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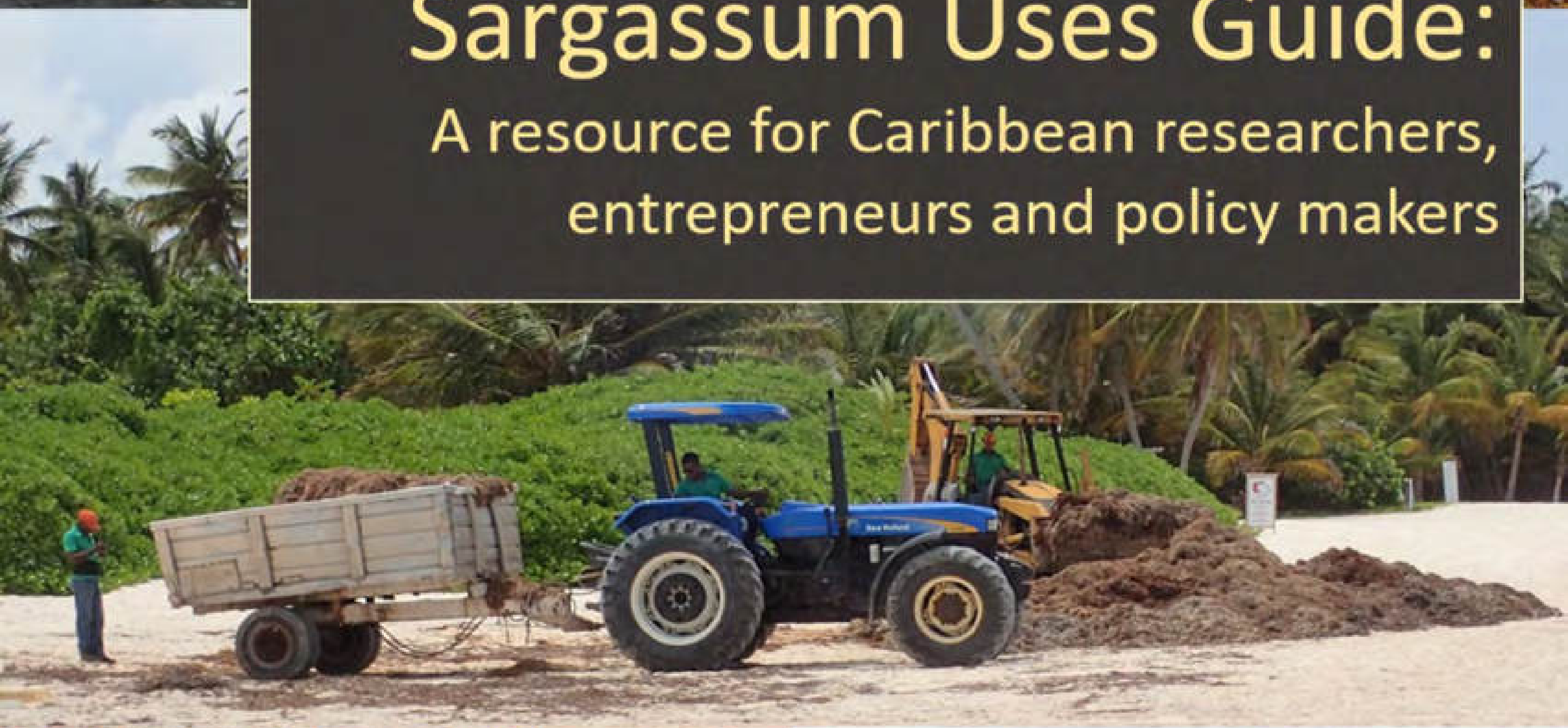
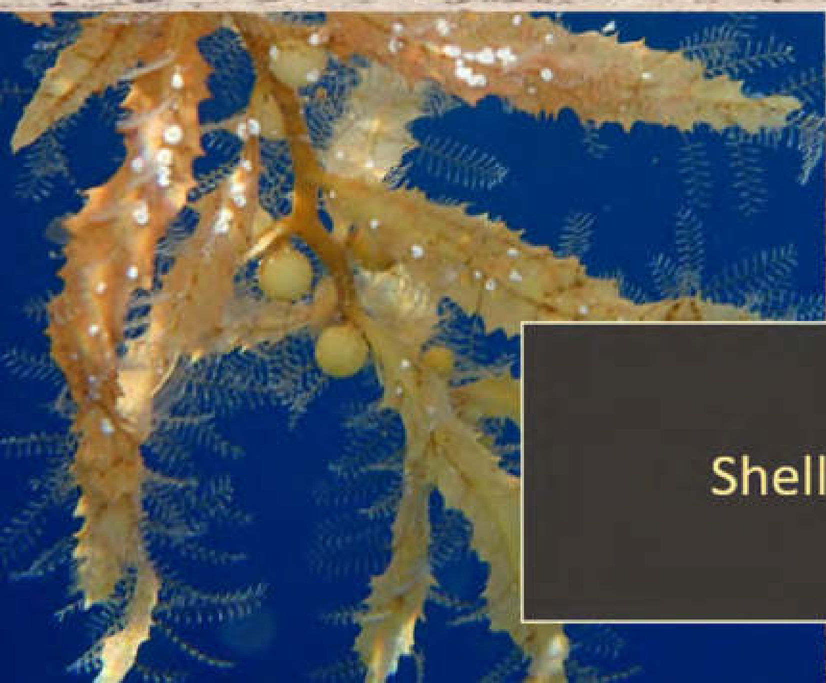
Sargassum Uses Guide:

A resource for Caribbean researchers, entrepreneurs and policy makers





Anne Desrochers,
Shelly-Ann Cox, Hazel A. Oxenford,
Brigitta van Tussenbroek

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ADVANCED DRAFT

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Lead author

Anne Desrochers

Contributing authors

Shelly-Ann Cox, Hazel A. Oxenford

Brigitta van Tussenbroek

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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 a 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. Many entrepreneurs and research teams from across the region have been working arduously over the last few years 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 over the Internet. For this reason, we undertook 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.

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

The first section of the guide sets the context in which it has been developed and gives a brief general overview of pelagic sargassum; 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 using sargassum seaweed species where available. In so doing, we provide detailed technical explanations and examples of the demonstrated or potential use of sargassum in fifteen different sectors ranging from agriculture to food and beverages, biofuels, fashion, cosmetics, paper, bioplastics, construction, pharmaceutical, electrochemical, water and air purification, and environmental remediation, *inter alia*.

Warnings are indicated for certain uses, which do not currently have sufficient evidence demonstrating 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. A 'Sargassum Biomass Index' (SBI) was developed and included throughout this section to give a broad estimate of the amount of end products that can be produced with a given amount of fresh sargassum. Here we use both a weight (one metric tonne), and a volume (one cubic metre) 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 which can be developed with one metric tonne of sargassum, and a concise table summarising the current state of knowledge with regard to the potential uses of pelagic sargassum and current product-specific challenges.

