sargassum influxes. At the same time, this approach fosters environmental stewardship and resilience. Moving forward, collaboration among stakeholders, proactive government support, and robust community engagement will be essential in implementing holistic solutions that address the multifaceted impacts of sargassum on coastal communities.

5 Assessment of Technological Solutions

Given the rapid development of technological solutions in the sargassum space, this section seeks to (1) assess existing valorisation initiatives based on feedback from stakeholders; and (2) propose a rapid assessment methodology that can be used to advise and inform aspiring innovators of the most effective and sustainable uses. It must be noted that although scaling up sargassum businesses can lead to increased profits, it may also result in substantial operational and maintenance costs.

5.1 Stakeholder opinions regarding the different technological solutions

Across the Caribbean and Latin America, technological solutions developed to address sargassum influx events include onshore and in-water harvesting machinery as well as various sargassum by-products (e.g., compost, liquid extracts, bioplastics, biogas, construction material, clothing and footwear, and cosmetics). With the sargassum industry still in early stages of development, it is difficult to determine how the quality and performance of existing solutions compare to similar products on the market. Moreover, beyond functionality there is no assessment criteria to assess how existing technological solutions strengthen the resilience and adaptation of affected stakeholders. In this study, an initial assessment of existing solutions is provided based on feedback from entrepreneurs, sargassum scientists, government officials and community members.

Fifty stakeholders, distributed across various sectors of sargassum management, were interviewed to: (1) assess their knowledge of existing solutions; (2) understand stakeholder preferences, if any, on technological solutions; and (3) gather stakeholder opinions on what makes a solution efficient. Results indicate that although the majority (~ 60%) of stakeholders were aware of all the existing technological solutions, interviewed participants showed a

preference for solutions that directly/indirectly remove large quantities of sargassum and solutions that provide opportunities for community involvement and are easily adopted by communities. Specifically, participants expressed interest in compost and liquid fertilizers, construction materials, and onshore and in-water harvesting.

5.1.1 Compost and liquid extracts

Although many Caribbean countries import between 60-80% of their basic food requirements, the agricultural sector employs between 10-25% of the population (Phillips 2022). In addition to the high food imports, Caribbean countries also import the majority of their fertilizers that are used in agricultural practices. Sargassum, having high levels of micro and macro nutrients, can provide alternative locally produced compost, biofertilizers and biostimulants. During early sargassum influx events, composting and fertilizer production became widely adopted across agricultural practitioners due to their cost-effective and relatively straight forward production (Desrochers et al. 2022). To date, companies such as Algas Organics, Grogenics, Dianco de Mexico, and Red Diamond process between tens of thousands to over 200,000 tons of sargassum per year. Based on feedback from stakeholders the development of compost and liquid based fertilizers are one of the most preferred solutions based on the large quantities of sargassum biomass that can be utilised and by extension removed from beaches and the nearshore environment. Additionally, stakeholders showed a high interest in learning practical approaches for developing sargassum-based compost and fertilizers. Although there are concerns associated with high salt content and unknown arsenic levels, the high potential of this solution to reduce the levels of sargassum experienced during severe influx events; and the high interest among community members makes this solution ideal for increasing the resilience and adaptation of countries to sargassum influx events.

5.1.2 Construction materials

Within Latin America and the Caribbean, the market for construction material is bigger than most with increasing urbanisation and the need for low-cost building materials. Moreover, existing construction applications such as Sargablocks and Sargacreto have demonstrated that construction materials have the potential to use between 40-60% of sargassum; this is more than most existing applications.

To assess the potential of construction materials as a technological solution for increasing the resilience and adaptation of affected communities, this study uses BlueGreen Mexico as an example. Located in Mexico's northeastern Yucatán Peninsula this company produces sargassum blocks, 'Sargablocks' that have a composition of 40% sargassum. With sargassum arriving 'free' of cost and the fact that this application uses the entire sargassum thallus with minimal pre-treatment, Sargablock are sold for affordable prices (USD 0.42 to 0.51 per block) providing a low-cost building material to families throughout Riviera Maya Mexico. In addition to providing families with low-cost housing, BlueGreen also engages approximately 300 families in sargassum harvesting efforts.

Taking, functionality, the quantity of sargassum utilised, and the importance of the technological solution to the community, Sargablocks and other similar applications, ranks high among existing applications. Sargablocks use large volumes of sargassum (a production rate of 2000 blocks per day), has a high market demand, and facilitates large-scale community involvement, making this a viable application for increasing the resilience and adaptability of affected communities.

5.1.3 Onshore and in-water harvesting

Across the interviewed participants, there was a high preference for technological solutions that significantly reduced the quantities of sargassum within the nearshore environment and on beaches. Harvesting solutions, whether onshore or in-water, can reduce the quantities of sargassum that impacts communities during severe influx events. Since the arrival of sargassum, harvesting technologies have expanded to include innovative systems of beach rakes, barriers, harvesting barges and cleaning vessels that effectively capture and remove sargassum. To date, companies such as AlgeaNova, Thalasso Ocean, SOS Carbon and SEMAR are capable of harvesting between 20-200 tons of sargassum per day. Existing harvesting solutions vary in efficiency based on the quantity of arriving sargassum and local site conditions. Thus, evaluating the quality and efficiency of the various harvesting technologies is context dependent and requires future individual assessments.

Within the context of valorisation, harvesting solutions alone are not enough to increase the resilience and adaptability of communities. While these technological solutions can indeed increase a country's ability to withstand sargassum influx events, adaptability should be reflected in an observable adjustment in behaviours (e.g., increased sargassum uses and improved sargassum management). With that said, harvesting solutions will undoubtedly remain an important component of valorisation as it is required to attain the large quantities of sargassum needed for other applications. Considerations for future assessments could potentially include: the cost of harvesting solutions (initial and operating cost), the number of persons required to carry out the harvesting, and any existing harvesting regulations to which the chosen harvesting method must comply.

5.2 Determining the effectiveness and sustainability of technological solutions (Sargometer)

During the initial assessment, technological solutions were evaluated based on stakeholder preferences, the quantity of sargassum utilised, and the community importance of that solution. In this section, the Sargometer is proposed as a method for determining the effectiveness and sustainability of the full range of technological solutions. The Sargometer concept is a recommended assessment designed to give entrepreneurs an understanding of the major factors that would affect the sustainability and effectiveness of a particular solution. Beyond this initial assessment, sargassum value chain analyses should be undertaken to support feasibility analyses and determine the level of investment required for each potential initiative.

Ten (10) factors/criteria are proposed to support a rapid assessment of the solutions featured in Section 3 (Table 1).

Table 2. Descriptions of the proposed 10 factors/criteria to assess the effectiveness of valorisation applications

	Factors/Criteria	Description
1	Harvesting logistics	The detailed coordination of sargassum collection. Indicates the number of persons required, the required machinery/equipment and the type of harvesting (i.e., shoreline vs offshore) that will be undertaken.
2	Land Space requirements	Total size of the coastal land space required for sargassum offloading (from harvesters) and onloading (onto transport vehicles). Also considers the total inland space required for sargassum drying, storage and processing.
3	Need for additional feedstock	Sargassum by-products require supplementary raw materials to improve the product quality.
4	Processing time	The overall time required to process the raw sargassum biomass to achieve a specific product.
5	Specialised equipment requirements	Specific equipment/technology required during the development of sargassum products (e.g., extraction machinery needed to attain high value compounds).
6	Waste management requirements	Refers to all actions taken, and plans created to manage waste generated during the development of sargassum by-products.
7	Marketability/return on investment	Gauges the 'attractiveness' of the sargassum product to potential consumers, the ability of that product to be sold or marketed and the profitability of a valorisation application by comparing the gain or loss to its cost.
8	Regulatory Requirement	Currently there is a lack of national and regional regulatory requirements governing sargassum valorisation. For the purpose of this assessment, valorisation applications were ranked based on potential harvesting and arsenic regulations outlined in Section 8 of this study.
9	Community impact or national importance	Assesses the significance of the innovation in addressing community challenges (e.g., mass inundations reduce beach use and hinders access to fishing vessels) and estimates the value provided to the community (e.g., improved living conditions, jobs, support blue economy development and renewable energy sector).
10	Environmental impact	Measures the contribution to greenhouse gas emissions, biodiversity preservation, reduction of environmental pollution and resource efficiency.

The rapid assessment, proposed by the Sargometer concept, assigns a score 0 to 5, with 0 being the most effective and 5 being the least effective, to each of the ten factors/criteria. Annex 3 provides a detailed score breakdown for each of the identified factors/criteria used in Sargometer assessment. The proposed score breakdown is based on information provided during interviews with entrepreneurs, government officials, and scientists.

After a score of 0 to 5, with 0 being the least effective and 5 being the most effective, is assigned to each of the 10 factors/criteria for a given solution, the final Sargometer rating is attained by finding the sum of those values (Table 3). The scores are based out of 50 with a higher score suggesting a more viable and effective solution that can be sustained for commercialisation.

Table 3. Proposed Sargometer scoring sheet to be completed by innovators and entrepreneurs

Technological Solution	SARGOMETER RATING										Overall Score
	Harvesting logistics	Land space requirements	Need for additional feedstock	Processing time	Specialised equipment requirements	Waste management requirements	Marketability/ return on investment	Regulatory requirements	Community or national importance	Environ-mental impact	
Compost											
Liquid extracts (biotonics, fertilizers)											
Bioplastics											
Biogas											
Construction material											
Clothing and footwear											
Cosmetics											
Onshore and in-water harvesting											

5.2.1 Challenges, limitations and benefits of the Sargometer

The proposed Sargometer provides a quick and relatively straightforward method for determining the effectiveness and sustainability of technological solutions. However, it is important to acknowledge that the proposed factors/criteria for determining the effectiveness of each solution may not be the only factors that should be considered. Additionally, the proposed score breakdown is based on the information provided by a relatively small sample size and thus limits our ability to determine how factors may change when technology solutions are operating at vastly different scales. For example, this study only included one company within the cosmetics industry operating at a small scale. It was therefore difficult to fill the Sargometer scoring sheet for cosmetic technological solutions based on a single entry. While the score breakdown and Sargometer proposed in this study can and should be used as a starting point for initial assessments, it is recommended that a deeper analysis, with multiple participants of the same technological solution, be conducted.

6 Regional Case Studies

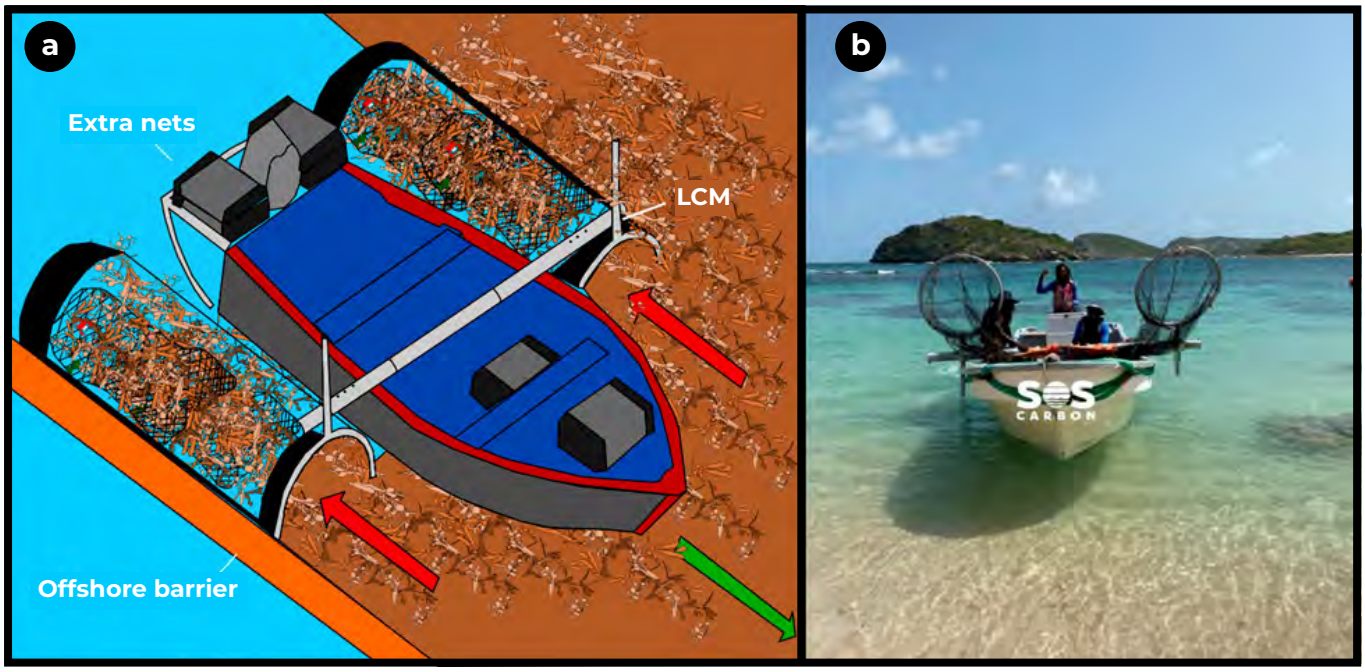
In this emerging industry, numerous inspiring innovators across the region have risen to become leaders, surmounting the considerable challenges that exist in creating sargassum businesses. This section is dedicated to sharing their stories, shedding light on their product development journeys, successes, challenges, and words of wisdom. Through these narratives, we gain insight into their remarkable achievements and the lessons they have learned along the way. Many of the featured case studies have already begun commercialising their products and services and hold significant potential for scalability and replication in other countries.

6.1 SOS Carbon- Riding the Wave of Innovation

Across the WCR, the year 2018 marked a significant increase in bloom events with record breaking quantities of sargassum biomass observed within the GASB (e.g., > 20 million metric tons in June 2018) (Wang et al. 2019). For SOS Carbon, 2018 was the year a young group of engineers, who had a mission to develop technologies that transform environmental crises into opportunities, focused their efforts to address the sargassum crisis.

SOS Carbon tackles the environmental, social, and economic issues caused by sargassum in the Caribbean via a series of products and services to collect, pre-process, and valorise sargassum. The business idea started when Andrés Bisonó-León, Founder and CEO, partnered with a professor at Massachusetts Institute of Technology (MIT) to develop a solution that would address the large quantities of sargassum and generate a lasting impact. After spending 2 years in the Research and Development phase, the Littoral Collection Module (LCM) was developed. The LCM is a low tech, adaptable mechanism that mounts onto artisanal fishing vessels without any required changes to the vessel itself (Figure 18).

Figure 18. Schematic of the Littoral Collection Module (LCM) (Panel a) and the LCM attached to a vessel at sea (Panel b)



Within this system sargassum is collected in nets that remain in the water until they are detached at the shore (Figure 19). Adapting to the different coastal environments within the Caribbean, the nets of sargassum can be collected from beached environments using all-terrain-vehicles (ATVs) or from rocky environments with the use of a crane. The selected collection method depends on what is more appropriate for a given location.

Figure 19. Nets of sargassum that were collected using the Littoral Collection Module (LCM)

Although the LCM appears small in size, it has made major strides within the sargassum harvesting sector. One vessel with an attached LCM is capable of harvesting ~70 tons of sargassum per day and covers 1km of beach. Since starting their harvesting efforts in 2020, SOS Carbon has collected ~25 million tons of sargassum and expanded their operations across four Caribbean countries (Dominican Republic, Mexico, Antigua and Barbuda, Puerto Rico). In addition to their harvesting efforts, the company launched a Marketplace for sargassum where they have exported varying volumes (e.g., samples weighing a couple grams to container loads) of sargassum to more than 10 countries located in Europe, Asia, and the United States.

Within their LCM operations, SOS Carbon provides environmental, social, and economic benefits. Harvesting sargassum at sea allows them to avoid coastal inundations and by extension protect valuable nearshore ecosystems, tourism dependent facilities, and social activities. Additionally, their low tech easy to use LCM allows them to actively engage local communities in collection efforts. Each operating vessel generates up to 10 jobs with 5 individuals tasked with onboard operations and another 5 based on shore. To date, fishers have been key players in SOS Carbon day-to-day operations. After receiving initial training from SOS Carbon, local fishers are formally hired by SOS Carbon or by the Client in case of deployment through their licensing program. Fishers' monthly compensation have increased as much as 20% in comparison to what they would typically make within the fishing sector. CEO Andrés Bisonó-León points out that this relationship is mutually beneficial as fishers are very familiar with the marine environment in which operations occur and they offer valuable insights. As the company continues to expand their operations, they hope to reach and actively involve more communities and stakeholders.

