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Pelagic sargassum

A guide to current and potential uses in the Caribbean

Cover photograph:

Free-floating pelagic sargassum viewed from below.

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Anne Desrochers
Consultant
Centre for Resource Management and Environmental Studies (CERMES)
University of the West Indies, Cave Hill Campus, Barbados

Shelly-Ann Cox
Postdoctoral Research Associate
Centre for Resource Management and Environmental Studies (CERMES)
University of the West Indies, Cave Hill Campus, Barbados

Hazel A. Oxenford
Professor of Marine Ecology and Fisheries
Centre for Resource Management and Environmental Studies (CERMES)
University of the West Indies, Cave Hill Campus, Barbados

Brigitta van Tussenbroek
Senior Researcher
Reef Systems Unit, Instituto de Ciencias del Mar y Limnología
Universidad Nacional Autónoma de Mexico, Cancún, Mexico

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Preparation of this document

This report was commissioned by the Food and Agriculture Organization of the United Nations (FAO) with the aim of increasing resilience and reducing vulnerability to climate change impacts in the Eastern Caribbean fisheries sector, through the introduction of adaptation measures such as capacity-building of fisherfolk and aquaculturists and mainstreaming climate change into fisheries governance.

The report was produced as part of the project Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) (GCP/SLC/202/SCF), funded by the Global Environment Facility (GEF) and implemented by FAO. The document is adapted from the *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers,* CERMES Technical Report 97. Production was led by Anne Desrochers, Shelly-Ann Cox and Hazel A. Oxenford (Centre for Resource Management and Environmental Studies, UWI-CERMES, Barbados), with input from Brigitta van Tussenbroek (Reef Systems Unit, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de Mexico). Technical review was provided by Iris Monnereau, FAO CC4FISH Project Coordinator. The adaptation of the original *Sargassum uses guide* into this abridged report was undertaken by Juan Vilata, CC4FISH Knowledge and Communications consultant.

Abstract

Pelagic sargassum - A guide to current and potential uses in the Caribbean has been developed as a resource for researchers, business entrepreneurs and policymakers by providing, under one cover, a comprehensive overview of the wide range of current uses of sargassum in the Caribbean and the challenges faced to date. It also provides insights into potential uses, based on examples and research from other parts of the world involving different sargassum species or other seaweeds. The first section of the guide sets the context in which it was developed and gives a brief general overview of pelagic sargassum, including its basic biology and chemical composition, as relevant to developing uses for sargassum biomass. Section 2 presents a range of potential uses of sargassum based on research and examples of uses of macroalgae (seaweeds) in general, and brown algae in particular, highlighting those using sargassum seaweed species where available. Section 3 provides a comprehensive summary of the challenges faced to date, the new knowledge that is helping to address these, and gaps that remain.

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Abbreviations and acronyms

AC	activated carbon
ADEME	Agence de l'environnement et de la maîtrise de l'énergie (French Agency for Environment and Energy Management)
ANR	Agence nationale de la recherche (French National Agency of Research)
ANSES	Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail
CC4FISH	Climate Change Adaptation in the Eastern Caribbean Fisheries Sector Project
CEC	cation exchange capacity
CERMES	Centre for Resource Management and Environmental Studies
C:N	carbon to nitrogen ratio
C:P	carbon to phosphorus ratio
CO_2	carbon dioxide
COVACHIM-M2E	Connaissance et valorisation: Chimie des matériaux, environnement, énergie (Knowledge and Valorisation: Chemistry of materials, environment, energy)
CRFM	Caribbean Regional Fisheries Mechanism
DENR	Department of Environment and Natural Resources, Government of Bermuda
EDLC	electrochemical double layer capacitator
FAO	Food and Agriculture Organization of the United Nations
FDA-CVM	Center for Veterinary Medicine of the U.S. Food and Drug Administration
GEF	Global Environment Facility
GCFI	Gulf and Caribbean Fisheries Institute
IMO	International Maritime Organization
IMTA	Integrated Multi-Trophic Aquaculture
INRA	Institut national de la recherche agronomique (National Institute of Agronomic Research)
IT2	Institut technique tropical (Technical Tropical Institute)
JICA	Japan International Cooperation Agency
m^3	cubic metre
MUFA	mono-unsaturated fatty acid
n-3	omega-3
NST	NUM SMO (solar microwave oven) technologies
pH	potential of hydrogen
PHA	polyhydroxyalkanoate
PLA	polylactic acid
ppm	parts per million
PUFA	polyunsaturated fatty acid
PYROSAR	Valorization of sargassum by pyrolysis – application for food safety
SARGOOD	holistic approach to sargassum valorization
SARtrib	tribological and electrochemical valorization of sargassum
SAVE	Sargassum Agricultural Valorization and Energy production
SAVE-C	Study of holopelagic sargassum responsible for massive beachings: valorization and ecology on Caribbean coasts

SBI	Sargassum Biomass Index
SFA	saturated fatty acid
SPAW-RAC	Specially Protected Areas and Wildlife (protocol of the Cartagena Convention)-Regional Activity Centre for the wider Caribbean
UNAM	Universidad Autónoma de Mexico
UNEP	United Nations Environment Programme
UV	ultraviolet
UWI	University of the West Indies
WIRRED	Walkers Institute for Regeneration Research, Education and Design, Barbados
WHO	World Health Organization

Executive summary

The year 2011 marked the start of repeated mass influxes of pelagic sargassum into the Caribbean. These events continue to have significant negative impacts on national economies and coastal livelihoods. As a result, there has been growing interest across the Caribbean region in utilizing stranded pelagic sargassum as a primary resource for various purposes, turning this hazard into an opportunity. The past few years have seen entrepreneurs and research teams from across the region working to raise funds and develop innovative businesses and projects that can derive benefits from using sargassum seaweed, and at the same time, help to mitigate damage caused by repeated strandings and defray costs of clean-up and disposal.

Information about these initiatives is scattered and not well documented or easily accessible via the Internet. For this reason, the authors of this report undertook a thorough investigation of the current and potential uses of sargassum within the Caribbean, in order to share progress and lessons learned in working with sargassum to develop economically viable products and solutions.

Pelagic sargassum - A guide to current and potential uses in the Caribbean has been developed as a resource for researchers, business entrepreneurs and policymakers by providing, under one cover, a comprehensive overview of the wide range of current uses of sargassum in the Caribbean and the challenges faced to date. It also provides insight into potential uses, based on examples and research from other parts of the world involving different sargassum species or other seaweeds.

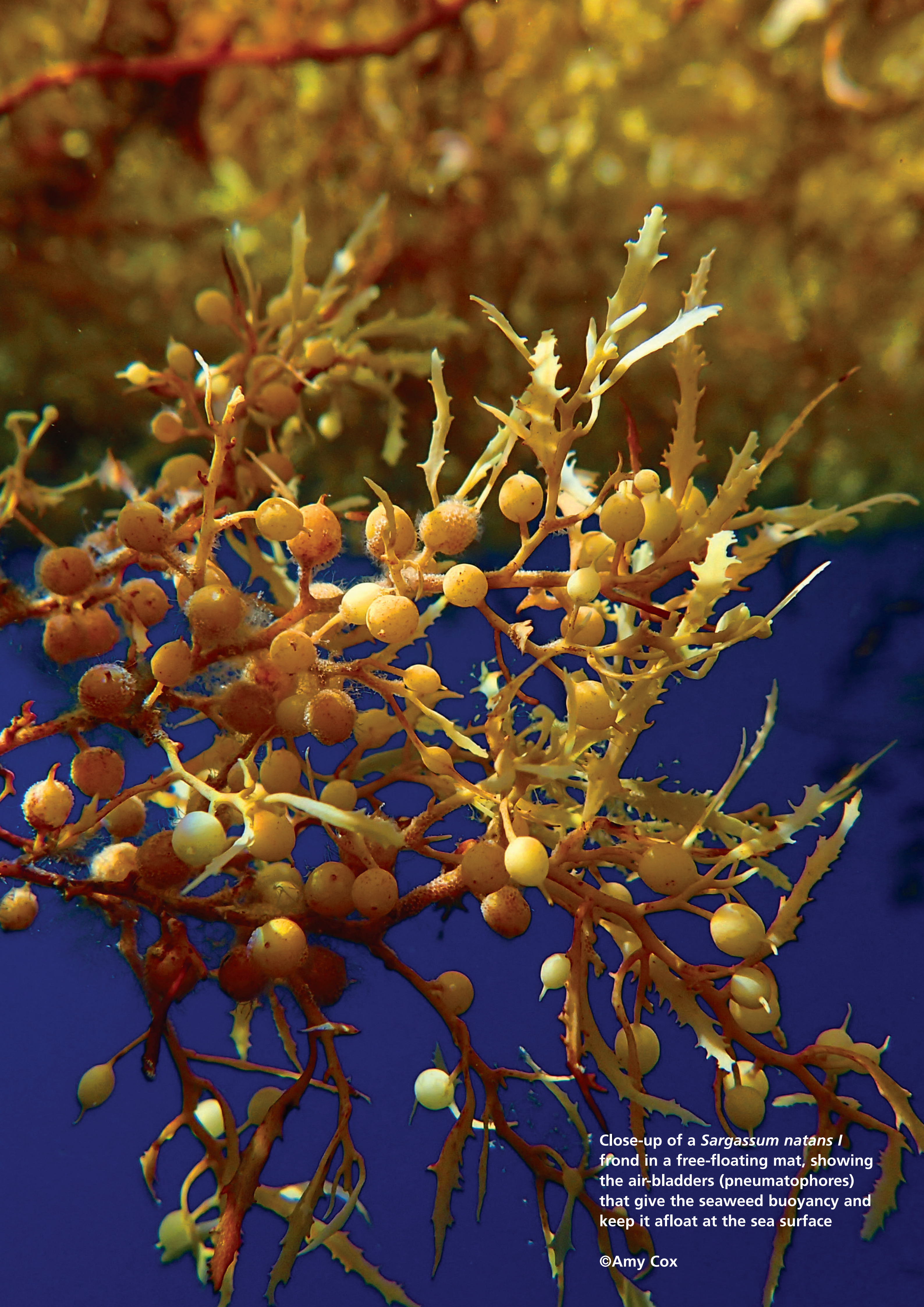
The first section of the guide sets the context in which it was developed and gives a brief general overview of pelagic sargassum, including its basic biology and chemical composition, as relevant to developing uses with sargassum biomass. This section features diagrams showing the sargassum compositional profile and the wide range of possible uses for the different components found in sargassum.

Section 2 presents the range of potential uses of sargassum based on research and examples of use of macroalgae (seaweeds) in general, and brown algae in particular, highlighting those that involve using sargassum seaweed species where available. This section provides detailed technical explanations and examples of the demonstrated or potential use of sargassum in 15 different sectors, ranging from agriculture to food and beverages, biofuels, fashion, cosmetics, paper, bioplastics, construction, pharmaceuticals, electrochemicals, water and air purification, and environmental remediation, *inter alia*.

Warnings are indicated for certain uses, where there is currently insufficient evidence to demonstrate that they do not pose any harm to humans or the environment. This section also provides summaries of the different ongoing initiatives across the Caribbean region that are using sargassum. In order to give a broad estimate of the amount of end products that can be produced with a given amount of fresh sargassum, a Sargassum Biomass Index (SBI) has been developed, and this is included throughout this section. The SBI uses units of both weight (1 tonne) and volume (1 cubic metre (m^3)) as the measure of fresh sargassum. Section 2 concludes with a summary diagram of the SBI, giving a visual overview of the number of valuable products that can be developed with 1 tonne of sargassum. It also provides a concise table summarizing the current state of knowledge with regard to the potential uses of pelagic sargassum and current product-specific challenges.

Section 3 provides an important summary of the challenges faced to date, the new knowledge that is helping to address these, and gaps that remain. It also highlights major constraints that have been shared with the authors by sargassum entrepreneurs, business owners and researchers from around the region in their efforts to valorize sargassum and share knowledge with others. These are grouped into five broad categories: (1) Unpredictable supply; (2) Chemical composition; (3) Harvest; (4) Management; and (5) Funding. This section offers guidance, of particular relevance to policymakers and funding agencies, on gaps and challenges that need to be addressed in order to move forward, scaling-up successful and sustainable solutions and providing an enabling environment that fosters innovation and creativity.

The authors anticipate that this guide will help to promote a viable approach to the management of stranded sargassum across the region by enhancing knowledge and connectivity of the growing community of practice for sargassum managers, researchers and innovative business enterprises. What is needed now are more initiatives to translate science into action.



Close-up of a *Sargassum natans I* frond in a free-floating mat, showing the air-bladders (pneumatophores) that give the seaweed buoyancy and keep it afloat at the sea surface

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1. Introduction and background

1.1 Context

A significant emerging phenomenon is the unprecedented blooming of pelagic sargassum seaweed across the Equatorial Atlantic which, since 2011, has been advecting into the Caribbean Sea and resulting in mass strandings of the seaweed along windward shorelines across the region (Franks, Johnson and Ko, 2016; Wang *et al.,* 2019). This has disrupted fisheries, had devastating impacts on tourism, damaged critical nearshore ecosystems and coastal livelihoods, and caused significant health problems for populations exposed to rotting sargassum (UNEP, 2018). This phenomenon is also affecting West Africa, where mass strandings of pelagic sargassum have been occurring since 2009 (Addico and deGraft-Johnson, 2016).

After initial uncertainty, this new sargassum source has been linked to climate change and ocean eutrophication and is likely to continue supporting significant sargassum blooms into the future (UNEP-CEP, 2021). As such, annual mass influxes of sargassum into the Caribbean Sea are now being considered as the "new normal", requiring sustainable management responses and long-term adaptation.

The current cost and manpower required to repeatedly clean and dispose of stranded sargassum is unsustainable, and has already resulted in several countries declaring a state of emergency (Trinidad and Tobago in 2015, Barbados in 2018, Mexico in 2019), implying that state or federal funds and manpower (such as the army) can be utilized in order to tackle the onslaught of thousands of tonnes of stranded sargassum. Furthermore, the cost to the national economies of many countries from lost revenue in the tourism sector in particular, and in fisheries and other coastal livelihoods is substantial and a matter of significant concern. As such, there is rapidly growing interest across the region in turning this hazard into a benefit by developing industries that can utilize stranded sargassum as a raw material (ANR, 2019; UNEP-CEP, 2021).

It is within this context that the FAO Climate Change Adaptation in the Eastern Caribbean Fisheries Sector Project (CC4FISH) commissioned the University of the West Indies Centre for Resource Management and Environmental Studies (UWI-CERMES) to develop a "Sargassum uses guide" as a resource for Caribbean researchers, entrepreneurs and policymakers. The intention was to undertake a thorough investigation of the current and potential uses of sargassum within the Caribbean in order to share progress and lessons learned and to provide a directory of researchers, innovators and businesses that are currently working with sargassum to develop economically viable products and solutions.

1.2 Development of the guide

The information gathered for this guide has been collected through: (1) a desk review of scientific literature, newspaper articles, webpages, conference proceedings and presentations; (2) attendance at the 2019 International Sargassum Conference and Sarg'Expo in Guadeloupe; (3) travel to a number of sargassum industry hubs across the Caribbean (Guadeloupe, the Dominican Republic and Mexico) for interviews and site visits to learn first-hand from businesses and researchers who have already successfully valorized sargassum, or have achieved promising results in research and marketing trials; and (4) direct communication by e-mail, phone and video conference with sargassum entrepreneurs, business owners and researchers in other Caribbean territories.

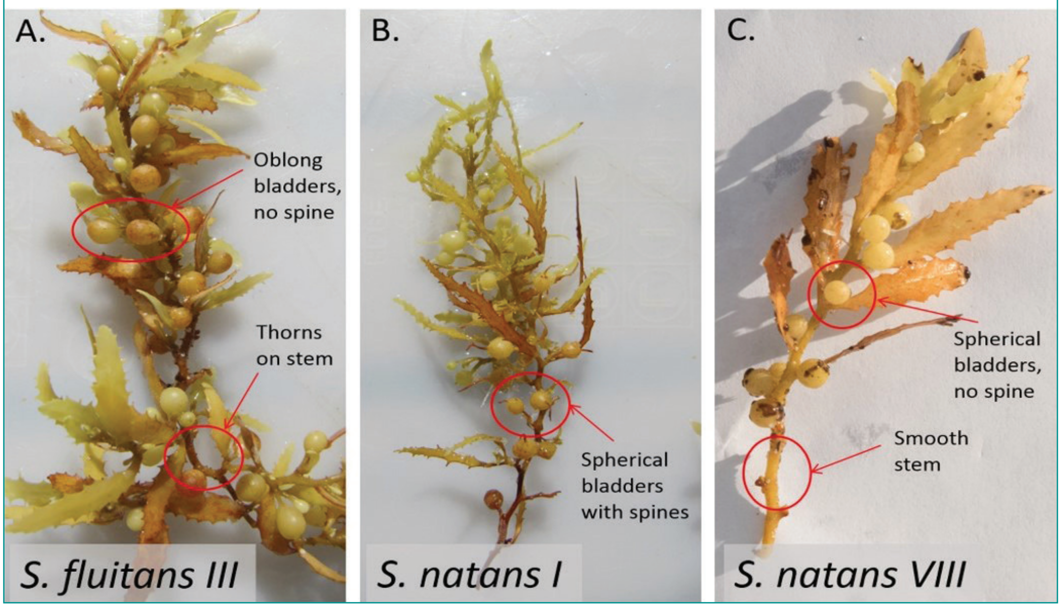
This guide is not exhaustive, as it was not possible to find, visit or communicate with all sargassum business and research stakeholders across all Caribbean countries. However, it is intended as a resource for researchers, business entrepreneurs and policymakers by providing, under one cover, an overview of the wide range of current uses of sargassum in the Caribbean, the lessons learned and challenges faced to date. It also provides insights into potential uses based on examples and research from other parts of the world involving different sargassum species or other seaweeds. Ultimately it is intended to help promote a sustainable approach to the management of stranded sargassum across the region.

The first section of the guide sets the context in which it was developed and gives a brief general overview of pelagic sargassum, including its basic biology and chemical composition as relevant to developing uses for sargassum biomass. The second section presents the range of potential uses of sargassum and highlights those currently being implemented in the Caribbean. Finally, the third section examines the current challenges to date, together with their implications and suggestions for moving forward.

1.3 Pelagic sargassum species

Pelagic (free-floating) sargassum (belonging to the brown seaweed group) from the Equatorial Atlantic comprises a mixture of two or possibly three different *Sargassum* species (see Figure 1), namely *Sargassum fluitans III, Sargassum natans I* and *Sargassum natans VIII* (Schell, Goodwin and Siuda, 2015). These species are unique among the 300+ species of sargassum known across the world, in being the only ones to spend their entire life cycle afloat, instead of attached to the seafloor. As such, they are considered to be "holopelagic". They are also thought to occur only in the Atlantic Ocean (floating sargassum rafts reported in other parts of the world are not these same holopelagic species, but comprise other sargassum species with a benthic phase in their life cycle). The Atlantic holopelagic sargassum is thought to only reproduce vegetatively through growth and fragmentation, and is able to double its biomass very quickly under the right conditions (9–20 days; Hanisak and Samuel, 1987; Lapointe, 1986). Floating sargassum travels with ocean currents

Figure 1. Morphological differences between pelagic sargassum species and/or morphotypes



Source: Govindarajan AF, Cooney L, Whittaker K, Bloch D, Burdorf RM, Canning S, Carter C, Cellan SM, Eriksson FAA, Freyer H, Huston G, Hutchinson S, McKeegan K, Malpani M, Merkle-Raymond A, Ouellette K, Petersen-Rockney R, Schultz M, Siuda ANS. 2019. The distribution and mitochondrial genotype of the *hydroid Aglaophenia* latecarinata is correlated with its pelagic *Sargassum* substrate type in the tropical and subtropical western Atlantic Ocean. *PeerJ* 7:e7814 https://doi.org/10.7717/peerj.7814

and is also influenced by surface winds. It floats as scattered individual thalli or more often in rafts comprising many individuals tangled together to form long lines (windrows) or teardrop-shaped patches that can be a few metres to several hundred metres across (Ody *et al.*, 2019). Very little is known about its growth and mortality rates as it travels, although nutrients, especially phosphates, salinity and temperature are known to affect its growth rate (Hanisak and Samuel, 1987).

1.4 Chemical composition

Chemical composition here refers to three main groups of chemicals: (1) “elements” (such as carbon (C), sodium (Na), iron (Fe), nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca)); (2) “inorganic compounds” (such as water, salts, carbon dioxide (CO2), oxygen; and (3) “organic compounds” (such as carbohydrates, lipids, proteins).

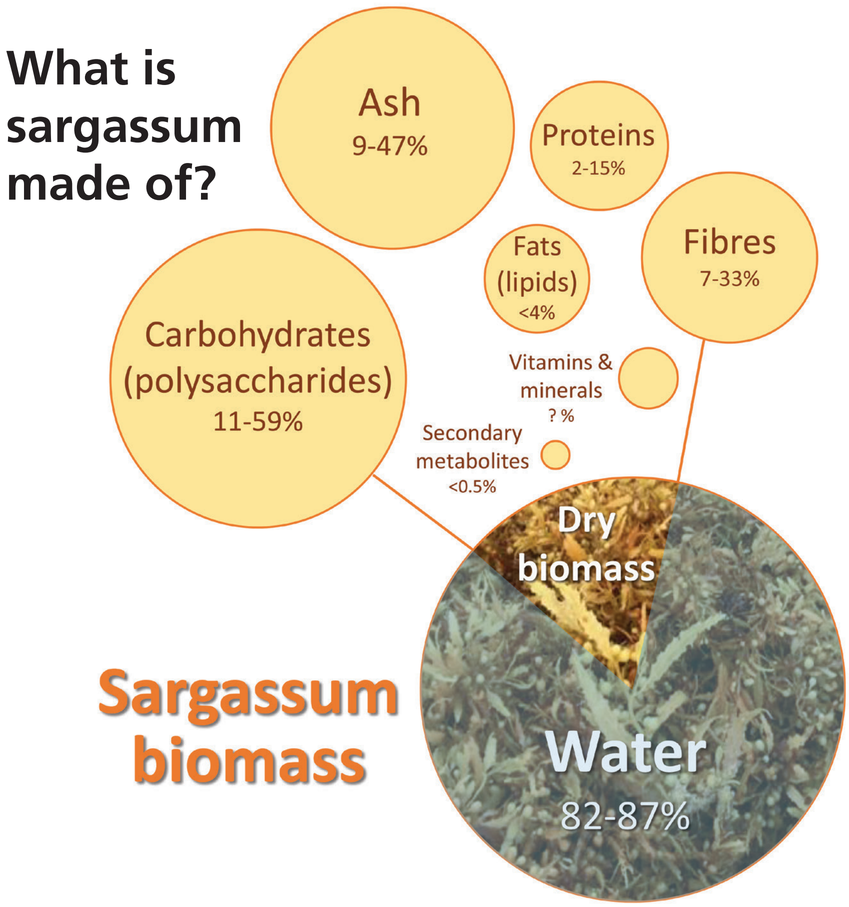
In general, seaweeds contain 70 to 90 percent of water by weight, and the dry biomass is composed mostly of carbohydrates, fibres and proteins, with small amounts of lipids (fats) and different minerals. The exact proportions of the constituent chemicals, however, are known to vary widely among seaweeds, especially among the three broadly different groups (green, red and brown seaweeds) (Mouritsen, Johansen and Mouritsen, 2013).

The main constituents of pelagic sargassum are shown in Figure 2. While water accounts for 82–87 percent of total biomass, the dry biomass comprises carbohydrates (mostly as polysaccharides), ash (mostly carbon left after heating to very high temperatures), fibre, proteins (comprising amino acids), lipids (comprising fatty acids), and small amounts of vitamins, minerals and secondary metabolites. Each of these components plays specific roles in the maintenance of the seaweed and has potential value for use in a large number of applications, as depicted in Figure 3 and demonstrated in this guide.

From the literature it can be noted that the exact chemical composition and nutrient value is likely to vary based on the species composition of the pelagic sargassum, as well as the location, time of year and environmental conditions (see *Challenges Section 3.2 Chemical composition)*.

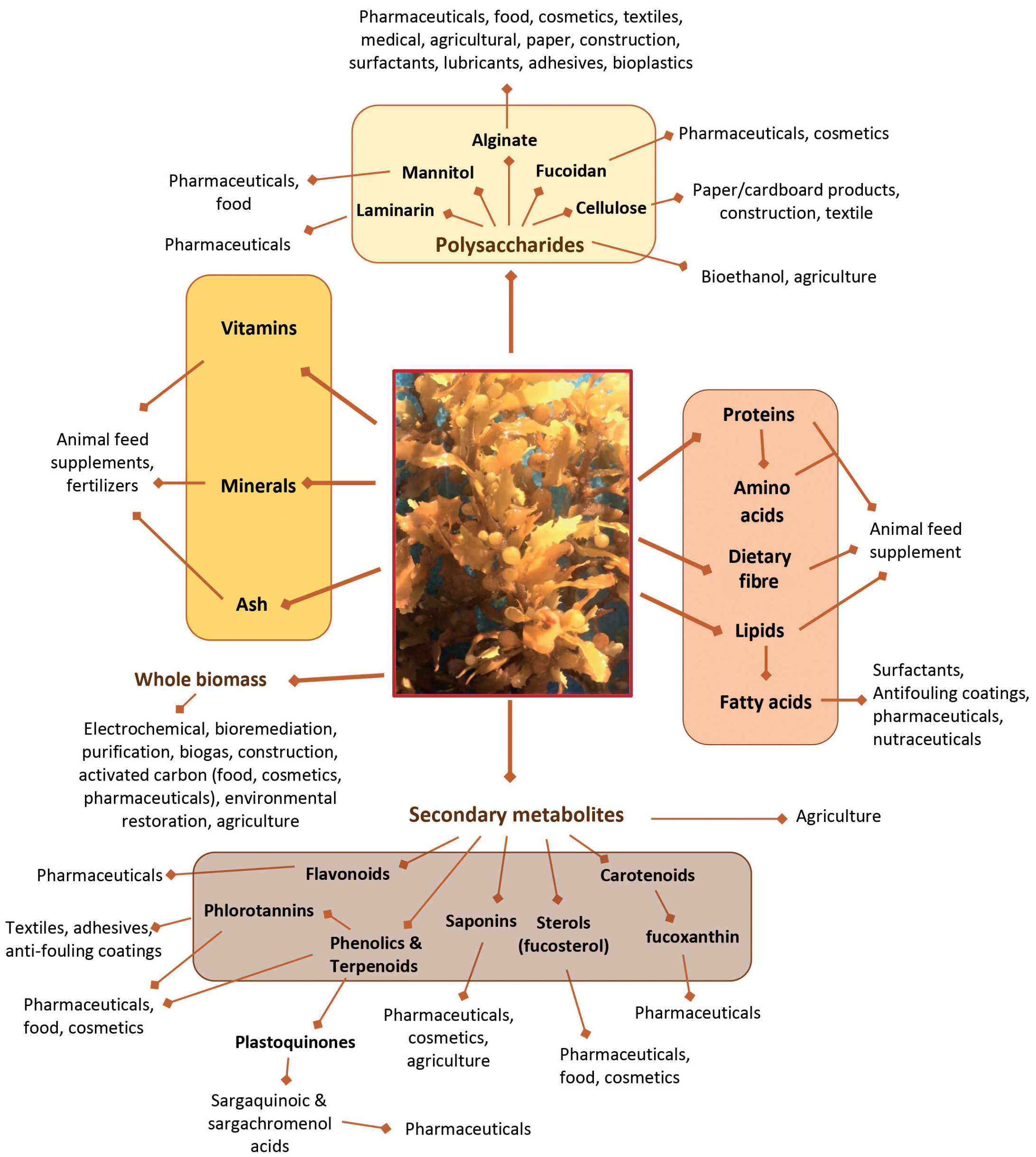
Also of note, pelagic sargassum is composed of two species (three morphotypes) that grow and float together, such that most chemical analyses to date have been conducted on “whole pelagic sargassum” samples, comprising this mixture of species. There are, however, a few recent studies that have separated the three sargassum morphotypes so as to examine differences in composition among them (Webber *et al*., 2019; Milledge *et al*., 2020; Rodríguez-Martínez *et al*., 2020).