Section 3 provides details from a wide variety of case studies that we have been fortunate enough to learn about, to visit, or to communicate with, and who were willing to share their stories. They also provided information about their successes, challenges and lessons learned for the benefit of others wishing to take part in developing and scaling up opportunities presented by pelagic sargassum influxes. Nine business enterprises are featured, from across the region, who have been successful in valorising sargassum or who are at an advanced stage of developing a commercial use. These case studies range from those making construction blocks to a variety of paper and cardboard products, renewable energy, various agricultural applications, fashion and beauty care products, and activated carbon. We also look at ongoing research from around the region, providing details of those involved and their progress to date. This includes current research at universities in Barbados, Cuba, Dominican Republic, French Antilles, Jamaica, Mexico, Trinidad and Tobago, USA, and their international collaborators in North and South America and Europe. This research covers the range of potential uses reviewed in Section 2.

In Section 4, we provide an initial directory of entrepreneurs, businesses, researchers and others currently using or developing commercial uses for sargassum in the Caribbean region. This directory aims to assist in better networking and collaboration among the players in this community of stakeholders.

Section 5 provides an important summary of the challenges faced to date, the new knowledge that is helping to address these, and gaps that remain. We also highlight major constraints that have been shared with us by sargassum entrepreneurs, business owners and researchers from around the region in their efforts to valorise 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. We offer guidance, of particular relevance to policy makers and funding agencies, on gaps and challenges that need to be addressed in order to move forwards, scaling-up successful and sustainable solutions and providing an enabling environment that fosters innovation and creativity.

We anticipate that this guide will help 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.

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)
BOREA	Biologie des organismes et écosystèmes aquatiques – Laboratoire de l'Université des Antilles (Biology of Organisms and Aquatic Ecosystems, Laboratory of the University of the French West Indies)
CC4FISH	Climate Change Adaptation for the Eastern Caribbean Fisheries Sector Project
CERMES	Centre for Resource Management and Environmental Studies
CHU	Centre hospitalier universitaire (University Hospital Centre)
C:N	Carbon to Nitrogen Ratio
C:P	Carbon to Phosphorus Ratio
CICY	Centro de Investigación Científica de Yucatán (Scientific Research Centre of Yucatan)
CNRS	Centre national de la recherchee scientifique (National Centre of Scientific Research)
CONACyT	Consejo Nacional de Ciencia y Tecnología (National Council of Science and Technology)
COVACHIM-M2E	Connaissance et valorisation : Chimie des matériaux environnement, énergie (Knowledge and Valorisation: Chemistry of Material, Environment, Energy)
CREDDI-LEAD	Centre de recherche en économie et en droit sur le développement insulaire - Laboratoire d'économie appliquée au développement (Centre for Research in Economics and Island Development Law – Laboratory of Applied Economics Applied to Development)
CRFM	Caribbean Regional Fisheries Mechanism
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environment Facility
GTSI	Groupe de technologie des surfaces et interfaces (Surfaces and Interfaces Technology Group)
INRA	Institut national de la recherche agronomique (National Institut of Agronomic Research)
Interreg	Better-known synonym of the European Territorial Cooperation (ETC)
IRD	Institut de recherche pour le développement (Institut for Research and Development)
IT2	Institut technique tropical (Technical Tropical Institute)
JICA	Japan International Cooperation Agency
L3MA	Laboratoire des matériaux et molécules en milieu agressif (Laboratory of Material and Molecules in Harsh Environments)
LCA	Laboratoire de chimie agro-industrielle (Agro-Industrial Chemical Laboratory)
NST	NUM SMO (Solar Microwave Oven) Technologies
PUFA	Polyunsaturated Fatty Acids
PYROSAR	Valorisation of Sargassum by pyrolysis - application for food safety
SARGOOD	Holistic approach to Sargassum valorisation
SARGACARE	Human health effects of chronic exposure to gaseous fumes of decomposing brown algae in the French West Indies
Sarg As Cld	Environmental impacts of Sargassum leachate due to arsenic and chlordecone: quantification, mitigation and social perception
SARGSCREEN	Pharmaco-toxicological screening of molecules extracted from Caribbean sargassum

SARtrib	Tribological and electrochemical valorisation of Sargassum
SAVE	Sargassum Agricultural Valorisation and Energy production
SAVE-C	Study of holopelagic Sargassum responsible for massive beachings: valorisation and ecology on Caribbean coasts
SBI	Sargassum Biomass Index
SPAW-RAC	Specially Protected Areas and Wildlife (protocol of the Cartagena Convention)- Regional Activity Centre for the wider Caribbean
UNAM	Universidad Autónoma de Mexico
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UA	Université des Antilles (University of the French West Indies)
UWI	University of the West Indies