Most recently, SOS Carbon has been focused on the development of a bio-stimulant (Figure 20) from sargassum.

Figure 20. Biostimulant being used in field applications

Research and development for the bio-stimulant is being conducted with SOS Carbon partners at the Universidad Católica de Valencia San Vicente Mártir in Spain. The developed formulation, Ocean Sustain, meets EU standards on impurities and heavy metal content levels. SOS Carbon is currently validating the efficiency of the sargassum-based bio-stimulant and plans to produce 1 million gallons per year in their first phase. They anticipate that this product will increase crop yield, reduce the quantity of fertilizers used, and serve as an organic alternative to the chemical fertilizers that are currently on the market. Production of the bio-stimulant falls within the company's larger goal to be a platform for propelling the transformation of environmental crises in the Caribbean into value chains.

Since the start of their operations the SOS Carbon team has grown substantially, now consisting of experts in engineering, business development, operations, research, and development, biorefinery and fishing. As their team continues to grow so does their capacity to find scalable and adaptive management solutions to the sargassum crises. The SOS Carbon team has successfully navigated through all the challenges they have encountered (e.g., seasonality and volume fluctuations) and it is their mission to serve as a supplier for reliable feedstock to other sargassum entrepreneurs across the Caribbean.

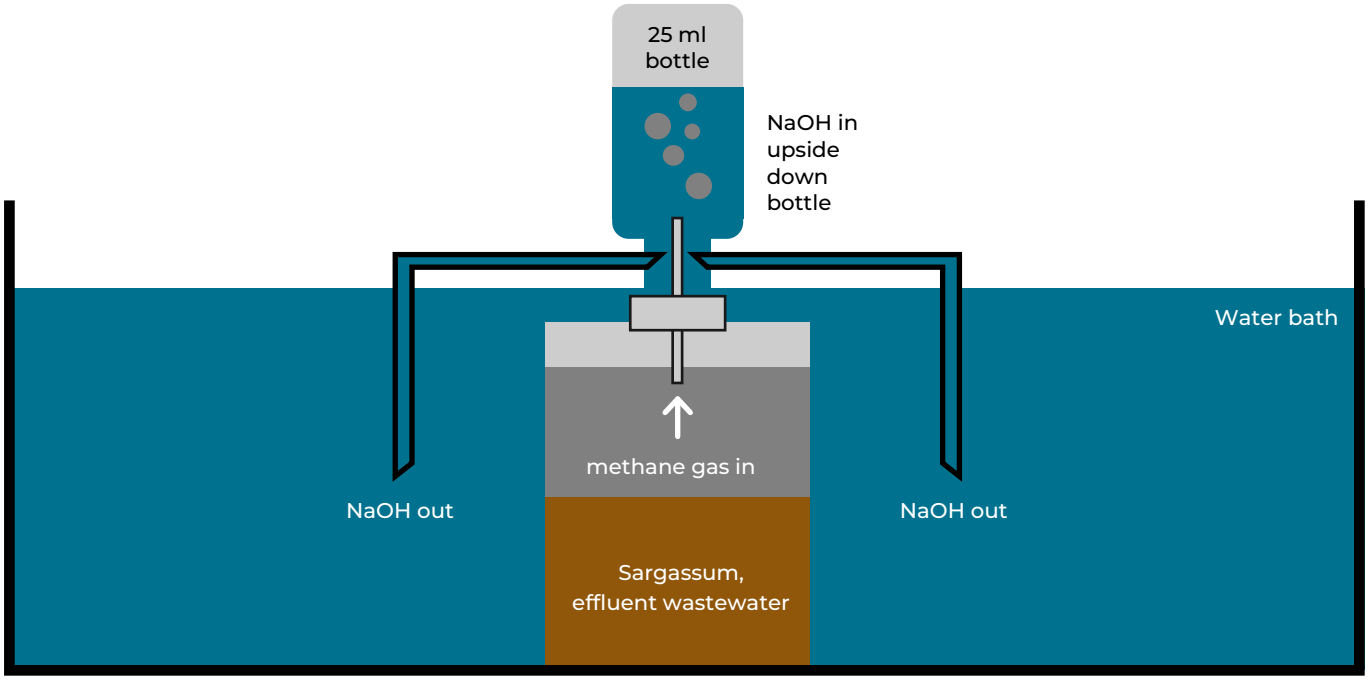
6.2 Rum and Sargassum- Fuelling Barbados' Green Revolution

The global movement to combat climate change has resulted in the transformation of energy systems as well as policies, government and business agendas and civil society at large (International Renewable Energy Agency 2019). Within the next three decades the world is expected to shift away from fossil fuels, towards electrified transport (International Renewable Energy Agency 2019). In alignment with global initiatives, Barbados is on a mission to become fossil fuel free by the year 2030. To help Barbados achieve this mission, Dr. Legena Henry (Founder and CEO of Rum and Sargassum) and her team has been working arduously to produce bioenergy solutions using a combination of sargassum and the waste product from local rum distilleries in Barbados.

Within their process, fresh sargassum is collected at sea and then pretreated to reduce potential damage to the digesters. Once pretreated, sargassum is dried and placed in anaerobic digesters that contain varying quantities of effluent and high Chemical Oxygen Demand (COD) rum distillery waste in order to produce biogas (Figure 21). Dr. Henry explains that the biogas produced at this stage of the process is raw biogas which contains carbon dioxide, water, hydrogen, and methane. Since the primary objective is to obtain a gas that is predominantly methane, the raw biogas needs to go through a purification process. After purification, methane can then be compressed to fill cars.

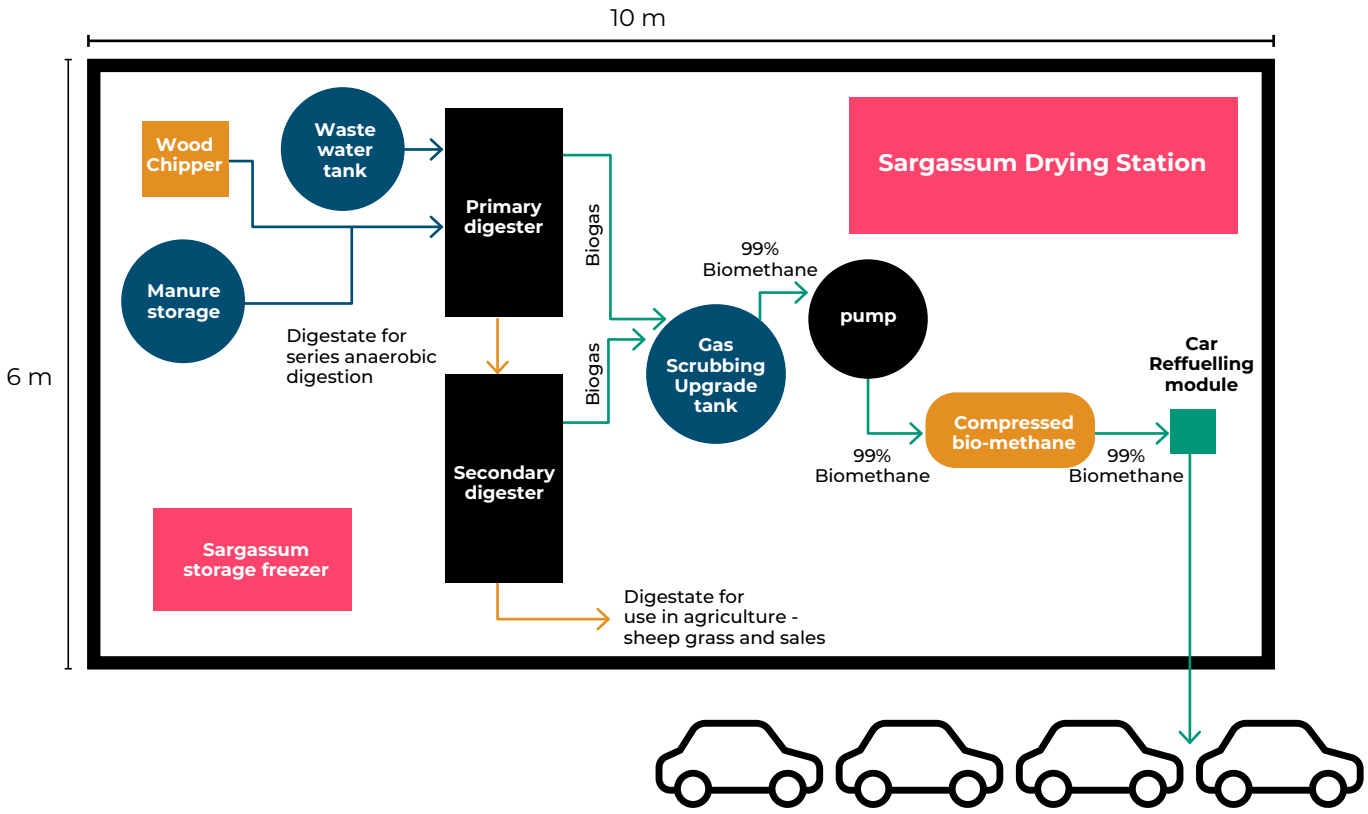
Currently, Rum and Sargassum has two ongoing pilot projects and recently received European Union (EU) funding for a third pilot project. The first pilot project is being conducted in collaboration with the Barbados National Oil Company (BNOP) and aims to drive 6 cars in Barbados on sargassum for 6 months to raise awareness, and to garner support (Figure 22). The second pilot project focuses on the production of cooking gas at the MIC Institute of Technology in Tobago and the third project aims to use their product for a commercial kitchen in Grenada.

Figure 21. **Experimental setup for biomethane potential test**



Source: Inter-American Development Bank (2021).

Figure 22. **Schematic of a potential lab/operations layout**



Source: Henry et al. 2021.

Since formalising the business in 2021, Dr. Henry stated that it has been challenging navigating the path from university research to commercialisation. Taking their lab research into the pilot phase costs approximately US$600,000 and after completing the pilot phase it will cost approximately US$2 million to enter the pre-commercial phase before they can officially take Rum and Sargassum into the marketplace. Following their current plan, Rum and Sargassum aims to be fully operationalised with their first sales at the pump occurring in 2026. Dr. Henry noted that her vision for Rum and Sargassum to become a large-scale business that produces fossil free transport fuel is shared by her multifaceted team of researchers (e.g., mechanical engineers, microbiologists, environmentalists, data scientists) and her technical advisory team who are all being paid with 1% of future equity.

Barbados is now 6 years away from a national goal of 100% fossil fuel free transport and almost 100% of the 134,600 registered vehicles in Barbados have internal combustion engines (powered by gasoline). However, Rum and Sargassum believes that the solution to the energy demand lies in the tons of sargassum that arrives yearly at the country's shoreline. Under their current model, approximately 120 kg is required to supply one car with fuel for two weeks. Dr. Henry acknowledges that the transition to clean energy can typically be expensive, stating that most persons find the idea of acquiring and maintaining an electric vehicle beyond financial reach. However, Rum and Sargassum aims to be an inexpensive renewable energy solution for the average person. As such, their biomethane product can be used in any gasoline car with a one-time installation of a Compressed Natural Gas (CNG) kit that typically takes 2-4 hours to install. Furthermore, to make their solution economically feasible, Rum and Sargassum aims to supply a product that will allow consumers to pay half of what they are currently paying for every kilometre driven.

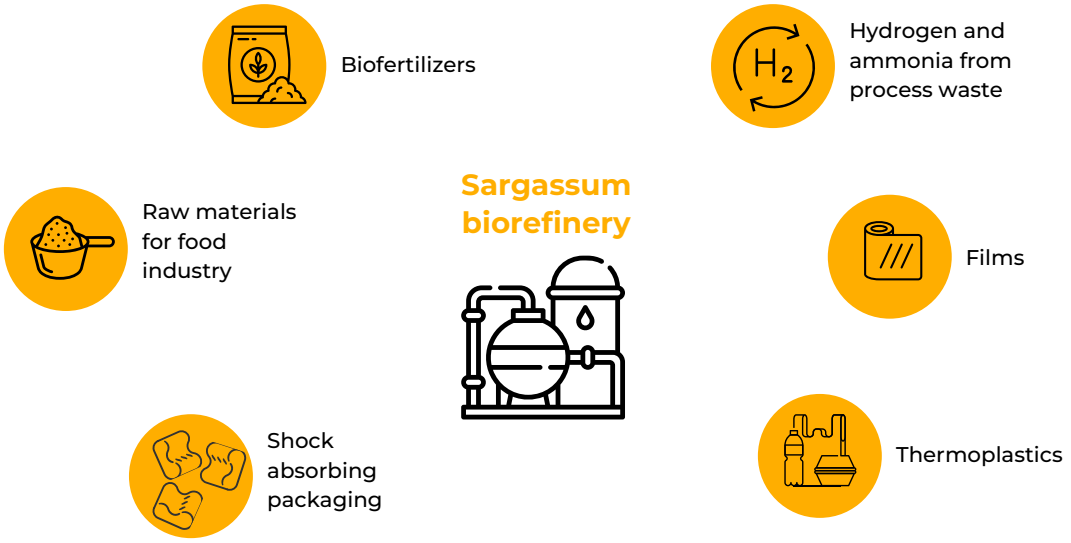
While the initiatives of Rum and Sargassum primarily seek to provide sargassum free beaches as well as a clean and inexpensive energy solution, there is also a huge carbon emission potential. Under their project, approximately 70 million metric tons of carbon dioxide can be removed from the atmosphere for every 100,000 cars. What initially started as a threat stands to become the fuel that powers the future. Dr. Henry states that "when the rest of the world realises the value of sargassum they will come after it". To this end, she urges policy makers to create policies that (1) protect sargassum as a bioresource and (2) ensure that the quality of life for Barbadians is improved because there is sargassum.

6.3 BioPlaster- Turning Sargassum into Sustainable Solutions for a Plastic-free Future

Plastics are a part of our daily consumption habits, they can be found in household goods, beauty products and even in the food we eat. For many, a world without plastics may seem unimaginable; however, the Mexican company 'BioPlaster Research Inc.' has made it their mission to change the plastic industry through the development of biomaterials. BioPlaster aims to find solutions to two pressing environmental issues in the Caribbean, the plastic crisis, and the extraordinary volumes of sargassum biomass that inundate Caribbean shorelines.

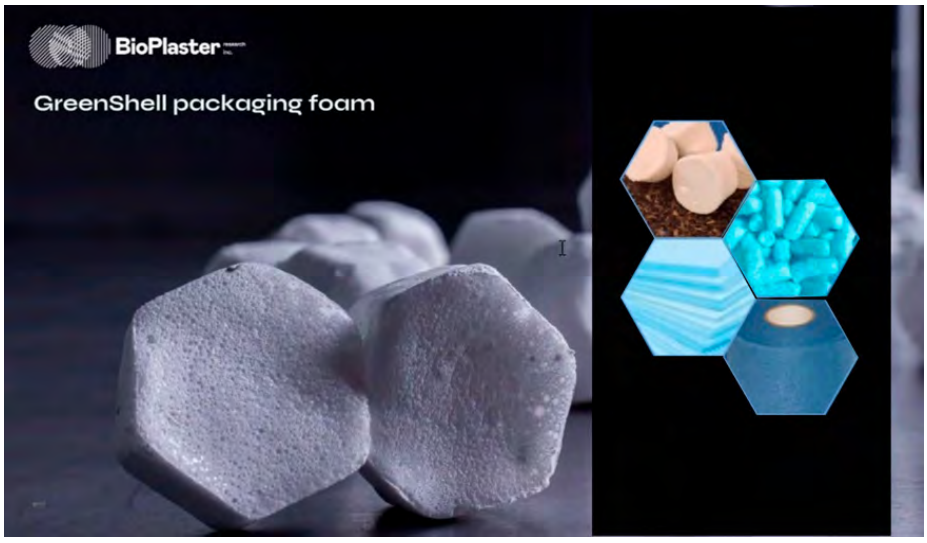
The company's initial goal was to extract alginate from the sargassum seaweed however due to low alginate yields in early trials it became evident that a new plan was required. Founder and CEO Dr. Andrea Bonilla explained that it was at this point that her research team faced an important question, "what can we extract from sargassum to make the solution profitable?". For BioPlaster the solution was to extract as much as they possibly could from sargassum; this resulted in the adoption of a biorefinery approach. The company has designed a multistep input/output system of by-products that fits perfectly into the industrial areas of textiles, packaging, agrochemicals, thermoplastics, and energy (Figure 23).