Figure 2. Main constituents of pelagic sargassum



Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

Figure 3. Diagram to show sargassum compositional profile and associated uses



Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

In this section, focus will be placed on mixed sargassum samples, since separation into species and morphotypes is tedious and unlikely to be practical for commercial applications, although relative morphotype composition is further explored in the Challenges Section 3.1, Unpredictable supply. Focus is also placed on pelagic sargassum from the "new" Equatorial Atlantic population that has been stranding along the coastlines of West Africa and the insular Caribbean and Caribbean coasts of South and Central America since 2011. However, comparative reference is made to studies of the pelagic sargassum population from the Gulf of Mexico/Sargasso Sea where appropriate. The quantitative analysis of compounds reported for pelagic sargassum varies considerably among studies (see Table 1).

1.4.1 Main components

A summary of results from various biochemical analyses of the main components found in pelagic sargassum is given here. As can be seen in Table 1, protein content reported by different studies varies between 2.2 and 15.4 percent dry weight of pelagic sargassum, and is considered to be low compared with other brown seaweeds (Angell *et al*., 2016). Protein content is known to be highly variable in seaweeds according to species, and seaweed comprise a wide range of amino acids. It should however be noted that analytical methods used to determine protein content are under debate, and protein content is said to be overestimated in most instances. Amino acid analysis is thought to be a better option than total protein analysis because it reduces the problem of results being affected by interference from other substances (Maehre *et al*., 2018). Based on a single sample of mixed sargassum, Milledge *et al*. (2020) determined the amino acid content to be 4.2 percent. Water (moisture) content of fresh sargassum is reported to be 82 to 87 percent. Other studies report the moisture content of dried sargassum to be between 9 and 14.3 percent. Ash content of sargassum has been reported to be between 8.7 and 46.9 percent, and fibre content between 7.2 and 33.3 percent. Generally, high ash and fibre content indicates that the biomass can be difficult to break down, which could complicate biogas production by anaerobic digestion (Milledge *et al*., 2020).

Carbohydrates vary at between 11.3 and 58.7 percent of the dry weight of pelagic sargassum. Again, this large difference in values could be due to different analysis methods. Carbohydrates in brown seaweeds such as sargassum are composed largely of polysaccharides (complex sugars), present in the cell walls, and these include mannitol, laminarin, alginate, fucoidan and cellulose. According to one study (see Table 1), sargassum was found to contain 10.3 percent dry weight mannitol, 12.6 percent laminarin, 15.6 percent alginic acid and 6.2 percent fucoidan. In another study, pelagic sargassum was found to contain 20 percent of alginates and 20 percent fucoidans (see Table 1). Other sulphated polysaccharides found in sargassum in smaller amounts include those composed of glucose, fucose, galactose, xylose, arabinose, mannose and rhamnose, which are all below 4.5 percent of dry weight.

Lipid (fat) content is typically low in seaweeds (Milledge and Harvey, 2016). Based on three Caribbean studies, mixed sargassum lipid content was found to vary at between 0.3 and 3.9 percent of dry weight, which falls within values reported for single sargassum species elsewhere: 0.7 percent reported for *Sargassum natans* sampled near the Azores in the North Atlantic (van Ginneken *et al*., 2011) and 1.9 percent for *S. fluitans* in Nigeria (Solarin *et al*., 2014).

Table *1*. Summary of compositional analyses of main components of pelagic sargassum as % dry weight unless otherwise indicated

Location* (sampling year)	Sample type** (no. of samples)	Protein (%)	Moisture (%)	Ash (%)	Fibre (%)	Carbohydrate polysaccharides (%)	Lipids (%) & fatty acids (% of TFA)***	C:N****
British Virgin Islands (2016a)	Mixed from beach (N/A)	2.6	12.68	-	-	10.25 mannitol 12.6 laminarin 15.55 alginic acid 6.19 fucoidan	-	-
British Virgin (2016b)	Mixed + *Turbinaria* sp. (1)	3.3	-	22.4	-	11.3 total sugars 4.5 glucose 4.2 fucose 1.2 galactose 0.8 xylose 0.2 arabinose 0.2 mannose 0.1 rhamnose	-	-
Turks and Caicos Islands (2019)	Mixed nearshore (1)	4.19 (total % amino acids)	81.98 (as received i.e. assumed not dried)	46.94	33.31	11.68	Lipids: 3.88 SFA: 36.71 (mainly palmitic acid) PUFA: 29.3 (Omega-6 & 3) MUFA: 19.33 (mainly oleic acid)	16.08
Martinique (2015)	Mixed fresh onshore (2)	-	-	-	-	-	-	17–35
Jamaica (2019)	Average of *S. fluitans* & *S. natans* (1)	2.2	87 (assumed to be wet weight)	-	-	20 total carbohydrates 20 alginates 20 fucoidan	0.27 (total fat)	-
Brazil (1998)	*S. fluitans* at low tide (N/A)	12.8	-	-	-	-	-	-
Nigeria (2012a)	Mixed (N/A)	15.4	9.0	8.65	7.15	57.3	2.5	23
Nigeria (2012b)	*S. fluitans* onshore (N/A)	6.55	14.33	18.5	17	58.72	1.9	-

Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

*Reference for each location: British Virgin Islands (2016a): Ocean Harvest Technology (2016); British Virgin Islands (2016b): de Vrije and López-Contreras (2016); Turks and Caicos Islands: Milledge *et al.* (2020); Jamaica: Webber *et al.* (2019); Brazil: Ramos *et al.* (2000); Nigeria (2012a): Oyesiku and Egunyomi (2014); Nigeria (2012b): Solarin *et al.* (2014).

**Sample type: Mixed: refers to mixed *Sargassum natans* and *S. fluitans.*

***Fatty acids: Total fatty acids (TFA); saturated fatty acids (SFA); mono-unsaturated fatty acids (MUFA); polyunsaturated fatty acids (PUFA).

****C:N refers to the carbon to nitrogen ratio.

Lipids encompass different molecules such as fatty acids, their derivatives and other bioactive compounds. Fatty acids are generally subdivided into three broad classes: (1) saturated fatty acids (SFA); (2) mono-unsaturated fatty acids (MUFA); and (3) polyunsaturated fatty acids (PUFA). Fatty acids and lipid profiles vary according to the species of seaweed (Milledge and Harvey, 2016). Based on a single sample, pelagic sargassum fatty acids were found to be mainly composed of SFAs (36.7 percent of total fatty acids), particularly palmitic acid. PUFAs were also found in large amounts (29.3 percent of total fatty acids), particularly Omega-6 (arachidonic and linoleic acids) and Omega-3 (Docosahexaenoic acid). These values align with those for *S. natans* from the Azores, reported by van Ginneken *et al*. (2011), where palmitic acid was determined to make up 41 percent of the total fatty acids. Floating sargassum mats in the Gulf of Mexico (believed to be part of the Sargasso Sea sargassum population) were also found to contain PUFAs of between 16 and 62 percent (Turner and Rooker, 2006).

Carbon to nitrogen ratios (C:N) and carbon to phosphorus ratios (C:P) in sargassum were found to vary according to nutrient availability in the seawater, as expected given that sargassum does not have "roots" and therefore obtains nutrients (nitrates and phosphates) from the surrounding water. C:N and C:P ratios are usually high in open ocean, resulting in low growth rates and productivity, whereas C:N and C:P ratios are usually lower in neritic areas (coastal waters) that generally have a higher nutrient loading, resulting in higher growth rates and productivity (Lapointe *et al*., 2014). C:N ratios for pelagic sargassum (from the Gulf of Mexico and Sargasso Sea population) have been reported by Lapointe *et al*. (2014) to average 47 in open ocean and 27 in neritic waters. These numbers concur with other studies of pelagic sargassum in the Caribbean summarized here, where sargassum sampled from coastal waters and even onshore had a C:N varying between 16 and 35. In terms of sargassum uses, low C:N could be beneficial for agricultural uses, while high C:N is better for the production of biofuels (Milledge and Harvey, 2016).

1.4.2 Minerals and nutritional components

Pelagic sargassum is composed of a wide range of macronutrients and micronutrients and minerals that show significant variation (by several orders of magnitude) in reported values, as summarized in Table 2.

Nitrogen values vary greatly among studies, where values between <1 to 7 600 parts per million (ppm) have been reported. Highest levels of nitrogen are reported for sargassum samples from St. Andrew in Barbados. Some studies reported nitrogen as nitrate (NO_3), where values also vary greatly between <1 and 2 377 ppm. Phosphorus varies between 110 and 1 460 ppm and phosphate (PO_4) between <1 and 51 ppm. Potassium was also found to vary greatly among samples, from <1 to 69 359 ppm. Magnesium varies between 30 and 18 241 ppm. Calcium is relatively high, at between 2 035 and 136 146 ppm. Likewise, sodium is high, varying from 109 to 78 094 ppm. Highly variable amounts of aluminium are reported for the Dominican Republic and for chlorine in Mexico. Iron is also highly variable among studies from <3 to 5 910 ppm. Zinc, copper, manganese and iodine were all found in relatively low levels.

1.4.3 Heavy metals

Here we summarize reports of heavy metals found in pelagic sargassum (see Table 3). In general, arsenic has been found in high concentrations across all studies, varying between 11.5 and 172 ppm.

Table 2. Summary of compositional analyses of mineral/nutritional components of pelagic sargassum. Units are ppm dry weight

Location* (sampling yr)	Sample** type (# samples)	Mineral/nutritional components***												
		N (ppm)	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Fe (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Al (ppm)	Cl (ppm)	Na (ppm)	I (ppm)
Mexican Caribbean (2018–2019)	Mixed nearshore & offshore (63)	-	228–401	1 990–46 002	<2 915–13 662	23 723–136 146	<3–11	<5–17	<6–540	40–139	<140–517	747–53 101	-	-
British Virgin Islands (2016)	Mixed from beach (N/A)	-	-	-	-	-	-	-	-	-	-	-	-	85.3
Martinique (2015)	Mixed fresh onshore (2)	9 800 (Tot. N)	440–1 460	71.54	11 820	38 060	685–2 120	11–14	3.14	33–49	-	-	34 000–52 230	-
Turks and Caicos Islands (2019)	Mixed nearshore (1)	171	501	69 359	12 053	70 306	3 811	5.81	2.51	30.15	37.5	-	-	-
Barbados (2015)	Mixed (1)	7 600	110	-	30	-	200	5.5	9.9	-	-	-	78 094	-
Dominican Republic (2015)	Mixed (12)	-	761–1 145	2 208–33 602	10 211–18 241	96 901–133 400	2–655	13–21	2–12	16–32	303–4 188	-	3 802–21 068	-
Jamaica (2019)	Average of *S. fluitans* & *S. natans* (1)	2 377 (NO_3)	51 (PO_4)	348	1 013	2 035	894	-	264	-	-	-	109 (Na ii)	-
Nigeria (2012a)	Mixed (N/A)	63.6	965.0	280.0	427.5	-	87.0	0.5	-	-	-	-	-	0.4
Nigeria (2012b)	*S. fluitans* onshore (N/A)	0.48 (NO_3)	16.7 (PO_4)	170	-	-	-	-	-	-	-	-	-	-
Ghana (2015)	Mixed offshore & onshore (24)	0.62–1.04	0.83–1.55 (PO_4)	0.72–2.48	-	-	1 209–5 910	16–100	22–36	-	-	22.5–1 353.2	-	-

Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

*Reference for each location: Mexican Caribbean: Rodríguez-Martínez et al. (2020); British Virgin Islands: Ocean Harvest Technology (2016); Martinique: IT2 & ADEME (2015); Turks and Caicos Islands: Milledge *et al.* (2020); Barbados: Wilson-Howard (2015); Dominican Republic: Fernández *et al.* (2017); Jamaica: Webber *et al.* (2019); Nigeria (2012a): Oyesiku and Egunyomi (2014); Nigeria (2012)b: Solarin *et al.* (2014); Ghana: Addico and deGraft-Johnson (2016).

**Sample type: Mixed: refers to mixed Sargassum natans and S. fluitans.

***Elements: Nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), aluminum (Al), chlorine (Cl), sodium (Na), total nitrogen (Tot N), nitrate (NO3), phosphate (PO4).

Table 3. Summary of compositional analyses of heavy metals in pelagic sargassum. Units are ppm dry weight of sargassum unless otherwise indicated.

Location* (sampling year)	Sample** type (# samples)	Heavy metals***						
		Total As (ppm)	Org. As (ppm)	Inorg. As (ppm)	Cd (ppm)	Hg (ppm)	Pb (ppm)	Cr (ppm)
Mexican Caribbean (2018–2019)	Mixed nearshore & offshore (63) Mixed	24–172 (median 80)	-	-	<2	-	< 2–3	<8
British Virgin Islands (2016)	from beach (N/A) Mixed fresh &	45	17.3	27.7	0.169	<0.005	0.32	-
Martinique, Guadeloupe (2015–2016)	dry onshore (11) Mixed	11.50–100.8 (average 68.26)	-	-	<0.2–1.02	<0.1	<5.3–1.2	5.2–10.6
Turks and Caicos Islands (2019)	nearshore (1)	123.69	-	-	0.13	0.01	0.26	<0.3
Dominican Republic (2015)	Mixed (12)	14–42	-	-	0.1–0.3		1–2	2–56
Atlantic, east Gulf of Mexico, Florida Straits and Key West (1974)	*S. fluitans* mixed offshore (4)	4.2–19.5 (wet weight)	-	1.9–19.5 (wet weight)	-	<0.01–0.07	-	-
Ghana (2015)	Mixed offshore & onshore (24)	13–53.5	-	-	78–119	1–2	86–335	-

Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

*Reference for each location: Mexican Caribbean: Rodríguez-Martínez *et al*. (2020); British Virgin Islands: Ocean Harvest Technology (2016); Martinique and Guadeloupe: IT2 & ADEME (2015) and Tirolien (2019); Turks and Caicos Islands: Milledge *et al.* (2020); Dominican Republic: Fernández *et al.* (2017); Atlantic, eastern Gulf of Mexico: Johnson and Braman (1975); Ghana: Addico and deGraft-Johnson (2016).

**Sample type: Mixed: refers to mixed Sargassum natans and S. fluitans.

***Heavy metals: Total arsenic (Total As), organic arsenic (Org. As), inorganic arsenic (Inorg. As), cadmium (Cd), mercury (Hg), lead (Pb), chromium (Cr).

However, it is important to make a distinction between organic and inorganic arsenic, where the latter is considered as highly toxic. Very few studies have looked at the speciation of arsenic, to determine the proportion of both inorganic and organic arsenic forms. Based on a sample from the British Virgin Islands, 62 percent of the total arsenic content was found to be in the form of inorganic arsenic (Ocean Harvest Technology, 2016). This is similar to the value obtained from a single sargassum sample from Martinique, where 70 percent of the total arsenic was found to be inorganic arsenic (Tirolien, 2019). In a study carried out in the 1970s on the Gulf of Mexico/Sargasso Sea sargassum population, four samples of pelagic sargassum were collected at different locations (320 km off Bermuda, eastern Gulf of Mexico, Straits of Florida and off Key West in deep water) and analysed for arsenic, germanium and mercury, including speciation analysis (Johnson and Braman, 1975). In three of the samples, over 82 percent of the total arsenic was found to be inorganic, in the form of arsenite (As III) and arsenate (As V), and one sample contained 29 percent of inorganic arsenic. Maximum permitted levels of arsenic vary by country and according to what is being tested (for example soil, water, fertilizer). Some of these standards are further discussed in different sections of this guide.

Cadmium, mercury and lead levels are reported to be much higher in samples collected from Ghana compared with other locations. This is thought to be linked to intensive mining and industrial activity in some of the sampling locations of this study (Addico and deGraft-Johnson, 2016). These elements have not been evaluated in Caribbean sargassum samples, as far as the authors are aware.

1.4.4 Secondary metabolites

There is very little information currently available on the composition of secondary metabolites in pelagic sargassum. Data on phenols were found, where total phenolic content of mixed sargassum was reported to be 29.5 mg phloroglucinol equivalent per gram of dry matter for sargassum collected in the Turks and Caicos Islands (Milledge *et al*., 2020). This was considered to be quite high, and it was noted that it could have an inhibitory effect on anaerobic digestion of pelagic sargassum for the production of biogas. Tapia-Tussell *et al*. (2018) found that the “macroalgae consortium” comprising a mixture of seagrass and seaweeds, including sargassum collected from the Mexican Caribbean shore, had 18.7 percent phenolic content. A single sample was analysed for carotenoids from Jamaica, with a content of 0.115 micrograms per gram of sargassum (average of results from *S. fluitans III*, *S. natans I* and *S. natans VIII*) (Webber *et al*., 2019). Further research is clearly needed to determine other secondary metabolites contained in sargassum, such as flavonoids, saponins and sterols.

Physical barriers have been set in key touristic coastal areas to keep sargassum off beaches. The photo shows one such barrier holding sargassum off the shoreline at Punta Cana, the Dominican Republic.

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2. Potential uses of sargassum biomass

2.1 Overview

Use of seaweeds in a wide range of industries is not new, with an estimated 12 million tonnes of seaweeds being used each year across the globe, particularly in Asia and the Pacific, where the food industry accounts for the largest share of earnings (Henry, 2016). In the Caribbean, however, the use of seaweeds has traditionally been quite limited, with only scattered examples of wild harvesting or small-scale mariculture to produce various seaweed products for consumption (Radulovich *et al*., 2015). It is therefore unsurprising that the region has been relatively slow in responding to the unprecedented influxes of pelagic sargassum as an opportunity rather than just a hazard.

This section examines the multiplicity of uses for seaweeds across the globe, with a particular focus on brown seaweeds (Phaeophyceae) – the major group to which the sargassum species belong. It also highlights some examples of sargassum species being used in other regions and within the Caribbean.

2.1.1 Scaleability: the Sargassum Biomass Index (SBI)

In order to gauge the amount of sargassum biomass needed for different products, and thus to assess the scaleability of a particular use, the authors developed a Sargassum Biomass Index (SBI). This index is a very crude estimate of the amount of end product that could be made from 1 m^3 of fresh sargassum biomass, and the amount of end product that could be made from 1 tonne wet weight of fresh sargassum biomass.

The SBI is indicated throughout this guide, for each potential use of sargassum biomass wherever possible, using the standard graphic shown here. The index is based on information provided by stakeholders with regard to the amount of product that they are currently able to make from a known weight or volume of fresh sargassum.

The conversion of sargassum volume to weight is based on the authors' own findings, that one 22.3 litre bucket of loosely packed fresh wet sargassum weighs approximately 2.72 kg, resulting in 122 kg wet weight per m^3. However, the authors recognize that there is considerable variation in the weight-to-volume conversions used across the region for sargassum (see Table 4), largely due to the degree of compression of samples, as well as to the state (freshly landed, beach dried, partially decomposed), sand content and mix of species. As such, it is important to note that although the SBI presented here is a crude guide, it can serve as a useful relative index, since it can be applied across the entire range of uses and therefore enable some comparison between these.

Representation of the Sargassum Biomass Index (SBI) developed for this guide indicating the amount of end product that could be made from a standard amount of fresh sargassum.

This "scaleability" index gives a broad indication of sargassum biomass usage, which may be of interest to researchers, entrepreneurs and policymakers, especially when considering the value of sargassum biomass versus clean-up, transport and storage costs. Other important factors that should be considered in developing a more comprehensive scaleability index include:

- **quantity:** availability of fresh sargassum needed for a specific use;
- **expertise**: technical knowledge required to develop a specific use;
- **financial:** 1) economic cost of the initial investment for equipment or material to develop the use; 2) maintenance cost; 3) value of the end product; and 4) consumer/market demand;
- **environment:** environmental impacts of the transformation process; and
- **social:** social impacts of the transformation process on local communities.

Table *4*. Summary of the variation in values for the weight (kg) of 1 m^3 of sargassum

Weight (kg)	Sample type	How processed	Data source
867–972	Fresh wet (air-dried for 5 min.)	Volume measured by water displacement. Conversion equation: Wet wt. = 1.1605 volume + 1.2183	Sissini *et al*. (2017) Seagrass lab-UNAM
114–154	Fresh (oven-dried at 65 °C for 48 hrs.)	Volume measured by water displacement. Conversion equation: Dry wt. = 0.132 wet wt. + 0.1301	
532	Fresh (wet)	Compressed in 1 litre cylinder	Seagrass lab-UNAM
84	Fresh (oven-dried)	Compressed in 1 litre cylinder	
270–420	Undefined	Not stated	Various collectors in Mexico
275	Undefined	Not stated	Guidelines, Mexico
122	Fresh wet	Weighed in 22.3 litre bucket (loosely packed)	UWI-CERMES, Barbados
20	Fresh (oven-dried)	Conversion equation: Dry (kg) = 0.1651 wet (kg) + 0.0184	
262	Fresh wet	Weighed in 22.3 litre bucket (compressed)	
43	Fresh (oven-dried)	Conversion equation: Dry (kg) = 0.1651 wet (kg) + 0.0184	

Source: Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

2.1.2 Warning

There are a number of potential applications for sargassum biomass that may turn out to be unsuitable or unsafe, based on environmental or human and animal health concerns which, in the authors' opinion, have not yet been adequately researched and reported. In these cases, a warning graphic is given, as shown here. Also provided a brief bulleted summary of the key issues that may be of concern for each section (highlighted in a text box), with extra details, research results and possible solutions supplied in the main text, in cases where such information is available.

Warning graphic to indicate possible health concerns with a particular use of sargassum.

2.2 Agriculture: animal husbandry

Seaweeds have traditionally been used in animal husbandry in many parts of the world, especially in coastal areas, mainly as a feed supplement for livestock and also in aquaculture (Indergaard and Minsaas, 1991; Rajauria, 2015). In some areas where animal feedstuff has been scarce during long periods of the year, sheep, cattle and horses have been allowed to graze on dry seaweed (Indergaard and Minsaas, 1991; Makkar *et al*., 2016). Still today, it is not uncommon for animals living in coastal areas in some parts of the world to supplement their diet with seaweeds that wash ashore (see Figure 4).

Figure 4. North Ronaldsay sheep originating from the northernmost island of Orkney, Scotland, United Kingdom of Great Britain and Northern Ireland, survive on a diet composed almost entirely of seaweed

2.2.1 Feed supplement

Scientific studies prior to the 1970s failed to clearly demonstrate the advantages of including seaweed in animal diets. However, today extensive research on the effects of incorporating seaweed directly in animal feeds, as well as of spraying seaweed extracts on forages, and detailed analyses of seaweeds, have shown that these are rich in proteins, minerals, vitamins, polyunsaturated fatty acids, carbohydrates, fibres and bioactive compounds, and that they can increase animal growth, development, productivity, overall health, immunity and product quality (Evans and Critchley, 2014). Benefits have now been documented for a wide range of animals including cows, chickens, sheep, goats, horses, dogs, rabbits, ducks, fish, shrimp, oysters and other molluscs. Examples of benefits reported in the literature, including some that have used *Sargassum* species, are listed here:

- increased animal productivity and quality of marketable products:
  - improved meat quality (greater marbling and longer shelf life) (Allen *et al*., 2001; Braden *et al*., 2007);
  - improved milk quality and yield (fat levels and iodine content) (Singh *et al*., 2015; Chaves Lopez *et al*., 2016);
  - increased egg weight, albumen height, shell thickness and omega-3 (n-3) fatty acid content, improved yolk colour and reduced egg cholesterol and triglyceride content (Carrillo *et al*., 2008; Al-Harthi and El-Deek, 2012; Carrillo, Bahena *et al*., 2012; Carrillo, Ríos *et al*., 2012; Wang, Jia *et al*., 2013);
  - improved fertility and birth rate (Kaladharan, 2006; Bowen, 2015);
  - improved digestibility and gut health due to a rise in metabolites produced by prebiotic bacteria, which in turn affects the gastrointestinal microbiota (Leupp *et al*., 2005; Bach, Wang and McAllister, 2008; McDonnell, Figat and O'Doherty, 2010); and
  - reduction of cholesterol content of shrimp (Casas-Valdez, Portillo-Clark *et al*., 2006).
- increased stress tolerance (including oxidative stress and heat stress) (Allen *et al*., 2001; Fike *et al*., 2001; Williams *et al*., 2009);
- improved immune system functions (Saker *et al*., 2001);
- potential replacement for antibiotics after animal weaning (McDonnell, Figat and O'Doherty, 2010); and
- reduction of risk of food-borne disease contamination caused by pathogenic microorganisms (Braden *et al*., 2004; Bach, Wang and McAllister, 2008; McDonnell, Figat and O'Doherty, 2010; Wang, Jia *et al*., 2013).

When formulating animal feeds with sargassum, it is important to be aware of:
- Potentially high levels of heavy metals and other pollutants (organochlorines) that are toxic and readily transferred along the food chain.
- High concentrations of other elements (such as iodine) that may be harmful to some animals.

Given the high adsorption properties of brown seaweeds, and the high levels of arsenic that have been reported for pelagic sargassum in particular, routine analysis of potential toxins should be carried out for feeds containing seaweed supplements, in order to avoid the transfer of toxins into the food chain and ensure animal well-being and human food safety.

Many toxins, such as inorganic arsenic, cadmium, lead and mercury, which are readily picked up by brown seaweeds, are of particular concern for the formulation of animal feed since they can bio-accumulate and are readily transferred through the food chain (Adamse, Van der Fels-Klerx and de Jong, 2017). As a result, a number of countries have tolerance guidelines or standards establishing maximum permitted levels in animal feed, as indicated in Table 5 for Europe, Canada and the United States of America.

Several recent analyses of Caribbean pelagic sargassum samples have all detected high levels of total arsenic (14–172 ppm; see *Heavy Metal Composition Table 3 in Section 1.4).* Of particular note is the study by Rodríguez-Martínez *et al*. (2020), in which 86 percent of 63 samples collected over an 11-month period (August 2018 to June 2019) from approximately 370 km of the Mexican

Caribbean coastline were above the 40 ppm maximum allowed for use in animal fodder established in Europe.

A study conducted from 2007 to 2013 in the Netherlands to investigate the presence of heavy metals in a wide variety of animal feed materials identified seaweed meal and feed materials derived from seaweed as a high priority for arsenic monitoring due to the high percentage of samples exceeding the maximum limit set by the European Commission (Adamse, Van der Fels-Klerx and de Jong, 2017).

High salt content is also a problem if seaweed is used in animal feed because it can cause diarrhoea and dehydration-related health issues (or even death in poultry) (Berger, 2006; Abou El-Ezz and Younis, 2010).

In the United States of America, the Center for Veterinary Medicine (CVM) of the Food and Drug Administration (FDA) conducts an annual Mineral Surveillance Program, as part of the Animal Feed Contaminants Program, in which samples of domestic and imported animal feeds are analysed for heavy metals. The FDA-CVM has not established specific tolerances or guidelines for heavy metal levels in animal food; however, it takes action on a case-by-case basis, and considers levels established by the National Research Council and the Association of American Feed Control Officials (Deemy and Benjamin, 2019). Table 5 shows heavy metal thresholds allowed in animal feed by several institutions in various countries and regions.

Table 5. Summary of heavy metal tolerances or guidelines established for animal feed by different countries

Agency	Arsenic (ppm)		Cadmium (ppm)	Lead (ppm)	Inorganic mercury (ppm)
	Total	Inorganic			
European Parliament and Council*	40	2	0.5	10	0.2
Canadian Food Inspection Agency**	8	-	0.2 (horses) 1 (fish) 0.4 (all other livestock species)	8	-
US NRC***	-	30 (domestic animals) 5 (fish)	10	10	0.2

Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

* Directive 2002/32/EC (feedstuffs with 12% moisture content): Cadmium 0.5 ppm for other complementary feedstuffs for cattle, sheep and goats. Lead 10 ppm and mercury 0.2 ppm for complementary feedstuffs. Amendment to Annex I of Directive 2002/32/EC is referred to as Directive 2009/141/EC: Arsenic 40 ppm for seaweed meal and feed materials derived from seaweed.

** Canadian Food Inspection Agency RG-8 Regulatory Guidance: Contaminants in feed, Section 4: Metal contaminants. Maximum levels in total livestock diets. Mercury is monitored for fish by-products only.