TABLE OF CONTENTS

Section 1
Introduction

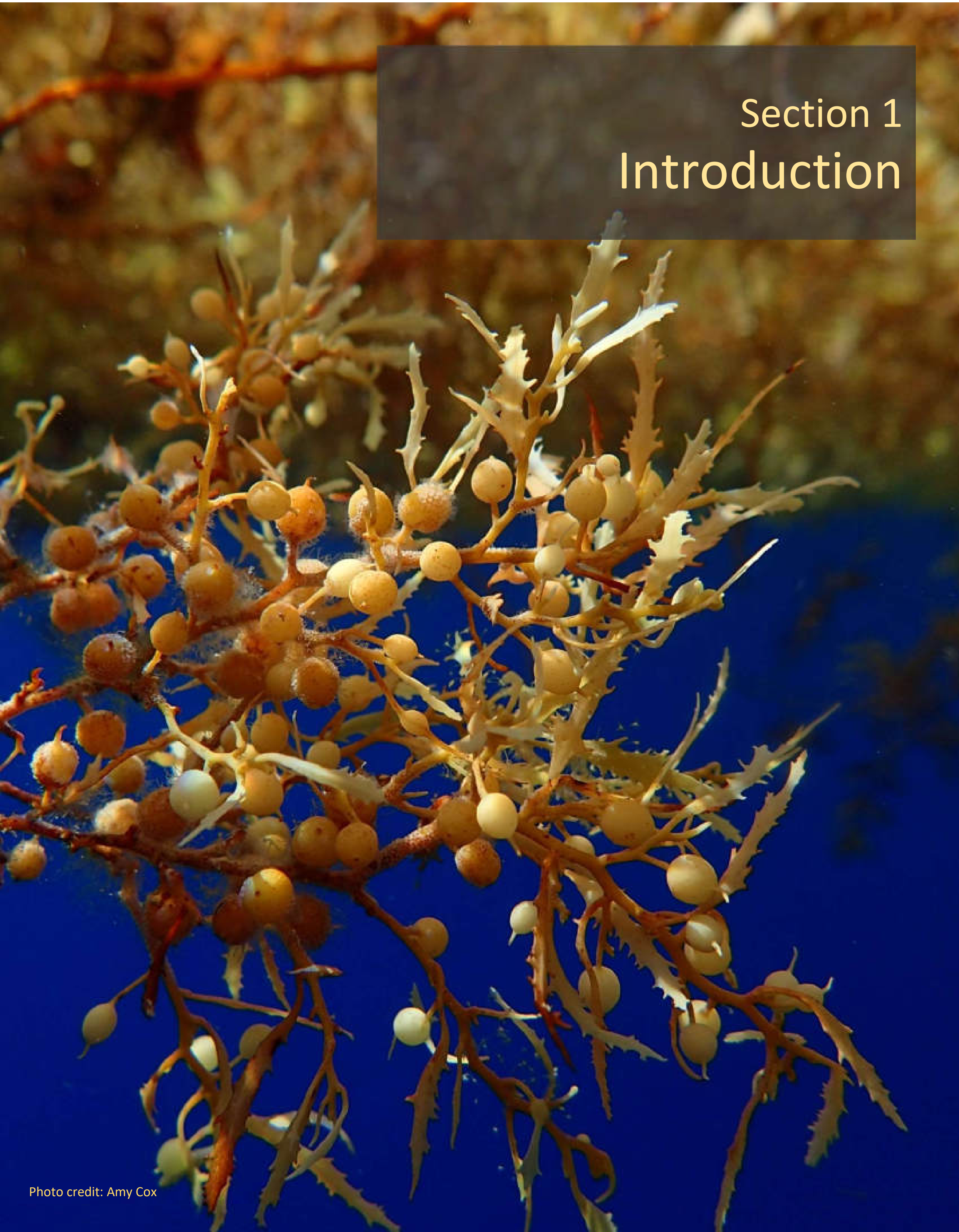


Photo credit: Amy Cox

1. Introduction

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, as well as 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 also been occurring since 2009 (Addico and deGraft-Johnson 2016).

After initial uncertainty, this new sargassum source region has been linked to climate change and ocean eutrophication and is likely to continue supporting significant sargassum blooms into the future. 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 (Tobago in 2015, Barbados in 2018, Mexico in 2019) declaring a 'state of emergency' implying that State or Federal funds and manpower (such as the army) can be utilized in order to tackle the onslaught of thousands of tons of stranded sargassum. Furthermore, the cost to the national economies of many countries from lost revenue in the tourism industry in particular, and in fisheries and other coastal livelihoods is substantial and a matter of significant concern. As such there is a 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 (e.g. UNEP 2018, ANR 2019).

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 policy makers. 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 (i.e. Guadeloupe, Dominican Republic and Mexico) for in-person interviews and site visits to learn firsthand from businesses and researchers that have already successfully valorised sargassum, or have achieved promising results in research and marketing trials; and

(4) direct communication by email, 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 policy makers by providing, under one cover, a good overview of the wide range of current uses of sargassum in the Caribbean, the lessons learnt and challenges faced to date. It also provides insight into potential uses based on examples and research from other parts of the world using different sargassum species or other seaweeds. Furthermore, it provides an initial directory of Caribbean researchers and business entrepreneurs working to develop uses for sargassum to assist in networking and the development of partnerships to stimulate faster and more efficient ways of benefitting from stranded sargassum. 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 has been developed and gives a very brief general overview of pelagic sargassum; its basic biology and chemical composition as relevant to developing uses for sargassum biomass. Section 2 presents the range of potential uses of sargassum based on research and examples of use of macroalgae (seaweeds) in general, brown algae in particular, and highlights those using sargassum seaweed species where available. This section also links to the ongoing initiatives using sargassum in the Wider Caribbean[1] examples of which are presented as case studies in Section 3. In Section 4 we provide an initial directory of entrepreneurs, businesses, researchers and others currently using or developing commercially viable uses for sargassum in the Wider Caribbean. Section 5 examines the current challenges to date, their implications and suggestions for moving forwards.

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).

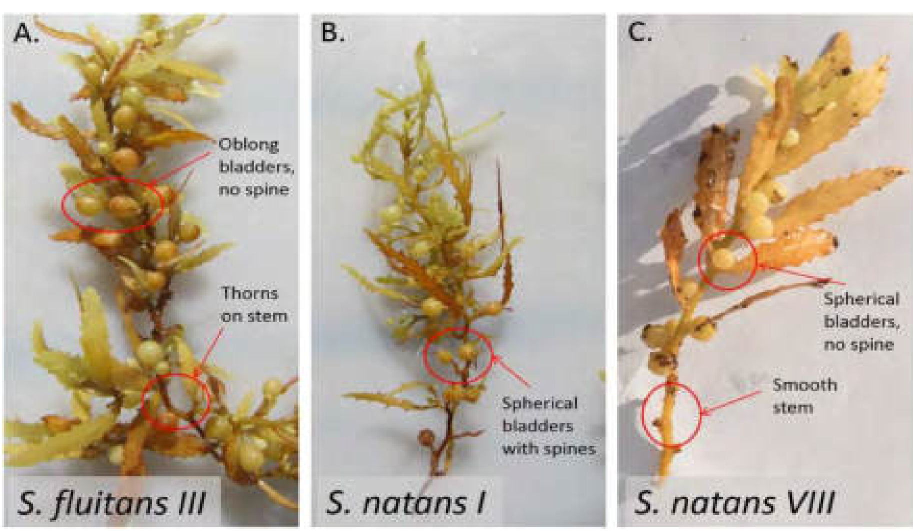


Figure 1. Morphological differences between pelagic *Sargassum* species and/or morphotypes (Govindarajan *et al*. 2019).

[1] Wider Caribbean is used in this guide to refer to the Caribbean Sea, Gulf of Mexico and countries bordering these seas.

These species are unique among the 300+ species of sargassum known across the world, in being the only ones to spend their entire lifecycle 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 also 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 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 hundreds of 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' (e.g. carbon (C), sodium (Na), iron (Fe), nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), etc.); (2) 'inorganic compounds' (e.g. water, salts, CO_2, O_2, etc.) and (3) 'organic compounds' (e.g. carbohydrates, lipids, proteins etc.).

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. Whilst water accounts for 82-87% 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 play specific roles in the maintenance of the seaweed and have potential value for use in a large number of applications as depicted in Figure 3 and demonstrated in this guide.

We note from the literature, that the exact chemical composition and nutrient value is likely to vary based on the species composition of the pelagic sargassum, the location, the time of the year and environmental conditions (see Challenges Section 5.2 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 done on 'whole pelagic sargassum' samples, comprising this mixture of species. There are, however, a few recent studies that have separated the three sargassum morphotypes to examine differences in composition among them (Milledge *et al*. 2020, Rodríguez-Martínez *et al*. 2020, Webber *et al*. 2019).