Figure 23. Schematic of the products produced from sargassum during BioPlaster's biorefinery process



At the moment BioPlaster is focused primarily on two compounds, alginate and cellulose with ongoing research and development for a biofertilizer. Within their process sargassum needs to be collected at sea, sun dried and grinded before they can start the alginate and cellulose extractions. Both compounds are typically extracted within 1-2 days depending on the volume of sargassum and then combined with other biodegradable materials, polymers, polysaccharides, and bio-compounds to produce bioplastics. Using sargassum, the company has developed their 'GreenShell' packaging foam (Figure 24) which is a completely sustainable alternative to Styrofoam and costs 60% less than other bio-based solutions. Their innovative GreenShell packaging solution has optimal mechanical properties (e.g., shock resistance, density, elasticity) and can be used for a diverse set of applications (e.g., packaging peanuts, plates, and foam).

Figure 24. GreenShell packaging foam



Although the company aims to produce sustainable alternatives to plastic products, Dr. Bonilla emphasised that BioPlaster is not simply a bioplastic producer but rather a technology developer. This is evident in the company's range of products and ongoing research. In addition to their GreenShell packaging foam, BioPlaster works with different industries (e.g., Sigma Alimentos, Cabonwave, Procter & Gamble) to manufacture specific materials such as thermoplastics and packaging films. With research and technological advancements at the core of the company, BioPlaster is currently trying to develop biodegradable fishing nets made from sargassum in collaboration with the University of Miami. Additionally, they are also striving to develop thermoplastics that will start to decompose when they become exposed to high methane levels in landfills.

Amid their many technological strides, BioPlaster also seeks to find ways to involve the local community. The company has developed a social program that aims to help fishers who are impacted by sargassum. In this program, fishers that encounter sargassum at sea can collect the sargassum and sell their collections to BioPlaster in a pre-processed state (i.e., dried, and grinded). Additionally, the company is also engaged in conversations with local hotels to encourage hoteliers to use sargassum-based plastics for the packaging materials that they would typically use to distribute guest information.

To date, BioPlaster's remarkable milestones were achieved under pre-seed funding. However, by the third quarter of 2024, BioPlaster hopes to close their seed funding round that will allow them to open an industrial pilot plant. Ideally, this facility should be capable of processing 171 tons of sargassum per year which will lead to yearly production rates of 27 tons of alginate, 41 tons of cellulose and 1,800 tons of their GreenShell films. Dr. Bonilla stated that BioPlaster views sargassum as a formidable resource and they will continue in their efforts to transform the sargassum crisis into opportunities for communities and push for technological advancement in the region.

6.4 Thalasso Ocean- Seaweed Harvesting and Micro Biorefinery Approach

Thalasso Ocean co-founders, Mr. Frode Stolen Sønstebø (CEO) and Ms. Paulina Zanela (COO) met during a World Bank Competition in Panama that aimed to find the best solutions to solve the world's water issues. Following their initial introductions in Panama, Ms. Zanela returned to Mexico where she was met with alarming volumes of sargassum and no clear solutions to the problem. Given their shared passion for solving environmental and social challenges, Ms. Zanela reached out to Mr. Stolen Sønstebø and his Norwegian team to find innovative ways to address the sargassum crisis. Mr. Stolen Sønstebø explained that as a serial entrepreneur his curiosity was piqued, and their collaboration resulted in the formation of Thalasso Ocean in 2019.

In the beginning, both co-founders had very little knowledge on sargassum. Assessing the problem from the outside they identified in-water harvesting as the solution to the problem and initially planned to use a large vessel with vacuums to 'suck' sargassum out of the water before it could make landfall. However, upon a deeper analysis and several consultations with local communities and the Mexican government they realised that they needed to find a better solution that: (1) addressed the in-water harvesting concerns as it relates to sargassum associated biodiversity; and (2) provided opportunities for impacted communities.

As the company pivoted away from their initial idea, Ms. Zanela had the opportunity to participate in sargassum collection efforts onboard a state-owned harvester. During this time,

she became acutely aware of physical demands of onboard harvesting operations. Following in-water harvesting, substantial manpower was required to lift and bag tons of heavy wet sargassum. Additionally, she observed how difficult it was for traditional harvesters to access and effectively operate in impacted sites with high wave energy. Ms. Zanela explained that the experience provided very valuable insights and gave her a renewed vision to develop a harvesting technological solution that was capable of operating where others simply could not. After much research and development, Thalasso created the Ocean Harvester, a high tech, fully autonomous harvesting solution that was capable of operating in rough water conditions (Figure 25). The Ocean Harvester has the capacity to collect 20-30 tons of seaweed per hour and Thalasso has been using this solution to harvest sargassum since 2021.

Figure 25. Thalasso's Ocean Harvester

Although the Ocean Harvester effectively addressed in-water collections, the company realised early on that if they only collected seaweed and delivered it to landfills, they were not solving the problem but rather transferring the problem from ocean to land. Being a Mexican-Norwegian company, Ms. Zanela and Mr. Stolen Sønstebø had the opportunity to converse with experts in Norway and across Europe who were working with different seaweed species to produce pharmaceuticals, food products and cosmetics. This exposure led them to ponder on two main questions: (1) why was the Caribbean managing sargassum as a waste instead of managing it as a biomass; and (2) why were the applications in Europe not being utilised in the Caribbean where the sargassum arrive 'free' of charge? Their dedication to find a truly sustainable solution to the sargassum crisis led to the formation of Thalasso Biotech, a subsidiary of Thalasso Ocean that focuses on extracting high valued compounds from sargassum through a micro biorefinery approach.

Although the concept of sargassum biorefineries has been proposed by various countries, Thalasso has taken it a step further with a vision to implement a system of container based

biorefineries. Rather than having a central biorefinery, the company explains that their decentralised approach to sargassum operations will allow them to have a network of micro biorefineries at different impacted locations, create jobs within communities and reduce carbon emissions that would be generated with the transportation of sargassum. Additionally, the container micro biorefinery system can easily be packed up and moved to another location when an unexpected influx occurs. Ms. Zanela noted that it is easier and more efficient to move a couple containers to another location than having tons of sargassum shuttled back and forth. The container based micro biorefinery approach is scheduled to be piloted in Puerto Rico in the second quarter of 2024.

Within their system, sargassum collected by the Ocean Harvester will be delivered to deposit stations which should ideally be within close proximity to a micro biorefinery. At the refinery sargassum will be divided into two batches, one batch that will undergo immediate processing and a second batch that will be dried and stored for later processing. Based on their initial trials they were able to obtain their maximum yields with fresh sargassum that typically started the extraction phase within three hours of collection. However, given the fluctuating daily quantities of sargassum they will be required to dry some of the sargassum during periods of high sargassum influx. Currently the company is focused on polysaccharides (alginate and cellulose) extractions and intends to extract proteins in the future. Their research team is also working on the formulation of a bio-stimulant and simultaneously refining their methodology for the isolation and removal of arsenic. In preparation for commercial export of their sargassum high value products, the company has established a network of companies (e.g. Carbonwave, L'Oréal, Nestlé, Lululemon) that seek seaweed ingredients for various applications.

Together the Ocean Harvester and Thalasso Biotech provides a holistic management approach to the sargassum crisis through the mitigation of environmental and social impacts and the creation of economic opportunities. Ms. Zanela explained that the company's efforts to improve the lives of impacted communities extends beyond the removal of sargassum. Within their system each biorefinery only requires one research/engineer to be onsite, all other jobs will be opened to community members and training will be provided. Additionally, the company is developing a social program specifically for women within the communities where they will teach them how to make biostimulants and equip them with business, research, and marketing skills thereby giving them the capacity to start their own sargassum-based businesses.

The magnitude of the sargassum crisis requires the creation of adaptable and sustainable solutions across the region. In his experience, Mr. Stolen Sønstebø, states that "entrepreneurs working within the same sphere often label each other as competitors, however this should not be the same with sargassum as we are all trying to address the same problem." His advice to entrepreneurs is to network as much as possible, do not be afraid to ask for help and be very open to pivoting when one idea doesn't work as planned. There is enough sargassum for everyone to benefit and with a regional effort he is convinced that we can effectively manage the sargassum crisis and generate lots of opportunities.

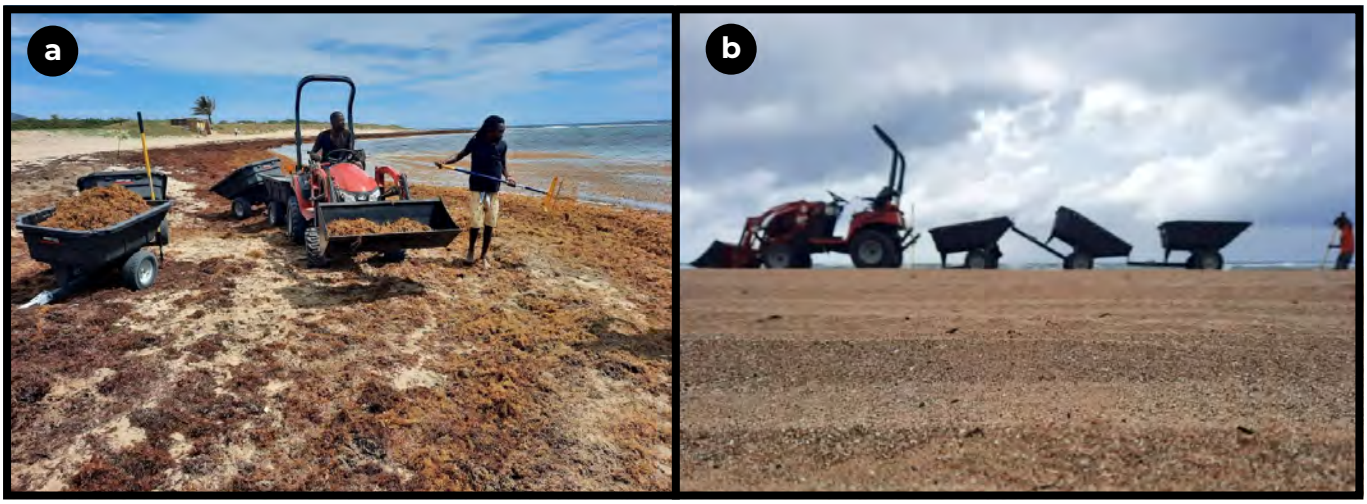
6.5 Grogenics- Sargassum Management for Agriculture and Circular Blue Economy

Grogenics leads the charge in addressing the ecological crisis sparked by sargassum while tackling the broader challenge of organic waste management, a significant contributor to global greenhouse gas emissions. Leveraging sustainable, innovative, and cost-effective solutions, Grogenics devised methods to efficiently collect, contain, and repurpose sargassum.

Founder and CEO Michel Kaine revealed that by employing pyrolysis and composting, the company processes sargassum and biodegradable organic matter, with both technologies emerging as leading contenders meeting stringent and multifaceted criteria. Beyond job creation and community empowerment, Grogenics' solutions safeguard fragile oceanic ecosystems, fortifies the fishing industry, and plays a pivotal role in reducing greenhouse gas emissions.

The process starts with employing low-impact noise free electric UTVs and carts to harvest sargassum on the beach (Figure 26), ensuring minimal disturbance to the environment. Collected sargassum is then swiftly transported to composting sites via tractor, eliminating any delays or reliance on landfills. At the composting site, the sargassum undergoes a transformative journey, including windrow spreading, addition of local green waste, and incorporation of sargassum-based biochar produced through pyrolysis. Following this, the compost material is mechanically turned to allow for adequate aeration.

Figure 26. Low-impact noise free electric UTVs and carts to harvest sargassum (Panel a and b)



Source: https://www.grogenicssg.com/

Figure 27. Windrow turner

Source: https://www.grogenicssg.com/

A proprietary microbial formula is then added to neutralise the heavy metals, rendering them inaccessible to plants. Michel shared that their holistic approach to heavy metal remediation integrates phyto-, bio-, and mycoremediation techniques. He further explained that plant growth-promoting microorganisms are used to alter the speciation of arsenic in the compost. These microorganisms methylate arsenic, changing its bioavailability to plants. Specifically, Grogenics employs heterotrophic arsenite-oxidising bacteria for this purpose. Maximising binding sites using biochar and other sorbent materials is another technique used to reduce the availability of heavy metals to plants. Michel mentioned that through strategic partnerships with esteemed institutions like the Monaco Scientific Centre, The Ocean Foundation, the Smithsonian Institute, and Dalhousie University, Grogenics ensures their methodologies are grounded in scientific rigour and expert knowledge.

Grogenics compost has been distributed to 15 farmers during their pilot project in the Dominican Republic, resulting in remarkable improvements in agricultural yield and quality. Farmers have reported yield increases, accompanied by larger flowers, enhanced fruit production, and overall healthier crops. The company has also initiated training programs to educate farmers on the composting methodology, empowering them to adopt sustainable practices and maximise their agricultural potential.

The Grogenics project has been supported by The Ocean Foundation and the Caribbean Biodiversity Fund, and their initiatives have garnered widespread recognition and support from esteemed institutions and organisations. The company has received accolades such as the Coastal Tourism Challenge UpLink-World Economic Forum award and recognition as a top climate innovator in the UNICEF Innovation30 competition. Furthermore, the company is in the process of certifying its carbon offsets under the Gold Standard SDG 13 through its methodology for collection of sargassum and other macroalgae to avoid emissions from decomposition and to use for beneficial products. Michel shared that Grogenics will soon offer their carbon credits to the voluntary market. Driven by a commitment to reduce social vulnerability, increase food security, and enhance climate resilience across the Caribbean region, Grogenics is poised for further expansion.

6.6 Spargassum- Turning Waste into Wealth with Sargassum Skincare

Spargassum, a pioneering venture spearheaded by two visionary female founders, Gennike Mayers and Donna Lisa Philips (Figure 28), stands as a testament to the transformative power of faith and innovation. This enterprise is the first in Trinidad and Tobago to commercialise products derived from sargassum, offering spa products including moisturising body oils and exfoliating soaps infused with the unique properties of sargassum (Figure 29).

Figure 28. Founders of Spargassum Gennike Mayers (left) and Donna Lisa Philips (right)

Figure 29. Spargassum body oils and exfoliating soap bar

Driven by Gennike's intellectual curiosity and Donna Lisa's formulation expertise, the journey of Spargassum began with a simple yet profound idea: to harness the potential of sargassum in the cosmetics industry. Inspired by the antifungal, antibacterial, and antioxidant properties of sargassum, Gennike embarked on a mission to explore its potential uses, eventually teaming up with Donna Lisa to bring their vision to life.

Their journey took a significant leap forward when they pitched their idea to the IDB Tobago Blue Economy Ideas Competition in 2022, emerging as one of the six winners and securing a US$10,000 grant. This initial funding served as the seed capital for laying the foundation for the development of Spargassum.

Central to Spargassum's production process is a commitment to simplicity and sustainability. Gennike's hands-on approach involves personally harvesting sargassum from nearby Tobago shores, washing using rainwater, drying on trays made from chicken wire, and grinding the dried sargassum into fine grains using her kitchen blender for further processing. These granules are then sent to Donna Lisa in Trinidad, where she creates Spargassum's signature spa products in the comfort of her kitchen. For the oil, Donna Lisa mixes the sargassum grains with natural oils (olive oil, sunflower oil, sweet almond oil, vitamin E oil) and adds a secret fragrance. For the exfoliating soap bar, the sargassum grains are mixed with distilled water, sodium hydroxide, vegetable oil, canola oil, and castor oil. Safety and quality are paramount for Spargassum, with each batch of products undergoing rigorous testing at the University of the West Indies (UWI) Mona Lab in Jamaica to ensure compliance with international standards for heavy metal content.

Despite initial hesitancy from consumers, Spargassum has garnered traction through strategic marketing efforts, targeting niche markets such as hotels and private spas. The versatility of their products, catering to both men and women, has further fueled their popularity, with customers enjoying the exfoliating benefits of the soap and the nourishing properties of the oils.