*** United States National Research Council (US NRC) *Mineral tolerance of animals: Second revised edition, 2005*. In complete feed for most sensitive species.

Signs of subacute and chronic arsenic toxicity reported in livestock include appetite loss, wasting, indigestion, thirst, depression and neurological symptoms (Government of Canada, 2017). According to the Canadian Food Inspection Agency, signs of toxicosis in fish can be seen when feed containing 10 ppm of inorganic arsenic is consumed, while for terrestrial species, toxicosis is not seen below 30 ppm arsenic per kg of total diet. However, the Government of Canada has lowered the maximum level of arsenic permitted in animal feed to 8 ppm, in order to limit potential human exposure.

Table 6 provides an approximate composition of the Tasco-14® seaweed-based animal feed supplement made with the brown seaweed *A. nodosum*, in Canada, compared with that of pelagic sargassum (as presented in Section 1.4).

Table 6. Summary of the approximate composition of a commercialized seaweed-based food supplement for livestock compared with that of pelagic sargassum (as % or ppm dry matter).
Red text denotes values that differ by at least 10-fold

Item	Tasco-14 - *A. nodosum* seaweed meal*	Pelagic sargassum
Crude fibre (%)	6	7–33
Carbohydrates (%)	52	11–59
Ash (%)	22	9–46
Moisture (%)	12	9–14
Crude protein (%)	6	2.2–15.4
Minerals:		
Al (ppm)	20–100	< 140–4 188
As (ppm)	< 3	4–172
Ca (%)	1–3	20–1 361
Cu (ppm)	4–15	2–540
I (ppm)	< 1 000	0.4–85
Mg (%)	0.5–1	0.30–182
Mn (ppm)	10–50	16–139
P (%)	0.1–0.2	1–15
K (%)	2–3	0.0072–694
Na (%)	2.4–4	38–781
Zn (ppm)	35–100	0.5–100

Source: Adapted from Allen, V.G., Pond, K.R., Saker, K.E., Fontenot, J.P., Bagley, C. P., Ivy, R.L., Evans R.R., Schmidt, R.E., Fike, J.H., Zhang, X., Ayad, J.Y., Brown, C.P., Miller, M. F., Montgomery, J.L., Mahan, J., Wester, D.B. & Melton, C. 2001. Tasco: Influence of a brown seaweed on antioxidants in forages and livestock – A review. Journal of Animal Science, 79 (suppl_E):E21-E31. doi: 10.2527/jas2001.79E-SupplE21x.).

Given the number of components that are present in very different quantities, it is difficult to determine the suitability of pelagic sargassum for use as an animal feed supplement without further research.

Seaweed meal (fine powder) for animal feed supplement was first commercialized in the 1960s by Norwegian businesses, using the brown macroalgae *Ascophyllum nodosum*. Later, *Laminaria digitata* was also used in seaweed meal for animals in France and Iceland (McHugh, 2003). Today, several seaweed species are used in different countries to produce seaweed meal and are considered as a sustainable feed source for livestock and aquaculture (Rajauria, 2015). Although *A. nodosum* is the most frequently used and documented seaweed for animal feeds, others include: *Sargassum* spp., *Laminaria* spp., *Lithothamnion* spp., *Ulva* spp., *Macrocystis pyrifera* and *Palmaria palmata* (Evans and Critchley, 2014; Makkar *et al*., 2016). In the United States of America, organic dairy farms commonly use seaweed meal as a feed supplement in low amounts (less than 5 percent dry weight of total feed intake) (Erickson *et al*., 2012; Makkar *et al*., 2016).

When formulating animal feeds, consideration is given to the quantity of energy (carbohydrates and fats), proteins, minerals, vitamins, fibre and water. All of these are essential for animal health, maintenance of body functions, and product yield, but requirements vary according to the type of animal (poultry, pigs, small and large ruminants, aquatic animals, etc.), the age or stage of production of the animal, as well as the type of end product desired (meat, eggs, milk, etc.). Minerals are generally only needed in relatively small amounts (macrominerals: calcium, phosphorus, potassium, sodium, sulphur, chloride and magnesium), or as trace amounts (microminerals: iron, iodine, copper, cobalt, fluorine, manganese, zinc, molybdenum and selenium) (*Infonet*, undated). Dietary fibres are required to ensure that animals are able to assimilate nutrients and maintain a healthy digestive system. Water is essential in regulating body temperature and allowing feed to be swallowed and digested. Feed supplements are generally given to animals to add specific benefits or to supplement their diet during wet or dry periods, or when there are mineral deficiencies.

BOX 1. Improved Digestibility in ruminants

- Ruminants (such as cows, sheep, goats) have a complex digestive system with a four-chambered stomach, the largest of which is called the rumen.
- Coarse plant material is broken down in the rumen by mechanical digestion and fermentation with the help of microbes that produce methane gas as a by-product.
- According to FAO, the world's ruminant livestock emit a very significant amount of methane per year by enteric fermentation, representing 44 percent of anthropogenic methane emissions, and thus contributing to greenhouse gas emissions that are driving global climate change (Gerber *et al.*, 2013).
- Several recent studies have reported that methane emissions are reduced when ruminant livestock are fed with seaweed additives (up to 0.5 percent of feed dry matter), with reductions of up to 80 percent (Penn State, 2019).
- As such, the addition of seaweed to ruminants' feed could potentially represent an important greenhouse gas mitigation measure. However, the long-term effectiveness has not yet been determined, since rumen microflora are known to be highly adaptable.

Brown seaweeds generally have the lowest protein content (mean of 10 percent dry weight) (Peng *et al.*, 2015; Angell *et al.*, 2016) compared with other seaweed groups. For example, red and green seaweeds may contain up to 50 percent and 30 percent of protein by dry weight, respectively (Makkar *et al.*, 2016). However, the chelated microminerals found in seaweeds are considered to be more efficient at delivering microelements to animals compared with conventional inorganic sources. Additionally, the wide array of synergistic polysaccharides found in seaweeds has been attributed to increased prebiotic activity, contributing to enhanced performance in animals (Wiseman, 2012; Evans and Critchley, 2014). Therefore, although the composition of seaweeds includes essential elements for animal feeds, their value lies mainly in their rich trace mineral, polysaccharide and secondary metabolite content.

The amount of seaweed that can be beneficially added to animal feed will vary according to the type of animal, as shown in Table 7.

Table 7. Summary of recommended maximum seaweed amounts in the diet of animals to achieve beneficial results. Values are in % dry weight (DW) of total feed intake. Data are based on several different species of seaweed

Animal	Max. seaweed amount (% DW of total feed*)	Reference
Cattle	2–5	Makkar *et al.* (2016)
Sheep and goats	30	
Pigs	1–2	
Chickens	1–5	Wang, Jia, *et al.* (2013); Wang, Shi, *et al.* (2013); Zahid, Ali and Zahid (2001)
Ducks	12–15	El-Deek and Mervat Brikaa (2009)
Rabbits	Variable effects	El-Banna *et al.* (2005); Makkar *et al.* (2016)
Fish*	5–10	Yangthong, Oncharoen and Sripanomyom (2014); Rajauria (2015); Moutinho *et al.* (2018)
Shrimp	2–5	Casas-Valdez, Portillo-Clark *et al.* (2006); Rajauria (2015); Sudaryono *et al.* (2018)
Molluscs**	10–30 (% body weight)	Rajauria (2015)

*Fish: 5% Sargassum spp. fed to supplement sex-reversed tilapia diets; 10% Ulva rigida fed to Senegalese sole diets. 5–10% seaweed meal was also reported for different fish species by Rajauria (2015).

**Molluscs: fresh seaweed is a preferred feed of molluscs during a period of their life cycle, where a mix of at least two seaweed species. Juvenile abalone consume 10–30% of their body weight in seaweed per day. Another source indicates 5% seaweed requirement daily (wet weight basis) for abalones 10 mm and 1% for those 70 mm (FitzGerald, 2008).

Relatively low proportions of seaweeds are generally used for most animals due to the low digestibility of the complex carbohydrates. Exceptions are found where diets lack iodine or animals need supplemental vitamin A or B (Chapman and Chapman, 1980).

Adding seaweed to animal feed in large amounts could result in detrimental effects such as decreased animal growth performance and weight loss (Makkar *et al.*, 2016).

Although it has been proved that goats and sheep can benefit from relatively high seaweed content (for example, *M. pyrifera* and *Sargassum* spp.) in their diets (up to 30 percent), the animals will want to drink more water due to an increase in mineral salt concentration (such as sodium and potassium). This limits the practicability of this type of feed during dry periods (Marín *et al.*, 2003; Casas-Valdez, Hernández-Contreras *et al.*, 2006; Marín *et al.*, 2009; Mora Castro *et al.*, 2009; Makkar *et al.*, 2016). The effects of adding seaweed to rabbit feed have been variable to date, with some studies showing a lowering of cholesterol and increased growth performance and digestibility, while others have reported serious detrimental effects, including death (Blunden and Jones, 1973; El-Banna *et al.*, 2005; Okab *et al.*, 2013, Makkar *et al.*, 2016). Further research is clearly needed to ensure the safety of seaweed supplements for rabbits.

Livestock farmers in the Dominican Republic, Jamaica, Mexico and other countries of the Wider Caribbean Region have reported exploring the use of pelagic sargassum as a feed supplement.[1] As indicated in Box 2, there are a few ongoing research projects investigating the potential uses of sargassum in animal husbandry. However, only one entrepreneur, in Jamaica (Awganic Inputs), is known to be working to commercialize a sargassum-based feed supplement for goats.

[1] Throughout this document, "Caribbean countries" refers to countries of the Wider Caribbean Region, which comprises insular and coastal states and territories with coasts on the Caribbean Sea and Gulf of Mexico.

BOX 2. Animal husbandry applications of pelagic sargassum in the Caribbean[1]

- **Amadéite Group** (Guadeloupe): Pilot project financed by the Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME) to determine potential use of sargassum for improving animal, plant and human health.
- **Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán – Department of Animal Nutrition** (Mexico): Dr Silvia Carrillo Domínguez is leading research projects to investigate the use of natural ingredients, including sargassum, for chicken and small ruminants feed supplements.
- **PYROSAR project** (Guadeloupe and collaborators): Valorization of sargassum by pyrolysis and application for food safety.
- **SARGWA Consortium** (Guadeloupe): A pilot project was conducted to determine the potential valorization of sargassum for animal feed.
- **Awganic Inputs** (Jamaica): Young entrepreneurs looking to commercialize a sargassum-based goat feed.

[1] These and other examples of applied sargassum uses can be consulted in the full document published by UWI-CERMES: *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers* (Desrochers *et al*., 2020). The same applies to all other initiatives mentioned in subsequent boxes.

2.3 Agriculture: crop production

Seaweeds have been used in agriculture for many years throughout the world, especially in coastal areas and in areas characterized by degraded infertile soils (Abdel-Raouf, Al-Homaidan and Ibraheem, 2012). Seaweeds have been used in crop production as fertilizers, compost, biostimulants, bio-elicitors, soil conditioners or soil amendments, mulch, biopesticides and even growth substrate

When developing agricultural uses for sargassum, it is important to be aware of:

- potentially high levels of toxins (such as inorganic arsenic, other heavy metals, pollutants and certain compounds found in high concentrations); and
- the high concentration of sodium (salt).

Mandatory analysis of metal content (and also general compositional analysis of end products) should be carried out on a regular basis for uses that have any risks of entering the food chain or involving direct human contact.

Over the long term, applying products with high salt content may cause soil salinization, which can render soils unproductive and unusable for agricultural purposes. Soaking and washing algae in freshwater can significantly reduce salt content; however, care must be taken, particularly in water-scarce countries in the Caribbean, to factor in this issue and avoid further negative impacts on the environment.

A recent study in Mexico determined that all 63 sargassum samples collected over an 11-month period (August 2018 to June 2019) across eight localities along the Mexican Caribbean coastline were above the 22 ppm maximum allowable concentration for arsenic in Mexican agricultural soils (Rodríguez-Martínez *et al*., 2020).

2.3.1 Soil amendments

Soil amendments, also known as soil conditioners, are materials used to improve different aspects of the physical properties of soil, such as nutrients, water-holding capacity, potential of hydrogen (pH), etc. Seaweeds are known to be good soil amendments since they can improve the soil's physical properties, such as water and nutrient retention capacity, aeration, drainage and structure. They can be added to soil in a number of different ways, as explained here.

Direct field spreading

Spreading algae directly on fields for different soil amendment purposes is common practice. For example, calcareous red algae are often applied in the United Kingdom of Great Britain and Northern Ireland, France and Ireland to lower soil acidity and replenish trace elements of grasslands (Tye, Fullen and Hocking, 2001). In Bermuda, located in the Sargasso Sea, sargassum beaching has always been a common occurrence and the local population traditionally collects sargassum, wash out the salt, and spread it around banana trees as a mulch and fertilizer (DENR, 2020).

Although seaweeds have been applied directly to fields by incorporating them during ploughing, a recent study carried out with pelagic sargassum by the Institut Technique Tropical in Martinique has raised concerns and warned gardeners and farmers of the potentially detrimental effects. The team evaluated the agronomic potential of sargassum (dry, dry ground, fresh and decomposed) on soils and crop growth through laboratory analysis and field trials. Results indicate that collected sargassum generally contained high levels of arsenic (98 ppm of dry weight), potassium, calcium, sodium and iron (Tirolien, 2019). General conclusions drawn were that there was no agronomical benefit to spreading fresh sargassum on fields, given the high risks of soil salinization and potential levels of arsenic being higher than permitted. Guideline values of arsenic in soil differ by country, although Argentina, Canada, Norway, New Jersey (United States of America) and the European Union all have recommended maximum arsenic levels in soil of 20 ppm (FAO and WHO, 2011; Tarvainen *et al*., 2013).

It is, however, important to differentiate between organic arsenic and inorganic arsenic, where the latter is highly toxic. An arsenic speciation analysis of a single sargassum sample determined that 70 percent of the total arsenic was found in the form of inorganic arsenic (Tirolien, 2019). Importantly, the same study did not detect arsenic uptake by sugar-cane plants, which supports the findings of Reimann *et al*. (2009), who found that plants (with some exceptions) hardly take up arsenic from soils, although it can accumulate in soils over time. More research is needed to understand the environmental and human health impacts.

Biochar[2]

Biochar produced with different precursors, including algae, is used as a soil amendment to improve soil properties and nutrient-holding capacity, and can also be used for soil reclamation by removing contaminants and restoring soil fertility (Roberts *et al*., 2015).

Sargassum biomass can be used to produce biochar through a process of slow pyrolysis under limited oxygen. Using biochar not only improves degraded low-fertility soils, but can also be considered as long-term carbon sequestration when used as a source of carbon in agricultural fields. In this case, the biochar can be incorporated directly into the field during ploughing (Roberts *et al*., 2015). The use of biochar has also been shown to increase plant disease resistance (see *Section 2.3.2, on crop protection)* (Elad *et al*., 2010). Although seaweed usually yields biochar with lower carbon content compared with typical lignocellulosic feedstock (such as terrestrial plants), it generally yields higher amounts of biochar, contains high levels of exchangeable nutrients or "cations" (such as calcium, magnesium, potassium) and has a high cation exchange capacity (CEC) (Bird *et al*., 2011). CEC is an important soil property, which has an impact on soil structure stability, the amount of available nutrients that can be retained by the soil, and pH (Hazelton and Murphy, 2016). Soils with higher CEC are potentially more "fertile", leading to improved crop yields.

Roberts *et al*. (2015) provide comparative data on biochar yield and composition from six commercially cultivated seaweed species, including a *Sargassum* sp. The study concluded that although some seaweed biochar properties varied between species and location, all species yielded high amounts of biochar with relatively low carbon, but rich in nutrients including nitrogen, phosphorus, potassium, calcium and magnesium. In addition, the study determined that seaweed biochar has a relatively low carbon to nitrogen ratio (C:N) (<30), typically indicating that it could provide bio-available nitrogen and phosphorus to soils, while enhancing retention of other nutrients supplemented with fertilizers. This would benefit crop production and productivity.

One of the main drawbacks, however, is the high content of exchangeable sodium in seaweed biochar, which could contribute to increased soil salinity in the long term. This sodium is leachable (washes out with rainwater), so it was highly recommended that seaweed biochar should be added to soils well before beginning crop production, in order to allow the sodium to leach out first (Jeffery *et al*., 2015). Another proposed strategy to reduce the potentially negative impact of high levels of exchangeable sodium is to use a mixed seaweed and terrestrial plant-based feedstock to produce a biochar with lower sodium content and increased carbon content (Roberts *et al*., 2015).

The PYROSAR project led by Guadeloupe is determining the potential for use of sargassum-based biochar as a soil amendment and for bioremediation to reclaim soil in areas contaminated by chlordecone.[3]

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[2] **Biochar** defined by the International Biochar Initiative as "carbonised biomass obtained from sustainable sources and sequestered in soils to sustainably enhance their agricultural and environmental value under present and future management", from https://biochar.international/the-biochar-opportunity/what-is-biochar/

[3] **Chlordecone** is a persistent organochlorine pesticide that was commonly used in banana production to control banana weevil in both Guadeloupe and Martinique until it was banned in 1993. Pesticide residues are still present in the environment and are a threat in certain localities' agricultural and fisheries sectors, where the pesticide contaminates the food chain. More information: http://bit.ly/ChlordeconePOPs

Mulch

Seaweeds can be used directly as a mulch on the soil surface to protect the soil from erosion and weeds, increase moisture retention, and deter certain pests such as slugs and snails.

Another application is their use in the production of biodegradable films for plasticulture. Plasticulture refers to the use of plastic film in agriculture to act as a mulch or "row covering" to eliminate weed growth, increase water retention and facilitate the harvesting process.

Research by Immirzi *et al.* (2009) determined that a biodegradable sodium alginate-based spray could also provide an ecologically sustainable mulch alternative to synthetic petroleum-based polymers for soil mulching in agriculture. Recent studies report that microbially-induced and precipitated calcium carbonate-based seaweed biopolymer film is a promising candidate for plasticulture application in agriculture (Abdul Khalil *et al.*, 2018; Hasan *et al.*, 2019). Several ongoing projects are looking at the production of sargassum mulch, including a research project at the University of the West Indies, Cave Hill Campus in Barbados, and two businesses that are currently commercializing sargassum mulch in the Dominican Republic (see Figure 5) and Mexico.

Figure 5. Sargassum mulch produced and commercialized by AlgeaNova in the Dominican Republic

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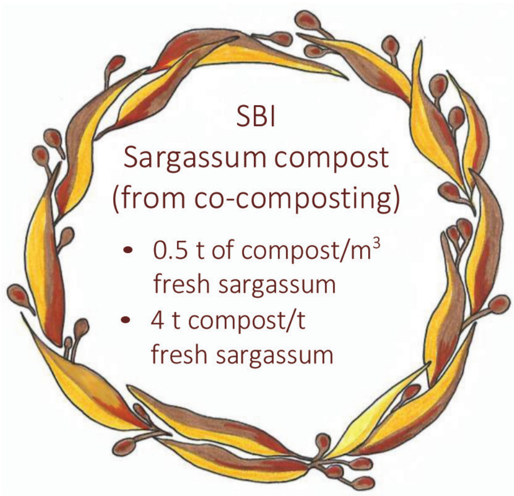
Veira and Lopez (2016) from the University of the West Indies undertook a study in Barbados over five months, during a drought period, and concluded that furrow application of unwashed aged sargassum mulch (four weeks ageing) four weeks after sweet potato planting at a rate of ten tonnes per hectare (t/ha) showed improved growth and yields. However, further investigation is needed to determine the effect of salt content from unwashed sargassum on soil, and the effect of mulch on different cultivars grown in different soil types and under non-drought conditions.

Compost

Using algal biomass for composting purposes has long been common practice in several countries, especially in coastal areas, and is considered to be one of the simplest, cheapest and most practical methods of effectively using large algal biomass (Eyras, Rostagno and Defossé, 1998). Green-tide seaweed composting has been studied extensively, particularly in France and Italy (Mazé, Morand and Potoky, 1993; Vallini *et al.*, 1993). The benefits of adding compost to soil are well known and include increased soil fertility, improved soil structure, enhanced water- and nutrient-holding capacity, better porosity and drainage, and the reduction of soil loss due to erosion. However, compost made with feedstocks containing high levels of salt and potentially toxic compounds must be closely controlled and monitored, to avoid soil salinization and the presence of toxic pollutants.

According to Eyras, Rostagno and Defossé (1998), strategies that have been effective in reducing the salinity of composts include (1) composting the biomass for longer periods; (2) mixing with other low-salinity feedstocks; and (3) the active turning of compost piles, allowing the salt to leach out. They report that compost aged for 20 months had significantly lower salt content compared with compost aged for 9 months. A subsequent study determined that composting of algae containing high levels of salt was enhanced when it was inoculated with the salt-tolerant bacterium *Halomonas* sp. and the alginate-degrading bacterium *Gracilibacillus* sp., which shortened the composting time, reduced compost phytotoxicity and improved quality (Tang *et al*., 2011). Another potential issue related to seaweed composting is the low C:N ratio and high moisture content. This could result in a very rapid breakdown of the biomass and loss of the nitrate via the release of ammonia. However, blending seaweed with other organic materials should counteract these problems (Han, Clarke and Pratt, 2014).

Several sargassum composting projects have been carried out in Guadeloupe and Martinique over the past few years. The SARGWA consortium was established in Guadeloupe to determine potential pre-treatments and valorization of sargassum, including pilot co-composting experimentation. Co-composting studies were carried out by the Institut Technique Tropical in Martinique, the Institut National de la Recherche Agronomique (INRA) and the Université des Antilles, with the collaboration of several municipal waste sites, to determine the potential integration of sargassum in the processing of green waste. A detailed study has been ongoing for several years in collaboration with the Holdex company in Martinique for large-scale co-composting of sargassum and commercialization of controlled-quality end products, where very promising results have been obtained. In total, three companies in Martinique have been authorized to produce sargassum-based compost: Holdex, Idex and Société Martiniquaise des Eaux. Co-composting by these companies is closely monitored by the Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME) and the Direction de l'Environnement, de l'Aménagement et du Logement, where the composition of each batch of compost produced is analysed to determine salt and heavy metal levels and product composition. Compost containing up to 10 percent sargassum is already being commercialized locally in Martinique.



In the Dominican Republic, AlgaeNova® is producing a sargassum-based compost, made with 60 percent sargassum and 40 percent *Leucaena leucocephala* (also known as river tamarind). The company has been carrying out field experiments on the effects of compost application on various crops (see Figure 6), and laboratory analysis to determine the composition of the end product.

Figure 6. Sargassum-based compost produced by AlgeaNova® in the Dominican Republic

©Anne Desrochers

In Mexico, several agribusinesses are said to be producing sargassum-based compost for use in agriculture. Moon Palace resort has also been producing sargassum-based compost for use in the hotel compound.

In the United States of America, Texas State University has been carrying out co-composting trials using sargassum (4 percent) mixed with food waste (48 percent) and wood chips (48 percent) and has been evaluating the quality of the resulting compost (Sembera, Meier and Waliczek, 2018). From the 19 m^3 of compost produced, quality analyses showed that sargassum-based compost was of equal or higher quality than traditional compost. In addition, washing the sargassum as a pre-treatment did not affect the salt content of the final product, which was within the safe range in the case of both the washed and unwashed sargassum compost. As such:

- This study concluded that pre-washing sargassum did not appear necessary to obtain a quality compost.
- However, caution must be taken to ensure that runoff from the composting site is safely treated and properly disposed of.

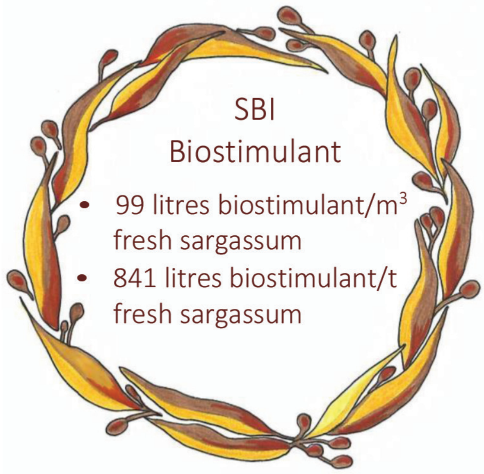
The compost produced had a nutrient content that met compost standards, and C:N ratios obtained indicated that the compost should increase plant-nutrient availability when applied to soil. Arsenic levels (4.2–7.2 ppm) were well within the Environmental Protection Agency standards for compost. Results from this research are in line with those obtained by Walsh (2019), who also carried out composting trials, but used a higher sargassum content (25–50 percent).

A composting project is ongoing at the University of the West Indies in Trinidad, to determine the potential for use in mangrove plant nurseries. The ECO_3SAR project is under way in collaboration with Holdex, a company located in Martinique, to determine sustainable valorization options for sargassum, with a focus on co-composting.

A small-scale vermicomposting project is being carried out in Guadeloupe by the Association pour une Agriculture Paysanne et Écologique dans la Caraïbe group, using sargassum. However, further research is needed to determine the full potential of this method.

Fertilizers and biostimulants

Seaweeds have been used as fertilizers for several centuries, especially by coastal communities (McHugh, 2003). With the revival of interest in organic farming, there has been an increasing demand for organic products. To date, there has been no large-scale industrial production of algal-based fertilizers, particularly due to the high costs related to drying and transportation of algae (McHugh, 2003). Seaweed-based fertilizers can be in the form of liquid (dilute or concentrate), dried and milled (seaweed meal), or in the form of digestate solids from anaerobic digestion. Brown macroalgae commonly used as biofertilizers include *Sargassum* spp., *Ascophyllum nodosum*, *Fucus* spp., *Laminaria* spp. and *Turbinaria* spp. (Khan *et al*., 2009).



Most algae contain low amounts of nitrogen and phosphorus; however, they are rich in potassium and trace elements. Algae-based liquid fertilizers are often marketed as biostimulants or plant growth stimulants or tonics because they provide supplemental plant feed rather than main feed (not all macronutrients are provided in sufficient amounts), unless products are blended with other materials to provide a higher supply of nitrogen and phosphorus. Red and brown seaweed are most commonly used as organic liquid fertilizers (Abdel-Raouf, Al-Homaidan and Ibraheem, 2012; Makkar *et al*., 2016).

Much research has been carried out on seaweed extracts and their beneficial use in horticulture, such as improved germination and yields, increased nutrient uptake and better resistance to certain pests (McHugh, 2003). Digestate is the solid fraction remaining from anaerobic digestion; it is rich in nutrients and is often used for agricultural purposes. However, if contaminants such as arsenic and cadmium are present in the raw material, they are likely to remain in the digestate after anaerobic digestion (Nkemka and Murto, 2010). Digestate rich in heavy metals is problematic to dispose of and cannot be used as fertilizer. Maximum allowable heavy metal content for fertilizers varies by country, as can be seen in Table 8.

Biostimulants, also called "metabolic enhancers", are products used to: reduce the amount of fertilizer needed; enhance plant and growth; promote early germination; and increase resistance to

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

Country	Arsenic	Cadmium
New Zealand[4]	75 ppm	280 ppm in phosphorus fertilizers
United States of America - 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 4 400 kg/ha/yr application rate of product)	20 ppm product (based on 4 400 kg/ha/yr application rate of product)

Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.0

[4] https://tinyurl.com/2p9fetf7

biotic and abiotic stresses (Khan *et al*., 2009; Feitosa de Vasconcelos and Garófalo Chaves, 2019). Biostimulants usually take the form of concentrated liquid products that require applications in small amounts. Although seaweed-based biostimulants are often used in agriculture and horticulture, more research is needed on the biostimulatory potential of seaweed, the processes behind their mode of action and how these affect plant growth and resistance mechanisms (Khan *et al*., 2009; Thomas *et al*., 2013b).

Although biostimulants are often used as a foliar application (sprayed directly onto leaves), they are also applied directly onto the soil or introduced into an irrigation system. Biostimulants have been made with a wide range of seaweed species, and composition will vary according to species, the period during which the seaweed was collected, additives used to produce the end product and the production method employed. The following are some examples of biostimulants made using brown seaweed extracts:

In India, biostimulants were extracted from *Sargassum tenerimum* using solvents and also by fermentation using sour milk. It was found to be an excellent source of minerals and vitamins for plants (Thomas *et al*., 2013a; Thomas *et al*., 2013b).