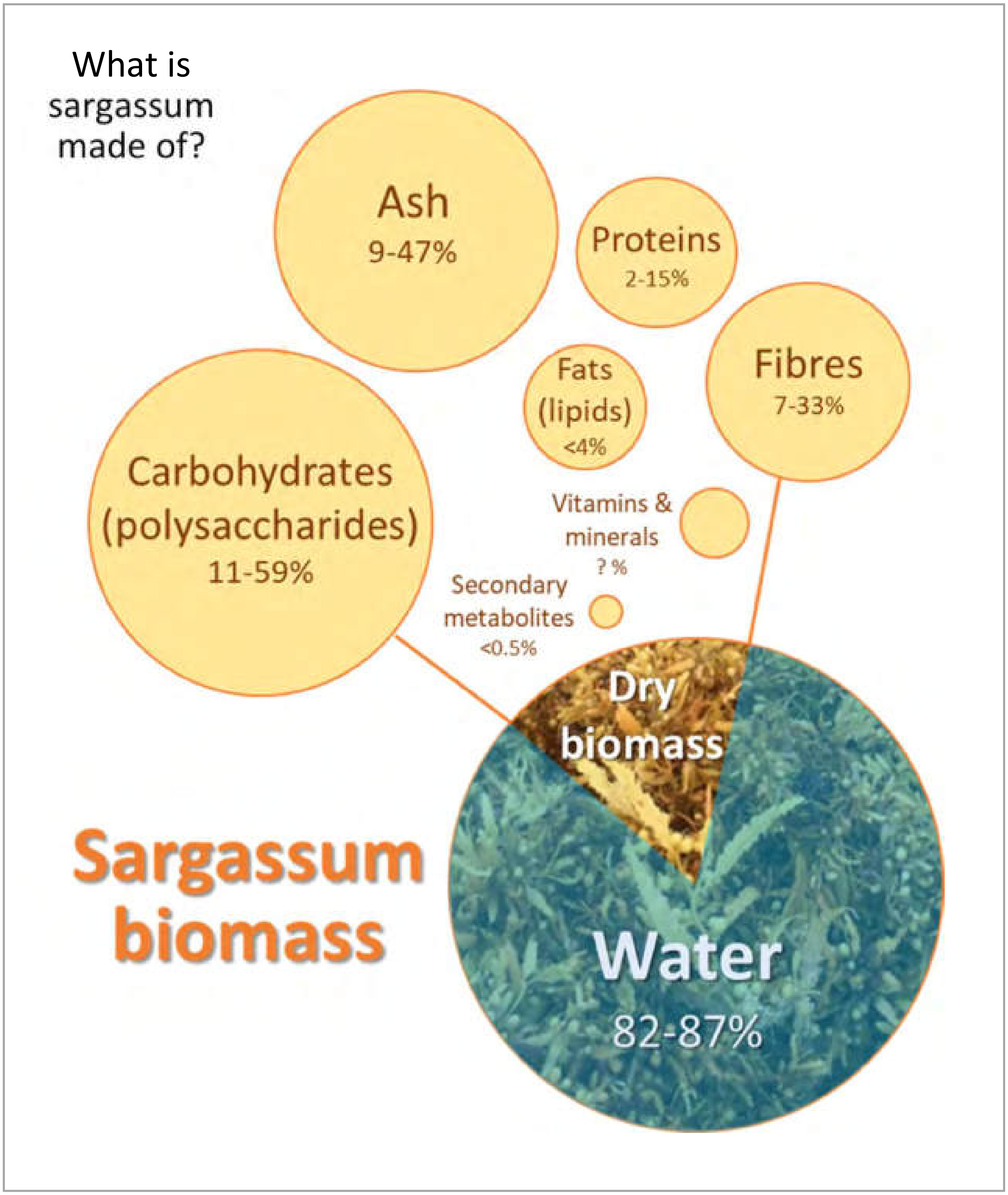


Figure 2. Representation of the main constituents of pelagic sargassum biomass

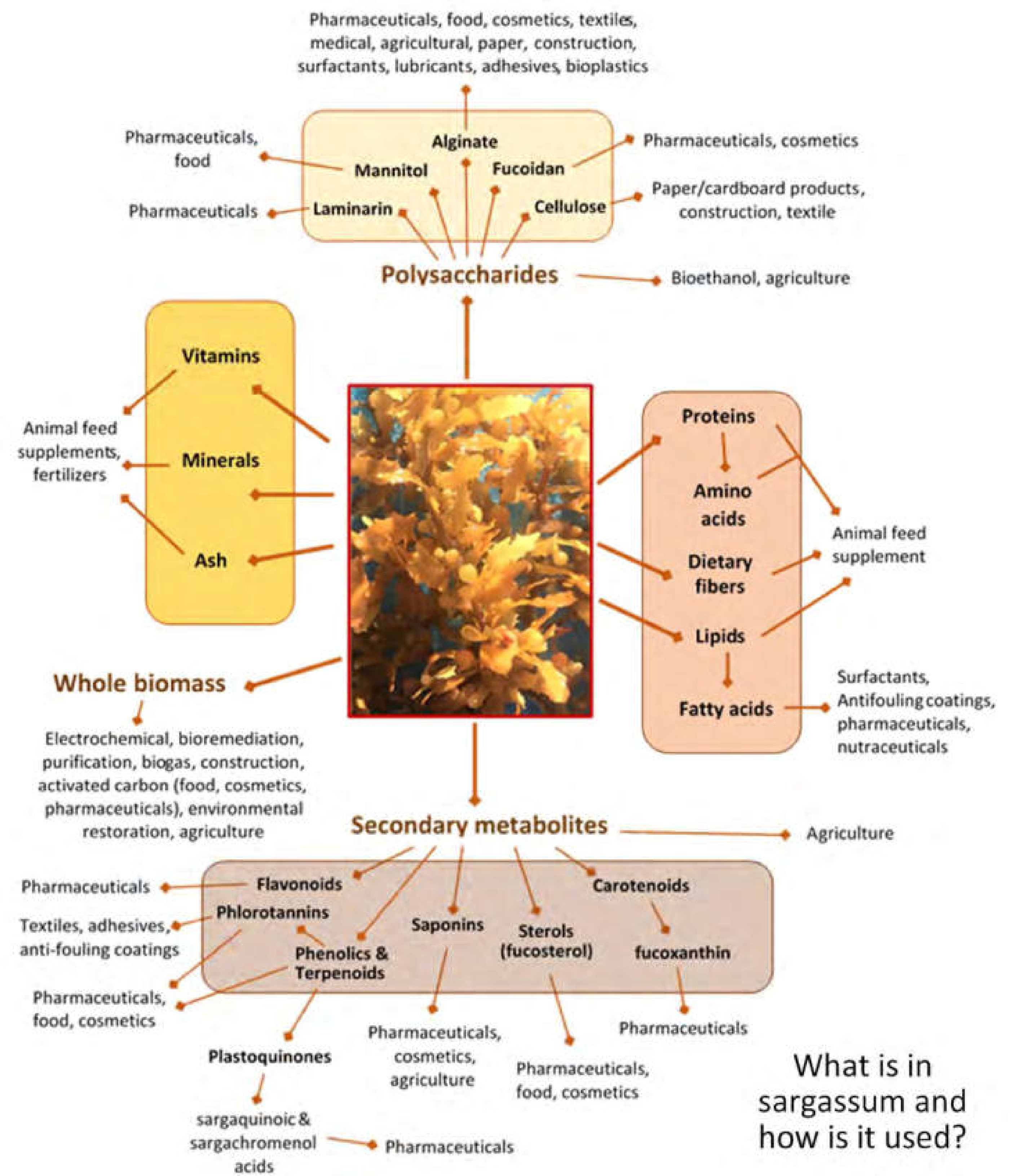


Figure 3. Diagram to show sargassum compositional profile and associated uses

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 5.1 Unpredictable supply. Our focus is also on pelagic sargassum from the 'new' Equatorial Atlantic population that has been stranding along the coastlines of West Africa, the insular Caribbean and Caribbean coasts of South and Central America since 2011. However, we do make comparative reference 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 as can be seen by the summary of results presented here.