Acknowledging the invaluable support of partners such as the IDB, Compete Caribbean, and the Caribbean Industrial Research Institute, Spargassum is poised for growth. With plans to scale up production, expand their product line, and seek additional grant funding for research, Spargassum continues to lead the way in transforming waste into wealth in Trinidad and Tobago, one sargassum-infused product at a time. As Gennike Mayers advises, the key to success lies in constant experimentation, social media engagement, and simply talking about sargassum.

6.7 Red Diamond Compost - From Nuisance to Nourishment

While many view sargassum seaweed as a nuisance, one Barbadian entrepreneur, Joshua Forte, views sargassum as nothing short of a godsend. Leading the charge at Red Diamond Compost, Joshua has embarked on a transformative journey, turning sargassum seaweed into a powerful biostimulant.

In 2014, Joshua started Red Diamond Compost, a Biotech social enterprise that focuses on creating clean and green agrochemical solutions. Initially, Joshua's vision revolved around harnessing the potential of conventional plant and animal sources to create organic compost, fertilizers and biostimulants. However, a pivotal moment in 2015, marked by a massive influx of sargassum, prompted a swift change in strategy. With a background in science and a bold spirit of experimentation, he embarked on a journey to unlock the secrets of sargassum. Thus, the idea of transforming sargassum into a biostimulant was born.

Through mentorship from a soil microbiologist and extensive desktop research, Joshua began harvesting fresh sargassum and initiated the development of his liquid extraction technique. After several months of experimentation and refinement, he successfully formulated a methodology which had to be tested. He used peanuts as the test crop, and conducted multiple trials and the outcomes were highly encouraging, particularly in terms of the development and structure of plant roots.

While acknowledging the proprietary nature of the production process, he offered a glimpse into some of the steps involved in crafting the biostimulant (Figure 30). He explained that the process begins with collecting sargassum in the nearshore using netted produce bags. The freshly harvested sargassum is then rinsed with fresh water to remove plastics, other debris and sand and then dried. Afterwards, the dried sargassum undergoes a grinding or milling process before entering the proprietary low temperature extraction phase. Joshua highlighted that this phase is crucial, as it facilitates the extraction of valuable bioactive compounds including plant growth hormones, such as auxins, cytokinins, salicylic acid and jasmonates that help to boost root and seedling development and provide plants with a host of defence mechanisms against stresses (e.g. disease, pests, environmental).

Figure 30. Founder and CEO Joshua Forte showcasing elements of the production process (Panel a and b)

Source: Reclaimingourbeaches.com

Joshua further elaborated that buffers are then added to mitigate the heavy metal and salt content along with a series of plant-based stabilisers to increase the soil microbiome and the shelf life of the product. This is followed by filtration which produces a concentrated solution with all the beneficial compounds. After curing and screening, the final product is created, bottled and marketed as 'The Supreme Sea Biostimulant'.

The entire process of product development took approximately two years. Joshua estimates that from 1 tonne of fresh sargassum, they can produce a few thousand litres of the final product. The strategy has been to collect as much as possible during influx events. He was happy to inform that during periods of low to no sargassum influxes, operations can continue smoothly, as they store an unrefined version of the product for just over 6 months without compromising quality.

In a bid to reduce waste, Joshua highlighted that the solid residue generated during the process is repurposed as compost. However, this compost product has not yet been introduced to the market. He explained that The Supreme Sea Biostimulant can be applied through drip irrigation or via spray cans. The benefits to plants include: faster plant and root growth, improved immune system, enhanced colour and appearance, increased nutrient uptake, and stimulated soil microbial activity. He noted particularly good performance with sweet peppers, cucumbers, pomegranate trees, bananas, dwarf golden apples. Distribution initially began with small-scale farmers and marketing efforts at trade shows, along with partnerships with landscapers. Over time, distribution has expanded, now reaching major hardware stores across Barbados.

Figure 31. Red Diamond's 'Supreme Sea Biostimulant' product (Panel a) and application to crops (Panel b)

Source: Reclaimingourbeaches.com

Joshua emphasised that the journey had not been without its challenges. Initially, the company faced financial hurdles such as limited access to funding and difficulties in securing investments for necessary equipment to develop the products. However, through participation in various competitions and entrepreneurship events worldwide, coupled with securing grant funding, the company successfully overcame these hurdles and obtained the necessary capital

to scale up production operations. Competitions and initiatives such as the Young Americas Business Trust, the Caribbean Innovation Competition, the Global Entrepreneurship Summit, the ClimateLaunchpad, and the Young Leaders of the Americas Initiative played significant roles in facilitating this journey.

With support and grant funding from the Bloom Cleantech Cluster and Export Barbados, the company conducted efficacy field trials on the Supreme Sea Biostimulant. In 2022, turf trials in North Yorkshire, England demonstrated a 50% reduction in chemical fertilizer use, lowering environmental nitrogen levels. In 2023, tomato and cucumber trials in Catalunya, Spain showed a 23% yield improvement compared to commercial standard products. Joshua shared that partnership with an international company 'Diproinduca' not only helped the biotech company to expand the scale of their efficacy trials but also expand the capacity for rigorous scientific testing and analysis of the products to ensure consistency, safety and scalability.

As Red Diamond Compost continues to progress, exciting developments lie ahead. Joshua was pleased to announce that the company will be acquiring a new official location this year (2024) and piloting a sargassum offshore collection process. He also shared that the company is constantly seeking ways to enhance the product, with a focus on conducting further investigations into its interaction with soil medium. The goal is to determine which soils and crops would derive the greatest benefit. Additionally, plans are in place to diversify the product line and potentially expand into other sectors.

Joshua remains an advocate for increased regulatory oversight to guarantee the safety of agricultural products before they enter the market. Additionally, he advises aspiring entrepreneurs looking to start a sargassum-based business to thoroughly understand the product they are developing, understand the regulatory aspects and requirements, assess associated costs, and identify strategic partners to help achieve milestone successes.

6.8 The Marine Box- Pioneering Innovative Cremation Solutions

In Martinique, a unique endeavour is taking shape, one that harmonises reverence for departed loved ones with a commitment to environmental stewardship. At the forefront of this innovative initiative is The Marine Box, a project spearheaded by Siniamin Funéraires, of Siniamin Funeral, a company deeply rooted in the funeral industry.

Siniamin, with his extensive experience in the funeral business, envisioned a sustainable alternative to traditional cremation coffins. The idea emerged in 2017 when he recognized the potential of utilising sargassum seaweed for crafting eco-friendly coffins. Convinced that sargassum can be recycled to create coffins, Siniamin embarked on a journey to explore this concept. Along the way, he learned about the concerns of the heavy metal content present in sargassum seaweed. Mindful of the environmental considerations, he decided that coffins specifically designed for cremation would offer a more ecologically sound solution. Cremation also offers more flexibility in choice of materials and requires no finishing touches or elaborate detailing, considering the coffin's ultimate purpose for cremation.

To materialise The Marine Box concept, Siniamin forged partnerships with an industrial processing facility in Spain, which specialises in manufacturing products from organic materials. Together, they developed a prototype coffin comprising 60% sargassum seaweed, 30% banana fibre, and 10% coconut fibre.

Traditionally, cremation coffins are fashioned from wood or cardboard, often sourced from forest resources. However, Siniamin has sought alternatives that can mitigate deforestation and reduce funeral costs. He believes that sargassum is a cost-effective solution for sustainable funeral practices.

The Marine Box project has garnered support from SAVE-C, an international initiative led by the University of Brest and the Ecological Transition Agency (ADEME) in Martinique. Through these partnerships, The Marine Box received the necessary financial and technical support needed to develop the product.

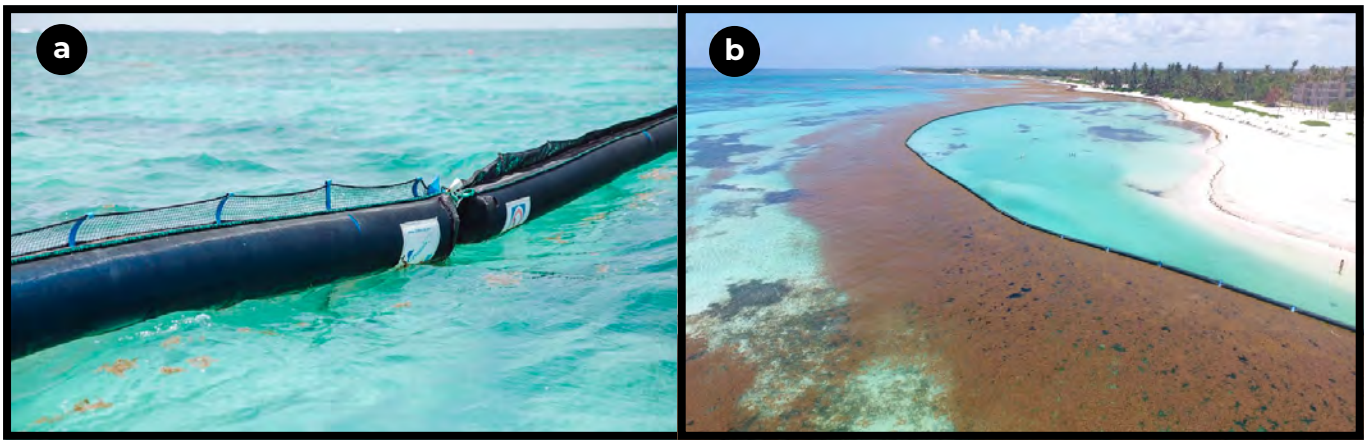
Looking ahead, The Marine Box envisions diversifying its offerings to include funeral urns designed for immersion. The concept behind the urns is to facilitate rapid dissolution when submerged in water. He mentioned that 20kg of dried sargassum will be utilised to create 1 urn. In regions where burial space is limited, cremation emerges as a practical choice. With 571 cremations recorded in Martinique in 2023 alone, Siniamin anticipates a promising market for its eco-friendly solutions.

6.9 AlgeaNova- Harvesting Solutions, Cultivating Sustainability

AlgeaNova, a subsidiary operating under the HoldiNova group, is well known for its integrated solutions to tackle the sargassum crisis, particularly in Punta Cana, Dominican Republic. Through a holistic approach that includes barrier installation, harvesting, and processing, AlgeaNova effectively addresses the multifaceted challenges presented by sargassum while simultaneously tapping into its potential to produce value-added products.

The company's proprietary sargassum barriers, crafted with lightweight, inflatable materials, serve as a frontline defence, intercepting sargassum before it reaches the pristine shores (Figure 32). These barriers, extending up to 7 km, are portable in design, facilitating rapid deployment, and storage. The barriers can be disassembled with a small team within 3-4 days. Rigorous safety evaluations and context-specific adaptations (e.g. the type of anchors) ensure optimal performance, safeguarding coastal ecosystems effectively. The barrier system requires periodic maintenance, such as cleaning and replacement of broken areas or damaged nets. This upkeep involves weekly cleaning using a specialised boat equipped with brushes and pumps, as well as the fabrication of replacement nets. Local personnel based in Punta Cana are responsible for carrying out these maintenance tasks.

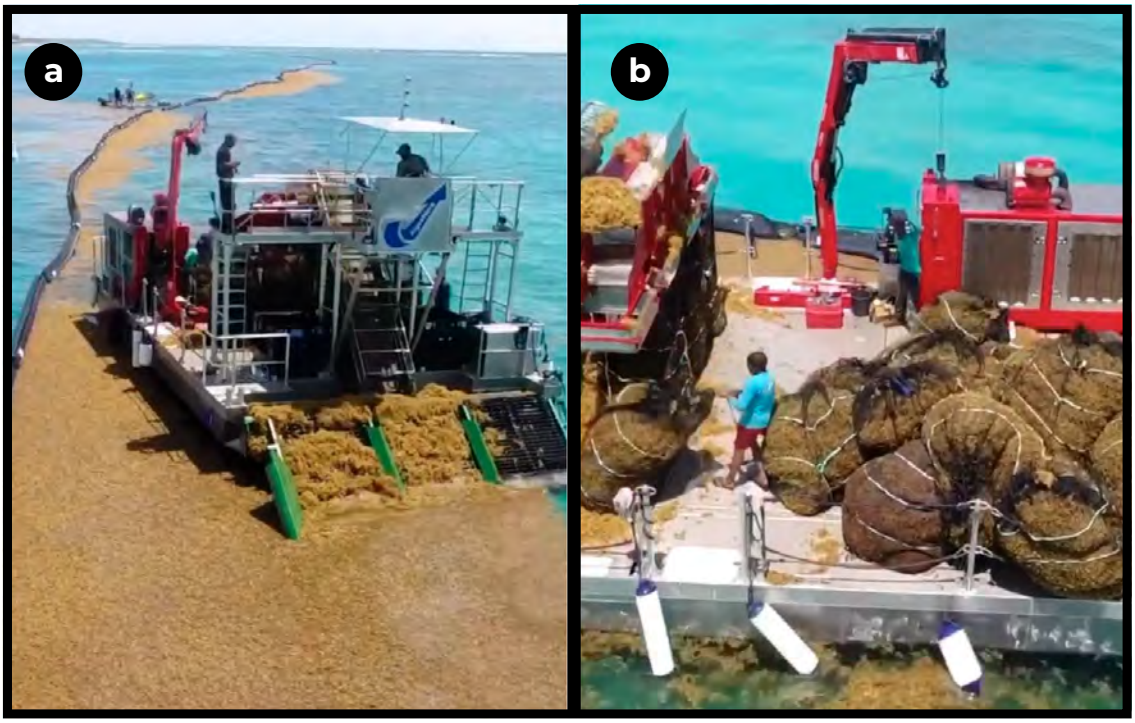
Figure 32. AlgeaNova sargassum barriers installed in Punta Cana (Panel a and b)



Source: AlgeaNova.

Behind the barriers, specialised industrial barges harvest fresh sargassum, for further processing (Figure 33). With a harvesting capacity of 500 cubic metres per day, AlgeaNova ensures swift and efficient removal of sargassum from marine environments, mitigating potential environmental hazards. At the time of interview, AlgeaNova was not engaged in sargassum collection activities in the Dominican Republic. Instead, the company exclusively provides prevention services through barrier installation along with processing and product development services which are offered based on client requests.

Figure 33. AlgeaNova sargassum harvester (Panel a) and collection barge (Panel b)



Source: AlgeaNova.

At the heart of AlgeaNova's operations lies its state-of-the-art processing facility in Punta Cana, where harvested sargassum undergoes a transformative journey. Through meticulous drying, grinding, and refining processes, sargassum is converted into a diverse array of value-added products, including energy, compost for agriculture, and biodegradable disposable items such as plates and utensils.

Sargassum-enriched compost, derived from a blend of organic matter and sargassum biomass, enhances soil fertility and promotes sustainable agricultural practices. With a meticulous composting process spanning approximately 70 days, AlgeaNova delivers high-quality compost suitable for diverse agricultural applications, including farming, landscaping, and gardening. The process begins with the crushing of organic matter obtained from gardening pruning (Figure 34a), which is then combined with sargassum in a compost windrow measuring approximately 70 metres in length. The mixture consists of 40% green organic matter and 60% sargassum. A bacterium is then introduced to neutralise salts and heavy metals present in the sargassum, after which the components are further crushed to achieve a final mixture and initiate the decomposition process (Figure 34b). Monitoring and management procedures are implemented until the product attains the desired properties, with strict control maintained over the temperature and humidity levels within the windrows.

Figure 34. Crushing of organic matter (Panel a) and monitoring of the fermentation process in the windrow (Panel b)

Source: AlgeaNova

AlgeaNova also produces biodegradable plates and utensils in their processing module (Figure 35), offering eco-friendly alternatives for food packaging and consumption. With a production capacity of up to 2,000 plates per day, these biodegradable disposables cater to hospitality, retail, and consumer markets, fostering sustainable consumption practices. The process kicks off with the drying of sargassum, then grinding and sifting to obtain a fine powder. The ground sargassum is then adjusted to the correct humidity level to initiate the proprietary transformation process, which involves blending with other components. Approximately 4 to 4.5 grams of sargassum are utilised to craft a single plate. Subsequently, the sargassum goes through a manufacturing process lasting roughly 15 to 20 minutes, resulting in the creation of the final biodegradable product (Figure 36). Notably, these plates are equipped with a membrane designed to isolate food from the sargassum material for a duration of up to 8 hours.