Extracts from *Ascophyllum nodosum* are commonly used to produce biostimulants. They have been shown to promote plant growth, improve crop resilience to environmental stress, provide crop protection against pests and stimulate soil-microorganisms (Shukla *et al*., 2019).

In India, a biostimulant made from *Sargassum wightii* is being commercialized under the brand name Somzyme, and used for a wide range of crops. It is said to enhance vegetative growth in the early stage of plant development, as well as root development, nutrient uptake, resistance to drought and to stimulate soil microorganisms.

There are several companies that have commercialized pelagic sargassum biostimulants across the Caribbean. In addition, a number of farmers have reported using sargassum to fertilize coconut trees (Antigua and Barbuda) and citrus trees (Dominica) (JICA and CRFM, 2019). In Barbados, consideration has been given to using sargassum as a fertilizer in the sugar-cane industry, where it has been estimated to have potential for increasing yields by 20 percent (JICA and CRFM, 2019).

2.3.2 Crop protection

Macroalgae contain secondary metabolites, polysaccharides, derived oligosaccharides and other components that play different roles in terms of protection against environmental pathogens. Antifungal, antibacterial, antiviral, antimicrobial and antiprotozoal properties have been widely studied (Vera *et al*., 2011; Perez, Falque and Dominguez, 2016). Extracts from these compounds have been isolated from different macroalgae species and, when applied to plants, can have an “elicitation effect”, stimulating plants to overcome diseases by strengthening their defence mechanisms and restricting pathogen growth (Ben Salah *et al*. 2018). Macroalgae are said to be good bio-elicitors, with different components working in synergy to stimulate phyto-elicitor and phytostimulatory responses in plants (Vera *et al*., 2011). Bio-elicitation is considered as an innovative crop protection strategy and a promising alternative to chemical fungicides. Some examples of studies that have explored the bio-elicitor effects of various compounds in brown macroalgae include the following:

- Phenolic acids and flavonoids extracted from *Sargassum vulgare* have shown antifungal activity against *Fusarium sambucinum* and *F. solani* on potatoes (Nawaim *et al*., 2017).
- *Ascophyllum nodosum* extract has been shown to reduce the incidence of several plant diseases, including:
    - *Xanthomonas campestris* pv. *vesicatoria* and *Alternaria solani* on tomatoes and sweet peppers (Ali, Ramsubhag and Jayaraman, 2019);
    - *Alternaria radicina* and *Botrytis cinerea* on carrots (Jayaraj *et al*., 2008);
    - *Alternaria cucumerinum*, *Didymella applanata*, *Fusarium oxysporum* and *Botrytis cinerea* on cucumbers (Jayaraman, Norrie and Punja, 2010); and
    - Powdery mildew on strawberries (Bajpai *et al*., 2019).
- β-1,3-glucan laminarin derived from *Laminaria digitata* showed an efficient elicitor defence response in grapevines to reduce the development of *Botrytis cinera* and *Plasmopara viticola*, two pathogens that have significant negative impacts on vineyards (Aziz *et al*., 2003).

In addition, Veira and Lopez (2016) determined that sargassum mulch application reduced pest damage from *Euscepes postfaciatus* weevil. Application of sargassum has shown observational deterrent effects against giant African snails in Antigua and Barbuda and against nematodes in Saint Lucia (JICA and CRFM, 2019).

Although not many research projects have looked at sargassum's bio-elicitor properties and potential crop protection applications, it is anticipated that the ongoing SARGOOD project (holistic approach to sargassum valorization) will provide more information on this potential use.

2.3.3 Growth substrate

Agricultural products such as mushrooms are highly adaptable and can be grown on a wide range of substrates, including straw, sawdust, coconut coir, coffee grounds, seaweed and many others. Several studies have been carried out to determine the potential of several seaweed species blended with lignocellulosic materials as growth substrate for mushrooms (Molloy *et al*., 2003; Kaaya *et al*., 2012; Mshandete, 2014). According to Kaaya *et al*. (2012), 10 percent of seaweed (*Laminaria schinzii*) was revealed to be the optimum amount to be blended into the substrate. This amount will, however, greatly depend on the species of mushrooms cultivated and the composition of seaweed used. In the United Republic of Tanzania, a study was carried out to determine mushroom yield effects when supplementing grass substrate with different parts of *Sargassum poligocytum* (Mshandete, 2014). It was found that incorporating 15 percent of *Sargassum* sp. tips with grass substrates was promising with regard to increasing *Coprinus cinereus* mushroom yield.

In Mexico, research on the potential of pelagic sargassum for use as mushroom growth substrate is being undertaken by the Centro de Investigación Científica de Yucatán, in collaboration with the Colegio de Postgraduados (Campus Puebla) and the Universidad Popular Autónoma del Estado de Puebla.[5,6]

[5] https://tinyurl.com/2un7e8kc
[6] http://colpospuebla.mx/sargazo/sargazo

BOX 3. Crop production applications of pelagic sargassum in the Caribbean

Research:

Amadéite Group: It offers solutions based on algae, clays and trace elements for improving plant, animal and human health. Six-month project to calibrate sargassum treatment process and optimization of extract of compounds.

Centro de Investigación Científica de Yucatán, Colegio Postgraduados, Puebla Campus & Universidad Popular Autó noma del Estado de Puebla (Mexico): Ongoing research on the use of sargassum as growth substrate for mushroom cultivation.

ECO3SAR project (France and Guadeloupe): Valorization of sargassum, with a focus on composting.

INRA-Université des Antilles (Guadeloupe): Sargassum analysis of pollutants, composting and direct spreading.

Institut Technique Tropical - IT2 (Martinique): Agronomic and toxicological analyses of effects resulting from application of pelagic sargassum compost and direct field spreading.

PYROSAR project (Guadeloupe and collaborators): Valorization of sargassum by pyrolysis and application for food safety. Use of biochar for soil amendment.

SARGOOD project (Guadeloupe and collaborators): Holistic approach to sargassum valorization, including developing bio-elicitors, biostimulants and other agricultural products.

Sargassum Agricultural Valorization and Energy production (SAVE) project (France and Martinique): Sargassum agricultural valorization, including digestates.

SAVE-C project (France, Martinique and collaborators): Valorization of sargassum, including biopesticides.

Several municipal co-composting projects financed by ADEME (Guadeloupe and Martinique).

University of the West Indies: Researchers at the three campuses have been working on various projects for agricultural uses.

Commercialization:

Algas Organics (Saint Lucia): A pioneer in the development of sargassum-based plant tonics in the Caribbean.

AlgeaNova (the Dominican Republic): Using sargassum for co-composting with other organic wastes and also producing 100% sargassum mulch.

Alquimar (Mexico): Commercializing a biofertilizer called Alquifert.

Dianco México (Mexico): In the process of developing a sargassum-based fertilizer.

Holdex (Martinique): This company has been using sargassum in co-composting with other organic wastes and has an interest in producing sargassum biochar.

Moon Palace Resort (Mexico): It has been producing sargassum-based compost and using it in the hotel compound.

Red Diamond Compost (Barbados): It has been commercializing a sargassum-based biostimulant called Super Seaweed.

Salgax (Mexico): It is commercializing a range of sargassum-based fertilizer and mulch.

Sargasso Organics (Barbados): It has commercialized a sargassum-based fertilizer in stores across Barbados.

Suez (Guadeloupe): Sargassum co-composting.

Summary of uses in agriculture

Extensive research over the past few decades has shown multiple benefits of using seaweed in general for both animal husbandry (as animal feed supplements) to boost animal health and productivity, and for crop production (as fertilizer, biostimulants, soil amendments, etc.) to improve soil properties and fertility, for better resistance against certain pests, and for increased crop yields.

However, although there are many examples of sargassum being used in a variety of agricultural applications, it is important to keep in mind that high salt content and high levels of arsenic and heavy metals could be problematic for animal health and may be passed up the food chain. High salt and arsenic content, as well as high levels of other components detected in several pelagic sargassum samples can also damage soils over the long term and may potentially be passed up the food chain through food crops.

Several research initiatives across the Caribbean are currently investigating the value of pelagic sargassum in animal feed and there is one example of potential commercialization of sargassum-based feed for goats. There are many other Caribbean examples of research and commercial development of pelagic sargassum in crop production applications. A long-term study on sargassum co-composting in Martinique is said to have obtained promising results (awaiting final report) and several agribusinesses from a number of countries in the region are currently commercializing sargassum-based fertilizers and biostimulants.

2.4 Antifouling

Marine biofouling presents a range of challenges for marine vessels and for industries with marine installations (such as those using piped seawater for cooling, mariculture operations, desalination plants). When aquatic organisms settle and grow on vessel hulls and propellers, they reduce hull efficiency and vessel speed, resulting in additional fuel usage and increased emissions of air pollutants and greenhouse gases (IMO, 2020). Biofouling is also a source of invasive alien species when vessels travel to different places or even through different oceans. In addition, biofouling can reduce the efficiency of or even block pipes, and stop moving parts from functioning (such as pumps), as well as weighing down mariculture infrastructure (such as cages, nets and floats) (Amara *et al*., 2018). As such, there is high demand for antifouling treatments globally.

However, some of the most effective antifouling paints contain chemical compounds such as tributyltin, which are highly toxic to a broad range of marine organisms, even at very low concentrations. Substitute compounds that are less toxic often contain copper and supplementary booster biocides, but concerns remain about the toxic effects in the broader marine environment; other compounds such as polyethylene oxide, acrylic resins and silicon are not nearly as effective, especially for fixed structures (Amara *et al*., 2018).

As such, there is now considerable interest in the development of new eco-friendly antifouling compounds from the natural chemical defence mechanisms used by marine organisms such as algae, sponges, corals, sea urchins and others to protect their own surfaces from biofouling (Chambers *et al*., 2006).

A recent laboratory study has shown that green seaweeds (*Ulva fasciata* and *Codium tomentosum*) and red seaweeds (*Corallina mediterranea*) are highly promising as safe, economically viable biocide additives for antifouling paints (Ibrahim *et al*., 2019). Another laboratory study has indicated that both a crude extract and isolated bioactive compounds (fatty acids) of the brown algae *Laminaria* "sanhai" have good antifouling capabilities and no cytotoxicity, and thus show promise for use in environmentally-friendly antifoulants (Li *et al*., 2018). Secondary metabolites accumulated by macroalgae are assumed to play a role in their defence against grazers and bacterial colonization. In brown algae, the production of phenolic compounds (such as phlorotannins) was found to be the main actor responsible for this defence mechanism, and suggests that these compounds could have potential for antifouling applications (Plouguerné *et al*., 2006). Palmitic acid extracts from *Sargassum muticum* fatty acids were found to have promising potential antifouling properties (Bazes *et al*., 2009).

BOX 4. Potential antifouling applications using pelagic sargassum in the Caribbean

Research:

- CORSAIR project (Guadeloupe): research on the impact of chemical products extracted from sargassum and the characterization of natural molecules with antifouling properties. This would allow for a transition to the use of "green antifouling coatings" (free of biocidal molecules) in the maritime navigation industry.

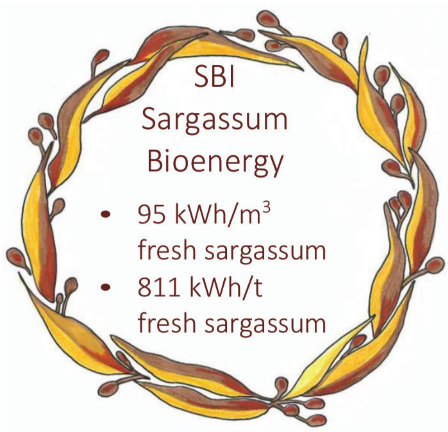
Further characterization of fatty acid and phenolic profiles of pelagic sargassum is needed to determine their antifouling potential. So far, preliminary results reported by Milledge *et al*. (2020) from limited samples of pelagic sargassum from the Turks and Caicos Islands indicated a fatty acid profile comprising: saturated fatty acids (37 percent), polyunsaturated fatty acids (29 percent), mono-unsaturated fatty acids (19 percent) and unidentified fatty acids (15 percent), as described in the *Composition section.* Palmitic acid was the predominant fatty acid, followed by oleic acid.

Summary of uses for antifouling

Recent research has shown that various extracts from brown seaweeds (used in their own chemical defence mechanisms) have potential as effective active ingredients in eco-friendly antifouling paints. One project in the Caribbean is studying the potential of pelagic sargassum for antifouling applications.

Bioenergy

Bioenergy is a term used to describe the use of organic material derivatives to produce energy, which can take the form of liquids (such as biofuels), gas (such as biogas) or solid (such as wood). Many types of biomass, including algae (microalgae and macroalgae), have suitable composition and properties for use in the production of bioenergy, including liquid, gaseous and solid forms. Bioenergy derived from algae is considered a more sustainable option than those using food crops such as corn, sugar cane and oilseed (Chaker Ncibi, Menyar Ben Hamissa and Gaspard, 2014). Use of algae as feedstock to produce bioenergy/biofuels, referred to as "third-generation biofuels", is proving highly



promising due to their fast growth and high yield, low lignin content and ability to capture CO_2 (meaning that the fuel produced is carbon neutral). This section reviews four potential renewable energy options using algae: (1) bioethanol; (2) biodiesel; (3) biomethane; and (4) biopellets.

2.5.1 Bioethanol

Bioethanol, used as a transport fuel, can be produced from algae by converting the carbohydrates to ethanol using a multi-step process, involving: pre-treatment, hydrolysis and fermentation. Pre-treatment converts the algal biomass to complex carbohydrates (complex sugars), and is an important and generally costly step of the process (Li *et al*., 2018). Pre-treatments of algae can include physical, physico-chemical, chemical and biological processes (Li, Liu and Liu, 2014). Enzymatic or chemical hydrolysis is then carried out to convert the complex carbohydrates to simple monomers (that is, simple fermentable sugars such as glucose), a step that is referred to as "saccharification". This is followed by fermentation of the simple sugars with microorganisms to produce ethanol.

Numerous studies have been carried out with different macroalgae to determine the optimal combination of pre-treatments, hydrolysis and microorganisms required for fermentation to produce the highest bioethanol yield. Examples include the following:

- Kim *et al*. (2011) propose an effective pre-treatment of macroalgae for ethanol fermentation that uses acid hydrolysis followed by simultaneous hydrolytic enzyme treatment and inoculation with *Escherichia coli* KO11 bacteria. This study determined that brown algae hydrolysates, high in mannitol polysaccharides, such as those extracted from *Laminaria japonica*, can be economically viable for microbial ethanol production.

- Lee *et al*. (2013) investigated the potential of brown seaweed *Saccharina japonica* as a substrate for bioethanol production using a low acid pre-treatment (weak acid at high temperature), followed by simultaneous saccharification and fermentation with the yeast *Saccharomyces cerevisiae*. They note that the remaining hydrolysates containing mannitol and alginate-derived oligosaccharides could be used to further the fermentation processes for bioethanol production.

- Yeon *et al*. (2011) incorporated a surface aeration fermenter culture method to improve the production of bioethanol from the hydrolysate of brown seaweed *Sargassum sagamianum*. Results indicate a promising and practical strategy for commercial bioethanol production from sargassum seaweed.

- *Sargassum* spp. are abundant in the Philippines and have been studied by several researchers to determine the bioethanol production potential. Borines, de Leon and Cuello (2013) proposed processing the seaweed with an acid pre-treatment, hydrolysing it with cellulase enzymes supplemented with β-glucosidase, and fermenting it with *Saccharomyces cerevisiae.* This resulted in an ethanol conversion rate of 89 percent, which highlights the strong potential of *Sargassum* spp. as renewable feedstock for bioethanol production. Wardani and Herrani (2019) took a slightly different approach, using a *Sargassum* sp. to determine the effect of fermentation time on ethanol production, where the bacterium *Zymomonas mobilis*, tape yeast and bread yeast were used. Results showed that peak ethanol levels were attained after 6 days of fermentation, reaching almost 25 percent ethanol content.

Although algae are generally considered one of the most important and eco-friendly sources of biomass for the production of renewable biofuels, their commercialization in bioethanol production remains challenging. This is primarily due to the cost of pre-treatments because of the complex composition of algae cell walls, the need to find specific marine bacteria for each kind of algae, and the high cost of enzymes (Li, Liu and Liu, 2014). In addition, high salt content of seaweed can increase salinity levels during fermentation and result in negative impacts on the production of ethanol yields (Maneein *et al*., 2018).

As indicated in Box 5, research is being carried out at the University of the West Indies in Barbados to determine the potential of pelagic sargassum to produce bioethanol.

2.5.2 Biodiesel

Biodiesel is a renewable and highly versatile transport fuel that is derived from natural oil sources, including vegetable oil and animal fats, and is considered to be a better option than petroleum diesel in terms of environmental impacts since it is carbon neutral (its production and use does not add CO_2 to the atmosphere) (Chaker Ncibi, Menyar Ben Hamissa and Gaspard, 2014). Feedstocks used in different countries depend on the raw biomass available, such as rapeseed or soybeans in the United States of America and palm oil in Asia. Feedstocks have been classified into different categories and can be described based on their fatty acid profiles: algal lipids, oilseed, used cooking oil and animal fats (Chaker Ncibi, Menyar Ben Hamissa and Gaspard, 2014).

Most research with algae as feedstock for biodiesel production has focused on the use of microalgae (microscopic algae) as opposed to macroalgae (seaweeds), since the former generally have high oil content (lipids) and high biomass productivity. Microalgae have been recognized as being the only renewable source of biodiesel that could meet global transport fuel demand (Balat, 2011). Macroalgae are not suitable for biodiesel production because they do not contain sufficient lipids. Since this guide focuses on pelagic sargassum macroalgae, it will not examine microalgae-based biodiesels in any more detail here. To the authors' knowledge, no research projects in the Caribbean are currently exploring biodiesel production using pelagic sargassum.

2.5.3 Biogas (biomethane)

Biogas can be produced from a wider range of feedstocks than bioethanol, which requires high sugar content, or biodiesel, which needs high oil content (Chaker Ncibi, Menyar Ben Hamissa and Gaspard, 2014). Feedstock such as wastewater sludge, municipal solid wastes, animal manure and food waste go through an anaerobic digestion process (using microorganisms) to produce biogas. Biogas is composed primarily of methane and carbon dioxide and trace amounts of other gases, such as carbon monoxide, hydrogen sulphide and ammonia.

In order to produce biomethane, trace elements are removed through a cleaning process and the calorific value is then adjusted through an upgrading process. If all transformation steps are met, biomethane can contain up to 97 percent methane and 1 to 3 percent carbon dioxide (Chaker Ncibi, Menyar Ben Hamissa and Gaspard, 2014).

The use of microalgae biomass in anaerobic digestion has been widely researched, but information related to biofuel production from macroalgae is much more limited, and further research is needed to investigate the efficiency of using seaweed biomass.

In a review to examine the potential of macroalgae to produce biogas, it was reported that these have viable biofuel potential as biogas, since all components can be converted to biogas through anaerobic digestion (Chen *et al*., 2015). In addition, macroalgae generally have a low lignocellulose content, which favours biogas production. In this same review, the potential of different macroalgae types to produce methane was compared, where brown macroalgae were reported to show promising methane production. However, for an optimal methane yield, a carbon to nitrogen ratio (C:N) of 20 to 30 is needed. If the ratio is lower than 20, more ammonia will be produced, leading to a reduced yield of methane (Chen *et al*., 2015). The C:N ratio of macroalgae is generally around 10 and macroalgae can contain some toxic compounds, which make them unsuitable for mono-digestion, but suitable for co-digestion when blended with high C:N biomass, such as straw, sawdust, woodchips, paper and cardboard. (Chen *et al*., 2015; Paul, Melville and Sulu, 2016). Pre-treatments are recommended to further break down the algae cell walls, thereby making organic matter available for microorganisms and increasing the biogas production efficiency and yield. It is important to note that large amounts of polyphenols and ash content, including saline elements such as sodium, potassium, calcium and magnesium, can limit the growth and productivity of anaerobic microorganisms, and hence methane yield. However, this can be improved with water and weak acid pre-treatments (Chen *et al*., 2015; Milledge *et al*., 2019).

The brown macroalgae *Laminaria* spp. and green macroalgae *Ulva* spp. are highly recommended as feedstock for biogas production (Montingelli *et al*., 2016). The biogas yield can be increased by using a combination of a pre-treatment and co-digestion methods (Paul, Melville and Sulu, 2016). Methane yield is said to vary according to the substrate/inoculum ratio and the lipid content of the biomass, where different pre-treatments can be used for different algae species and conditions (Paul, Melville and Sulu, 2016). There are several pre-treatment methods available to improve the digestibility of algal biomass. These include mechanical (such as milling); physical (such as thermal, pressure, microwave, ultrasound); chemical (such as acid, alkali); and use of enzymes. The effectiveness of pre-treatments depends on several variables, including the type of algae used (Montingelli *et al*., 2016; Paul, Melville and Sulu, 2016). It is worth noting that certain macroalgae with low lignin content do not require any pre-treatment before anaerobic digestion.

To improve the C:N ratio, reduce certain toxic compounds and increase methane production, a wide range of co-digestion methods have been investigated for use with seaweed, including the use of brewery wastewater, sewage sludge, agricultural waste and other biodegradable waste materials (Paul, Melville and Sulu, 2016).

Research on two species of brown macroalgae (*Macrocystis pyrifera* and *Durvillea antarctica*) investigated their suitability as feedstock for biogas production in a two-phase anaerobic digestion system (Vergara-Fernández *et al*., 2008). Results showed that the biogas produced had a methane concentration of 65 percent. Similarly, Milledge *et al*. (2019) determined from reviewing published studies that anaerobic digestion of seaweeds typically produces biogas containing 50 to 70 percent methane, 30 to 45 percent carbon dioxide, 3.5 percent or less of hydrogen sulphide and less than 2 percent hydrogen. Anaerobic digestion of brown macroalgae is considered to yield more methane than green macroalgae; however, methane yield is typically at least 50 percent less than currently used commercial feedstocks (Milledge *et al*., 2019).

Due to the fact that algae composition varies widely, further investigation is needed on a wider range of macroalgae species to determine their potential application using both mono- and co-digestion methods. Literature on mono-digestion of algae in a continuous process is limited and there has not been any establishment of long-term viable anaerobic digestion technology using mono-digestion of macroalgae (Tabassum, Xia and Murphy, 2017). The reasons for low methane yield of algae in anaerobic digestion are associated with several factors, such as cell wall structure, polysaccharides, polyphenols, organic sulphur, toxins and heavy metals (Milledge *et al*., 2019).

According to Thompson, Young, and Baroutian (2020), pelagic sargassum has a low carbon to nitrogen ratio, low bioavailability of carbohydrates and high insoluble fibre, salt, polyphenols and sulphur, all of which contribute to low methane recovery. As such, sargassum mono-digestion (that is, use of sargassum as the sole feedstock) is unsuitable for methane production, but co-digestion with other organic waste material can increase the amount of energy recovered by up to fivefold (Thompson, Young and Baroutian, 2020). A pilot project carried out in Saint Lucia determined that older beached sargassum had low biochemical methane potential and is not suitable for anaerobic mono-digestion systems (Morrison and Gray, 2017). However, another pilot anaerobic digester study being undertaken in the Dominican Republic indicates that approximately 55 percent of methane and 35 percent of CO_2 can be produced from co-digestion of sargassum with organic waste, and that the optimum ratio is 25 percent sargassum to 75 percent organic waste (Rodriguez Cuevas, Rivera and Gil, 2020)

A recent study indicated that the mixed macroalgae biomass (pelagic sargassum and *Ulva* sp.) commonly found on Mexican Caribbean coasts is a promising feedstock for biofuel and that using the fungus *Trametes hirsuta* as an anaerobic digestion pre-treatment increased methane yield by 20 percent (Tapia-Tussell *et al*., 2018). This effective pre-treatment could enable the scale-up of biogas production using macroalgae such as sargassum.

Ongoing projects in the Caribbean that are testing the potential of sargassum anaerobic digestion to produce biomethane using different methods and feedstock mixtures are summarized in Box 5.

2.5.4 Biopellets

Biopellets are made of biodegradable materials such as agricultural waste (crop stalks, husks, shells, bagasse), forest residues (sawmill residues, branches, leaves) and solid waste (such as paper). They can be used to heat buildings and for cooking, and at industrial scales to reduce energy costs of large-scale operations. Biopellets are considered to be a sustainable alternative to petroleum-based fuel because they are made from renewable materials, and are efficient, clean, economical, environmentally-friendly and sustainable.[7]

To date there has been very little research published on the use of seaweeds (macroalgae) for the production of biopellets for energy storage. However, lessons can be learned from the few studies that are currently available. One study examined the potential for production of biobriquettes from carbonized brown macrolagae,[8] but found this feedstock unsuitable, due to falling stability of binders and a concentration of inorganics after carbonization. The study did report, however, that the briquettes had good compressive strength characteristics (Haykiri-Acma, Yaman and Kucukbayrak, 2013). Maceiras *et al.* (2015) analysed eight different seaweeds for their use as biopellets in boilers, and found that none was suitable for direct use. However, it was determined that they could be used for other industrial purposes or for animal feed. Despite a lack of successful application of macroalgae in biopellet production from published literature to date, promising results have been obtained by Mexican renewable energy company Energryn in mixing sargassum with other organic waste to produce biopellets for use in local hotel boilers (see Figure 7).

Figure 7. Sargassum-based biopellets being developed and tested in Mexico by Energryn

[7] www.renewableenergyworld.com/2016/05/19/whats-biomass-pellet-and-biopellets-species/#gref
[8] http://biomassmagazine.com/articles/5148/biomass-briquettes-turning-waste-into-energy

BOX 5. Bioenergy production using pelagic sargassum in the Caribbean

Research:

Centro de Investigación Científica de Yucatán (Mexico): Raúl Tapia Tussell and his team have developed a prototype methodology (patent pending) that involves mixing sargassum with a locally sourced fungus, able to degrade lignin, and a bacterial inoculum to produce methane.

Ecodec (Guadeloupe): Recipient of ADEME grant in 2016 for a pilot trial to evaluate sargassum's potential as a fuel to power a biomass boiler.

Innovation Développement (Guadeloupe): Recipient of ADEME grant in 2016 for a pilot sargassum methanization trial.

SAVE (France/Guadeloupe/Martinique): Ongoing study on anaerobic digestion of sargassum and factors affecting methane production.

University of the West Indies (Barbados and Trinidad): Researchers at both Cave Hill & St. Augustine campuses are investigating the potential of sargassum to produce biogas and bioethanol.

Commercialization:

Biogen (Barbados): This company is investigating anaerobic co-digestion of sargassum.

Damen/Maris Group (the Netherlands): This group has been investigating further use of sargassum in biofuel applications.

Energryn (Mexico): Investigating the use of sargassum blended with other organic wastes to produce biopellets for use in local hotels.

EnergyAlgae (Israel and the Dominican Republic): This collaborative project between Y.A. Maof, Universidad APEC and AlgeaNova has implemented a pilot in Punta Cana (the Dominican Republic) to determine the use of sargassum in anaerobic biogas co-digestion units.

Hotels in Cancun, Mexico, and neighbouring areas: Several hotels are in the process of implementing on-site biogas facilities to use sargassum and hotel organic waste in anaerobic co-digestion units.

Mécaméto (France): This company is investigating the potential of sargassum as feedstock in the patented dry methanization mobile technology Hemer.

Num SMO Technologies (Guadeloupe): Pyrolysis of sargassum to produce electricity and activated carbon.

SARA (French Guyana and Guadeloupe): The GARAS project is an industrial consortium of three companies, where SARA, a major refinery business in the region, is investigating the potential use of sargassum to develop a thermo-conversion process (such as pyrolysis) to produce biofuel.

The Pelikan System (Saint Barthélemy): Private company Green Engineering S.A.S. proposes a complete "autocombustore" (autocombustion) system fed with bio-sargassum pellets to generate electricity through an electric turbine generator.

Summary of uses for bioenergy

Pelagic sargassum has demonstrated potential for use in the bioenergy sector for the production of liquid, gas and solid biofuels. These have the advantage of not only being sustainable and carbon neutral, but also – since sargassum grows at sea– their production does not compete with agriculture (food production) for arable land.