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 from the 'Main Components' 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 they comprise a wide range of amino acids. We note, however, 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 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 between 0.3 to 3.9 percent dry weight, which falls within values reported for single 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

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 (2016)a	Mixed from beach (N/A)	2.6	12.68	-	-	10.25 mannitol 12.6 laminarin 15.55 alginic acid 6.19 fucoidan	-	-
British Virgin Islands (2016)b	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 & Caicos (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 wt)	-	-	20 total carbohydrates 20 alginates 20 fucoidan	0.27 (tot fat)	-
Brazil (1998)	*S. fluitans* at low tide (N/A)	12.8	-	-	-	-	-	-
Nigeria (2012)a	Mixed (N/A)	15.4	9.0	8.65	7.15	57.3	2.5	23
Nigeria (2012)b	*S. fluitans* onshore (N/A)	6.55	14.33	18.5	17	58.72	1.9	-

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

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

Nigeria (Solarin *et al*. 2014). 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) monounsaturated 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% of total fatty acids), particularly palmitic acid. PUFAs were also found in large amounts (29.3% of total fatty acids), particularly Omega-6 (arachidonic and linoleic acids) and Omega-3 (Docosahexaenoic acid (DHA)). These values corroborate 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 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 they do not have 'roots' and therefore obtain 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, whilst 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 macro and micronutrients and minerals that show significant variation (by several orders of magnitude) in reported values, as summarized in the 'Mineral/Nutritional Composition' Table 2 presented here.

Nitrogen values vary greatly amongst studies, where values between <1 to 7,600 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 to 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 amongst samples from <1 to 69,359 ppm. Magnesium varies between 30 and 18,241 ppm. Calcium is relatively high, between 2,035 and 136,146 ppm. Likewise, sodium is high, varying from 109 to 78,094 ppm. Highly variable amounts of aluminum are reported for 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 Heavy Metal Composition Table 3). In general, arsenic has been found in high concentrations across all studies, varying between 11.5 and 172 ppm. However, it is important to make a distinction between organic and inorganic arsenic,

Table 2. Summary of compositional analyses of mineral/nutritional components of pelagic sargassum. Units are parts per million (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	1990-46002	<2915-13662	23723-136146	<3-11	<5-17	<6-540	40-139	<140-517	747-53101	-	-
British Virgin Islands (2016)	Mixed from beach (N/A)	-	-	-	-	-	-	-	-	-	-	-	-	85.3
Martinique (2015)	Mixed fresh onshore (2)	9800 (Tot N)	440-1460	71.54	11820	38060	685-2120	11-14	3.14	33-49	-	-	34000-52230	-
Turks & Caicos (2019)	Mixed nearshore (1)	171	501	69359	12053	70306	3811	5.81	2.51	30.15	37.5	-	-	-
Barbados (2015)	Mixed (1)	7600	110	-	30	-	200	5.5	9.9	-	-	-	78094	-
Dominican Republic (2015)	Mixed (12)	-	761-1145	2208-33602	10211-18241	96901-133400	2-655	13-21	2-12	16-32	303-4188	-	3802-21068	-
Jamaica (2019)	Average of *S. fluitans* & *S. natans* (1)	2377 (NO_3)	51 (PO_4)	348	1013	2035	894	-	264	-	-	-	109 (Na ii)	-
Nigeria (2012)a	Mixed (N/A)	63.6	965.0	280.0	427.5	-	87.0	0.5	-	-	-	-	-	0.4
Nigeria (2012)b	*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	-	-	1209-5910	16-100	22-36	-	-	22.5-1353.2	-	-

*Reference for each location: Mexican Caribbean: Rodríguez-Martínez *et al*. (2020); British Virgin Islands: Ocean Harvest Technology (2016); Martinique: IT2 & ADEME (2015); Turks & Caicos: Milledge *et al*. (2020); Barbados: Wilson-Howard (2015); Dominican Republic: Fernández *et al*. (2017); Jamaica: Webber *et al*. (2019); Nigeria (2012)a: 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 (NO_3), phosphate (PO_4).

Table 3. Summary of compositional analyses of heavy metals in pelagic sargassum.
Units are parts per million (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)	24-172 (median 80)	-	-	<2	-	<2-3	<8
British Virgin Islands (2016)	Mixed from beach (N/A)	45	17.3	27.7	0.169	<0.005	0.32	-
Martinique, Guadeloupe (2015-2016)	Mixed fresh & dry onshore (11)	11.50-100.8 (average 68.26)	-	-	<0.2-1.02	<0.1	<5.3-1.2	5.2-10.6
Turks & Caicos (2019)	Mixed 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 & 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	-

*Reference for each location: Mexican Caribbean: Rodríguez-Martínez *et al*. (2020); British Virgin Islands: Ocean Harvest Technology (2016); Martinique & Guadeloupe: IT2 & ADEME (2015) and Tirolien (2019); Turks & Caicos: 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).

where the latter is considered as highly toxic. Very few studies have looked at the speciation of arsenic, todetermine 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 (200 miles 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 what is being tested (e.g. soil, water, fertilizer, etc.). 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 to other locations. This is thought to be linked with 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 we are aware.

1.4.4 Secondary metabolites

There is very little information available to date 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). They considered this to be quite high and 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 analyzed for carotenoids from Jamaica, where 0.115 µg/g (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.