Figure 35. AlgeaNova sargassum processing module

Source: AlgeaNova.

Figure 36. Manufacturing of AlgeaNova sargassum-based biodegradable plates (Panel a), final product (Panel b) and product in use (Panel c)

Source: AlgeaNova.

AlgeaNova's sargassum-derived energy offers a sustainable and cost-effective alternative to conventional sources, with an estimated cost of US$14 per kilowatt compared to US$31 per kilowatt for conventional energy in Punta Cana. By harnessing sargassum's energy potential, AlgeaNova contributes to reducing carbon emissions and promoting renewable energy adoption.

Despite facing challenges such as high operating costs and limited government support, AlgeaNova remains steadfast in its commitment to innovation and sustainability. Through strategic partnerships with research institutions and industry experts, including Biotren, Maof, and Grogenics, AlgeaNova continues to refine its sargassum utilisation processes and develop new product lines. AlgeaNova's vision extends beyond immediate challenges, with plans to expand its operations and make sargassum management systems more accessible to commercial clients. Securing funding for widespread implementation remains a top priority. The company recently submitted a public tender which elaborated a management plan to protect 40 km of coastline. This plan involves deploying six collection barges, which have the capacity to harvest between 1,500 and 1,800 cubic metres of sargassum per day in the Punta Cana coastal region.

6.10 BlueGreen- Innovating Sustainable Construction with Sargablock

Founder of Blue Green based in Mexico and innovator behind the famous sargassum brick house 'Casa Angelita', Omar Vazquez Sanchez, is a prime example of how skill, innovation, and

determination, can effectively utilise minimal resources to transform a problem to generate significant value (Figure 37). Blue green was founded in 2014 and the Sargablock project was launched in 2018 in Puerto Morelos, one of municipalities most impacted by sargassum. Through his efforts, Omar is effecting positive change within communities by building and generously donating affordable housing to those most in need.

Figure 37. Founder of BlueGreen Omar Vázquez Sánchez (Panel a) and first sargassum house 'Casa Angelita' built with SargaBlocks (Panel b)

Omar shared a touching story about overcoming poverty and addiction, which gave him the ability to radically reimagine the potential for this problematic weed. It all started in 2018 when Omar was given a contract with the local government for sargassum beach cleaning. He hired 300 people in order to do this work, unfortunately this contract was cancelled 20 days after starting it by the government. This turn of events compelled him to seek alternative solutions, ultimately leading to the conception of the sargassum adobe idea. With just US$55 and a whole set of determination, he started to make his idea a reality. Inspired by the memory of his family's little adobe house, he started to develop Sargablock.

Local authorities and some hotels provide Omar with sargassum at a 3000m^2 facility in Puerto Morelos from where the blocks are manufactured. The process starts with washing, grinding, and blending sargassum to create a mixture comprising clay, sargassum (40%), and other organic materials. Subsequently, the mixture is homogenised and fed into a machine that compresses and shapes it into blocks. Following this shaping process, the blocks undergo a sun-drying period lasting six hours. The facility produces 200 tons of fresh sargassum over 5 days. The blocks are mechanically compacted to a compression of 112 kg x cm^2 at a speed of 435 blocks per hour. Omar emphasised that for every 2,000 sargassum blocks utilised in construction, they contribute to the removal of over 20 tons of sargassum from the beaches. An overview of the process to create the blocks is shown in Figure 38 below.

Figure 38. **Authors' graphical representation of the process to create Sargablocks drawing from existing literature**

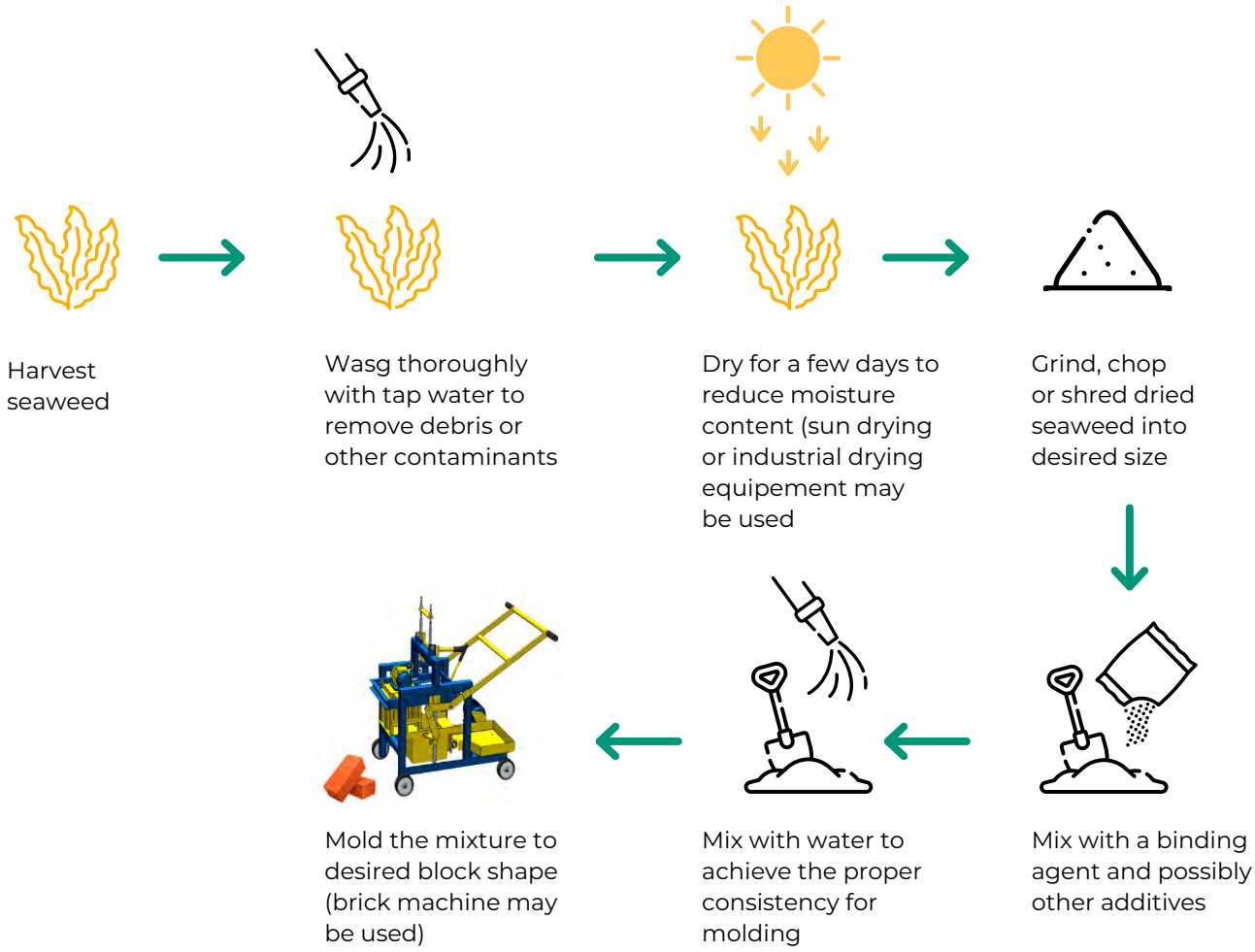


Figure 39. **Machinery used in the manufacturing of Sargablocks (Panels a and b)**

Figure 40. **Sargablocks**

According to Omar, Sargablock is thermic (lowers temperature 6-8 grades), improves acoustics, is organic and can be recycled. Durability tests carried out show a lifespan of roughly 120 years. Furthermore, Casa Angelita is a testament to the strength of Sargablock, as it has been through 5 hurricanes and 6 tropical storms and is still standing strong. Omar even highlighted that the blocks are bullet proof. Price wise, Sargablock competes favourably with traditional blocks, making it an affordable building material for constructing homes across the Riviera Maya, enabling families to realise their dream of homeownership.

BlueGreen enforces rigorous quality control in Sargablock production. This includes thorough inspection of raw sargassum seaweed, standardised processing, and regular testing for strength and durability. The company also ensures compliance with environmental regulations and industry standards, emphasising continuous improvement and traceability in the production process.

Omar refers to BlueGreen as a virtuous cycle, cleaning the beaches, creating jobs for vulnerable populations, generating social, environmental and economic impact. The facility employs 16 full-time staff, many from surrounding communities, and increasing to 100 during peak seasons. As much as 90% of these employees have undergone rehabilitation for drug and alcohol addiction. The facility provides jobs in production, management, logistics, sales, marketing, administration, environmental sustainability, and community outreach to promote the benefits of using seaweed-based materials in construction.

Omar's vision is to find a partner that loves the planet, family and shares his faith. He believes that faith can move mountains and he cares a lot about environmental impact but more importantly, social impact. His objective is to continue with the improvement of the product and expand to biostimulants production. His ultimate goal is to replicate his model in all the countries impacted by sargassum, to foster positive outcomes for local communities. Sargablock is not only poised to diversify the construction industry but generate major social benefits especially for low-income families.

6.11 Maralive- Sargassum Harvesting Solutions

In the Caribbean, initial efforts with sargassum harvesting were primarily linked to clean-up and disposal of the sargassum. However, Maralive, a Mexican company dedicated to the transformation of beaches that are impacted by sargassum, has linked their sargassum collection efforts to valorisation.

The company innovates technology, equipment, and logistics that offer tailored solutions to sargassum challenges. Under their current operating procedures, Maralive has the capacity to construct one of their sargassum harvesting vessels (Figure 41) within 15 days with the vessel fully operational in a months' time.

Figure 41. Construction of a Maralive harvester (Panel A), example of the conveyor system for the harvester (Panel B), an operational harvester at sea (Panel C)

Within their system, sargassum harvested at sea is transported to the processing facility (approximately 2000 m^2 in size) where it undergoes washing, separation of sand, and compression. The compressed sargassum is then either directly sold to clients that produce sargassum by-products or further dried depending on the client's requirements.

Since the design and creation of their first sargassum harvester in 2018, the company has developed 3 different harvester models with 12 vessels currently available for operations. With the expansion of their harvesting fleet, Maralive is now capable of supplying around 50 jobs across their harvesting, processing, maintenance, administration, and logistics teams during peak sargassum periods.

6.12 Dianco de México- Transforming Sargassum into Sustainable Agriculture

Industrial scale sargassum processing and product development will play a pivotal role in reducing the large quantities of sargassum that impact shorelines and occupy landfill space. However, sargassum businesses across the Caribbean have had difficulties transforming their start-up businesses into large-scale operations. Dianco de México, a Mexican company that focuses on resilience and adaptation to climate change, has successfully overcome the many challenges associated with large-scale valorisation and today they are the only company producing organic fertilizers at an industrial level in Latin America (Figure 42).

Figure 42. **External view of Dianco's facility (Panel A), front desk/receptionist area (Panel B), storage area for biofertilizer (Panel C), equipment and machinery (Panel D)**

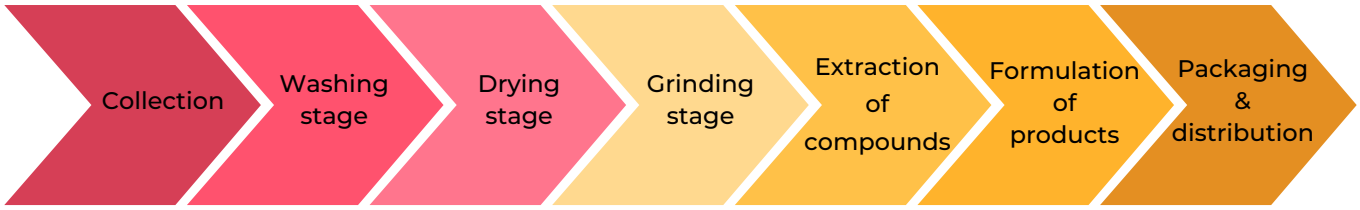
The Dianco team, made up of businessmen, environmentalists, engineers, biotechnologists, agronomists, and phycologists who combine their knowledge and expertise to address the sargassum phenomenon. To date, they have transformed thousands of tons of sargassum from the coasts of Quintana Roo, to produce tons of biostimulants and biofertilizers (Figure 43).

Figure 43. **Dianco's bio-stimulant (NUTRIMAXX) and biofertilizer (NutriKam)**

Within their operations, sargassum is collected at sea and/or on the beach and transported to their industrial facility which is located within close proximity to their collection sites. At the facility, sargassum is washed using a system of conveyors and washers and then dried in industrial dryers. Once dried, sargassum undergoes a grinding stage and then valuable

compounds are extracted, and materials are formulated into the end products that are then packaged and distributed (Figure 44).

Figure 44. Steps involved in transforming sargassum biomass into end products at Dianco de México



The operating facility is approximately 7,800 m^2 with 5,300 m^2 designated as an outdoor storage area and 2,500 m^2 designated for indoor production and office space. Operating at its maximum capacity, Dianco's facility has a production capacity of approximately 600 tons of fresh sargassum daily. Employment opportunities at the facility vary by sargassum 'season' with approximately 30 available jobs during low influx periods and 50 jobs during high influx periods. Jobs provided include roles such as operations staff, technicians, quality control inspectors, and administrative personnel. Additionally, Dianco is currently undertaking outreach efforts to engage community members in employment opportunities. Once hired, staff receive training in equipment operation, safety protocols, and quality assurance. Within their organisation, staff training is essential to ensure that standard operating procedures adhere to industry level. Moreover, to ensure their products maintain the highest quality, procedures for quality assurance and control are implemented throughout the processing stages, where their trained staff monitor parameters such as moisture content, nutrient composition, and product purity.

With regards to their future plans, Dianco is determined to make a bigger impact as they hope to double their current production capacity and increase their product line. Efforts made by the company serve as an example that from a 'problem', opportunities can arise and the production of sargassum products may very well be the solution to the current environmental crisis.

7 Updated sargassum businesses directory

Companies across Central America, Mexico, and the Caribbean are actively exploring diverse applications for sargassum. The directory compilation process involved investigation and data collection from various online sources to identify businesses involved in sargassum utilisation. Additionally, information provided by in-country coordinators added valuable insights into local businesses and activities within the sargassum sector.

Despite these efforts, it is recognized that the directory may not be exhaustive and could exclude businesses not featured online, those in the initial development phase or those that have ceased operations. While acknowledging its limitations, the directory remains a valuable resource for stakeholders interested in sargassum utilisation, providing insights into the diverse landscape of businesses operating in this sector.

Company	Country	Products/Services
Abaplas	Mexico	Bioplastics
Algas Organics	St. Lucia	Plant amendment
AlgeaNova	Dominican Republic	Compost, biodegradable material
Alquimar	Mexico	Textile, food and pharmaceutical industries
Biomaya	Mexico	Soaps
BioPlaster	Mexico	Bioplastics
BlueGreen	Mexico	Construction blocks, compost
Carbonwave	Puerto Rico	Agriculture, bioplastics, textiles, cosmetics
Dakatso	Mexico	On-shore and in-water removal
Dianco	Mexico	Fertilizer
Disefio y Decorativos del Caribe Maya	Mexico	Decorative plant pots, ornaments
EcoMyco	Barbados	Bioplastics
EnergYAlgae	Dominican Republic	Biogas & digestate
Grogenics	Saint Kitts and Nevis	Compost
Group Metco	Mexico	Alginates
Holdex Environnement	Martinique	Compost
Kee Farms	Jamaica	Cardboard paper
Maralive	Mexico	Containing, harvesting, compressing, drying
NADIS	Antigua	Sargassum alerts and monitoring
Nopalimex	Mexico	Biogas
Num SMO Technologies (NST)	Guadeloupe	Activated carbon & biochar
Red Diamond Compost	Barbados	Biostimulant
Renovare Ocean	Mexico	Footwear
Rum and Sargassum	Barbados	Biogas
Salgax	Mexico	Paper, cosmetics, biofertilizer
Sargacreto	Mexico	Construction material (sidewalks, blocks, joists, and vaults)
Sarganico	Mexico	Paper products
Sargazbox	Mexico	Cardboard boxes
SOS Carbon	Dominican Republic	Collection, exports, biostimulant
Spargassum	Trinidad	Spa products
SUEZ	Guadeloupe	Compost
Sway	Puerto Rico	Bioplastics, compost
Thalasso Ocean	Mexico	Harvesting, processing, bioplastics
The Marine Box	Martinique	Coffins, urns

8 The Governance Landscape

Sargassum influxes have been labelled as a “wicked problem”, suggesting that the problem is difficult to specify and understand, while having no clear solution (McConney et al. 2024). Initially, there was great uncertainty whether this phenomenon would be a recurring phenomenon, which discouraged the development of an appropriate governance mechanism for several years (Oxenford et al. 2021). Sargassum influxes are influenced by a complex interplay of both natural and anthropogenic factors and the social dynamics around response planning and management are subject to real-world constraints which hinder risk-free attempts to find a solution.