Liquid biofuels: The ability has been demonstrated of *Sargassum* spp. to produce reasonable yields of bioethanol through fermentation by microorganisms. However, commercialization of the process remains challenging, largely due to the high cost of pre-treatment to make the seaweed suitable for fermentation, and the need to identify suitable salt-tolerant microorganisms. Sargassum (and seaweeds in general) is unsuitable for the production of biodiesel due to the relatively low levels of fats (lipids) they contain.

Biogas: Brown seaweeds are considered to hold promise for the production of biomethane through anaerobic digestion, given their low content of lignin (compared with terrestrial plants). However, they generally have an unfavourable (low) carbon to nitrogen ratio (and may contain other components, such as sulphur and heavy metals, which interfere with the digestion process) and therefore need to be mixed with other types of biomass such as food waste and agricultural by-products (in a process known as co-digestion), to increase the methane yield.

Solid biofuel: So far, there has been limited success reported in the literature in the use of brown seaweeds to produce biopellets as a sustainable solid fuel.

Research into the feasibility of using pelagic sargassum to produce commercial quantities of bioethanol fuel is ongoing in at least one Caribbean institution. There are several projects across the Caribbean currently experimenting with pelagic sargassum and a variety of organic wastes in co-digestion systems to commercialize biomethane for small- and medium- to large-scale production. Some promising results have also been achieved by at least one company in the Caribbean using biopellets made from a mix of pelagic sargassum and other organic waste, for use in hotel boilers.

2.6 Bioplastics

Plastic pollution is a worldwide concern, with many plastics taking 1 000 years to decompose (Kale *et al*., 2015). More than 300 million tonnes of plastic are produced annually, of which as much as 43 percent ends up in landfills and up to 7 percent ends up in oceans (Gourmelon, 2018). Marine pollution by plastics is a major concern in the Caribbean, where there can be as many as 200 000 pieces per km^2 (Diez *et al*., 2019). Bio-based plastics or "bioplastics" were developed to provide a more "eco-friendly" alternative to petroleum-based plastics. In recent years, they have gained popularity and now support a fast-growing, multi-billion-dollar industry. Bioplastic is a general term used to cover a wide range of biodegradable polymers made from renewable biomass sources, of which the most common are starch-based (such as corn starch), cellulose-based (such as woodchips and sawdust), protein-based (such as wheat gluten, casein and milk), organic polyethylene (such as fermented agricultural waste) and aliphatic polyesters (such as polylactic acid (PLA), polyglycolide and polyhydroxyvalerate).

There are different end-of-life options for bioplastics, including recycling, composting, incineration, anaerobic digestion and feedstock recovery, depending on the type of bioplastic. To be considered as compostable or biodegradable, bioplastics must meet certain criteria, which are defined by different standards and certification bodies.[9] These criteria are mainly related to time, environmental conditions and the quality of compost produced.[10] Also considered by some standards is the amount of carbon dioxide or methane produced over a certain period of time. When producing bioplastics, it is essential that businesses adhere to local regulations and biodegradability standards and ensure access to adequate facilities to dispose of or recycle materials appropriately, avoiding further environmental impact.

Most bioplastics are currently made from plant-based agricultural feedstocks such as soybean, wheat, rice, corn, sorghum, barley, wood, cotton, hemp, sweet potatoes or sugar cane. However, these are not fully in accordance with the United Nations' Sustainable Development Goals because they need arable land and freshwater, which compete with food production (Karan *et al*. 2019). As such, there is a growing interest in the use of microalgae for bioplastic production since these do not compete with food production, are adaptable to different growth conditions and composting settings and do not require chemical fertilizers, which ensures compatibility with scaling circular bioeconomies (Karan *et al*., 2019). However, microalgae are not easily harvested compared with macroalgae.

Research supporting the commercialization of macroalgae-based bioplastics has recently gained ground, due to their high biomass, ability to grow in different environments, affordability and ease of cultivation (Rajendran *et al*., 2012). The polysaccharide composition of macroalgae makes many species ideal candidates for use in bioplastic manufacture. Macroalgae can be used in different ways for the production of bioplastics. For example, they can be used as feedstock for fermentation by microorganisms to produce lactic acid, or for direct extraction of polysaccharides, both of which are used in the manufacture of bioplastics. They can also be used directly as compressed biomass in the manufacture of materials suitable as alternatives for single-use plastics. For this application, some manufacturers are adding a protective layer of wax or other material, to avoid direct contact with food.

A recent study by researchers in Israel evaluated the carbohydrate composition of seven different seaweeds as feedstock for salt-loving microorganisms *Haloferax mediterranei*, to produce polyhydroxyalkanoate (PHA) bioplastic (Ghosh *et al*., 2019). Maximum PHA yield was obtained from the green seaweed *Ulva* sp. and the resulting biodegradable polymer does not require freshwater, produces zero toxic waste and can be recycled into organic waste.

A three-year European Union-funded project called SEABIOPLAS studied the production of seaweeds as feedstock in sustainable Integrated Multi-Trophic Aquaculture (IMTA) systems for the development of bioplastics (CORDIS, undated). IMTA systems incorporate waste products from one species into the diet of another species. In this study, nitrogen and phosphorus produced from aquaculture (fish and crustaceans) are used by seaweeds (*Ulva* sp., *Gracilaria vermiculophylla* and *Alaria esculenta*) to produce new biomass, which in turn is processed to produce lactic acid (a precursor for PLA). Leftover seaweed residues from this process are then used as animal feed additives on dairy farms. Results revealed two bioplastic supply chains from two distinct seaweed species: PLA from *Ulva lactuca* and polysaccharide films from *Gracilaria vermiculophylla*.

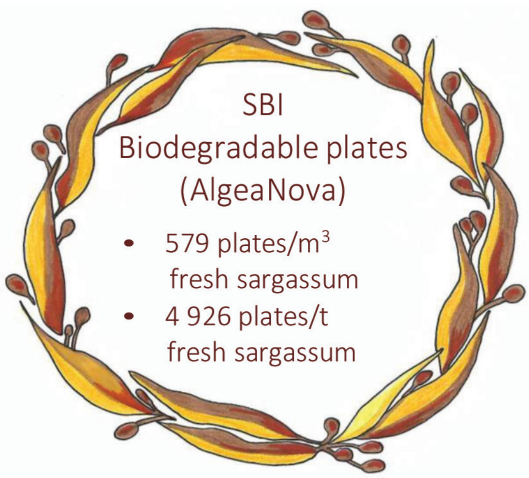
9 www.bioplastics.guide/ref/bioplastics/standards-and-certifications
10 https://bpiworld.org

ALGOPACK, a company founded in Brittany, France in 2010, is the first manufacturer of bioplastics made from cultivated brown algae (ALGOPACK, 2020). After the seaweed is harvested, it is turned into granules using a patented process and used in two different bioplastics: Algoblend (50 percent seaweed and 50 percent oil-based plastic) and Algopack (100 percent seaweed). Algoblend is considered more versatile and is used for more permanent items such as office equipment, construction materials and toys. It is also suitable for industrial extrusion, thermoforming and injection processes without needing any technical adjustments, and improves the energy output of presses (25 percent energy savings due to reduced manufacturing temperature). Algopack is used for single-use items such as disposable packaging (see Figure 8). Algopack granules are completely biocompostable and biodegrade within 12 weeks in soil, and 5 hours in water.

Figure 8. Examples of Algopack and AlgeaNova bioplastic products made from 100% seaweed. Algopack flowerpots (top left), Algopack disposable food packaging (bottom left) ©Algppack and AlgeaNova® sargassum and cassava single-use plates (right) ©Algeanova

©Algopack

Several studies have investigated the use of sargassum species as feedstock and as a source of extracts to produce bioplastics. *Sargassum* sp. was reported to be a promising feedstock for the bacterium *Cupriavidus necator* to produce polyhydroxybutyarte bioplastic (Azizi, Najafpour and Younesi, 2017). Another study showed that alginates extracted from *Sargassum siliquosum* hold promise for the synthesis of bioplastic film (Lim *et al.*, 2018). A recent study carried out in the United States of America determined that novel seaweed nanocomposite biopolymer films can be made from *Sargassum natans* and *Laminaria japonica* extracts (Doh, Dunno and Whiteside, 2020). These have strong potential for use in food packaging applications, and their antioxidant properties reveal that these could improve food preservation when used as food films.



As shown in Box 6, several companies in the Caribbean region are seeking to commercialize sargassum-based bioplastic.

BOX 6. Bioplastics made from pelagic sargassum in the Caribbean

Research:

Clemson University and Rochester Institute of Technology (United States of America): Nanocomposite films with *Sargassum natans*.

NOVUNDI Environnement and AlgoPack (France and Guadeloupe): Recipient of a grant from ADEME in 2016 to evaluate the feasibility of producing sargassum-based bioplastics.

University of the West Indies (Barbados and Trinidad): Researchers at both Cave Hill and St. Augustine campuses are exploring sargassum for use in the manufacture of bioplastic.

Commercialization:

Abaplas (Mexico): Currently testing production of a bioplastic made of 30 percent sargassum and 70 percent plastic for use in different applications, including ecological housing.

AlgeaNova/EnergyAlgae (the Dominican Republic): The team has started to produce single-use plates made with 50 percent sargassum and 50 percent cassava waste.

Algopack (France): With its knowledge of using brown seaweed in France, the company is exploring the possibilities of using sargassum to produce bioplastic.

EnerGryn (Mexico): Currently testing production of two types of bioplastic – biodegradable pellets and recyclable bioplastic for use in making water heaters, cups and plates.

Groupe CAÏALI (Martinique): An industrial consortium of three companies is investigating the valorization potential of sargassum for bioplastics under the GARAS project.

Le Floch Depollution (France): Currently testing development of two different types of bioplastic made with (1) 30 percent sargassum and 70 percent thermoplastic resins; and (2) 40 percent sargassum and 60 percent polylactic acid.

Summary of uses for bioplastics

Bioplastics are typically made from plant-based material, especially agricultural crops (such as corn, sugar cane and sugar beet). However, the manufacture of bioplastics is now possible from seaweeds, which has the added advantage of not competing for land space for food production.

Several recent studies have successfully demonstrated that brown seaweeds, including *Sargassum* spp., are suitable for this application, as a result of their polysaccharide composition. They can either be used as feedstock for fermentation by microorganisms to produce lactic acid or for extraction of polysaccharides (alginates), both of which are used in the manufacture of bioplastics. They can also be used directly as biomass and compressed with other materials to make products that can replace single-use plastics, although they may need to be coated with a protective layer if in direct contact with food.

There are now multiple examples of ongoing research and commercialization ventures across the Caribbean region that are experimenting with pelagic sargassum to manufacture a variety of bioplastics.

2.7 Bioremediation and purification

2.7.1 Water and wastewater treatment

A recent review of the literature on use of seaweeds for wastewater treatment indicates that these have good biosorption[11] properties and show promising results in removing pollutants such as dyes, heavy metals and other compounds, including nitrogen, phosphorus and phenols (Arumugam *et al*., 2018). Seaweeds are used to help maintain the water quality in intensively-fed aquaculture systems (fish, shrimp and shellfish farms) in open-water, enclosed and land-based systems, to absorb up to 90 percent of nutrient discharge, and thereby reduce detrimental nutrient enrichment of the natural environment (Lüning and Pang, 2003).

Research has also demonstrated that high-quality activated carbon (see Box 7) can be produced from different types of seaweed, including brown seaweeds (Altenor *et al*., 2012; Salima *et al*., 2013). Activated carbons are known to be highly effective in removing metal ions, dyes and chlorinated compounds from drinking water and wastewater.

The adsorption capacity of activated carbons varies according to the botanical composition of the precursors, as well as the microporosity, physico-chemical properties and the activation processes used (Gaspard *et al*., 2014). Porous carbons derived from kelp have been tested for use as electrode material in capacitive deionization units, with indications that they are highly efficient in removing salt when applied to electric double-layer capacitive deionization (Sun *et al*., 2019).

However, according to a study carried out by Patrón-Prado *et al*. (2010) using *Sargassum sinicola*, the solution salinity reduced cadmium biosorption from 89 to 5.8 percent.

[11] Biosorption is defined as a "physiochemical process that occurs naturally in certain biomass which allows it to passively concentrate and bind contaminants onto its cellular structure" (Narwal and Gupta, 2017).

BOX 7. Activated carbon

Activated carbon (AC) is characterized by a well-developed network of pores enclosed by carbon atoms, and a large surface area, giving AC very good absorptive capacity.

AC has been mass produced since the early twentieth century.

Traditional materials used as precursors for AC include coal, coke, wood, bamboo, sugar-cane bagasse and coconut husks. There is increasing interest in using low-cost abundant biomaterials such as agricultural waste, bacteria, yeasts, fungi and algae biomass as precursors.

Conventional activation of carbon is based on physical methods (exposed to very high temperatures, e.g. pyrolysis) or chemical methods (impregnation with acid, base or salt at high temperatures).

Large quantities of pollutants can be captured and concentrated in AC pores.

AC is used in a wide range of applications and sectors, but air purification and water treatment applications largely dominate the market. Other sectors include pharmaceuticals, biomedicals, food and beverage processing, and the automotive industry.

The global market value of AC is estimated at USD 4.72 billion (2018).
There is a large market opportunity in the Caribbean (the Dominican Republic alone imports > 1 700 metric tonnes per year of granular AC).

2.7.2 Air and gas purification

Activated carbon is also widely used as a sorbent material to filter particles and adsorb chemical compounds in air and gas purification and odour-control applications for industrial and personal uses.

Several studies have shown that seaweed-based activated carbons, including those derived from brown macroalgae of the genus *Sargassum*, are promising candidates for use in air and gas purification filters to adsorb pollutants (Liu *et al*., 2019; Xu *et al*., 2019).

2.7.3 Bioremediation

Activated carbon is used for bioremediation purposes, to reduce the toxicity of pollutants in contaminated sites, including land-based and marine environments.

There has been increasing interest in the use of seaweed-based activated carbon, from a wide range of seaweeds including *Sargassum* spp., to remove contaminants (metals, hydrocarbons, micropollutants, trace elements and macronutrients) from coastal waters, soil, oil spills and aquaculture effluents (Neori *et al*., 2004; Perelo, 2010; Ron and Rosenberg, 2014; Yu *et al*., 2014; Marinho *et al*., 2015; Koul and Taak, 2018; Neveux *et al*., 2018).

Examples of research and commercialization of sargassum for bioremediation and purification in the Caribbean are given in Box 8.

BOX 8. Bioremediation and purification applications of pelagic sargassum in the Caribbean

Research:

Center for Applied Physics and Advanced Technology, Autonomous University of Mexico (UNAM) (Mexico): developing sargassum filters for bioremediation, removing contaminants such as metals, sulphates and pigments from water.

COVACHIM-M2E laboratory (University of Antilles in Guadeloupe and French Guyana): creating sargassum AC for soil remediation, pesticide sequestration in animals and water treatment applications.

Instituto Tecnológico de Santo Domingo (the Dominican Republic): testing sargassum-based AC for water treatment and other applications.

PYROSAR project (Guadeloupe/Martinique): optimizing the production of sargassum AC and biochar to adsorb the pesticide chlordecone in contaminated areas to enable safe food production.

SARtrib project (Guadeloupe): examining potential of sargassum nano-carbon and nano-oxide for use in filtering pollution gases.

Commercialization:

Grupo TMM (Mexico): implementation of an industrial plant to produce gas, electricity and AC through sublimation using sargassum and organic waste (municipal and cruise ships).

NBC and Tecmalab (French Guyana and the Dominican Republic): commercialization potential of sargassum-based AC for water and air treatment applications.

Num-Smo Technologies (Guadeloupe): using solar pyrolyzer to transform biomass (including sargassum) into gas, electricity and AC.

Summary of uses for bioremediation and purification

Living pelagic sargassum (like most seaweeds) has excellent biosorption properties, meaning that it is capable of removing a variety of contaminants (such as high nutrient loads, heavy metals, dyes, phenols) from water. It can therefore be used to treat polluted sites and wastewater effluents, although the seaweed itself must then be collected and treated as toxic waste.

Pelagic sargassum is also suitable for conversion to high-quality activated carbon (through exposure to very high temperatures in a process known as pyrolysis). Activated carbon has a wide range of applications, including bioremediation and purification. For example, it is used: (1) in filters for purifying air and other gases; (2) for odour control; (3) for bioremediation of contaminated soils and coastal waters; and (4) in water filters. There are many examples across the Caribbean of ongoing research and commercialization ventures involving the use of sargassum in environmental bioremediation and purification systems.

2.8 Clothing, footwear and accessories

Algae are being used as a new resource to produce sustainable fibres and dyes for the textile and footwear industries (Sustainable Fashion Earth, 2020). Algae cellulosic fibres can be blended or woven with other fibres for use in fabrics. Research and development have improved the use of technologies and application of seaweed fibres in the textile industry. The following are some examples:

- "SeaCell" is a trademark exclusive to the German company Smartfiber AG, which uses the innovative and eco-friendly lyocell production process to combine seaweed with eucalyptus extracts to produce a high-quality fibre for clothing. The process uses very little water and no chemicals. SeaCell is said to offer comfort and positive skincare effects, due to the beneficial properties of seaweed (Rana *et al.,* 2014).[12] SeaCell has gained popularity for sportswear, yoga wear, sheets, towels, blankets and baby clothing (Rana *et al.,* 2014).

- The Israeli and German-based Algalife company has created the brand "Algae Apparel", using algae biofibre and eco-friendly dye. In the textile industry, the dyeing process is problematic, both in terms of water use and pollution. The clothing is said to have beneficial properties, as it releases antioxidants, vitamins and other nutrients to the skin.[13]

- The Swiss-based Beyond Surface Technologies company has teamed up with California biotech start-up Checkerspot to develop a textile finish using algae-generated oils. The resulting fabric has a quick-drying finish, which is an attractive property for sportswear.[14]

- The Hong Kong-based Fabric Workshop company, in collaboration with Chaintex, has developed an algae-based fibre called "Celp", using cellulose and algae yarn. Celp fibres have anti-bacterial properties and generate negative ions that are said to be beneficial to humans.[15]

- The Mississippi-based Algix company in the United States of America is commercializing Bloom Algae Foam, a microalgae-based foam used in footwear, yoga mats, backpacks, surfboard traction pads and other applications.[16] It has teamed up with a Taiwanese supplier and has been producing the algae foam for 5 years in 70 factories, for 63 brands.

- AlgiKnit, a Brooklyn-based biomaterials company, also in the United States of America, is creating durable yet rapidly degradable yarns made with kelp macroalgae, for use in footwear, accessories, interiors and garments. The yarn is said to start degrading only when exposed to humid, fungi-rich environments such as compost.[17]

Sodium alginates extracted from brown seaweed are often used in the textile printing industry. They are used to thicken dye pastes for textiles, and are considered superior to traditional starches, especially for reactive dyes, since they result in higher colour yields (McHugh, 2003). However, alginates are more costly than starch, which is why they are not used as often as starch for textile applications. Nevertheless, textile printing accounts for about 50 percent of the global alginate market (McHugh, 2003). Research results using the seaweed *Stoechospermum marginatum* indicate that this species of brown algae is a good candidate for use as a natural dye for textile applications (Rani *et al*., 2020).

[12] www.smartfiber.de/en
[13] alga-life.com
[14] checkerspot.com/Matthias-foessel
[15] prefaceshow.com/the-fabric-workshop
[16] algix.com/#bloom
[17] algiknit.com

To the best of the authors' knowledge, there has been no specific research or development of new textile products using pelagic sargassum in the Caribbean region. However, as indicated in Box 9, a Mexican company is using sargassum for the soles of footwear.

BOX 9. Clothing and footwear from pelagic sargassum in the Caribbean

Commercialization:

- **Renovare** (Mexico): This company has developed an eco-friendly shoe using recycled plastic, biodegradable resins and sargassum seaweed in the soles of their Ocean Ova shoe.

Summary of uses for clothing, footwear and accessories

Seaweeds can be used to produce eco-friendly fibres, foams, dyes and coatings for the fashion industry and are increasingly being used for sportswear and accessories. Sodium alginate, extracted from brown seaweeds, is also used in the textile printing industry for thickening and enhancing dyes, although it is more expensive than the widely used starch.

To date, the only known use of pelagic sargassum in the Caribbean fashion industry is as a component of shoe soles.

2.9 Construction materials

Biomaterials are attracting more interest and commercial attention for use as part of sustainable architectural buildings. There have been some research advances in the use of algae as a biomaterial for such purposes. Selected examples of projects that are exploring the use of algae in building materials are given here:

- The Algix company Algix combines microalgae biomass with plastic polymers to create bioplastics and resins, used to make foam boards, insulation and plastic sheeting for construction material. Algae-based foam sheets are used for insulation in walls for soundproofing and temperature control for houses, as well as to cover pipes and other applications.
- Microalgae residues have been used in the production of bio-asphalt (Audo *et al.*, 2015).

Examples where brown seaweed (macroalgae) is being used for building material include the following:

- The United States of America-based Tamarisk Technologies Alginix company uses an alginate extracted from kelp to make algae slabs which are reported to be much stronger than concrete.
- In Denmark, designers Jonas Edvard and Nokolaj Steenfatt are using a mixture of brown seaweed and paper to create unique furniture and lamps.
- In Australia, a research team at the University of New South Wales has been investigating the use of brown seaweed and mollusc wastes as secondary fillers in wood-plastic bio-composite particleboard for building applications. Results indicate that incorporating marine bio-fillers improves the moisture-resistant properties of the bio-composite panels, which suggests that these are suitable for high moisture environments (Echeverria *et al.*, 2017). Prototype panels

have applications in interior design, cabinetry, furniture, acoustic and insulating panels, division panels and screens, architectural linings and ceiling panels (Echeverria *et al.*, 2017).

- Biopolymers extracted from brown seaweed have shown to be useful as additives in unfired clay bricks to increase particle bonding. Unfired clay bricks are considered an environmentally-friendly alternative to traditional fired bricks and concrete blocks. Alginates have been shown to increase the flexural and compressive strength of bricks, depending on the type of alginate and soil used (Dove, Bradley and Patwardhan, 2016). The highest strength was observed when using soil with low clay content, combined with medium viscosity alginate from the brown seaweed *Laminaria hyperborean* stem. Meanwhile, the SargaBlock® initiative in Mexico is producing Sargassum-based bricks (see Figure 9).

Figure 9. SargaBlocks produced in Mexico

©Omar Vazquez

As shown in Box 10, several ongoing projects in the Caribbean region are using pelagic sargassum to develop different building materials, including eco-panels, resin-board, construction blocks and bio-asphalt.

BOX 10. Construction materials from pelagic sargassum in the Caribbean

Research:

- **SARGOOD project** (Guadeloupe): This initiative is conducting research and development on innovative eco-materials and panels.

Commercialization:

- **Biogen** (Barbados): This company has carried out trials to make a sargassum-based resin board for industrial development.
- **Sargablock** (Mexico): Since 2015, Omar Vázquez Sánchez has been making sargassum-based construction blocks to build housing for low-income families.
- **The Marine Box** (Martinique): This start-up company is looking to add sargassum to bio-asphalt for use in paving roads.

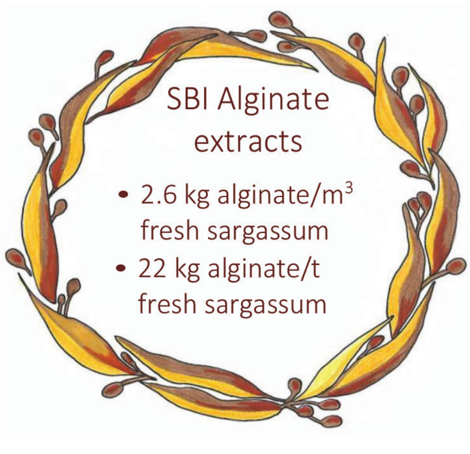
Summary of uses for construction materials

Seaweeds are being used in the production of a variety of composite construction materials, such as resins, foam boards, plastic sheeting, particleboards, slabs, bricks, bio-asphalt and even materials for furniture.

In the region, pelagic sargassum has been used to create prototype resin board and is being considered for use in other innovative eco-materials for panelling, and as an additive in bio-asphalt. Furthermore, one company in the region has already successfully developed and commercialized a pelagic sargassum-based brick, now being used in the construction of low-cost housing and other applications in Mexico.

2.10 Cosmetics

Algae derivatives such as alginates are known to have many valuable properties and are widely used in the cosmetics industry. They have high levels of nutrients and minerals and antibacterial, anti-inflammatory and anti-ageing properties, as well as high moisture retention capacities, which are all beneficial properties for skincare products.



A recent review of cosmeceutical (both cosmetic and pharmaceutical) uses of seaweed bioactive compounds for skin care indicates that these have excellent skin protection ability, particularly for use as anti-acne, anti-bacterial, anti-microbial, antioxidant and anti-ageing products (Jesumani *et al.*, 2019). Bioactive compounds in seaweeds can absorb ultraviolet (UV) UV radiation and act as UV filters, and therefore also have good potential for use in sunscreen and sun protection cosmetics (Balboa *et al.*, 2017). Seaweed extracts are also used in hair care products, to protect damaged hair and add shine.

BOX 11. Alginates

- Alginates are one of the main components of brown algae cell walls.
- Quantities of alginate vary according to the species of brown algae and can comprise up to 45 percent of their dry weight. However, pelagic sargassum is said to contain 7 to 10 percent alginate based on its dry weight.
- There are different alginates, derived from alginic acid salts and their ester. They are valued according to their ability to thicken in water and form gels, films and fibres.
- Sodium, potassium, calcium, ammonium and propylene glycol alginates are used as stabilizers, emulsifiers, thickeners and gelling agents in many products, including in the food and beverages, pharmaceutical, agriculture, biomedical, cosmetics, paper, ceramics and welding sectors.
- The textile printing industry accounts for almost half of the global alginates market, where sodium alginate is used as a thickener for dye paste.
- The biomedical and pharmaceutical industries account for about 20 percent of the global alginates market.
- The paper industry accounts for only 5 percent of the global alginates market, where alginates are used for surface sizing of the paper (grease-proofing and fluffing reduction).
- Calcium alginate is insoluble in water and used in fibres for the textile industry, bandages and beads (encapsulation medium).
- Magnesium alginate has medicinal properties and is used to treat peptic ulcers, gastro reflux disease and coronary disease.
- Propylene glycol alginate is widely used as a food additive. For example, it is used to stabilize beer foam, increase shelf life, and preserve the colour and consistency of many processed foods.

Seaweed polysaccharides are of particular interest in cosmeceutical products due to their natural biofunctional, physical and chemical properties. The sulfated polysaccharide fucoidan, which is found mainly in brown seaweed species, is known for its wide range of cosmetic effects, including preventing freckles, wrinkles and blotches related to skin ageing and UV exposure (Shanura Fernando *et al*., 2018). Brown seaweeds also synthesize phlorotannins, a diverse set of polyphenolic polymers, well known for their potential in anti-melanogenesis (inhibition of the production of melanin pigments) and anti-ageing (Creis, Gall and Potin, 2018). Alginate, which is extracted from brown seaweeds, is a ubiquitous ingredient in cosmetics, and is used as a thickener, emulsifier, stabilizer and gelling agent.

Research carried out with different species of sargassum show strong potential for use in the cosmetics industry. Recent research on *Sargassum plagyiophyllum* extract showed promising results for use in anti-wrinkle cosmetics (Mansauda, Anwar and Nurhayati, 2018). In addition, fucoidans from *Sargassum polycystum* were found to have promising antioxidant, anti-inflammatory, whitening and anti-wrinkling effects (Shanura Fernando *et al*., 2018). Another example is the potential use of *Sargassum muticum* extracts in products to promote hair growth, since research shows increased proliferation of dermal papilla cells following treatment (Kang *et al*., 2016).

There is also potential for sargassum-derived activated carbon in the cosmetics industry; demand has been increasing for skincare and personal care products using activated carbon and charcoal in scrubs, facewashes, masks, soaps, pore strips, toothpastes and toothbrushes.

There are a number of examples in the Caribbean region related to research and commercialization of pelagic sargassum for several cosmetic applications (see Box 12). Oasis Laboratory, a company in Barbados, makes soap bars, using sargassum as one of the ingredients. Seaweed soaps are said to confer moisturizing and regenerating effects to the skin.