Section 2
Potential uses of sargassum biomass

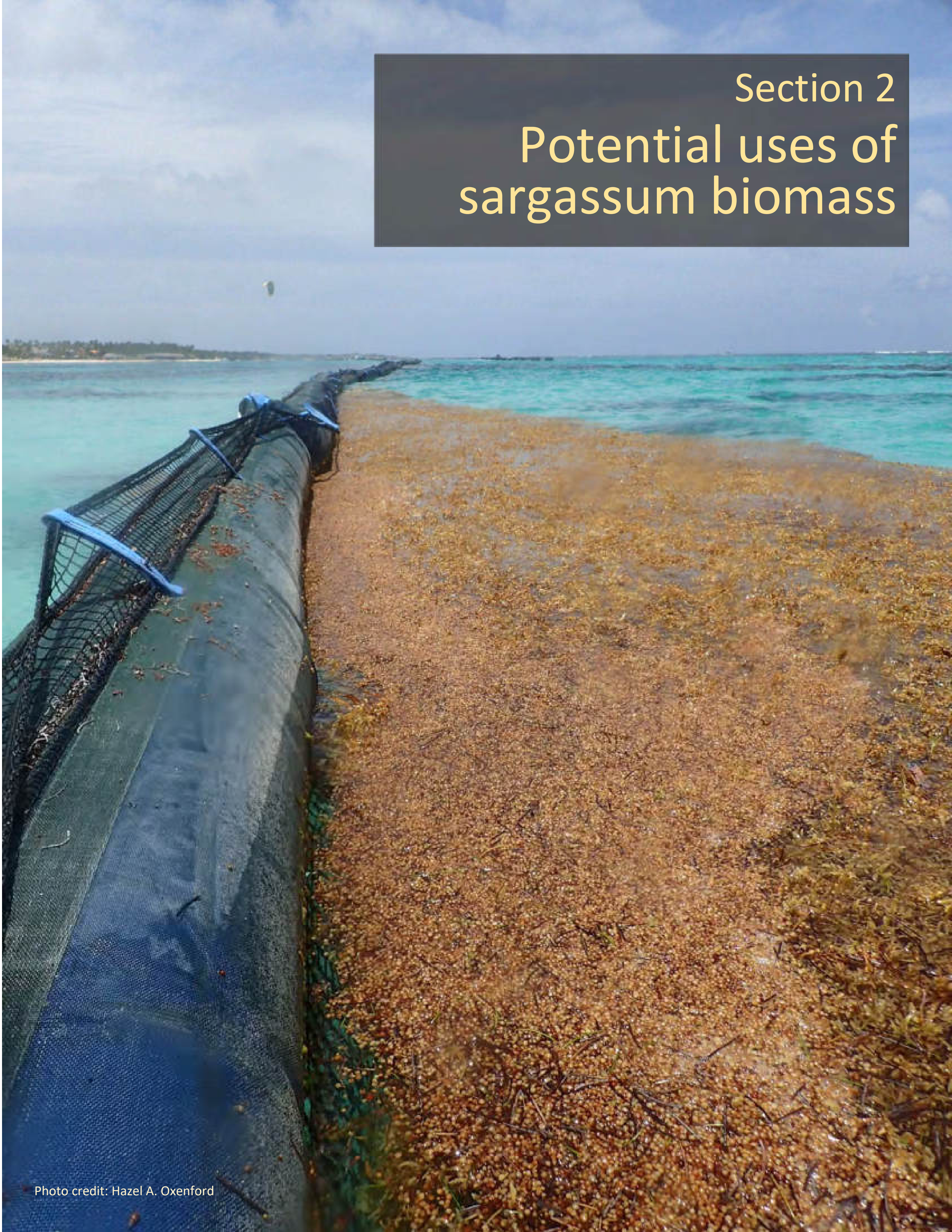


Photo credit: Hazel A. Oxenford

2. Potential uses of sargassum biomass

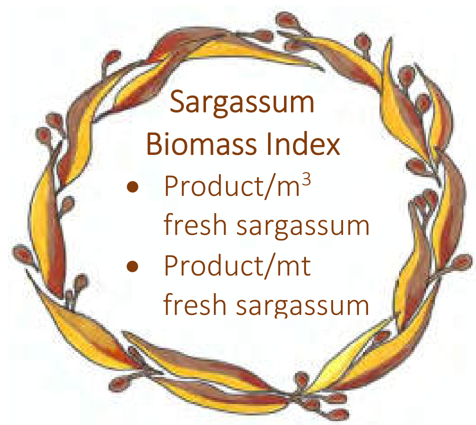
2.1 Overview

Use of seaweeds in a wide range of industries is not new, with an estimated 12 million tons of seaweeds being used each year across the globe, particularly in Asia and the Pacific, where the food industry takes 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 not surprising that the region has been relatively slow in responding to the unprecedented influxes of pelagic sargassum as an opportunity rather than just a hazard.

In this Section we examine the multiplicity of uses for seaweeds across the globe, with a particular focus on the brown seaweeds (Phaeophyceae) - the major group to which the sargassum species belong. We also highlight some examples using sargassum species from other regions and within the Caribbean, linking these to the examples detailed in Section 3.

2.1.1 Scalability: Sargassum Biomass Index (SBI)

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



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.

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 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 our 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. We recognise however, that there is considerable variation in the weight to volume conversions used across the region for sargassum (see Table), largely due to the degree of compression of samples and also on the state (freshly landed, beach dried, partially decomposed), sand content and mix of species. As such we reiterate that our SBI is a crude guide, but a useful relative index, since it is applied across all uses and therefore comparable among uses.

This 'scalability' index gives a broad indication of sargassum biomass usage, which could be informative for researchers, entrepreneurs and policy makers, 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 scalability 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;
- **Social:** social impacts of the transformation process on local communities.

Summary of the variation in values for the weight (kg) of one cubic metre (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 hr)	Volume measured by water displacement. Conversion equation: Dry wt = 0.132 wet wt + 0.1301	
532	Fresh (wet)	Compressed in 1litre cylinder	Seagrass lab-UNAM
84	Fresh (oven-dried)	Compressed in 1litre 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) = 0.1651wet (kg) + 0.0184	
262	Fresh wet	Weighed in 22.3 litre bucket (compressed)	
43	Fresh (oven-dried)	Conversion equation: Dry (kg) = 0.1651wet (kg) + 0.0184	

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 our opinion, have not yet been adequately researched and reported.

In these cases, we have included a warning graphic as shown here. We have also provided a very brief bulleted summary of the key issues that may be of concern for each section (highlighted in an orange outlined box), and have given extra details and research results (outlined in grey) and possible solutions (outlined in green) in the main text, in cases where such information is available.

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

BEWARE

2.2 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 areas where animal feedstuff was scarce during long periods of the year, sheep, cattle and horses grazed on dry seaweed (Indergaard and Minsaas 1991, Makkar *et al*. 2016). Still today, it is not uncommon for animals living in coastal areas to supplement their diet with seaweeds that wash ashore.

North Ronaldsay sheep originating from the northernmost island of Orkney, Scotland, 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 spraying seaweed extracts on forages, and detailed analyses of seaweeds have shown that they 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, rabbits, ducks, fish, shrimp, oysters, molluscs and dogs. 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) (Chaves Lopez *et al*. 2016, Singh *et al*. 2015)

Acadian Seaplants Ltd., Canada, lists examples of benefits from using their Tasco ® seaweed-based food supplement for livestock production

  - Increased egg weight, albumen height, shell thickness and n-3 fatty acid content, improved yolk colour and reduced egg cholesterol and triglyceride content (Carrillo *et al*. 2008, Carrillo, Ríos, *et al*. 2012, Carrillo, Bahena, *et al*. 2012, Al-Harthi and El-Deek 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 being 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)
  - 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)
- ✓ Reduction of food-borne disease risk of 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)

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 for feeds containing seaweed supplements to avoid the transfer of toxins into the food chain and ensure animal wellbeing and human food safety.

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 (e.g. iodine) that may be harmful to some animals.

Many toxins, such as inorganic arsenic, cadmium, lead and mercury, that 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, many countries have tolerance guidelines or standards establishing maximum permitted levels in animal feed, as indicated here in the summary Table of heavy metal standards for Europe, Canada and the USA.

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) and 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 investigating the presence of heavy metals in a wide variety of animal feed materials from 2007-2013 in the Netherlands, identified seaweed meal and feed materials derived from seaweed as a high priority for arsenic monitoring because of 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 being used in animal feed because it causes diarrhea and dehydration related health issues (or even death in poultry) (Berger 2006, Abou El-Ezz and Younis 2010).