8.1 Regional governance

Regional governance mechanisms are crucial for effectively managing and mitigating the impacts of these influxes given the transboundary nature of this phenomenon. However, several factors contribute to the complexity of regional ocean governance arrangements in addressing this issue. Weaknesses in existing natural resources governance frameworks, including gaps in legal frameworks and institutional capacities, hinder effective management and response. Limited human capacity and financial resources and the lack of political will further impede the development and implementation of comprehensive strategies for sargassum management. Additionally, external dependency on international organisations and donor agencies may lead to sovereignty issues and conflicting interests, complicating the development of locally driven solutions (UNEP-CEP, 2021).

Despite the governance challenges, some signs of self-organisation are visible among regional bodies, with the initiation of meetings, symposia, workshops, conferences, grassroots activities, development of model protocols and formal projects over the years. Many of these efforts are documented and outlined in the Sargassum White Paper published in 2021 and in

the journal article written by Van der Plank et al. (2022). These provide valuable insights into the collective efforts to address the sargassum issue at the regional level. Van der Plank et al. (2022) highlight that the regional actors that have been engaging in these activities primarily consist of established entities in ocean governance operating at the science-policy interface (e.g., UWI-CERMES, UNAM), livelihood lobby groups (e.g., CHTA, CAST) intergovernmental organisations e.g CRFM Secretariat, and international and regional institutions (SPAW-RAC, UNDP, UNEP, IOCARIBE, Caribbean Sea Commission, ACS).

8.2 National governance

At the national level, governmental responses were also slow to materialise. However, as sargassum influxes persisted and scientific research indicated their likelihood of becoming a recurring occurrence, several Caribbean territories began to form multi-agency/multi-sectoral Task Forces or National Committees to provide support and coordination in addressing sargassum influxes. In many cases, efforts are challenged by limited funding (UNEP-CEP, 2021) and dedicated budgets to facilitate response planning. Several national strategic documents including management plans, briefs, adaptive management strategies and removal guidelines/protocols began to emerge but there is a marked difference in detail among them (Van der Plank et al. 2022). Additionally, most, if not all, still need to be approved by Cabinet or other competent authorities and resources allocated to support implementation. Notably, these documents have predominantly favoured removal strategies to mitigate the coastal impacts of the strandings, while regulations to support valorisation of sargassum are lagging behind. Oxenford et al. (2021) assert that the lack of well-developed governance arrangements and incentives to support valorisation of sargassum in most countries has led to a poor environment for encouraging investment in large-scale commercial enterprises.

However, countries are now gradually transitioning their perspective on sargassum from considering it as a problem to seeing it as a potential opportunity and its prospective economic value. This transition in perspective is driven by increasing awareness of the diverse applications of sargassum. For instance, management approaches of Saint Lucia and Dominica both emphasise the economic opportunities to be gained from sargassum product development (Van der Plank et al. 2022). Additionally, draft national sargassum plans for Grenada, St. Kitts and Nevis, and St. Vincent and the Grenadines include strategies to encourage investment in innovation and entrepreneurship to capitalise on the potential opportunities presented by sargassum influxes (UNEP-CEP, 2021).

8.3 Recommendations

8.3.1 Policy frameworks

National policy frameworks tailored specifically for micro, small, and medium enterprises (MSMEs) need to be mainstreamed. These frameworks should incentivize and facilitate the development of sustainable sargassum businesses by providing regulatory clarity, financial support, and market access (Oxenford et al. 2021). Furthermore, by promoting trade agreements, export incentives, and market development initiatives, governments can facilitate market access for sargassum products, enabling businesses to expand their operations to enter regional and international markets. Other incentives including duty free concessions on the import of specialised equipment for processing and free zones to facilitate the acquisition of property can create an enabling environment for catapulting the development of a regional sargassum industry. Reducing bureaucratic barriers for sargassum businesses is critical for establishing conducive environments for entrepreneurship.

8.3.2 Spatial mapping

Collecting spatially explicit information through mapping to identify areas where sargassum accumulates, can be quite useful to businesses looking to streamline harvesting operations and valorise sargassum (UNEP-CEP, 2021). This data, combined with clear policies and regulations, can help to create an enabling environment by reducing uncertainty for investors on the consistent supply. With accurate mapping, stakeholders can better understand the distribution of sargassum seasonally and annually, and discern trends and patterns, which are critical for making informed decisions about investment opportunities.

8.3.3 Ownership and rights

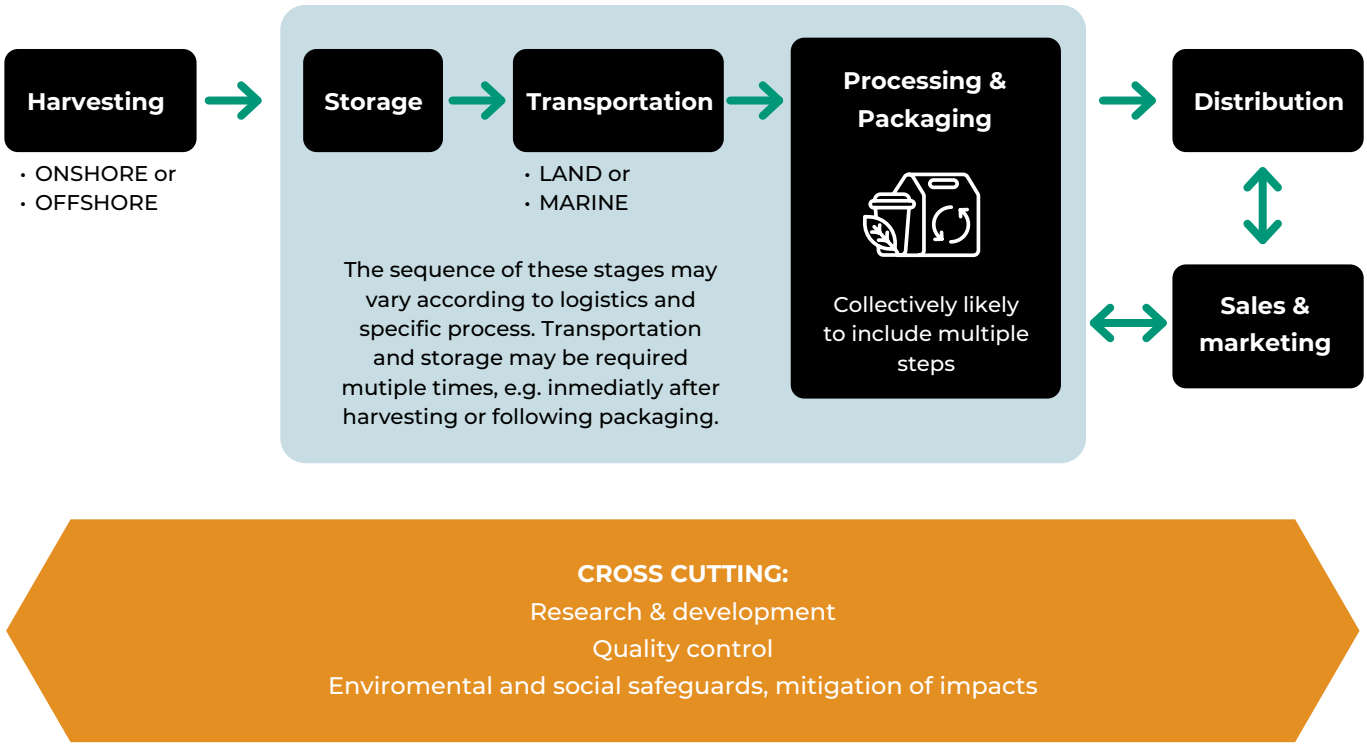
Given the transboundary nature of sargassum, concerns regarding ownership and rights to the sargassum resource should not be ignored. As sargassum valorisation gains more traction, the absence of clear ownership rights, may spur conflicts among various competing stakeholders (Oxenford et al. 2021). Coastal communities, fishers, entrepreneurs, and governments may all have competing interests and visions for the use of sargassum, leading to potential disputes over access, control, and allocation of resources. While there is some ongoing research on this matter, policymakers are advised to evaluate how sargassum aligns with current legislation and policies regarding natural resource ownership and rights in their jurisdiction within Exclusive Economic Zones (UNEP-CEP, 2021). There should be greater focus on ways for sargassum entrepreneurs to access the marine space, for instance through licensing mechanisms that include issuing harvesting permits. Licensing provides a legal framework for regulating access to sargassum resources while ensuring sustainable management practices.

8.3.4 Value chain analysis and market research

Although there is considerable potential for sargassum valorisation in the region, as evidenced by success stories outlined in this study, the existence of stalled businesses cannot be overlooked. Small-scale ventures, despite having promising ideas, face challenges such as inadequate collection capacity, supply-demand imbalances, insufficient research capacities, and logistical hurdles, among others. Many of these challenges can be attributed to insufficient analysis of every aspect of the sargassum value chain. In the emerging landscape of sargassum valorisation, there is an urgent need for more comprehensive value chain analysis and market research to ascertain the feasibility of production and gauge financial profitability. Such efforts can make a compelling case to policymakers of the economic potential and societal benefits of investing in this emerging sector. This involves delineating each stage of the value chain, identifying key activities, stakeholders, inputs, and outputs, and assessing the associated costs and efficiencies (See Figure 45).

Market research in particular, should analyse data on consumer preferences, market trends, competitive landscape, and regulatory environment to inform strategic decision-making. Of particular importance is assessing the economic cost of the initial investment, operational costs and maintenance expenses required for equipment or materials to develop sargassum-based products. Equally important is the assessment of the value of the end product derived from sargassum to gauge the demand and pricing thresholds of sargassum-based products and services to optimise revenue generation and profitability.

Figure 45. Sargassum value chain schematic



Source: UNEP-CEP (2021).

8.3.5 Capacity building

Finally, capacity building initiatives targeting innovators and small- and medium-scale entrepreneurs can also increase chances of success. Innovations must be guided by scientific principles to ensure the safety, quality, and effectiveness of products and services derived from sargassum. However, many innovators may lack the technical capacity to conduct the necessary testing and analysis, to ensure safety and quality of sargassum-based products and services. This has been a significant challenge for those involved in developing sargassum-based products for agricultural purposes, and regrettably, some of these products fail to reach the market. Technical assistance and training programs in regulatory standards as well as business development, grant funding acquisition, marketing strategies, financial management, project management and technology integration can equip entrepreneurs with essential skills and knowledge and empower them to navigate the complexities of starting and growing sargassum ventures. Therefore, investing in research consortia, state owned enterprises and institutions and facilitating knowledge exchange and partnerships, will accelerate innovation in sargassum valorisation.

9 Global Outlook

Sargassum valorisation is an emerging concept in the Caribbean region, gaining traction as countries seek innovative solutions to address the challenges posed by sargassum influxes. By examining international seaweed frameworks and markets, valuable insights and opportunities can be uncovered to guide the development of quality, safe and sustainable sargassum-based industries in the Caribbean. Leading nations in seaweed cultivation and utilisation include China, Indonesia, and Norway, while the European seaweed market has shown notable growth in recent years (World Bank, 2023).

In 2022, the EU published a communication titled 'Towards a Strong and Sustainable EU Algae Sector' which proposes 23 actions aimed at jumpstarting the algae sector in Europe. The actions focus on four different areas: improving the governance framework and legislation, improving the business environment, closing research gaps, and increasing social awareness and market exemptions (EU 2022). The document offers a roadmap for the development of the EU algae industry, emphasising the importance of an integrated and systemic approach. By adapting and applying some of the principles and strategies outlined in the document, the advancement of Caribbean sargassum markets can be enhanced.

The 2023 World Bank Global Seaweed "New and Emerging Markets" report serves as another valuable resource which analyses commercial opportunities for new seaweed market applications. It sheds light on those promising seaweed-based applications that have the greatest market potential in the short-term, medium-term, and long-term.

9.1 Short-term market opportunities (before 2025)

Biostimulants, animal feed, pet foods, and methane-reducing additives were identified as the most promising short-term markets for seaweed (beyond conventional market applications).

Projections indicate these markets could reach a value of USD 4.4 billion by 2030 (World Bank, 2023). Seaweed-derived products in these rapidly growing markets already demonstrate competitive value propositions and pricing. Additionally, they offer low processing complexity and present fewer challenges to scaling compared to other applications (World Bank, 2023). Of the four markets, sargassum-based biostimulants have garnered the most attention in the Caribbean region. Already, businesses like Algas Organics have successfully penetrated international markets.

9.1.1 Biostimulants

At the global level, utilisation of seaweed-based biostimulants has gained significant traction in recent years. Of all markets assessed in the World Bank report (2023), seaweed-based biostimulants held a commanding market share of 30-40 percent in 2022. The global industry for these biostimulants is currently valued at US$1 billion, with forecasts projecting a robust growth trajectory to reach US$1.8 billion by 2030 (World Bank, 2023). Geographically, Europe emerges as the largest market for biostimulants, followed closely by the Asia-Pacific region. The market is characterised by high competitiveness, characterised by relatively low barriers to entry compared to the conventional crop protection market (World Bank, 2023). Notably, the most current feedstock comes from wild-harvested seaweed. With the abundance of sargassum seaweed in the Caribbean region, this could offer an opportunity to expand the supply chain and meet growing market demand.

Despite the growing market for seaweed-based biostimulants, the regulatory landscape at the international level remains fragmented. According to the World Bank (2023) report, there is a notable lack of standards and uniform global legislation governing biostimulants. Recognizing this, the International Organization for Standardization (ISO) has initiated efforts to develop a standard on biostimulant terminology (World Bank, 2023). In 2022, the EU Fertilising Products Regulation (EU) 2019/1009 came into effect, providing a regulatory framework within the European Union. The United States is another jurisdiction where biostimulants are defined and regulated, as demonstrated by the 2018 Farm Bill (World Bank, 2023).

9.2 Medium-term market opportunities (2024–2028)

Alternative proteins, nutraceuticals, bioplastics and fabrics were identified as emerging medium-term market opportunities. However, challenges such as production costs, pricing, and functionality need to be addressed to realise their full potential or else only niche use cases will persist in the future (World Bank, 2023). Of these market opportunities, there has been highest interest in exploring sargassum-based bioplastics in the Caribbean region. Though in its early stages, sargassum-based materials have been commercialised at small to medium scales, with some businesses integrating sargassum-based bioplastics into their biorefinery processes.

9.2.1 Bioplastics

Packaging in particular, dominates the global bioplastics market, with a market value of US$11.5 billion in 2022 (World Bank, 2023). Furthermore, it is projected to grow at a compound annual growth rate of 20 percent between 2022 and 2030 (World Bank, 2023). The future market for seaweed-based bioplastics could be worth US$733 million by 2030. However, to compete in the bioplastics market, seaweed-derived products must contend with established manufacturers such as PTT MCC Biochem, NatureWorks LLC, Total Corbion PLA, and Newlight Technologies (World Bank, 2023). In the market for seaweed bioplastics, only niche

applications exist at present, primarily centred around biofilms, which are still in the initial phases of market adoption (World Bank, 2023).

Despite the potential of seaweed-based bioplastics, there are significant challenges to overcome. Currently, seaweed-based bioplastics are several times more expensive than competitive bioplastics, posing a barrier to widespread adoption. Additionally, the development of compatible seaweed-based resins and their integration into existing production systems require significant research and development efforts, with success not guaranteed (World Bank, 2023).

In terms of regulation, plastic production and performance are regulated by various certifications and global standards to ensure safety and environmental compliance. ASTM International, Biodegradable Products Institute (BPI), and TÜV are among the major organisations setting standards and certifications for plastics (World Bank, 2023).