BOX 12. Cosmetics made from pelagic sargassum in the Caribbean

Research:

- **Nexo project,** Tecnológico de Monterrey (Mexico): A group of students is extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses in bath gels, creams and other cosmetics.
- **University of the West Indies** (Barbados, Jamaica, Trinidad and Tobago): Researchers are working on alginate extract from pelagic sargassum for use in cosmetics and other products.

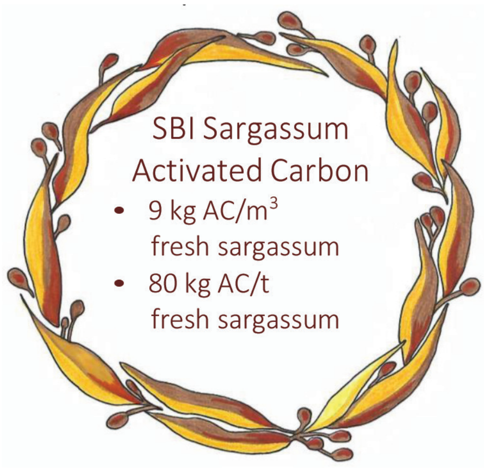
Commercialization:

- **Alquimar and Grupo Metco** (Mexico): Extracting alginate from pelagic sargassum for use in several sectors, including cosmetics.
- **Oasis Laboratory** (Barbados): Producing a sargassum skincare line, including bath bars.
- **Salgax** (Mexico): Looking to commercialize a sargassum hair treatment.

Summary of uses for cosmetics

Seaweed extracts are widely used across the globe in the cosmetics industry, especially alginates and bioactive compounds, the latter imparting many beneficial properties for skincare and haircare. Sargassum species have demonstrated potential in many of these applications, and the use of pelagic sargassum in cosmetics is being examined by several research initiatives in the Caribbean; it has already been commercialized by one cosmetics company. There is also strong potential for use of sargassum-based activated carbon in this industry, which uses activated carbon from other sources in many cosmetic products.

2.11 Electrochemical industry



There has been a boost in recent research focusing on developing improved electrochemical energy storage for renewable energy devices, and much progress has been reported on metal oxides, carbons and composites of both materials (Ji *et al*., 2019; Seok *et al*., 2019).

Super-capacitors (particularly electrochemical double layer capacitators (EDLCs)), lithium and sodium ion batteries and fuel cells are electrochemical energy storage devices that have received attention during the past 15 years due to their wide range of applications, including for electric vehicles and electronic devices (Taberna and Gaspard, 2014). Metal oxides and carbons have promising properties for use as electrode material in electrochemical energy devices. However, using only metal oxides for electrodes can reduce the performance of a battery due to its lower electrical conductivity and unstable structure while cycling, but using composites of metal oxides and carbons has brought many advantages and improved characteristics (Seok *et al*., 2019).

There are two main types of super-capacitor based on the electrode's composition: pseudo-capacitators (using mainly oxide materials for electrodes) and EDLCs (electrodes composed of activated carbon) (Taberna and Gaspard, 2014). That is why most EDLCs found on the market are made with carbon-based material (Taberna and Gaspard, 2014).

Carbon is a suitable material for use in electrodes because it is an efficient conductor, and stable in different types of solutions and at different temperatures, as well as available in a wide range of materials (such as activated carbon, graphite, coke, mesocarbon microbeads, aerogel, carbon black, carbon nanotubes and nanofibres) (Gogotsi and Presser, 2014; Inagaki *et al*., 2014).

Seaweeds are considered a valuable source of biomass for production of nanotextured carbons, since their cell walls contain a network of fibrillar constituents, such as cellulose and alginate (Zhao *et al*., 2015). While biopolymers such as alginates are considered affordable precursors, research has focused on direct carbonization (pyrolysis) of seaweeds rich in alginate in order to increase the performance and lower the costs of producing nanotextured carbons (Béguin, 2010). Alginic acid contained in seaweed cellular walls has high oxygen content after pyrolysis, which enables electrodes to better adsorb ionicelectrolytes (Taberna and Gaspard, 2014). Key characteristics when selecting a material for nanotextured carbons are accessibility, affordability, processability and adaptability (form, porosity and surface functionality) (Gogotsi and Presser, 2014).

Different types of seaweed, including brown macroalgae, have shown promising results for use as activated carbon electrode material in super-capacitors, as well as for use in high-capacity lithium-ion batteries (Bichat, Raymundo-Piñero and Béguin, 2010; Raymundo-Piñero *et al*., 2011; Pintor *et al*., 2013; Perez-Salcedo *et al*., 2020).

As presented in Box 13, ongoing research in the Caribbean region is examining the efficacy of using activated carbon produced from pelagic sargassum biomass in electrochemical applications.

BOX 13. Electrochemical applications using pelagic sargassum in the Caribbean

Research:

- **SARtrib project** (Guadeloupe): This project is investigating the potential for valorization of vacuum pyrolysis by-products of sargassum for use as lithium battery electrodes and super-capacitors.
- **COVACHIM-M2E** laboratory (University of Antilles in Guadeloupe and French Guyana): The team is investigating the valorization of sargassum biomass for energy storage purposes.

Summary of uses in the electrochemical industry

Brown seaweeds, being rich in cellulose and alginates, are considered a good source of carbon biomass for the production of nanotextured carbons (a form of activated carbon), used for electrode material in super-capacitors and high-capacity lithium-ion batteries.

In the Caribbean, at least two research initiatives are examining the potential of pelagic sargassum in the manufacture of sargassum-based nanotextured carbons for energy storage purposes.

2.12 Environmental restoration

2.12.1 Coastal vegetation

Coastal sand dune ecosystems represent a small area, but a highly dynamic and important zone located between the land and ocean. They are considered essential coastal ecosystems that provide a unique habitat for flora and fauna and act as a protective buffer to help reduce the impact of storm surges, waves and beach erosion by stabilizing the shoreline, thereby protecting landward ecosystems and built structures (Sigren, Figlus and Armitage, 2014). One of the strategies to help maintain dunes and prevent their erosion is to assist the establishment of natural dune vegetation. However, the typically low nutrient content of sand makes this quite challenging.

In Bermuda, due to the island's location in the Sargasso Sea, influxes of sargassum are common and considered by the Government to be a natural phenomenon. Coastal communities are accustomed to seeing sargassum drying on the beaches and becoming buried over time, and this is considered to be a critical process for dune formation, stabilization and natural fertilization of dune vegetation.[18]

There are several examples of using pelagic sargassum for environmental restoration within the Wider Caribbean Region.

In the United States of America, Texas A&M University has been carrying out research for several years on how sargassum landings play a role in enhancing dune plant growth. In Texas, the wrack line (beach debris line left along the high tide mark) is mainly composed of pelagic sargassum and provides an important source of soil nutrients for the growth of dune plants, but it is often removed by mechanical raking to make the beach more attractive for beach users (Williams and Feagin, 2010). The long-term removal of the wrack could affect the long-term structural integrity of dunes. Most local dune plants are salt tolerant and are thought to have adapted to this natural arrival of sargassum. Based on preliminary greenhouse trials, it was determined that the addition of multiple applications of unwashed sargassum spread along the base of dunes had a

[18] https://environment.bm/sargassum-seaweed

positive impact on the growth and establishment of dune plants by providing nutrients (Williams and Feagin, 2010). The authors cautioned, however, that further field trials are needed to determine threshold amounts.

The research team at Texas A&M University further investigated preliminary results from the greenhouse trial, by carrying out a field experiment on Galveston Island. The project tested the incorporation of compacted sargassum bales, called "seabales", into the berm of a 245-metre long test dune. The test dune was monitored over a one-year period to examine the seabale decomposition and vegetation growth, as well as patterns of erosion or accretion of sand (Figlus *et al.*, 2015). The team concluded that the addition of sargassum seabales to sand dune cores is a viable option for restoring dunes by enhancing vegetation growth and increasing dune resilience to climate-driven adversities, such as drought and erosion. Further studies have focused on the optimization of dune plants for ecosystem restoration to maximize coastal dunes' resilience to erosion caused by wave and storm surges, particularly focusing on the addition of sargassum and arbuscular mycorrhizal fungi inoculum (Sigren, Figlus and Armitage, 2014).

The Walkers Institute for Regeneration Research, Education and Design (WIRRED), located on the east coast of Barbados, is restoring the natural dune ecosystem damaged by years of commercial sand quarrying at the site. It is conducting research on the efficacy of using sargassum to enhance the growth of natural dune plants.

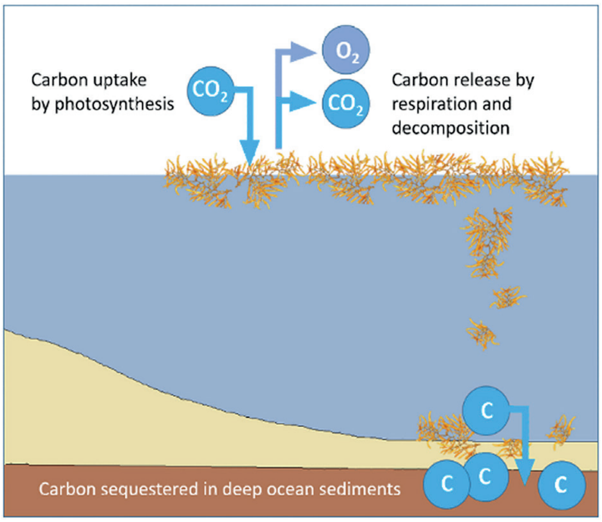
2.12.2 Climate change mitigation

Terrestrial and marine plants capture atmospheric carbon dioxide through photosynthesis, and are essential in the global carbon cycle. They are also of great interest in mitigating climate change through atmospheric reduction of CO_2, the principal greenhouse gas. This process is known as "carbon sequestration", whereby carbon is converted into long-lasting plant tissue and also incorporated into the soil, while oxygen is released back into the atmosphere. Forests, in particular, hold (sequester) a significant stock of carbon in trees and soils, and are important global carbon "sinks".

More recently, the importance of marine plants and animals in organic carbon sequestration has attracted attention and is referred to as "blue carbon" (see Figure 10). The blue carbon stored in the sediments of marine ecosystems such as salt marshes, mangrove forests and seagrass meadows is now recognized as being of global significance and important in mitigating climate change (Laffoley and Grimsditch, 2009). However, marine algae have not been considered important sequesters of blue carbon to date, mainly due to the fact that they are free-floating (phytoplankton) or commonly attached to rocks (macroalgae), where burial of carbon-rich organic matter is precluded (Hill *et al*., 2015). As such, the carbon captured by marine algae and temporarily stored in their tissues is released back into the environment in a relatively short time frame.

Nevertheless, new research is now highlighting the importance of macroalgae in storing blue carbon, especially in the deep ocean where the carbon is locked away from exchange with the atmosphere (Krause-Jensen and Duarte, 2016; Macreadie *et al*., 2019). The globally abundant benthic and free-floating *Sargassum* species are reported as being particularly important in sequestering blue carbon (Orr, 2014; Krause-Jensen and Duarte, 2016; Gouvêa *et al*., 2020; Paraguay-Delgado *et al*., 2020). Paraguay-Delgado *et al*. (2020) report that pelagic sargassum can capture carbon dioxide through photosynthesis and plant growth.

Figure 10. Conceptual diagram to illustrate how pelagic sargassum captures, transports and sequesters blue carbon in the deep ocean



Source: Adapted from Gouvea, L.P., Assis, J., Gurgel, C.F.D., Serrao, E.A., Silveira, T.C.L., Duarte, C.M., Peres, L.M.C., Carvalhoa, V.F., Batistaa, M., Bastosa, E., Sissinia, M.N. & Hortaa, P.A. 2020. Golden carbon of *Sargassum* forests revealed as an opportunity for climate change mitigation. *Science of The Total Environment*, 729. doi: 10.1016/j.scitotenv.2020.138745.

The carbon currently held as biomass of pelagic sargassum in the Atlantic (an estimated 7.52 Pg C)[19] (Gouvêa *et al*., 2020) has emerged as globally significant. When exported to areas with soft anoxic marine sediments, the dying tissues of sargassum (see Figure 10) are stored over long periods (from decades to hundreds or thousands of years, in the case of deepwater sediments), thereby contributing to global carbon sequestration. The act of sinking pelagic sargassum to the deep ocean floor, thereby potentially sequestering carbon, has recently been highlighted by both Gouvêa *et al*. (2020) and Paraguay-Delgado *et al*. (2020) as an opportunity for ocean-based climate change mitigation.

However, commercializing blue carbon credits of sargassum is currently constrained by a number of significant challenges, including: ownership of pelagic sargassum; development of appropriate technology to effectively sink sargassum; loss of biodiversity; potential creation of deep-sea dead zones due to excessive accumulation of biomass in oxygen minimum zones of the ocean; and the lack of a fully developed and functional governance mechanism for trading blue carbon in the region. This latter point means that obtaining certification for blue carbon projects is currently very time-consuming and expensive, and blue carbon has a relatively low value, although other sources of funds could possibly be leveraged to assist with costs (for example through Nationally Appropriate Mitigation Actions and the Green Climate Fund) (He, 2016).

Examples of blue carbon projects with funding from "voluntary carbon markets" in India, Kenya, Madagascar and Viet Nam reveal the strengths and challenges of implementation and policy implications (Wylie, Sutton-Grier and Moore, 2016).

[19] 1 Pg = 1 billion tonnes

Figure 11. View of the underside of floating sargassum showing plant material shedding and sinking

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However, it is important to note that part of the organic carbon sequestration may be offset by the production of calcium carbonate by sargassum epibionts (organism that lives on the surface of another living organism) such as bryozoans, tube worms and molluscs that secrete calcium carbonate shells, as well as the internal production of calcium carbonate (as calcite) within the sargassum tissue. This is because, counterintuitively, CO_2 is actually released during the process of calcification (Saderne *et al*., 2019). Paraguay-Delgado *et al*. (2020) estimate that the abundant pelagic sargassum in the Atlantic in recent years (2011–2019) could have fixed 5.3 million metric tonnes of inorganic carbon as calcium carbonate over this period. However, noting that the process of calicification is a net producer of CO_2, this would have resulted in an emission of 11.6 million metric tonnes of CO_2 into the atmosphere. Thus, more studies are needed to determine the net contribution of the new sargassum biomass to global carbon sequestration.

One joint Caribbean and US initiative, the SOS Carbon project, is pursuing the idea of sinking sargassum. The potential benefits of such a scheme would include: (1) prevention of negative impacts of mass strandings of sargassum along Caribbean coastlines; and (2) contributing to ocean-based climate change mitigation by sequestering blue carbon in the deep ocean. However, much caution is needed, since further studies are required to avoid enormous biomass accumulations on the seafloor in oxygen minimum zones in the oceans (usually between the surface photic zone and roughly 1 000 m depth), which may potentially create dead zones.

The use of biochar is also believed to hold potential for sequestering carbon in the soil. Since biochar is made up in large part of carbon, it can make a significant contribution to increasing carbon in the soil when applied for agricultural purposes. Much research is ongoing related to biochar and its potential for carbon sequestration (Matovic, 2011).

BOX 14. Environmental restoration applications using pelagic sargassum in the Caribbean

Research:

- **Sargassum Ocean Sequestration Carbon (SOS Carbon –** the Dominican Republic): This research project is developing technology to sink pelagic sargassum and potentially sequester blue carbon in the deep ocean.
- **Texas A&M University** (United States of America): Extensive research is being carried out using sargassum bales to protect dunes from erosion and promote plant growth.
- **PYROSAR project** (Guadeloupe and Martinique): This initiative is optimizing the production of sargassum AC and biochar.

Commercialization:

- **Moon Palace Resort** (Mexico): The resort is using sargassum-based compost to enhance coastal vegetation growth so as to reduce erosion and protect the beach and hotel structures.
- **WIRRED** (Barbados): Using sargassum to help regenerate dune vegetation in Walker's reserve.

Summary of uses in environmental restoration

Pelagic sargassum is already being used in several pilot projects in the Caribbean to restore coastal dunes, by stabilizing sand dunes and fertilizing dune vegetation. However, the wide application of this approach throughout the region is limited by narrow beaches and the encroachment of buildings in many locations.

Another application is to use sargassum to sequester carbon, thereby helping to mitigate climate change impacts by reducing carbon dioxide emissions into the atmosphere. A promising use of sargassum in this respect is the production of biochar as a soil amendment, which is being investigated by at least two Caribbean initiatives. There is also ongoing research into the efficacy of sinking pelagic sargassum in the deep ocean, although the risk of creating oxygen dead zones on the deep ocean floor must be taken into consideration and further investigated.

2.13 Food and beverages

Algae have been consumed by humans for thousands of years worldwide. The most widely consumed macroalgae are brown seaweeds (approximately 66.5 percent), followed by red seaweeds (33 percent) and to a much lesser extent, green seaweeds (5 percent) (Afonso *et al*., 2019). The majority of these are produced in mariculture systems, with China, Indonesia and Japan being the main producers. The leading producers of wild species are Chile, China and Norway (FAO, 2018). Approximately 221 species of algae have been recognized as having commercial value as food, and of these 10 genera are widely cultivated, as listed below (FAO, 2018):

- brown seaweed: *Saccharina japonica, Undaria pinnatifid* and *Sargassum fusiforme;*
- red seaweed: *Porphyra spp., Eucheuma* spp., *Kappaphycus alvarezii* and *Gracilaria* spp.; and
- green seaweed: *Enteromorpha clathrate, Monostroma nitidum* and *Caulerpa* spp.

Algae can either be consumed directly or processed into secondary food products and additives. An estimated 40 percent of the world's hydrocolloid[20] market for food use is derived from seaweed extracts (alginate, agar and carrageenan) (FAO, 2018). Apart from their recognized nutritional value, algae are also marketed as "nutraceuticals", meaning that they also contain other beneficial bioactive compounds.

2.13.1 Direct consumption

When developing food and beverage products from sargassum, it is important to be aware of:

- potentially high levels of toxins (such as inorganic arsenic, other heavy metals and pollutants); and
- concentrations of certain minerals (such as iodine) and secondary metabolites.

Further research is certainly warranted with regard to direct consumption of sargassum, given the relatively high arsenic content reported for pelagic sargassum (Rodríguez-Martínez *et al.*, 2020). Furthermore, Milledge and Harvey (2016) stated that the imbalance of amino acids contained in sargassum could potentially limit its value as a food.

According to Wells *et al.* (2017), although there is abundant literature showing evidence of nutritional and functional properties of macroalgae as food, limited research has been carried out to quantify the benefits and potential adverse effects (such as excess intake of toxic metals, allergenicity, cyanotoxins and secondary metabolites). Further discussion on challenges related to pollutants is included in *Section 3.2* of this guide.

The consumption of seaweed differs from country to country in terms of quantity and specific culinary use. Seaweed consumption in Southeast Asia is traditional, while in European and North American markets, seaweeds occupy more of the "food for health" or nutraceutical niche market (Buschmann *et al*., 2017). A good example of varying culinary use by country is the consumption of *Gracilaria* species, which in East Asia is consumed raw, pickled, dried or boiled; in Hawaii, it is used in salads; whereas in the Caribbean it is marketed as seamoss, and used as a porridge or non-alcoholic drink, although it is sometimes added to rum punch (FAO, 2018).

[20] Hydrocolloids are defined as "a substance which forms a gel in the presence of water", from Oxford Languages

Kombu (a mixture of *Laminaria* species), wakame (*Undaria pinnatifida*) and hiziki (*Hizikia fusiforme*) are three examples of brown seaweeds commonly consumed in East Asia, all rich in protein, dietary fibre, minerals and vitamins (McHugh, 2003). *Laminaria* species are particularly high in iodine (which is usually lacking in red seaweeds) compared with other brown seaweeds, and can play an important role in alleviating iodine deficiency in many countries (Teas *et al*., 2004), although it may be harmful in some circumstances.

Sargassum fusiforme is commonly consumed in China, where it is sold dried and processed. Steps used to process this popular food include: cleaning, cutting, hot pressing, removing arsenic and sand, seasoning, sterilizing, cooling, drying, weighing and packaging (FAO, 2018).

Sargassum fusiforme is known to contain high levels of inorganic arsenic when it is harvested, and methods have therefore been developed and patented to remove this toxic component from dried seaweed products (Yamashita, 2014). One of these methods involves boiling the dried raw seaweed in seawater up to four times (reducing total arsenic levels by 86–92 percent), then soaking it in distilled water at 20 °C for 30 minutes (Yamashita, 2014). Care must be taken in the disposal of remaining water, which may contain high levels of arsenic, in order to avoid further environmental impact.

2.13.2 Alcoholic beverages

Beers made with seaweed are gaining popularity. Seaweed-based beers are not new (they have traditionally been brewed in Germany, Ireland and Scotland). However, several breweries have a renewed interest in this ingredient and have begun to introduce different types of seaweed into their beer-making process.

2.13.3 Food additives

Seaweeds are also important to the food industry as sources of food additives such as carrageenan and agar extracted from red algae, and alginate extracted from brown algae (McHugh, 2003). They are widely used as thickeners, emulsifiers, preservatives, gelling agents and stabilizers (see Box 11 in Section 2.10) (FAO, 2018).

2.13.4 Activated carbon

Another potential use of seaweed biomass in food and beverage processing is as activated carbon (see Box 7 *Activated carbon* in Section 2.7). Plant-based activated carbons have a wide range of applications, such as colour correction in beverages, decolourization and removal of impurities in sugar-cane processing, edible oil purification and flavour modification in alcoholic beverages and food additives.[21] Black pizzas made with activated charcoal infused crusts are gaining in popularity among some consumers.[22]

As shown in Box 15, several initiatives in the Caribbean region are using pelagic sargassum in food and beverages, mostly as extracts.

[21] www.puragen.com/markets/food-and-beverage

[22] https://food.ndtv.com/food-drinks/no-this-pizza-isnt-burnt-its-black-pizza-made-with-activated-charcoal-2050982

BOX 15. Food and beverage applications using pelagic sargassum in the Caribbean

Research:

- **Texas A&M University** (United States of America): In 2015, students and researchers, in collaboration with Galveston Island Brewery, made and tested a sargassum craft beer.
- **University of the West Indies** (Barbados, Jamaica and Trinidad and Tobago): Researchers at all three campuses have been working on alginate extract for different uses.

Commercialization:

- **Alquimar & Grupo Metco** (Mexico): Alginate extracts for use in several sectors.
- **Bruno Lardelli** (Mexico): This mixologist has created the cocktail drink "Pineapple gift" using sargassum.
- **Tomfoodery Kitchen** (Cayman Islands): Chef Thomas Tennant has been experimenting with sargassum as an ingredient in different dishes.

Summary of uses in food and beverages

Although seaweeds are consumed in many parts of the world, including in the Caribbean as "seamoss" (comprising several species of red seaweed), direct consumption of pelagic sargassum is not advisable, since there is evidence that it can contain high levels of arsenic and other components that may be toxic.

Extracts of pelagic sargassum could have potential for use in food and beverages as additives, but thorough composition analysis must first be conducted. Alginates (typically found in high concentrations in brown seaweeds) are widely used in the food industry as thickeners, emulsifiers, preservatives, gelling agents and stabilizers.

Pelagic sargassum could also be used to manufacture activated carbon for a wide range of applications in the food industry. Several Caribbean initiatives are examining the commercial extraction of alginates and production of activated carbon from sargassum.

Although pelagic sargassum has been used in limited samples of alcoholic beverages and dishes in the region, further investigation is needed to determine its safety and true potential.

2.14 Lubricants, surfactants and adhesives

There have been recent advances in the production of lubricants, surfactants and adhesives using algae. A few examples are outlined below.

2.14.1 Lubricants

The majority of lubricants are made mostly of crude petroleum, due to its long-lasting effects (Panchal *et al*., 2017). However, widespread use of petroleum-based lubricants has raised concerns about the fact that they are non-renewable and toxic to the environment, potentially causing pollution. There is increasing pressure worldwide from environmental groups for petroleum-based lubricants to be replaced with bio-based lubricants, particularly for applications that are in close contact with water bodies (Panchal *et al*., 2017). A wide range of biolubricants is used in food, pharmaceuticals, cosmetics, agriculture, textile and biofuels. The following are a few examples of advances in using algae for biolubricants:

- TerraVia, which was formerly named Solazyme Industries, a Californian algae-based bio-product company, was engaged in developing uses with microalgae to produce eco-friendly, sustainable industrial oils, fuels and drilling lubricants under several trademarks. Lubricants made from algae also have anti-corrosive properties. Under the Tailored trademark, the company is producing a sustainable textile lubricant using oleic algae oils. Another product, Encapso™, is a green drilling fluid, comprising many capsules that contain pure, algae-based lubricating oil and which release lubricants only when needed. TerraVia has since refocused its algae oil production on food and personal care industries.[23]
- Algae-based biolubricants have strong potential as food-grade lubricants, which are in high demand in the brewing and wine industries. In the brewing industry, food-grade lubricants are used during several steps of the process, from grain handling to packaging.[24]

Further investigations are needed to determine the full potential for lubricant applications of brown algae in general, and more specifically the *Sargassum* genus, especially the pelagic sargassum species found in the Caribbean.

2.14.2 Surfactants

The development of surfactants using renewable resources is gaining ground in several applications (Benvegnu and Sassi, 2010). There has been an increase in consumer demand for eco-friendly surfactants, especially for personal use applications. However, viable production requires access to large volumes of low-cost renewable biomass. As such, marine algae are considered to be strong candidates, especially given that the lipids produced by algae are a source of naturally occurring surfactants. Examples of their use as surfactants include the following:

- In 2015, BASF and Solazyme (now named TerraVia) launched Dehyton AO45, the first commercial microalgae-derived betaine surfactant used to produce foam in personal care products, such as soap and shampoo.[25]
- Foley *et al.* (2012) report that brown algae are a good source of naturally occurring glycinebetaine, used to derive several classes of surfactants.
- Benvegnu and Sassi (2010) indicate that brown seaweeds are considered attractive as renewable raw materials that could be used in different biosurfactant applications, such as cosmetics, agrochemistry and health.

2.14.3 Adhesives

One of the greatest challenges of the adhesives industry is the development of substances capable of gluing surfaces in an aqueous environment (Bitton, 2015). Extensive research has focused on marine organisms such as algae to better understand their submerged adhesive abilities and how to mimic their biochemical process (biomimetic) in the development of artificial materials. Although the majority of research related to the biomimetic approach for adhesives has focused on marine organisms such as mussels, barnacles and starfish, researchers have recently turned their attention to algae (Bitton, 2015).

A study carried out on the brown algae wakame (*Undaria pinnatifida*) determined that the phosphate groups and monoester-sulphated polysaccharides were key components responsible for algal adhesive properties (Petrone *et al*., 2011). Comparatively, another study carried out on the fucoid brown algae *Fucus gardenri* determined that initial substratum adhesion properties were linked to the secretion of polyphenols, and that after algae germination, phenolic polymers and

[23] http://www.terravia.com/
[24] https://beerandbrewing.com/a-guide-to-the-use-of-food-grade-lubricants-in-the-brewing-industry
[25] www.basf.com/us/en/media/news-releases/2015/07/P-US-15-137.html

oxidases were responsible for algal adhesion (Vreeland, Waite and Epstein, 1998). It is believed that the polyphenols (phlorotannins) of brown algae are encapsulated by the alginate network, which would allow these components to form contact points (Bitton, 2015).

Following the biomimetic approach, the synthetic monomer phloroglucinol was developed, which was shown to have adherence capabilities similar to its natural algal polyphenol constituents, which have strong potential for bio-adhesive and eco-resin applications. Based on these results, Sealantis developed a commercial alga-biomimetic adhesive that has substantial adherence capabilities, even in wet conditions.[26] This adhesive is used in three main applications: surgical sealing, surgical adhesion and site-specific drug delivery.

Another application of brown algae as an adhesive is the addition of sodium alginate to starch in the production of corrugated boards, as it has the ability to stabilize adhesives' viscosity and hence regulate the rate of penetration (McHugh, 2003). Furthermore, as indicated in *Section 2.8 on Clothing, footwear and accessories*, as well as in *Section 2.15 on Paper products*, sodium alginate is used in the textile and paper industries to increase the adhesive properties of materials.