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

* Directive 2002/32/EC (feedingstuffs with 12% moisture content): Cadmium 0.5 ppm for other complementary feedingstuffs for cattle, sheep and goats. Lead 10 ppm and Mercury 0.2 ppm for complementary feedingstuffs. 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.
** CFIA 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.

In the United States, the Center for Veterinary Medicine (CVM) of the Food and Drug Administration (FDA) conducts an annual Mineral Surveillance Programme, as part of the Animal Feed Contaminants Programme in which samples of domestic and imported animal feeds are analyzed for heavy metals. The FDA CVM has not established specific tolerances or guidelines for heavy metal levels in animal food, however they take action on a case-by-case basis, and consider levels established by the National Research Council (NRC) and the Association of American Feed Control Officials (AAFCO) (Deemy and Benjamin 2019).

Signs of sub-acute and chronic arsenic toxicity reported in livestock vary from 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 kilogram of total diet. However, the Canadian Government lowered the maximum level of arsenic permitted in animal feed to just 8 ppm, in order to restrict potential human exposure.

The Table here 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).

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

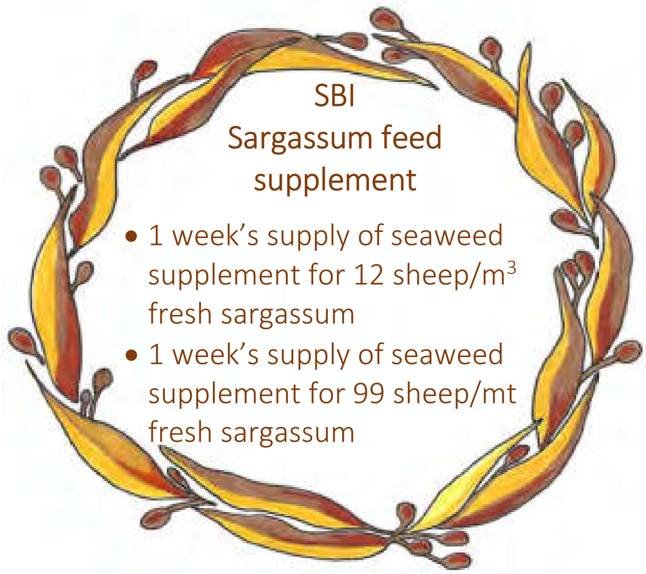
Item	Tasco-14 - *A. nodosum* seaweed meal*	Pelagic sargassum
Crude fiber (%)	6	7-33
Carbohydrates (%)	52	11-59
Ash (%)	22	9-46
Moisture (%)	12	9-14
Crude protein (%)	6	2.2-15.4
Minerals:		
Al (ppm)	20-100	< 140-4,188
As (ppm)	< 3	4-172
Ca (%)	1-3	20-1,361
Cu (ppm)	4-15	2-540
I (ppm)	< 1000	0.4-85
Mg (%)	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

* Results as published by Allen *et al.* (2001).

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 commercialised in the 1960s by Norwegian businesses, using the brown macroalgae *Ascophyllum nodosum* and 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, organic dairy farms commonly use seaweed meal as a feed supplement in low amounts (less than 5% 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 (macro-minerals: Ca, P, K, Na, S, Cl and Mg) or as trace amounts (micro-minerals: Fe, I, Cu, Co, F, Mn, Zn, Mo and



Improved digestibility in ruminants

- Ruminants (e.g. 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 the United Nations Food and Agriculture Organization (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 which 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% 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 mitigation measure. However, the long-term effectiveness has not yet been determined since rumen microflora is known to be highly adaptable.

Se)[2]. 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.

Brown seaweeds generally have the lowest protein content (mean of 10% dry weight) (Angell *et al*. 2016, Peng *et al*. 2015) 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 micro-minerals found in seaweeds are considered to be more efficient at delivering micro-elements 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 (Evans and Critchley 2014, Wiseman 2012). 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 the summary Table here.

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 & 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	Makkar *et al*. (2016); El-Banna *et al*. (2005)
Fish*	5-10	Moutinho *et al*. (2018); Yangthong, Oncharoen, and Sripanomyom (2014); Rajauria (2015)
Shrimp	2-5	Casas-Valdez, Portillo-Clark, *et al*. (2006); Sudaryono *et al*. (2018); Rajauria (2015)
Molluscs**	10-30 (% body weight)	Rajauria (2015)

*Fish: 5% *Sargassum* spp. fed to supplement sex-reversed tilapia diet; 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 mollusks 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 because of 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

[2] https://www.infonet-biovision.org/AnimalHealth/Animal-nutrition-and-feed-rations

animal growth performance and weight loss (Makkar *et al*. 2016).

Although it has been proven that goats and sheep can benefit from relatively high seaweed (e.g. *M. pyrifera* and *Sargassum* spp.) content in their diets (up to 30%), the animals will however drink more water due to an increase in mineral salt concentration (such as Sodium [Na] and Potassium [K]). This limits the practicability of this type of feed during dry periods (Marín *et al*. 2009, Casas-Valdez, Hernández-Contreras, *et al*. 2006, Makkar *et al*. 2016, Marín *et al*. 2003, Mora Castro *et al*. 2009). 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, whilst others have reported serious detrimental effects, including death (Makkar *et al*. 2016, El-Banna *et al*. 2005, Blunden and Jones 1973, Okab *et al*. 2013). Further research is clearly needed to ensure the safety of seaweed supplements for rabbits.

Animal husbandry applications of pelagic sargassum in the Caribbean

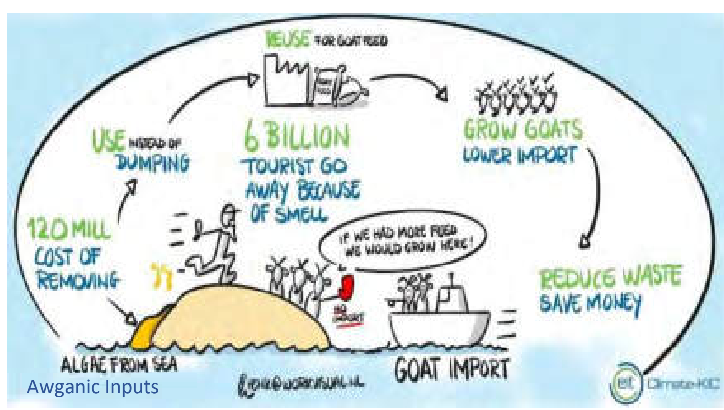
Research:

- **Amadéite Group** (Guadeloupe): Pilot project financed by ADEME to determine potential use of sargassum for improving animal, plant and human health (see Section 4);
- **Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán (INCMNSZ) – 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 (see Section 4);
- **PYROSAR project** (Guadeloupe & collaborators): valorisation of sargassum by pyrolysis and application for food safety (see Section 4);
- **SARGWA Consortium** (Guadeloupe): a pilot project was conducted to determine the potential valorisation of sargassum for animal feed (see Section 4).