9.3 Long-term emerging market opportunities (beyond 2028)

Seaweed holds promise in pharmaceuticals and construction markets, with potential for substantial revenue from a single pharmaceutical product (World Bank, 2023). Although the seaweed-based pharmaceutical market is still developing, ongoing research and trials indicate its growth potential. In construction, niche applications like fiberboard and bioplastic panels have advanced, yet challenges such as biomass availability and seaweed properties persist (World Bank, 2023). Despite hurdles, successes in the Caribbean, especially in construction blocks, suggest promising growth opportunities.

9.3.1 Construction material

In 2022, the global green building materials market was valued at US$312.5 billion with expected growth of 10% between 2022 and 2030 (World Bank, 2023). Reports indicate that the overall market remains relatively fragmented, with many small players owning small shares of the market. North America is considered the dominant market, but Asia-Pacific is showing high growth rates (World Bank, 2023). In Europe, North America, East Asia and Oceania, there is a clearer focus on applying technology to extract useful components of seaweed such as alginate or carrageenan for construction (World Bank, 2023).

Regulatory regimes worldwide are setting explicit targets for biobased products. For example, starting in 2025, 25 percent of public newbuilds in France must be bio-based (World Bank, 2023). By 2030, that percentage must reach 50 percent. Additionally, The Danish government, for instance, has now demanded that all newbuilds require life cycle analyses (LCAs) to ensure that the quality and consistency requirements of the seaweed used in construction materials are met (World Bank, 2023).

10 Future Considerations

Researchers across the Caribbean are working on various aspects of sargassum research to better understand the sargassum ecosystem, distribution patterns, and identify management solutions. However, to date, research focused on turning sargassum inundations from a threat to an opportunity has been mostly advanced in Mexico, the Dominican Republic and Barbados. To gain an understanding of the science direction as it relates to sargassum utilisation we interviewed five sargassum researchers across Mexico, the Dominican Republic and Barbados (Table 4) that are working on various aspects of valorisation (e.g., challenges faced by entrepreneurs, alginate extractions, biochar production, and the biorefinery concept).

Table 4. Interviewed sargassum experts from The Dominican Republic, Mexico, and Barbados

Name	Sargassum related research and interests	Country	Organisation
Professor Hazel Oxenford	Research focused on valorisation opportunities, challenges associated with valorisation, arsenic contamination, and in-water harvesting.	Barbados	University of the West Indies (Cave Hill Campus) - Centre for Resource Management and Environmental Studies (CERMES)
Dr. Brigitta van Tussenbroek	Assessment of the eco-toxicological impact of sargassum leachates and particulate organic matter (POM) on marine organisms and ecosystems. Other areas of research include sargassum growth rates.	Mexico	Universidad Nacional Autonoma de Mexico

Dr. Ulises Jauregui	Sargassum-based activated carbon for water treatment and other applications. Research also focuses on alginate extraction and the development of a liquid sargassum fertilizer.	Dominican Republic	Instituto Tecnológico de Santo Domingo (INTEC)
Ms. Sara Saldarriaga-Hernandez	Extraction of fucoxanthin and other polyphenol compounds to use for biological protectants (screen sunscreen).	Mexico	Danay Carrillo Nieves's lab | Tecnológico de Monterrey
Mr. Eduardo Joel López	Extraction of alginate and fucoidans.	Mexico	Danay Carrillo Nieves's lab | Tecnológico de Monterrey

Despite their different backgrounds, there is a consensus among the interviewed experts that the development of a sustainable sargassum industry requires several key considerations:

1. The adoption of a biorefinery approach
2. The value of sargassum as a raw material
3. Effective methods for reducing and testing arsenic levels
4. The establishment of regulatory guidelines

Some of the considerations overlap with elements of the five categories of challenges (unpredictable supply; knowledge gaps on micro-pollutants; harvesting, transport and storage; governance; funding) associated with sargassum valorisation (Oxenford et al. 2021; Desrochers et al. 2022). However, in addition to the challenges previously identified by Oxenford et al. and co-authors, the suggested considerations provide further guidance and advice for the way forward.

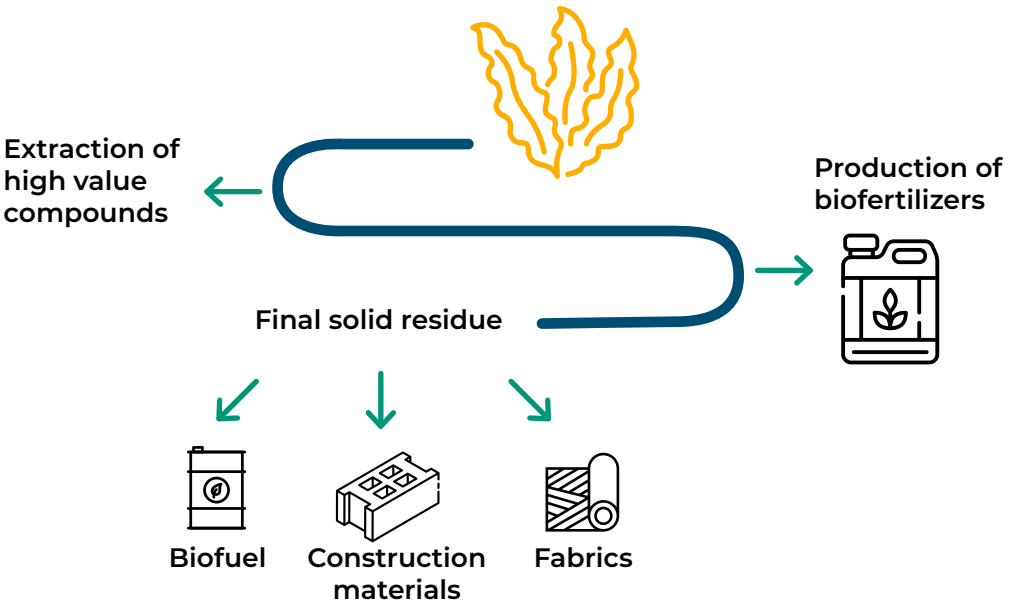
10.1 The adoption of a biorefinery approach

Despite the region's decade long efforts to valorise sargassum, there are very few examples of successful sargassum value chains that utilise large quantities of biomass (e.g., Algas Organics removes approximately 2 million pounds of sargassum annually, SOS Carbon exports containers of sargassum to vendors outside of the Caribbean). Even though there are many identified applications for sargassum, only a small amount of sargassum is used for products; thus, the potential impact on reducing biomass of severe sargassum influxes is quite low.

In an effort to tackle larger quantities of sargassum, researchers at the Tecnológico de Monterrey and Instituto Tecnológico de Santo Domingo (INTEC) are actively seeking ways to extract more molecules from sargassum and utilise the final solid residue (Figure 46). For example, Dr. Ulises Jauregui, a researcher at INTEC, and his team are conducting alginate extractions, conventional pyrolysis, and pyrolysis under microwave to obtain activated carbon

from sargassum to use for water treatment and they have also developed a liquid fertilizer. To take valorisation a step further, the INTEC team has developed research proposals to explore the potential use of sargassum, and the solid residue that remains after extractions, to produce plywood and biogas. Similarly, while researcher Mr. Eduardo Joel López at the Tecnológico de Monterrey primary focus is alginate and fucoidans extractions, he and his team have plans to explore the use of the solid sargassum residue for clothing fibres. Mr. López emphasised that it is important to view sargassum as a source for many applications because if it is only seen as a source for alginate 70% of the sargassum will not be utilised. Going forward he urges the region to approach sargassum utilisation with a circular economy concept in mind.

Figure 46. A proposed biorefinery approach sargassum



Under a biorefinery concept products with the highest added value are obtained first, and the solid residues generated at the end of the process are used for applications such as bioenergy, construction materials and fabrics. Adopting a biorefinery approach to sargassum valorisation will increase the amount of sargassum that is utilised and ultimately reduce the volumes that inundate Caribbean shorelines and reduce the volumes that end up in landfills. However, while there is merit to this approach, this solution requires considerable initial investment to cover industrial space for operations, the cost of equipment/technology for the extraction of high value products, and education/training sessions to ensure staff are familiar with extraction methodologies. Moreover, it is unlikely that each entrepreneur and/or company that are engaged in sargassum valorisation will have an interest in establishing a biorefinery.

Interviewed sargassum experts indicated that regional and combined efforts will be required to achieve the vision of large-scale sargassum use through the adoption of biorefineries. Within a regional plan, companies focused on harvesting could provide fresh sargassum to established biorefineries as well as individual entrepreneurs. In turn, companies using a biorefinery approach will be able to supply high-value compounds (e.g., alginates, fucoidans, flavonoid) and pre-processed sargassum to other companies and research institutions that are developing sargassum products. However, with national level management still lacking in many places, it will undoubtedly be difficult to achieve the level of organisation required at the regional level to address the sargassum phenomenon.

10.2 The value of sargassum as a raw material

As the region continues to develop the 'sargassum industry' companies responsible for supplying sargassum businesses with fresh sargassum will have to determine the price of sargassum as a raw material. To date, despite regional valorisation efforts, sargassum is primarily treated as waste where it is collected from beaches and disposed of in landfills. However, as the sargassum industry continues to develop, sargassum will be seen as a valuable bioresource for industrial applications. A key question then becomes: what should entrepreneurs pay for sargassum?

While it is true that sargassum arrives 'free' for all to use, Dr. Ulises Jauregui points out that not all entrepreneurs are interested in the collection process and its associated challenges (Oxenford et al. 2021). Therefore, it is important that sargassum is treated as a raw material that can be purchased bearing in mind that the cost of the sargassum will determine the cost of the final sargassum products and affect their competitiveness in the market. In the Dominican Republic researchers at INTEC are trying to solve this problem as they work with harvesting companies (e.g., SOS Carbon and AlgeaNova) to procure large quantities of sargassum. Currently, harvesting companies are paid by hoteliers to collect sargassum from beaches and dispose of it, however, if researchers want to purchase that sargassum, difficulties arise when negotiating the actual price of the sargassum. Since the cost of collection was already covered by the hotelier, a fair solution may be to charge researchers/entrepreneurs for the processing (e.g., drying), if any, and transportation of sargassum per volume being sold. Currently, there is no established solution to address this problem, however future considerations should be made to (1) ensure sargassum is treated as a raw material instead of waste and (2) determine the price of sargassum as a raw material.

10.3 Effective methods for reducing and testing arsenic levels

Sargassum, like many other brown seaweeds, bioaccumulates arsenic and other micropollutants from the environment (Devault et al. 2021). Across the Caribbean, reports of high arsenic content (both inorganic and organic) (Davis et al. 2020; Milledge et al. 2020; Chávez et al. 2020; Nielsen et al. 2021; Gobert et al. 2022; Alleyne et al. 2023) present valorisation barriers and raise concerns for applications that involve the direct consumption of lightly or unprocessed biomass.

According to experts, some valorisation applications, such as the extraction of specific compounds and the production of liquid biofertilizer, are not affected by the arsenic content of sargassum. However, arsenic is accumulated in the solid residue that remains and interventions should be made to effectively treat/dispose of this arsenic. Additionally, experts alluded to the urgent need to reduce arsenic for large-scale applications such as composting, that can be easily adopted by community members. Preliminary studies by Dr. Brigitta van Tussenbroek at the Universidad Nacional Autonoma de Mexico and Dr. Ana López-Contreras, and her team, at Wageningen Food & Biobased Research show that earthworms can effectively reduce the arsenic content of compost and may provide a viable solution for agronomic applications. Professor Oxenford at the University of the West Indies (Cave Hill Campus) stated that although arsenic reduction in compost using earthworms requires further research; it also presents an opportunity for governments to import the required worms for commercial scale operations. Careful consideration and stringent monitoring would be essential to ensure that the benefits outweigh the risks, particularly concerning the potential ecological impact of introducing non-native species. The final compost product can then be sold to farmers who are already making sargassum compost without testing for micropollutants.

In addition to finding effective ways to reduce arsenic levels, sargassum-based products, and the raw material, will likely require continued testing at all stages of the production process to ensure public and environmental safety. To date, the high cost associated with arsenic testing, especially testing for inorganic arsenic, has been a major barrier to valorisation applications. Research by Alleyne et al. (2023) compared the level of total and inorganic arsenic arriving in sargassum over a one-year period to better understand how arsenic levels change during influx events. According to their results, the level of inorganic arsenic (the more toxic form) was relatively consistent (on average accounted for 56% of the total arsenic) over the one-year period. This suggests that going forward entrepreneurs can simply test for total arsenic levels, as this is a more affordable option, to get an indication of the levels of inorganic arsenic present in sargassum.

Arsenic contamination has and continues to hinder valorisation applications for sargassum. To date, there have been several research efforts focused on understanding and addressing challenges associated with arsenic contamination and valorisation. However, the uptake of that research within management and policy remains limited. Future efforts need to be made to ensure that (1) better synergies among science, entrepreneurs, and management are established and (2) regional testing is accessible and affordable for all interested stakeholders.

10.4 The establishment of regulatory guidelines

The development of the 'sargassum industry' across the Caribbean is challenged by governance constraints and a lack of regulatory guidelines. Despite commendable efforts by entrepreneurs to produce sargassum-based products, entrepreneurs are currently operating within an arbitrary system which has the potential to affect processes along the value chain and market success of their products. While there are many areas for improvement, experts indicated that the sustainable valorisation of sargassum will require: (1) regulatory guidelines for harvesting; (2) standards for the allowable concentrations of arsenic and other micro-pollutants for sargassum-based products; and (3) regulatory standards that improve sargassum export potential.

10.4.1 Regulatory guidelines for harvesting

Within this Sargassum Landscape study, the majority (over 70%) of the interviewed entrepreneurs relied on fresh sargassum for their products, suggesting that in-water harvesting will play a pivotal role in the development of the sargassum industry. While there were initial concerns about in-water harvesting as it related to the biodiversity associated with sargassum rafts, research from Mexico (Monroy-Velázquez et al. 2019) and Barbados (Corbin et al. 2024) indicate that sargassum rafts within 0–3000 m of the shoreline harbour low biodiversity of no commercial value. As the industry develops, the uptake of these types of research will be important in creating evidence-informed policies and guidelines regarding where and when sargassum should be collected. Additionally, it will be important for the region to clearly outline who has the right to collect sargassum in order to protect what may very well transform into a valuable regional resource, as opposed to a waste material.

10.4.2 Standards for the allowable concentrations of arsenic and other micro-pollutants for sargassum-based products

To date, both scientists and management authorities have acknowledged the importance of

testing sargassum for arsenic and generally advise the public not to directly apply sargassum on agricultural products or consume it. However, there are no standards indicating the total allowable levels of arsenic (organic and inorganic) and other micro-pollutants for sargassum-based products. Experts indicated that in addition to product testing, the region needs to establish standards for the amount of arsenic that can be placed in the soil. Moreover, with wide-scale utilisation of sargassum-based fertilisers, there should be continuous monitoring of soil conditions to ensure arsenic levels remain within set standards.

10.4.3 Regulatory standards that improve sargassum export potential

As the region looks towards the future of sargassum valorisation, experts urge policymakers to establish regulatory standards that increase the potential of sargassum to be exported in bulk qualities. According to a recent World Bank report, the global seaweed market is estimated to surpass US$11 billion by 2030 (World Bank 2023). Companies around the world import various species of seaweed as biomass feedstock for biostimulants, bioenergy, nutraceuticals, and pharmaceuticals. However, unless sargassum is on the list of allowable imports, the region can't access the most valuable markets. Future considerations for regulatory standards should therefore ensure that procedures for handling sargassum within the region comply with international import policies with traceability procedures to understand where the biomass was collected and how it was treated prior to export.

11 Conclusion

In conclusion, this comprehensive study has identified and assessed a wide range of technological advancements employed in Central America, Mexico, and the Caribbean for sargassum utilisation. Sargassum-based compost, biofertilizers, bioplastics, biogas, construction materials, clothing, footwear, cosmetics, and the development of harvesting equipment demonstrates the breadth of commercial opportunities in this emerging sector within the region.

The proposed Sargometer framework based on 10 criteria was proposed as a framework that can be adapted and refined to further assess sustainability and effectiveness of sargassum utilisation solutions. This could be a valuable tool for decision-makers and stakeholders to support the valorisation of sargassum. The study also spotlighted several successful sargassum-based companies which further underscores the potential for economic growth and innovation in the region.