The production of adhesive properties has been studied for a wide range of macroalgae species with structurally different spores, and these seem to follow the same adhesive production processes (Fletcher and Callow, 1992).

However, the potential adhesive or anti-adhesive properties of pelagic sargassum species needs to be investigated, due to the fact that these fucoid brown algae are free-floating and do not attach to substrate during their entire life cycle.

As indicated in Box 16, to the authors' knowledge there is only one ongoing project in the Caribbean, to examine the potential of sargassum for use as lubricants, surfactants and adhesives.

BOX 16. Lubricant, surfactant and adhesive applications using pelagic sargassum in the Caribbean

Research:

- **SARtrib project** (Guadeloupe): This is investigating the potential for valorization of vacuum pyrolysis by-products of sargassum, for use in new generation lubricants, solvents and adhesives.

[26] www.sealantis.co.il

Summary of use in lubricants, surfactants and adhesives

Third generation biolubricants used for industrial applications such as drilling are now being made with microalgae, while the scope for using macroalgae, and sargassum in particular, is currently unknown. Microalgae are also being used in the production of surfactants to promote foaming in soaps and shampoos, and research suggests that brown seaweeds have potential for this application.

Brown seaweeds are also being studied for their suitability in the production of adhesives that are effective in wet conditions.

There is at least one ongoing research initiative in the Caribbean that is looking at the viability of turning the by-products of sargassum pyrolysis into new generation biolubricants, surfactants, solvents and adhesives.

2.15 Paper products

Cellulose fibre is the major constituent of paper products and is found in the cell walls of plants and seaweeds. Using algae rather than wood to produce paper pulp has several advantages, such as faster growth of algae compared with trees and negligible lignin content, which needs to be separated from the paper pulp using high levels of energy and chemicals. To date, most attempts to make algae-based paper products have been mainly limited to handmade artisanal products rather than large-scale commercial operations, although there have been several projects and attempts at commercial production of paper pulp from algae in different parts of the world. Most attempts have been undertaken using red algae and, to a lesser extent green algae. The following are a few examples:

- The Algae Research Lab at the Universiti Kuala Lumpur in Malaysia has been successfully making pulp using rhizoidal filaments of red seaweed (*Gelidium amansii* and *Gelidium corneum*). The research team has been promoting seaweed-based pulp because this process is much more environmentally-friendly than traditional wood pulp papermaking, requiring significantly less energy and fewer chemicals. Since most algae do not contain any lignin, but only cellulose and hemicellulose, no chemicals are required; only heated water. However, in order to produce at commercial scale, algae are being mass cultivated to ensure clean raw material without impurities (Seo *et al.*, 2010).

- In the 1990s, Italian company Favini created *Shiro Alga Carta* paper, using algae blooms that were invading the Venice lagoon, and was able to commercially produce this speciality paper and distribute it on a small scale, mostly in Europe. However, it is unclear which species of algae is used to make the algae paper, since the algal proliferations in the Venetian lagoon appear to be caused by several species.

- In Indonesia, two species of cultivated red algae (*Gracilaria* sp. and *Eucheuma cottonii)* were tested to produce algae pulp for papermaking purposes (Machmud *et al.*, 2013). Results indicate that tensile properties (elongation, strength and absorbed energy) of paper sheets made with both seaweeds were superior to those made from recycled paper and conventional wood pulp paper.

- Results from research carried out in Spain to determine the potential of two species of green algae (*Ulva* sp. and *Cladophora* sp.) for use as raw material for papermaking indicate that even though algae cellulose content is generally lower than that of vascular plants, they have sufficient amounts to be considered as a good alternative source or as reinforcing fibres (López *et al*., 2014).
- In Chile, collaboration between researchers from the Concepción University and the Bio Paper company has resulted in the development and production of algal-based paper for use in fruit protection and preservation during export. The team claims that the antibacterial and antifungal properties of the algal-based paper ensure additional preservation of fruit. It estimates that approximately 60 percent less fruit loss occurs due to oxidation and decomposition when the algal-based protection paper is used (CNN Chile, 2019).

Although it is not impossible to produce paper made from 100 percent algae fibre, its overall strength (resistance to bursting, tearing and folding) is improved when algal pulp is mixed with other raw materials (Mukherjee and Keshri, 2018). The general steps required to make seaweed-based paper include removing all impurities, washing with water, drying, milling into a seaweed flour, mixing with other raw materials or fibres (not always necessary), cooking with water at 100 ^{o}C for two hours, and setting the resulting jelly into a thin film (Mukherjee and Keshri, 2018).

Brown algae in general contain high levels of cellulose, although these vary according to species, season of harvest and environmental growth conditions (Siddhanta *et al*., 2009). Brown seaweed has been studied to a lesser extent for papermaking. However, UK start-up company Skipping Rocks Lab has recently been focusing on the use of natural materials extracted from seaweed and plants to create alternatives to single-use plastics. It is currently working on creating biodegradable, recyclable, waterproof and heat-resistant paper cups and other single-use food packaging based on brown seaweed. The aim is to obtain a product that can fully decompose within four to six weeks.[27]

In addition, alginates are used in the paper industry for surface sizing. This process consists of adding alginate to starch, resulting in a smoother and continuous surface film with less fluffing (Pereira and Cotas, 2020). Furthermore, the addition of alginate gives paper better oil resistance and greaseproof surface properties, which in turn improves the paper's ink holdout.

Limited research has been carried out to determine the potential of *Sargassum* species for papermaking applications. A study to evaluate cellulose contents of Indian seaweeds indicates that *Sargassum tenerrimum* has high levels of cellulose, which would be conducive for papermaking applications (Siddhanta *et al*., 2011).

In the Caribbean region, several start-up companies are exploring the use of pelagic sargassum in papermaking applications. As highlighted in Box 17, innovators are already making a wide range of paper and cardboard products, which are not only aesthetically pleasing, but also useful and environmentally sustainable.

[27] www.algaeindustrymagazine.com/using-brown-seaweed-to-make-sustainable-paper-cups

BOX 17. Papermaking with pelagic sargassum in the Caribbean

Commercialization:

- **Golden Tide project, Wouter Osterholt** (Curaçao): 100% sargassum-based artisanal paper made for paintings depicting skeletal remains of local marine fauna, killed by recent sargassum influx; proceeds from sales are donated to Amazon Watch.
- **Salgax** (Mexico): Although mainly focused on sargassum-based fertilizers, the team is also developing sargassum paper products.
- **Sargánico** (Mexico): Producing high-quality notebooks, folders, drink coasters, business cards, etc.
- **Sargasse Project** (Saint Barthélemy): Making 100% sargassum-based paper and cardboard products.
- **Sargazbox** (Mexico): Developing cardboard boxes with sargassum cellulose.
- **The Marine Box** (Martinique): Developing various paper and cardboard products made with sargassum. These even include coffins using cardboard made with sargassum.

Summary of use for paper products

Seaweed is considered to be a good ingredient for use in papermaking due to the presence of significant amounts of cellulose and negligible lignin content in its cell walls. Although most seaweed-based papers have so far been made from red and green seaweeds, brown seaweeds have also demonstrated potential. Furthermore, alginate extracts are used in the paper industry to improve the water resistance and smoothness of paper surface.

Several initiatives across the Caribbean are now successfully making paper, cardboard and paper-based products from pelagic sargassum.

2.16 Pharmaceutical and biomedical

Marine algae are widely recognized for their diverse source of bioactive metabolites, which have long been used in the pharmaceutical and biomedical industries. Each compound can be extracted from seaweeds and used in different applications according to their particular properties. However, their chemical composition and molecular weight vary according to the source species from which they are extracted, the season of harvest, environmental growth conditions and method of extraction employed.

Brown algae have unique polysaccharides and secondary metabolites that have been demonstrated to have beneficial effects on human health.

When developing pharmaceutical and biomedical products from sargassum, it is important to be aware of:

- potentially high levels of toxins (such as inorganic arsenic, other heavy metals and pollutants); and
- untested effects of bioactive compounds.

Appropriate *in vitro* and *in vivo* trials are essential for each bioactive compound to validate their therapeutic effect.

2.16.1 Polysaccharides

Alginate, fucoidan, mannitol and laminarin are all polysaccharides that can be extracted from brown seaweed cell walls and used in the pharmaceutical and biomedical industries. Alginates are mainly used in the pharmaceutical industry as thickeners, stabilizers and for controlled-release drugs. Alginates are also used in biomedical applications, for example in tissue culture, as antibiotic adjuvants, antiviral agents and for treatment of diabetes and neurodegenerative diseases (Szekalska *et al*., 2016). Calcium alginate is widely used as wound dressing material and an encapsulation medium for drugs, while magnesium alginate has medicinal properties and is mainly used to treat ulcers and reflux disease (Baldassarre *et al*., 2019). Another research study indicates that sodium alginates extracted from two species of brown algae (*Sargassum wightii* and *Padina tetrastromatica*) are suitable as film coating on textile fabrics for wound healing applications (Janarthanan and Senthil Kumar, 2018).

There is much interest in the use of fucoidans due to their wide-ranging properties and promising therapeutic effects. For example they have been shown to have the following properties: antioxidant, anti-inflammatory, antifungal, anti-angiogenic, antitumour, antiviral, antithrombotic, anticoagulant and immunoregulatory; and have also been used in cognitive protection and as an anti-hyperglycemic agent (Citkowska, Szekalska and Winnicka, 2019; Luthuli *et al*., 2019).

Mannitol has several pharmaceutical properties, and is used as a diuretic and vasodilator to treat glaucoma and to lower intracranial pressure (Saha and Racine, 2011).

Laminarin has antitumour effects and is considered for use in cancer prevention applications (Déléris, Nazih and Bard, 2016).

2.16.2 Secondary metabolites

Secondary metabolites found in brown algae that have value in pharmaceutical applications include polyphenols, terpenoids, carotenoids and sterols. Phlorotannin, a polyphenolic compound, has several potential pharmaceutical applications including antidiabetic, anticancer, anti-hypertension, anti-photoageing, antioxidation, antiviral, anti-allergy, anti-inflammatory and anti-adipogenesis (Creis, Gall and Potin, 2018). Like other compounds found in brown algae, phlorotannins vary according to the algal species, as well as to different abiotic and biotic factors and the extraction procedure employed (Generalić Mekinić *et al*., 2019).

Terpenoids from brown seaweed are also useful for the pharmaceutical industry due to their antifungal, cytotoxic, anti-inflammatory and antiviral activity (Campos de Paula, Vallim and Laneuville Teixeira, 2011). Likewise, the carotenoid pigment fucoxanthin has potential antioxidant, anti-inflammatory, anti-obesity, antitumour and UV-prevention effects (Wijesinghe and Jeon, 2011). Phytosterols (plant-based sterols) are used in pharmaceuticals to lower blood cholesterol level and have reported potential to inhibit colon cancer development (Lopes *et al*., 2013).

Other secondary metabolites found in brown seaweed that exhibit promising pharmaceutical applications include plastoquinones (significant antioxidant activity), saponins and flavonoids (analgesic effect) (Yende, Harle and Chaugule, 2014; Ruslin *et al*., 2018). Two plastoquinones, isolated from *Sargassum sagamianum* and *Sargassum micracanthum*, are sargaquinoic acid and sargachromenol. The former has shown potential for treatment of Alzheimer's disease and the latter has anti-inflammatory properties (Choi *et al*., 2007; Yang *et al*., 2013). Saponins are exploited for their antioxidant, antidiabetic and anti-obesity properties, and have potential for use in the synthesis of steroid hormones (Oyesiku and Egunyomi, 2014).

Many sargassum species have been used in traditional Chinese medicine for thousands of years and continue to be used in several pharmaceutical and biomedical applications (Liu *et al*., 2012). A review describing the therapeutic potential and health benefits of sargassum species indicates that some of the main health-related properties include antioxidant, cholinesterase inhibition, neuroprotection, antipyretic (fever reducer), analgesic, antitumour, anti-inflammatory, hepatoprotection (liver protection), immunomodulatory, antiviral and anticoagulant (Yende, Harle and Chaugule, 2014).

Algae-based lubricants are also used for the preparation of root canal treatment in dentistry, to dissolve necrotic pulp tissue and remove bacteria and smear layer. Recent results indicate that *Sargassum* sp. extract is effective for this purpose (Trilaksana, Kirana and Arisandi, 2020).

To date there has been limited research on pelagic sargassum and its potential health-related applications. However, *Sargassum fluitans* has been used for several years in the treatment of goiters (abnormal enlargement of thyroid gland) and lithiasis (formation of calculi or "stones" in the body) and has also shown anticoagulant, antimicrobial, anti-inflammatory and antioxidant properties (D'Amelio, 1999).

SBI
Sargassum
Pharmaceutical
extracts

- 2.6 kg algin/m^3 fresh sargassum
- 22 kg algin/t fresh sargassum
- 1.2 kg fucoidans/m^3 fresh sargassum
- 10 kg fucoidans/t fresh sargassum
- 0.03 kg tannins/m^3 fresh sargassum
- 0.27 kg tannins/t fresh sargassum
- 0.02 kg terpenoid/m^3 fresh sargassum
- 0.15 kg terpenoid/t fresh sargassum
- 0.2 kg flavonoid/m^3 fresh sargassum
- 1.72 kg flavonoid/t fresh sargassum
- 0.14 kg saponin/m^3 fresh sargassum
- 1.17 kg saponin/t fresh sargassum
- 0.02 kg phenolics/m^3 fresh sargassum
- 0.18 kg phenolics/t fresh sargassum

There are a number of ongoing projects in the Caribbean region to determine the pharmaceutical and biomedical potential of pelagic sargassum, as shown in Box 18.

BOX 18. Pharmaceutical and biomedical projects using pelagic sargassum in the Caribbean

Research:

- **Nexo project, Tecnológico de Monterrey** (Mexico): A group of students is extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses.
- **SARSCREEN project** (Guadeloupe): This initiative aims to determine the pharmacological potential of sargassum extracts against non-communicable diseases common and widespread across the Caribbean.
- **University of the West Indies** (Barbados, Jamaica and Trinidad and Tobago): Different researchers at the three campuses have been working on polysaccharide and secondary metabolite extracts for different uses.

Commercialization:

- **Alquimar and Grupo Metco** (Mexico): Both companies have been working on alginate extracts for use in several sectors; Alquimar has also been commercializing fucoidans nationally.

Summary of pharmaceutical and biomedical uses

Brown seaweeds contain unique polysaccharides (such as alginate, fucoidan and mannitol) and secondary metabolites that are known to have beneficial therapeutic effects on human health and are therefore useful in many pharmaceutical and biomedical drugs and applications.

Sargassum species are traditionally used in Chinese medicine, where many commercial dietary supplements are available.

There are several ongoing research and commercialization initiatives in the Caribbean, working to extract and test a number of polysaccharides and secondary metabolites from pelagic sargassum. As yet, however, the therapeutic effectiveness and safety of pelagic sargassum extracts remain unknown and should therefore be treated with caution until properly tested.

2.17 Summary of sargassum uses and scaleability

2.17.1 Geographical scope

There are numerous examples of sargassum research initiatives, innovations and sargassum-based businesses under development or already producing viable sargassum products across the Wider Caribbean Region (see Figure 12), many of which are described in the full version of this report (Desrochers *et al*., 2020).

Figure 12. Map showing the spread of sargassum entrepreneurs and researchers across the Wider Caribbean Region

Source: Adapted from United Nations Geospatial

2.17.2 Product-specific applications and challenges

Based on the detailed review presented in this section of potential uses of pelagic sargassum, Table 9 provides a summary of key potential uses, and the product-specific issues that represent current challenges to successful product commercialization. *Section 3* takes this process further by looking in greater detail at the general overarching challenges and constraints faced by researchers, entrepreneurs and businesses in developing commercially viable uses for sargassum, and the implications of these for policymakers, managers and funding agencies.

Table 9. Summary of potential applications for pelagic sargassum, showing current challenges and ongoing research (Res.), commercial development (Com. dev.) and full commercialization (Full com.) in the Wider Caribbean Region

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. dev.	Full com.
Agriculture	Animal feed supplement	• High salt content (risk of detrimental health effects & increased water consumption) • Potential high levels of arsenic, heavy metals and other toxins – need for continuous monitoring of final product • Variability in compositional profile • Insufficient animal-specific research to determine maximum amount of pelagic sargassum for benefits/negative effects	✓	✓	✗
	Direct field spreading – Not recommended	• High salt content (risk of soil salinization if no pre-treatment) • No reported benefits to crops	✓	✗	✗
	Mulch	• High salt content (risk of soil salinization if no pre-treatment) • Potential high levels of arsenic, heavy metals and other toxins – need for continuous monitoring of final product • Variability in compositional profile • Insufficient crop-specific research (determining effects of crops grown in different soil types)	✓	✓	✓
	Compost	• High salt content (risk of soil salinization if no pre-treatment; variable research results) • Potential high levels of arsenic, heavy metals and other toxins – need for continuous monitoring of final product • Variability in compositional profile • Co-composting with other organic material has been recommended	✓	✓	✓
	Biochar	• High salt content (risk of soil salinization if no pre-treatment)	✓	✗	✗
	Fertilizer/biostimulant/ digestate	• High salt content (risk of soil salinization if no pre-treatment) • Potential high levels of arsenic, heavy metals and other toxins in fresh sargassum – need for continuous monitoring of final product • Variability in compositional profile • Insufficient research/sample collection & analysis	✓	✓	✓
	Crop protection/bio-elicitor	• High salt content (risk of soil salinization if no pre-treatment) • Potential high levels of arsenic, heavy metals and other toxins in fresh sargassum – need for continuous monitoring of final product • Variability in compositional profile • Insufficient research on sargassum bio-elicitor properties	✓	✗	✗

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. dev.	Full com.
	Mushroom growth substrate	• High salt content (may limit mushroom growth) • Potential high levels of arsenic, heavy metals and other toxins in fresh sargassum – need for continuous monitoring of final product • Variability in compositional profile • Insufficient research – need to determine if co-blended growth substrate is recommended and maximum amount of sargassum	✓	✗	✗
Antifouling	Antifouling extracts for paints	• Limited research using brown seaweed • Insufficient research using pelagic sargassum • Little known about the fatty acid and phenolic profiles of pelagic sargassum due to variability in compositional profile	✓	✗	✗
Bioenergy	Bioethanol	• Insufficient research using pelagic sargassum • High cost of pre-treatment to make seaweed suitable for fermentation • Identification of suitable salt-tolerant microorganisms for fermentation due to high salt content • High investment needed for specialized equipment	✓	✗	✗
Bioenergy	Biodiesel – Not currently feasible	• Insufficient lipid (fat) content • Limited research available; macroalgae do not seem suitable for this use	✗	✗	✗
Bioenergy	Biogas/biomethane	• Limited research using macroalgae; limited research with pelagic sargassum • Low C:N ratio – need to mix with other organic materials (co-digestion is recommended) • Potential high levels of sulphur, heavy metals, ash and polyphenols can interfere with digestion • More research needed on potential pre-treatments to increase breakdown of material for microorganisms • High investment needed for equipment for large-scale facilities	✓	✓	✗
Bioenergy	Biopellets	• Limited research using macroalgae (variable results); limited research with pelagic sargassum • Need to mix with other organic material • High investment needed for equipment	✓	✓	✗
Bioplastics	Extracts for bioplastics and biomass for alternative materials	• Potential high levels of arsenic, heavy metals and other toxins in fresh sargassum – need for continuous monitoring of final products that have direct contact with food (may need protective lining) • More research needed on pelagic sargassum to determine if it needs to be blended with other materials and recommended amounts • High investment needed for equipment	✓	✓	✗

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. dev.	Full com.
Bioremediation and purification	Water and wastewater treatment (activated carbon, live floating seaweed)	• High salt content may reduce biosorption capacity – more research needed on pelagic sargassum • High investment costs needed for pyrolysis equipment • Need to plan for waste management strategies to dispose of used material containing high levels of toxic compounds	✓	✓	✗
	Soil bioremediation (activated carbon/ biochar)	• High investment costs needed for pyrolysis equipment • Need more research for use on different soil types	✓	✗	✗
	Air purification (activated carbon)	• High investment costs needed for pyrolysis equipment • Need to plan for waste management strategies to dispose of used material containing high levels of toxic compounds • Need for more research for application as air filters	✓	✗	✗
Clothing/ footwear	Extracts used for fibres, foams, dyes, textile printing thickener and dye enhancer	• Insufficient research using pelagic sargassum – apart from shoe soles	✗	✓	✓
Construction	Bricks	• Need to blend with other organic material – new research on 100% sargassum bricks is ongoing (need to test stability and durability) • Need for specialized equipment	✓	✓	✓
	Resin/particleboard and panels	• Insufficient research on pelagic sargassum • Need for specialized equipment	✗	✓	✗
	Bio-asphalt	• Insufficient research on pelagic sargassum	✓	✗	✗
	Furniture	• Insufficient research on pelagic sargassum	✗	✗	✗
Cosmetics	Skincare and haircare products (extracts and activated carbon)	• Limited research on beneficial properties & potential adverse effects in many products • Potential presence of arsenic and heavy metals in end product unknown (unknown implications for skin contact) • High investment costs for pyrolysis equipment (activated carbon)	✓	✓	✓
Electro-chemical	Nanotextured carbons for electrode material in super-capacitors and lithium-ion batteries	• Limited research using pelagic sargassum • High investment costs needed for pyrolysis equipment	✓	✗	✗
Environmental restoration	Coastal dune restoration	• The wide application of this is limited by the narrow beaches and building encroachment of buildings in many Caribbean locations.	✓	✗	✗

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. dev.	Full com.
	Carbon sequestration (potential application to earn blue carbon credits e.g. biochar, deep ocean sinking)	• High investment costs for equipment – both to produce biochar and to sink sargassum • Need more research for use of biochar on different soil types • Risk of creating oxygen dead zones on the deep ocean floor must be further researched • Lack of fully developed and functional governance mechanism for trading blue carbon credits in the region/no clear definition of sargassum ownership	✓	✓	✗
Food and beverage	Direct consumption – not currently recommended for humans	• Evidence of high levels of toxins, especially arsenic and some other heavy metals and pollutants • Inadequate research and testing for safety	✗	✗	✗
	Food and beverage additives and dietary supplements (extracts and activated carbon)	• Insufficient research on profile and benefits of secondary metabolites of pelagic sargassum • High investment costs for pyrolysis equipment	✓	✗	✗
Lubricants, surfactants, adhesives	Biolubricant (sargassum extracts)	• Insufficient research using pelagic sargassum	✓	✗	✗
	Biosurfactant (sargassum extracts)	• Brown seaweeds have potential to be used in the production of surfactants, but there is insufficient research using pelagic sargassum	✓	✗	✗
	Bio-adhesive (sargassum extracts)	• Brown seaweeds are being studied for their suitability, but there is limited research using pelagic sargassum	✓	✗	✗
Paper products	Paper products (sargassum biomass)	• Focus is currently on artisanal/craft papers and cardboards • Insufficient research on industrial paper production	✓	✓	✓
	Paper printing industry (alginate extracts)	• Extracts from pelagic sargassum may be more expensive than alternatives, increasing the cost of paper	✗	✗	✗
Pharmaceutical	Pharmaceutical and biomedical drugs and applications	• Research has focused on the potential of brown seaweeds, with limited research using pelagic sargassum • Therapeutic effectiveness and safety of pelagic sargassum extracts remain unknown	✓	✗	✗

Source: Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

2.17.3 Amount of sargassum needed

Based on case studies from around the region where the Sargassum Biomass Index has been applied, it can be seen that 1 tonne (1 000 kg) of fresh sargassum can potentially be used to create a large range of valuable products, as illustrated in Figure 13.

Although this is a crude relative index, it serves to illustrate the different scales of industry (amount of pelagic sargassum biomass needed) over the range of potential products, and will help to determine what might be appropriate for development of uses based on local objectives and circumstances.

Figure 13. Diagram showing the crude Sargassum Biomass Index to illustrate the relative product yields that could potentially be produced from 1 tonne (1 000 kg) of fresh sargassum

Source: Desrochers, A., Cox, S-A., Oxenford, H.A. & van Tussenbroek, B. 2020. *Sargassum uses guide: A resource for Caribbean researchers, entrepreneurs and policy makers.* Report funded by and prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of FAO. CERMES, UWI, Barbados. CERMES Technical Report No. 97.

Massive sargassum influx clogging the shoreline at Skeetes Bay fish landing site in Barbados

©Hazel A. Oxenford

3. Challenges and implications

Previous sections have featured the many ways in which sargassum influxes have motivated interventions to support entrepreneurship and innovation across several sectors in the Wider Caribbean Region. However, as has been described, exploring these opportunities has met with many challenges that present barriers to starting up, expanding, and scaling-up existing sargassum-related ventures. This section highlights the major constraints that have been shared with the authors by sargassum entrepreneurs, business owners and researchers from around the region. These are grouped into five broad categories (Unpredictable supply; Chemical composition; Harvest; Management; Funding) in the following subsections. Guidance is also offered on what needs to be done to move forward in addressing these challenges and promoting an enabling environment that fosters innovation and creativity. This is expected to be of particular relevance to policymakers and funders. Such an approach will allow the region to obtain benefits from sargassum influx events through the creation of industry, employment, cost recovery from beach clean-ups and disposal of sargassum, and improved adaptive capacity to sargassum influxes.

3.1 Unpredictable supply

Key challenges

- major uncertainty regarding sargassum influx timing, quantity and location;
- insufficient monitoring of volume and location of sargassum strandings; and
- Variability in relative abundance of different sargassum species and morphological forms.

3.1.1 When, how much and where?

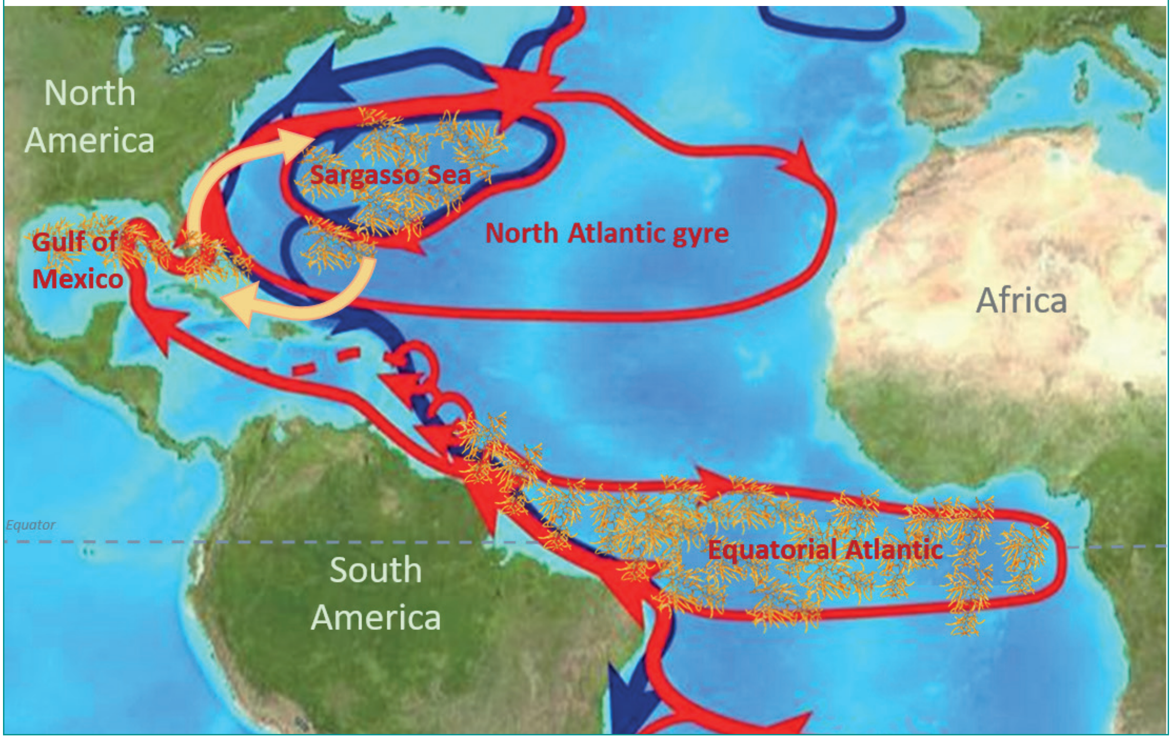
Not knowing when, how much or where sargassum influxes will occur is a major challenge that has hindered, and continues to impede, investment in developing uses for sargassum, and in scaling up existing small and medium-sized enterprises into major commercial ventures.