Moving forward, greater community engagement, proactive policy frameworks, regulatory guidelines, value chain analysis, and market research will be essential for implementing holistic solutions to address the multifaceted impacts of sargassum on coastal communities. The emerging biorefinery concept holds promise for optimising resource extraction and creating multiple product streams from sargassum biomass, enhancing economic viability.

Drawing insights from international seaweed frameworks and markets offers valuable guidance for the development of sargassum-based industries in the Caribbean, ensuring long-term sustainability and resilience. It is anticipated that this study will provide valuable information for policymakers and funding institutions, enabling them to make informed decisions and support sargassum valorization initiatives effectively. Through collaborative efforts and strategic investments, the region can harness the potential of sargassum to drive positive economic, environmental, and social outcomes for years to come.

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13 Annexes

Annex 1. List sargassum businesses presumed to be operational in Central America, Mexico and the Caribbean

Country	Business	Products/Services
Antigua	NADIS	Sargassum Alerts and Monitoring
Barbados	Rum and Sargassum	Biofuel
Barbados	Red Diamond Compost	Biostimulant
Barbados	EcoMyco	Bioplastics
Dominican Republic	AlgeaNova	Compost, biodegradable dishes and biogas
Dominican Republic	Maralive	Harvester
Dominican Republic	SOS Carbon	Exports to a cosmetic company called Origin by Ocean
Dominican Republic	EnergyAlgae	Biogas & digestate
Guadeloupe	SUEZ	Fertilizer
Guadeloupe	Num SMO Technologies (NST)	Activated carbon & biochar
Jamaica	Awganic Inputs	Animal feed
Martinique	The Marine Box	Coffins, urns
Martinique	Holdex Environnement	Compost
Mexico	Thalasso Ocean	Harvesting, processing
Mexico	Salgax	Paper, cosmetics, biofertilizer
Mexico	Dakatso	On-shore and in-water removal

Mexico	Alquimar	Bio stimulant fucoidan
Mexico	BioPlaster	Bioplastics
Mexico	Sargablock/BlueGreen	Construction blocks, compost, biofertilizers
Mexico	Biomaya	Soaps
Mexico	Dianco	Fertilizer
Mexico	Renovare Ocean	Footwear
Mexico	Transporte Maritima Mexicana (TMM)	Bioenergy & activated carbon
Mexico	Abaplas	Bioplastics
Mexico	Diseño y Decorativos del Caribe Maya	Particleboard
Mexico	Sargánico	Paper products
Mexico	Sargazbox	Cardboard Boxes
Mexico	Group Metco	Alginates
Puerto Rico	Carbonwave	Agriculture, textiles, personal care, cosmetics
Puerto Rico	Sway	Bioplastics, compost
Saint Barthélemy	Sargasse Project	Paper
Saint Kitts and Nevis	Grogenics	Compost
St. Lucia	Algas	Plant amendment
Trinidad	Spargassum	Spa products

Annex 2. Key researchers/experts in Central America, Mexico and the Caribbean studying potential uses of sargassum

Name	Affiliation	Position	Area of research
Prof. Hazel Oxenford	CERMES	Professor	
Dr. Bidyut Mohapatra	University of the West Indies, Cave Hill	Lecturer	Alginate extraction
Dr. Francis Lopez	University of the West Indies, Cave Hill	Lecturer	Mulch, fertilizer
Dr. Thierry Tonon	University of York	Professor	Application of Stranded Pelagic Sargassum Biomass as Compost for Seedling Production in the Context of Mangrove Restoration
Professor Valéria Laneuville Teixeira	Universidade Federal do Estado do Rio de Janeiro	Professor	Biosorbents
Dr. Ulises Jauregui	Instituto Tecnológico de Santo Domingo (INTEC)	Professor	Sargassum-based activated carbon for water treatment and other applications.
Dr. Trent Blare	University of Florida	Assistant professor	Cost Estimates for Producing Sargassum spp. Compost
Dr. Thierry Cesaire	Université des Antilles	Researcher AND project coordinator of SARtrib project	Electrodes
Prof. Sarra Gaspard	Université des Antilles	Professor	AC & biochar
Professor Valérie Stiger	Université de Bretagne Occidentale	Professor at Université de Bretagne Occidentale AND Project coordinator of the Save-C project	Biopesticides
Christophe Roos	Laboratory of Materials and Molecules in Aggressive Environments	Director of Laboratory of Materials and Molecules in Aggressive Environments	Antifouling properties of sargassum
Professor Marie-Ange Arsène	Université des Antilles	Professor	Ecomaterials
Prof. Rupika Delgoda	University of the West Indies, Mona	Lecturer	Anticancer properties of sargassum extracts
Dr. Winklet Gallimore	University of the West Indies, Mona	Lecturer	Bioactive compounds

Dr. Frederick Boyd	University of the West Indies, Mona	Lecturer	Medical botany & antimicrobial properties
Prof. Mona Webber	University of the West Indies, Mona	Professor	Compost
David Dural	Institut Technique Tropical (IT2)	Director of Institut Technique Tropical	application of pelagic sargassum compost and direct field spreading
Dr. Jorge Cantó	Polytechnic University of Quintana Roo (UPQRoo)	Lead researcher	This research project focuses on determining potential commercial value of sargassum
Dr. Silvia Carrillo Domínguez	National Institute of Medical Sciences and Nutrition Salvador Zubirán (INCMNSZ) - Department of Animal Nutrition	Researcher at INCMNSZ and an adviser at the National Poultry Institute	Animal Feed
Dr. Miriam Rocio Esteves Gonzalez	Center for Applied Physics and Advanced Technology (CFATA)	Professor	Purification & bioremediation, biofilters
Dr. Brigitta van Tussenbroek	Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de Mexico	Professor	Assessment of eco-toxological impact of sargassum leachates and particulate organic matter (POM) on marine organisms and ecosystems AND Growth studies
Prof. J. Ysmael Verde Gómez	Tecnológico Nacional de México /IT de Cancún	Researcher	Research aims to generate new knowledge towards future sustainable applications such as: biofuels, nanocarbons for energy and environmental applications, and extracts
Dr. Ana María Valenzuela-Muñiz	Tecnológico Nacional de México /IT de Cancún	Head of the Graduate Studies and Research Division	Research aims to generate new knowledge towards future sustainable applications such as: biofuels, nanocarbons for energy and environmental applications, and extracts
Dr. Héctor Ruiz	Biorefinery Group, Food Research Department, Faculty of Chemistry Sciences, Autonomous University of Coahuila	Researcher	Bioethanol production
Sara Saldarriaga-Hernandez	Tecnologico de Monterrey, School of Engineering and Sciences	Researcher	Biosorbents

Dr. Danay Carrillo-Nieves	Tecnologico de Monterrey, Escuela de Ingenieria y Ciencias	Professor	Valorization of pelagic sargassum biomass into sustainable applications
Dr. Raúl Tapia-Tussell	Renewable Energy Unit, Yucatan Center for Scientific Research	Researcher	Biorefinery potential
Dr. Liliana Alzate-Gaviria	Renewable Energy Unit, Yucatan Center for Scientific Research	Researcher	Methane production
Dr. Angel Trinidad Piñeiro-Vázquez	Facultad de Zootecnia y Ecología, Universidad Autónoma de Chihuahua,	Researcher	Biogas production
Dr. Valeria Chávez	Instituto de Ingeniería, Universidad Nacional Autónoma de México	Associate Researcher	Commercial Potential of Pelagic Sargassum spp. in Mexico
Dr. Juan Muñoz Saldaña	Laboratorio Nacional de Proyecci ón T érmica (CENAPROT)	Professor	Sargassum macroalgae from Quintana Roo as raw material for the preparation of high-performance phosphate adsorbent from aqueous solutions
Dr. Manuel Iván Girón-Pérez	Laboratorio Nacional de Investigación para la Inocuidad Alimentaria (LANIIA)-Unidad Nayarit, Universidad Autónoma de Nayarit	Professor	Production of a commecial fucoidan -Effect of Fucoidan on the Mitochondrial Membrane Potential ($\Delta\Psi$m) of Leukocytes from Patients with Active COVID-19 and Subjects That Recovered from SARS-CoV-2 Infection
Prof. Jayaraj Jayaraman	The University of the West Indies, St. Augustine	Lecturer	Biostimulant Properties
Prof. Jayaraj Jayaraman	University of the West Indies, St Augustine	Lecturer	Bio-elicitors, nanopesticides & biocontrol
Dr. Keeran Ward	University of the West Indies, St Augustine	Lecturer	Thin film composite - biodegradable water container AND Purification & bioremediation

Annex 3. Score breakdown for the 10 factors/criteria used to assess the effectiveness of valorisation applications

	Factors/Criteria	Score breakdown
1	**Harvesting logistics**	5: No machinery, equipment or person required 4: No machinery or equipment is required. Harvesting is carried out on the beach by one individual using hand collections and garbage bags. 3: No machinery or equipment is required. Harvesting is carried out on the beach and/or wading in the nearshore water by 1-2 persons using hand collections and garbage bags. 2: No machinery required. Shoreline collections are undertaken using manual tools (e.g., digging spades, rakes) with a team of 2-5 persons. 1: Mechanised shoreline equipment (e.g., surf rakes) as well as manual tools (e.g., digging spades, rakes) are used to collect sargassum by a team of more than 5 persons. 0: Mechanised offshore equipment (e.g., in-water harvesters) is used to collect sargassum by a team of 5 or more persons. Offshore harvesting may also be combined with shoreline harvesting efforts.
2	**Land space requirements**	5: No space required 4: Less than 500 m^2 3: More than 500 m^2 but less than 1000 m^2 2: 1000 m^2 or more but less than 2500 m^2 1: 2500 m^2 or more but less than an acre (4047 m^2) 0: More than an acre of land
3	**Need for additional feedstock**	5: No additional feedstock required 4: One additional feedstock is required 3: Two additional feedstocks are required 2: Three additional feedstocks are required 1: Four additional feedstocks are required 0: Five or more additional feedstocks are required
4	**Processing time**	5: No processing time required 4: One day (24 hours) or less required 3: More than one day but less than one week required 2: One to two weeks required 1: More than two weeks but less than one month is required 0: One month or more is required

5	**Specialised equipment requirements**	5: No specialised equipment required 4: One piece of specialised equipment, technology, or machinery is required 3: Two pieces of specialised equipment, technologies, or machineries are required 2: Three pieces of specialised equipment, technologies, or machineries are required 1: Four pieces of specialised equipment, technologies, or machineries are required 0: Five pieces or more of specialised equipment, technologies, or machineries are required
6	**Waste management requirements**	5: No waste is generated. The entire sargassum biomass is utilised during production. Additionally, no waste is generated during the packaging and distribution of the product. 4: The entire sargassum biomass is utilised during production, there is no remaining solid or liquid residue. Generated waste, low quantities, comes from materials used during the packaging and distribution of the product. 3: Waste generated mainly consists of liquid residue from the sargassum. All the solid sargassum biomass is utilised and there is little to no waste from materials used during packaging and distribution. 2: Waste generated mainly consists of solid residue from the sargassum. There is little to no waste from materials used during packaging and distribution. 1: Waste generated consists of solid and liquid residue from the sargassum. There is minimum waste generated from materials used during packaging and distribution. 0: Waste generated during the production process consists of solid and liquid residue from the sargassum and other feedstocks that may have been utilised. Additionally, there is moderate to high levels of waste generated from materials used during packaging and distribution.

7	**Marketability/ return on investment**	5: There is a high and growing demand for the valorisation application in national, regional, and international markets. High profitability (potential to achieve a net profit of 20% or higher). The application requires very little initial investment. Production/operating costs are significantly lower than the initial investment. 4: There is a high and growing demand for the valorisation application in national and regional markets but not international markets. Good profitability (potential to achieve a net profit of 10%). The application requires low initial investment. Production/operating costs are lower than the initial investment. 3: There is a moderate to high demand for the valorisation application only in national markets. Good profitability (potential to achieve a net profit of 10%). The application requires medium initial investment. Production/ operating costs are equal to the initial investment. 2: There is a moderate demand for the valorisation application in national and regional markets. Low profitability (potential to achieve a net profit of 5%). The application requires high initial investment. Production/ operating costs are higher than the initial investment. 1: There is a low demand for the valorisation application in national, regional, and international markets. Low profitability (potential to achieve a net profit of less than 5%). The application requires high initial investment. Production/operating costs are higher than the initial investment. 0: There is no national, regional, or international demand for the valorisation application. Not profitable. The application requires high initial investment. Production/operating costs are equal to or higher than the initial investment.

8	**Regulatory Requirement**	5: Products of the valorisation application will not be used for human and/or animal consumption and therefore does not require tests for arsenic and other micro pollutants. It is not critical to test soil conditions as the application will not be used for agronomic purposes. The application requires low quantities of sargassum, fresh or dry, and does not rely on large-scale in-water harvesting efforts. 4: Products of the valorisation application will not be used for human and/or animal consumption and therefore does not require tests for arsenic and other micro pollutants. It is not critical to test soil conditions as the application will not be used for agronomic purposes. However, the application requires moderate to large quantities of fresh sargassum sourced from in-water harvesting and will be subjected to harvesting regulations. 3: Products of the valorisation application will not be used for human and/or animal consumption and therefore does not require tests for arsenic and other micro pollutants. However, it is important to test soil conditions as the application will be used for agronomic purposes. The application requires low quantities of sargassum, fresh or dry, and does not rely on large-scale in-water harvesting efforts. 2: Products of the valorisation application will be used for human and/or animal consumption and therefore require tests for arsenic and other micro pollutants. However, it is not critical to test soil conditions as the application will not be used for agronomic purposes. The application requires low quantities of sargassum, fresh or dry, and does not rely on in-water harvesting. 1: Products of the valorisation application will be used for human and/or animal consumption and therefore require tests for arsenic and other micro pollutants. It is also important to test soil conditions as the application will be used for agronomic purposes. The application requires low quantities of sargassum, fresh or dry, and does not rely on large-scale in-water harvesting efforts. 0: Products of the valorisation application will be used for human and/or animal consumption and therefore requires tests for arsenic and other micro pollutants. It is also important to test soil conditions as the application will be used for agronomic purposes. The application also requires large quantities of fresh sargassum sourced from in-water harvesting and will be subjected to harvesting regulations.

9	**Community or national importance**	5: The valorisation application has the potential to alleviate challenges faced by communities during severe influx events. The application also provides numerous types of opportunities for community involvement (e.g., knowledge sharing, harvesting, training and employment) and supports national policy directions such as aspirations for building climate resilience, blue economy development and 100% renewable energy targets. 4: The valorisation application has the potential to alleviate some of the challenges faced by communities during severe influx events. The application provides few opportunities for community involvement. 3: The valorisation application has the potential to alleviate some of the challenges faced by communities during severe influx events. However, the application does not provide any opportunities for community involvement. 2: There is no potential for the valorisation application to alleviate any of the challenges faced by communities during severe influx events. However, there are numerous types of opportunities for community involvement. 1: There is no potential for the valorisation application to alleviate any of the challenges faced by communities during severe influx events. The application provides few opportunities for community involvement. 0: There is no potential for the valorisation application to alleviate any of the challenges that communities face during severe influx events and the application does not facilitate any form of community involvement.
10	**Environmental impact**	5: Production process and products of the application do not contribute to GHG emissions, have a highly positive impact on biodiversity, significantly reduce environmental pollution and exhibit an extremely efficient use of resources. 4: Production process and products of the application contribute minimally to GHG emissions, have a minor positive impact on biodiversity, largely reduce environmental pollution and exhibit a highly efficient use of resources. 3: Production process and products of the application contribute moderately to GHG emissions, have no impact on biodiversity, do not reduce environmental pollution and exhibit an efficient use of resources. 2: Production process and products of the application have noticeable GHG emissions, have a minor negative impact on biodiversity, slightly increase environmental pollution and exhibit an inefficient use of resources. 1: Production process and products of the application have high GHG emissions, have a negative impact on biodiversity, increase environmental pollution and exhibit an highly inefficient use of resources. 0: Production process and products of the application have significantly high GHG emissions, adversely impact on biodiversity, significantly increase environmental pollution and exhibit an extremely inefficient use of resources.


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