A key issue is the "newness" of the sargassum influx phenomenon and the significant knowledge gaps in our understanding of the system. In summary, extraordinary blooms of pelagic sargassum have been observed since 2011 in the Tropical Atlantic, where a system of persistent but seasonally variable ocean currents started to retain and consolidate the seaweed in large masses across the Equator (Franks, Johnson and Ko, 2016) (see Figure 14).

Forecasting sargassum influxes to the Caribbean is complicated by the somewhat unpredictable "release" of sargassum from this "new" source region. The uncertainty is further exacerbated by the complex mobility of pelagic sargassum as it travels vast distances (thousands of kilometres) from its source in the Equatorial Atlantic to its stranding locations along Caribbean coastlines, probably taking different routes in different months (depending on the highly variable and complex surface currents transporting it), and possibly coming from different source subregions within the Equatorial Atlantic (Johnson *et al.*, 2020).

Figure 14. Diagrammatic map of the Atlantic showing the sargassum accumulation areas (source regions).

Note: To the north is the long-established Sargasso Sea accumulation area, with the classic "sargassum loop" indicated (pale orange arrows) that links the Sargasso Sea and Gulf of Mexico and has always delivered relatively small amounts of sargassum seasonally to the NE Caribbean. Further south is the "newly established" Equatorial Atlantic accumulation area. The main ocean current gyres that retain sargassum and surface ocean currents that transport it when released are illustrated by red arrows (deepwater currents are shown in blue).



Source: Adapted from Lumpkin, R., & Pazos, M. 2007. Measuring surface currents with Surface Velocity Program drifters: the instrument, its data, and some recent results. Lagrangian analysis and prediction of coastal and ocean dynamics, 39, 67.

There have been many important advances in sargassum detection, monitoring and prediction over the past decade, which have begun to address some of these uncertainties (Hu *et al.,* 2016; Wang and Hu, 2016; Wang and Hu, 2017; Brooks *et al*., 2018; Putman *et al*., 2018; Wang *et al*., 2018; Wang *et al*., 2019; Johns *et al*., 2020). However, significant technical challenges remain that still inhibit accurate forecasting of sargassum influx events over more than a few days, and especially over time frames longer than three months. These challenges include:

- Limited optical satellite coverage in the cloud-covered sargassum source regions, meaning that sargassum presence cannot be detected in places that could ultimately deliver sargassum to the Caribbean.
- Relatively low satellite image resolution and optical noise (such as sun glint, Sahara dust, atmospheric moisture) and the difficulties associated with confirming the presence of sargassum in remote ocean areas to validate interpretation of satellite images. These pose challenges for detecting sargassum patches at the ocean surface and thus create difficulties for accurately "seeding" predictive transport models that use ocean current forecasting to predict arrivals.
- Lack of validation of regional wind-induced slippage added in the predictive models versus actual movement of sargassum mats *in situ*.
- Uncertainty in the accuracy of open ocean current models over long-distance paths through this complex and dynamic ocean region.

- Difficulty in combining predictions from open ocean models with local current and wind conditions nearshore.
- Generally elevated costs of high-precision satellite imagery and radar that could help in observing movements of sargassum nearshore and thus local predictions of strandings.
- Lack of information on the growth and mortality of sargassum as it travels through different environments constrains prediction model accuracy, since these will influence whether the biomass of sargassum changes significantly between tracked start and end points.
- Lack of consistent national and site-level monitoring of sargassum strandings, especially the quantity (as volume or weight) and location, constrains the ability to validate predictive models and/or provide ball-park figures of what could be expected in the future, based on past occurrences.

3.1.2 Variable species composition

The relative abundance of the three most commonly recognized species morphotypes of pelagic sargassum (*Sargassum fluitans III*, *S. natans I* and *S. natans VIII*) is quite variable, showing broad-scale spatial and temporal differences (Schell, Goodwin and Siuda, 2015; García-Sánchez *et al.*, 2020).

In the Caribbean, the relative proportions of the different forms have changed over time since the first inundations of 2011, and continue to show interannual as well as shorter-term (monthly) variations (García-Sánchez *et al.*, 2020). These authors report a marked change in the predominant form stranding along Mexican Caribbean shorelines, from an initial dominance of *S. fluitans III* and *S. natans VIII* to a current dominance of *S. fluitans III* and *S. natans I.* Similar observations have been made across other Caribbean locations (unpublished data). Stranding sargassum also becomes mixed with other beach wrack, especially seagrasses in many locations, and the relative amounts will change with season and sea conditions.

3.1.3 Implications

The highly variable supply and lack of reliable forecasts of sargassum influx events, exacerbated by a general lack of monitoring at national or site level, has several important implications for valorizing sargassum. Not knowing the approximate volumes of sargassum arriving at any given location over time makes it difficult to determine appropriate potential uses for this seaweed and the scale of the enterprise that could be developed. It also constrains the ability of potential investors to perform comprehensive cost projections and analysis to assess the economic feasibility and sustainability of proposed ventures.

Businesses generally need a reliable supply of raw material to support sustainable production. Given the uncertainty of a steady supply, storage becomes an important factor in ensuring reliable stock. This presents additional challenges that are considered in *Section 3.3.2.*

The variability in relative abundance of sargassum forms is, as yet, poorly understood and has implications for valorizing sargassum, since different forms appear to have different properties (Webber *et al.*, 2019; Milledge *et al.*, 2020; Rodríguez-Martínez *et al.*, 2020) and are therefore differently suitable for certain applications.

3.1.4 Moving forward

To overcome the current challenges, there are several important knowledge gaps that need to be addressed through actions that include:

- Continued research to improve the precision of sargassum influx forecasts, including: wider coverage of the Equatorial Atlantic; development of transport models that mimic sargassum movement and account for changes in biomass (for example through growth and mortality, natural subduction in Langmuir cells or during storms).
- Developing oceanographic models that aid in the prediction of sargassum strandings.
- Promoting comprehensive ground-truthing initiatives to validate the presence of sargassum at sea, and accuracy of forecasts.
- Developing simple harmonized monitoring protocols using remote sensing technology (such as drones, satellite imagery) and citizen science to improve the ease and geographical scale of monitoring the volume and location of sargassum strandings.
- Developing simple rapid assessment methodology to monitor the relative composition of pelagic sargassum forms (species and morphotypes) over space and time.
- Developing easily accessible platforms to make the sightings and predictions of the sargassum influxes at oceanic, regional and local scale available to the public.

3.2 Chemical composition

Key challenges

- high salt and ash content;
- large variation and uncertainty in the reported concentrations or relative proportions of most chemical components of sargassum;
- biosorption of heavy metals and other pollutants; and
- limited research on chemical composition, and difficulty accessing the existing knowledge and results.

3.2.1 High salt and ash content

Seaweeds are typically known for their high salt and high ash (inorganic residue) content. This holds true for sargassum, which has a high concentration of saline elements (such as sodium, potassium, calcium, magnesium and chloride) (See *Table 2 in Section 1.4.2*: Minerals and nutritional components) and high percentage of ash (see *Table 1 in Section 1.4.1: Main components).*

3.2.2 Uncertainty and variation in chemical composition

As indicated in this guide (see *Section 1.4 Chemical composition*), compositional analyses of pelagic sargassum in the Caribbean have been quite limited to date, with most involving small sample sizes (even a single sample), a mixture of species and morphotypes, a narrow geographical scope (only one or a few local sites), and a sample collection over a limited time period (Rodríguez-Martínez *et al*., 2020). Most analyses have also been restricted in terms of the number of chemical components examined.

Furthermore, there is a wide variation in the reported concentrations or relative proportions of most components (as summarized in *Table 1*, *Table 2* and *Table 3* in *Section 1.4*), which could possibly be attributed to the analytical method used, and/or to real differences in the chemical composition between pelagic sargassum species, and over space and time. For example, it is well known that seaweed chemical composition, in general, varies not only with biotic factors (such as species, stage of life cycle, age), but also with abiotic factors (such as pH, salinity, water motion, temperature, light availability, mineral content of seawater, and environmental pollutants) (Mišurcová, Machů and Orsavová, 2011).

Understanding and predicting the compositional variability is further complicated by the fact that pelagic sargassum is mobile, travelling vast distances (thousands of kilometres) from its source in the Equatorial Atlantic to its different stranding locations along African and Caribbean coastlines, most likely taking different routes over time, and possibly coming from different source subregions within the Equatorial Atlantic, where environmental conditions are likely to differ.

These observations are supported by the most extensive published study to date, which has found that the concentration of 28 elements in pelagic sargassum arriving along Mexico's Caribbean coastline, sampled at 8 widely spaced sites over a period of 11 months, showed considerable variation, not only among species and morphotypes, but also among locations, and over time, although there was no apparent seasonal pattern (Rodríguez-Martínez *et al*., 2020). The study authors suggested that much of the observed variation in element concentration was probably dependent on the route travelled by the floating sargassum and whether or not it passed through contaminated areas, given that brown seaweeds have excellent biosorption properties. Further investigation is needed to support this hypothesis.

Another example of this variability in chemical composition over space and time is the difference in the relative proportions (ratios) of inorganic carbon, nitrogen and phosphorous (C:N, C:P and N:P) reported for pelagic sargassum in different seasons and from different locations in the North Atlantic, and the observed long-term change in these ratios over the past three decades (Lapointe *et al.*, 2014). These authors reported higher C:N ratios in the 1980s compared with pelagic sargassum sampled in the 2010s, and lower C:P and N:P ratios in the 1980s compared with the 2010s, suggesting that the variations reflected changing ocean conditions.

3.2.3 Heavy metals and other toxins

The biosorption of certain heavy metals and other potential toxins (such as pesticides) and the presence of minerals in elevated concentrations is particularly problematic. For example, many (but not all) of the limited pelagic sargassum samples tested to date across the Caribbean have been found to contain concentrations of arsenic that exceed most countries' permitted concentrations for certain agricultural and nutritional uses (see *Section 1.4.3: Heavy metals*; *Table 5*, *Table 6* and *Table 7* in *Section 2.2*; and *Table 8* in *Section 2.3*). Similarly, concentrations of copper, molybdenum and manganese have been found to exceed safe limits in 5 to 22 percent of samples in Mexico (Rodríguez-Martínez *et al*., 2020). Chlordecone has been found in some sargassum samples in areas of high contamination off Martinique and Guadeloupe (Tirolien, 2019).

High concentrations of certain micronutrients and macronutrients (such as iodine) can be toxic for humans, animals and plants.

In general, there has been a relatively low level of testing in most places, especially with regard to heavy metals and speciation of arsenic, due to the cost of analysis and scarcity of laboratories with this capacity in the region.

3.2.4 Implications

High salt content presents a challenge for agricultural uses (including soil salinization, animals requiring more water or becoming dehydrated), for production of biomethane and ethanol, and for the bioremediation of metals (See *Section 2.2: Animal husbandry*; *Section 2.3: Crop production*; *Section 2.5: Bioenergy*; and *Section 2.7: Bioremediation*). Attempts to apply seaweed in the raw or composted form have resulted in soil salinization in some cases. Removing excess salt is not only costly and time-consuming, but also requires large amounts of freshwater.

Insufficient testing to date, and lack of standard methods, combine to produce considerable uncertainty over the chemical composition of sargassum. This constrains the assessment of potential valorization.

Variations in the concentrations of certain compounds can also be problematic, since components such as sulphur, salt, insoluble fibres and low carbon to nitrogen ratios can inhibit the growth of methanogenic bacteria. This means that anaerobic digestion rates and methane (biogas) yield will be inconsistent (Thompson, Young and Baroutian, 2020). In addition, these components may also be found in undesirable levels in the digestate, restricting its use in agriculture (Milledge, 2020). Although the high ash content of sargassum is beneficial for agricultural purposes (such as fertilizers and animal feed), it could lead to problems for the production of bioenergy, particularly for direct combustion and gasification. This is because the high ash content means a lower gross calorific value (also referred to as "higher heating value", resulting in a lower energy yield than is typical for most terrestrial plant biomass (Milledge *et al*., 2014; Milledge and Harvey, 2016).

For toxic elements, variability is especially problematic because it requires constant testing of end products to ensure safety.

3.2.5 Moving forward

To overcome the specific challenges associated with the chemical composition of sargassum, there are several important knowledge gaps to be addressed through actions that include:

- More extensive (over space and time) sampling and compositional analysis of pelagic sargassum from across the region to improve understanding of the geographical, seasonal and annual variation in chemical composition.

- More comprehensive compositional analyses (performed separately by species and morphotypes), using standardized analytical methods.

- More testing to determine concentrations of potentially harmful components, such as heavy metals, organochlorines and other pollutants, which are readily picked up by pelagic sargassum as it travels.

- Speciation of arsenic to determine the levels of inorganic (toxic) arsenic as opposed to total arsenic, which has been found in high concentrations in the majority of samples to date.

- Engaging in multiple trials using sargassum from different locations and seasons, and using the same analytical methods for samples, to determine the efficacy of certain sargassum-based products.

- Undertaking frequent testing of pelagic sargassum and/or sargassum-based end products and waste for the presence and potential accumulation of toxic components, to determine levels of safety for direct contact, consumption and agricultural uses, as well as appropriate disposal methods.

- Examining whether toxins such as arsenic transfer to crops and enter the food chain;

- Developing protocols to avoid the risks of toxins in sargassum entering the food chain or causing environmental degradation from widespread applications or inappropriate sargassum biomass storage or waste product disposal.

- Recognizing that currently, the most promising uses are those that do not enter the food chain, due to the uncertainty regarding toxicity and the lack of standards related to sargassum-based products.

3.3 Harvesting, transport and storage

Key challenges

- Although sargassum is free, the harvesting and transport is generally very costly, and often requires highly specialized equipment.
- Insufficient knowledge sharing with regard to suitable harvesting methods and equipment.
- Large interannual and seasonal variability in sargassum influxes and strandings.
- High risk of causing environmental damage if inappropriate equipment and methods are used for collection.
- Lack of policy and mechanisms for issuing harvesting permits in most places.

3.3.1 Harvesting and transport

Sargassum arrives "free of charge", but as the past decade has shown, it requires specialized machinery and equipment for effective large-scale shoreline or in-water collection in order to minimize environmental damage, and this tends to be very costly to purchase and maintain. It also requires methods and equipment that are customized to the wide range of physical conditions found at different sites, such as the prevailing winds and sea conditions, water depth, nearshore habitats, shoreline type (rocky, sandy, cliff, artificial), beach slope and width, and site access.

Since the first sargassum influxes of 2011, there has been very high interannual and seasonal variability in the amount of sargassum arriving and stranding (Ramlogan *et al*., 2017; Wang *et al*., 2019).

Important lessons were learned early on, largely through trial and error, but were not widely shared. As such, in many cases unsuitable, but readily available, heavy machinery was deployed and significant environmental and aesthetic damage occurred, especially through the compaction and removal of large amounts of beach sand.

Cleaning collected sargassum is also necessary to prevent environmental damage and provide a suitable raw material for many industries. Separating sand from sargassum collected on the beach, associated fauna (such as sea turtle hatchlings) and marine debris (such as plastics) from harvested sargassum is tedious and requires significant manpower or specialized separation equipment to automate this process, which can add considerably to the cost.

Transferring sargassum from boat harvesters and from onshore mechanized rakes and stockpiles to other means of transport also requires grabs or conveyors and further expense. The fact that fresh sargassum is wet, heavy and salty adds to the cost of transport and maintenance of equipment.

Some of these challenges have been addressed by repurposing existing machinery and equipment through modifications, or through the development of new purpose-built equipment that has significantly increased efficiency and reduced environmental impacts of sargassum collection and cleaning. Significant and continued efforts are also under way to gather information, assess sargassum collection methods, and develop informative materials and best practice guides, which recognize the importance of methods customized to local conditions. Among these are the UWI-CERMES *Sargassum management brief* (Hinds *et al.*, 2016); the GCFI *Sargassum fact sheet* (Doyle and Franks, 2015); a best practices infographic poster (GCFI, 2018); the Dutch Caribbean Nature Alliance's *Prevention and clean-up of Sargassum in the Dutch Caribbean* (Dutch Caribbean Nature Alliance, 2019); the Puerto Morelos Protocol[28], and the *Monitoring and evaluation of Sargassum collection operations* (see Box 19) (Chereau, 2019).

BOX 19. Sargassum collection options

- offshore barriers to concentrate sargassum;
- mechanized offshore collection (boat harvesters);
- manual onshore collection;
- mechanized onshore collection; and
- accessory equipment to move sargassum.

These five categories of sargassum collection methods and equipment are described in detail and assessed in a report by Chereau (2019).

Efforts are also ongoing to improve the communication of new knowledge through symposia and exhibitions dedicated to sargassum, as well as through formal networks and knowledge hubs that are sharing information, improving access to documentation and enabling the exchange of ideas and questions. Examples include: *Specially Protected Areas and Wildlife (protocol of the Cartagena Convention)-Regional Activity Centre for the wider Caribbean (SPAW-RAC)* basecamp, SargNet Listserv and Slack Workspace, Guadeloupe *Sarg'Expo*, and the *Sargassum Information Hub.*

[28] The Puerto Morelos Protocol was formulated by hotel owners, scientists from the Ocean and Limnological Sciences Institute of UNAM and authorities from the Reefs of Puerto Morelos National Park to place barriers, collect sargassum in the open sea and find ways to compact and reuse sargassum from the shores of Quintana Roo.

Challenges that remain include the following:

- Specialized equipment is still under development and/or has limited availability and is generally very costly.
- Limited access to, or use of, available knowledge is still resulting in the purchase of equipment and implementation of harvesting methods that are not well suited to local contexts and are therefore ineffective and continue to result in a waste of resources.
- Uninformed approaches to removing sargassum are still occurring across the region, leading to ongoing environmental damage.
- Lack of policy or legal frameworks in most countries for issuing harvesting permits.

3.3.2 Storage

Reliance on a raw material with a highly variable availability will require stockpiling and preservation of sargassum, to ensure a constant supply for industry in times of low sargassum influx. This requires significant physical space. Furthermore, inappropriate storage (or disposal) of harvested sargassum can lead to several challenges, including environmental and human health issues. For example, leachates (potentially containing high levels of nutrients and toxins) can pollute natural water bodies (van Tussenbroek *et al*., 2017). If sargassum is allowed to remain wet it will begin anaerobic decomposition, releasing toxic hydrogen sulphide and ammonia gases that present a health hazard for nearby communities (ANSES, 2017). A further challenge is that preservation methods for extending the storage time of sargassum are still being explored.

3.3.3 Implications

The process of harvesting, separation (cleaning), transport and storage significantly increases the cost of using sargassum as raw material, and thus the cost of end products. Fresh, clean sargassum is usually a prerequisite for developing high-end products, particularly those dependent on extracts. Cleaning the sargassum of sand if it is taken from the beach, or separation of sargassum from other wrack (such as seagrass) and marine garbage may add significantly to the cost in some areas.

The high variability in sargassum supply poses a challenge for harvesting and transport because expensive equipment (and personnel) will be inactive for uncertain periods of time.

Collection of large volumes of sargassum (whether onshore or in-water) can easily cause damage to the environment, and thus requires highly specialized equipment, machinery and methods customized to the physical and socio-economic characteristics of any given site.

The lack of policy or legal framework for permitting sargassum harvesting presents an additional challenge.

3.3.4 Moving forward

There are a number of knowledge gaps that need to be addressed and several actions that could be considered to address current harvesting, transport and storage challenges. These include:

- Where in-water harvesting is the preferred method, conducting biodiversity studies of floating sargassum at different distances from shore, so as to inform the most appropriate location for in-water harvest and avoid biodiversity loss.
- Developing low-cost machinery that efficiently and effectively separates sand and plastics from harvested sargassum.
- Investigating the best storage solutions for sargassum (for example dried, ground, preserved) to ensure an uninterrupted supply to industry during periods of low or no influxes.
- Conducting a value chain analysis to determine the lowest costs, including process, transactional and handling costs, for the entire supply chain.
- Improving access to knowledge and communication, so as to share lessons learned and promote best practices for onshore and in-water collection methods.
- Considering the local context, potential impact on the environment and types of use to be developed before investing in a specific type of harvesting equipment.
- Considering ways of reducing the cost of importing specialized sargassum harvesting equipment.
- Developing protocols and standards for safe harvesting, transport and storage of sargassum.

3.4 Management and regulation

Key challenges

- Mass influxes of sargassum are a relatively new phenomenon for this region and its arrival, collection and potential uses are characterized by high levels of uncertainty.
- Lack of guiding policy or governance framework specific to managing sargassum influxes.
- Limited focus on sargassum as an opportunity rather than just a hazard.
- No mechanism for issuing harvesting permits in most places and no regional policy.
- Lack of protocols and standards to support safe harvesting, transport, storage and production (for both processing and end products).

3.4.1 Uncertainty

Mass influxes and strandings of pelagic sargassum in the Caribbean are a relatively new phenomenon (unprecedented prior to 2011), which is characterized by many uncertainties with regard to arrival (timing, amount, location); composition (chemical and species); appropriate collection, transport and storage methodologies; equipment (new research and development is highly dynamic); feasibility of a myriad of potential uses; market demand for end products; and environmental impacts. This presents significant challenges for supporting (managing and regulating) the harvesting and use of sargassum.

3.4.2 Governance

The unexpected and unprecedented influxes of sargassum in 2011 meant that management strategies needed to be developed from scratch. Initially there was a complete lack of applicable guiding policy or governance framework to manage this new phenomenon (Oxenford, McConney and Sabir, 2019). Furthermore, the uncertainty as to whether or not this would be a recurring phenomenon discouraged the development of an appropriate governance mechanism for several years. The initial focus was on treating sargassum as a hazard and removing it from critical coastlines as rapidly as possible. Relatively little attention was, and still is, paid to the potential opportunities for valorizing sargassum.

Several countries in the Caribbean region have now established or are in the process of setting up taskforces or national committees comprising a mix of government and private sector agencies to provide support and coordination in addressing sargassum influxes. However, in many cases the ability of these taskforces/committees to function has been limited by inadequate funding and access to the most recent knowledge generated by the dynamic research environment that currently characterizes this new phenomenon. Several countries have also drafted sargassum management plans/strategies, most of which still need to be approved by cabinet or other competent authorities and assigned resources to support implementation. Regulations to support the management plans and valorization of sargassum are lagging behind (Cox, Oxenford and McConney, 2019).

Regional policies and statements that support the valorization and commercialization of sargassum include: the United Nations Environment Programme–Caribbean Environment Programme's white paper *Sargassum outbreak in the Caribbean: Challenges, opportunities and regional situation* (UNEP, 2018) and the 2019 Final declaration of the International Conference on Sargassum in Guadeloupe *Caribbean Programme for Sargassum*.[29]

3.4.3 Implications

The lack of well-developed governance arrangements or specific focus on supporting the valorization of sargassum in most countries continues to constrain the development of uses for sargassum, particularly by large-scale commercial enterprises, and is complicated by uncertainty and the transboundary nature of the mobile sargassum.

The lack of a regional policy for the harvesting of sargassum as a shared resource is a hindrance to the development of any large-scale, mobile, offshore harvesting enterprises. The lack of local harvest regulations increases the uncertainties faced by businesses using sargassum as a raw material.

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

3.4.4 Moving forward

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

- A focus on adaptive management strategies or plans tailored to local circumstances would be appropriate, especially given the current uncertainties, allowing frequent review, updating and incorporation of lessons learned.

- The general lack of governance arrangements (policies, management plans and regulations), applicable to sargassum harvesting and use, needs to be addressed.

- Government policies and programmes need to present a more attractive and enabling environment that fosters innovation and supports the expansion of existing enterprises and the development of new industries using sargassum biomass.

- Protocols and standards need to be developed to prevent environmental damage and ensure the safety of products for consumptive or contact uses.

[29] https://pressroom.oecs.org/final-declaration-of-the-international-conference-on-sargassum-a-commitment-to-cooperation-in-the-caribbean

3.5 Funding and support

Key challenges

- availability of funding for valorizing sargassum;
- difficulty accessing funding;
- low level of support for new ventures; and
- lack of industrial infrastructure.

3.5.1 Funding for developing sargassum uses

Given that sargassum influx events were totally unexpected back in 2011, and their recurrence was uncertain, it is not surprising that funding for research and development was initially unavailable and thereafter relatively slow to mobilize. Nonetheless, substantial funding has now been mobilized to support many initiatives across the Caribbean region aimed at addressing one or more aspects of sargassum influxes. These include (1) developing effective mitigation activities; (2) improving monitoring and prediction; (3) investing in applied research; (4) strengthening networking and information sharing among stakeholders; and (5) raising public awareness and increasing education.

However, most funding to date has been invested in research and education initiatives, with much less support given to valorizing sargassum. Investment in commercializing products and seed funding for marketing needs to be increased, in order to build sustainable sargassum industries that create jobs, build adaptive capacity, and address biomass removal.

Specific current challenges include the following:

- Very limited funding is available for small- and medium-scale entrepreneurs to develop commercially viable uses for sargassum and scale up their businesses.
- Young entrepreneurs may lack the collateral needed as security for repayment of loans (and often, accessing business loans is further complicated due to the unpredictable supply of raw material).
- Donor funding is generally extremely difficult to access, and the application process and reporting requirements can be daunting and time-consuming.
- Government budgets are generally not sufficiently adaptive to support new ventures, especially those with high levels of uncertainty.

3.5.2 Support for innovation and business enterprises

The region is typically characterized by cumbersome bureaucratic procedures for setting up, operating and growing a business, which present enormous hurdles, particularly for small and medium-sized enterprises. This is often exacerbated by burdensome taxes and the poor state of infrastructure and lack of effective institutional structures. Furthermore, most economies in the region (particularly the insular Caribbean) depend on marine (such as fisheries) and coastal (such as tourism) resources and lack industrial infrastructure.

3.5.3 Implications

The current difficulties in accessing funding to support the development and commercialization of sargassum businesses and the lack of a supporting environment to encourage entrepreneurship and new ventures serve as significant constraints to the growth of a sargassum industry. This is exacerbated by the general lack of industrial infrastructure in many countries. These factors combine to hinder the development of an industry that has the potential to help offset the enormous cost of clean-up efforts currently sustained by governments and the private sector.

3.5.4 Moving forward

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

- There are opportunities for sargassum innovations to be considered as blue growth initiatives, which can be integrated into blue economy strategic frameworks and roadmaps. This could support economic diversification and resilience, in order to reduce economic vulnerability and reliance on a small number of sectors.
- Increasing the number of public-private partnerships in the domain of applied research and product development would enable the risk of investment to be spread, while maximizing innovation.
- Creating a national policy framework for the development of micro-, small- and medium-sized enterprises could provide valuable support for sustainable sargassum businesses.
- Building the capacity of small- and medium-scale entrepreneurs is important in the areas of business development, accessing grant funding, marketing, and financial and human resources management.

- Creating an enabling environment for affected stakeholders (fisherfolk and coastal community residents) to pursue sargassum uses as an alternative livelihood.
- Providing incentives for businesses that contribute to governments' cost recovery arrangements for cleaning beaches of sargassum.
- Creating a "sargassum tax" through tourism or other initiatives (such as the one in Quintana Roo, Mexico, where USD 1 per day per visiting tourist is paid to local authorities for "sargassum relief").
- Fostering creativity through innovation hubs, hackathons and pitch competitions.

Sargassum fronds drifting in the surface waters of the Eastern Caribbean, near Barbados

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The year 2011 marked the start of repeated mass influxes of pelagic sargassum into the Caribbean. These events continue to have significant negative impacts on national economies and coastal livelihoods. As a result, there has been rapidly growing interest across the Caribbean region in utilizing stranded pelagic sargassum as a primary resource for developing uses, turning this hazard into an opportunity. *Pelagic sargassum - A guide to current and potential uses in the Caribbean* has been developed as a resource for researchers, business entrepreneurs and policymakers by providing, under one cover, a comprehensive overview of the wide range of current uses of sargassum in the Caribbean and the challenges faced to date. It also offers insight into potential uses based on examples and research from other parts of the world involving different sargassum species or other seaweeds.

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