Commercialisation:

- **Awganic Inputs** (Jamaica): Young entrepreneurs looking to commercialise a sargassum-based goat feed (see Section 4).

Livestock farmers in the Dominican Republic, Mexico, Jamaica and other Caribbean countries have reported exploring the use of pelagic sargassum as a feed supplement. As indicated in the orange box, there are a few ongoing research projects investigating the potential uses of sargassum in animal husbandry, however, there is only one entrepreneur in Jamaica (Awganic Inputs) that has been working to commercialise a sargassum-based feed supplement for goats.



Awganic Inputs cartoon promoting use of sargassum-based feed for local goat production.

2.3 Crop production

Seaweeds have been used in agriculture for many years across 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, bio-stimulants, 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).
- The high concentration of sodium (salt).

Poster produced by authorities in Martinique highlighting concerns with direct spreading of fresh sargassum resulting in soil salinisation

Mandatory analysis of metal contents (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 direct human contact.

Over the long-term, applying products with high salt content may cause soil salinisation, which can render soils unproductive and unusable for agricultural purposes. Soaking and washing algae in fresh water 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, 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 admendment purposes is common practice. For example, calcareous red algae are often applied in the United Kingdom, 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 collect sargassum, wash out the salt, and spread it around banana trees as a mulch and fertilizer[3].

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 is raising concerns and warning gardeners and farmers of the potential 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 to fields given the high risks of soil salinisation and potential levels of arsenic higher than permitted. Guideline values of arsenic in soil differ by country, although Canada, Argentina, Norway, New Jersey (USA) and the European Community all have recommended maximum arsenic levels in soil of 20 ppm (Tarvainen *et al*. 2013, FAO and WHO 2011).

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 sugarcane plants, which supports the findings of Reimann *et al*. (2009), who found that plants (with some exceptions) hardly take up arsenic from soils, however it can accumulate in soils over time. More research is needed to understand the environmental and human health impacts.

Biochar

Biochar produced with different precursors, including algae, is used as a soil amendment to improve soil properties, 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 have an increase in plant disease resistance (see section below on Crop Protection) (Elad *et al*. 2010). Although seaweed usually yields biochar with lower carbon content compared with typical lignocellulosic feedstock (e.g. terrestrial plants), it generally yields higher amounts of biochar,

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

contains high levels of exchangeable nutrients or 'cations' (such as calcium, magnesium, potassium etc.) and has a high cation exchange capacity (CEC) (Bird *et al*. 2011). CEC is an important soil property, which has 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) provides 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 yield 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.

Biochar produced from organic waste by Holdex in Martinique

One of the main drawbacks, however, is the high content of exchangeable sodium in seaweed biochar, which could contribute to increased soil salinity over 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 potential 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).

As indicated in the orange box below, the PYROSAR project led by Guadeloupe is determining the potential for use of sargassum-based biochar as a soil amendment and as for bioremediation to reclaim soil in areas contaminated by chlordecone[4].

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 to use in 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.

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[4] 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. Read more here: http://bit.ly/ChlordeconePOPs.

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).

As indicated in the orange box below, there are ongoing projects 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 commercialising sargassum mulch in the Dominican Republic and Mexico. Another company was also commercialising sargassum mulch in Barbados in 2011 under the brand name Ocean Surf[5].

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 (4 weeks aging) four weeks after sweet potato planting at a rate of 10 tons per hectare (mt/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 effects of mulch on different cultivars grown in different soil types and under non-drought conditions.

Sargassum mulch produced and commercialised in the wider Caribbean. Top: by Salgax, Mexico; bottom: by AlgeaNova in Dominican Republic

Compost

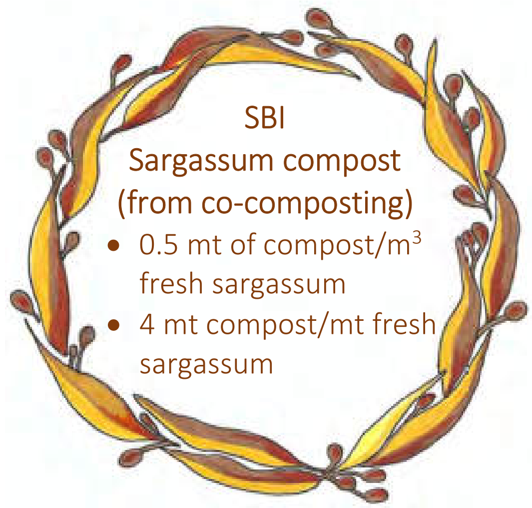
Using algal biomass for composting purposes has been a common practice in several countries, especially in coastal areas, and it is considered to be one of the simplest, cheapest and practical methods of effectively using large algal biomass (Eyras, Rostagno, and Defossé 1998). Green-tide seaweed composting 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 salinisation 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 of time, (2) mixing with other low salinity feedstocks and (3) the active turning of compost piles, allowing the salt to leach out. They

[5] https://www.nationnews.com/nationnews/news/1816/mulch-gain-sargassum

report that compost aged for a period of 20 months had significantly lower salt content compared with compost aged for 9 months. Another study determined that composting of algae containing high levels of salt was enhanced when 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).

Other potential issues 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 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 pretreatments and valorisation of sargassum, including pilot co-composting experimentation. Co-composting studies were carried out by the 'Institut Technique Tropical' in Martinique, '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 commercialisation 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 Agence de l'environnement et de la maîtrise de l'énergie (ADEME) and Direction de l'Environnement, de l'aménagement et du Logement (DEAL), where the composition of each batch of compost produced is analyzed to determine salt and heavy metal levels and product composition. Compost containing up to 10 percent sargassum is already being commercialised locally in Martinique.

Sargassum-based compost produced by AlgeaNova in Dominican Republic

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). They have been carrying out field experiments on the effects of compost application on various crops, and laboratory analysis to determine the composition of the end product.

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

Texas State University has also been carrying out co-composting trials using sargassum (4%) mixed with food waste (48%) and wood chips (48%) and have 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 for both the washed and unwashed sargassum compost. As such:

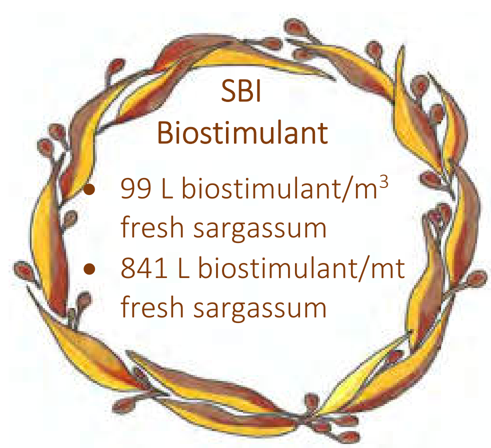
- This study concluded that pre-washing sargassum did not appear necessary to obtain a quality compost.
- However, caution must be taken to ensure runoff from the composting site is safely treated and properly disposed of.

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 EPA 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%).

A composting project is also ongoing at the University of the West Indies in Trinidad, to determine the potential for use in mangrove plant nurseries. The ECO$_3$SAR project is underway in collaboration with the company Holdex located in Martinique to determine sustainable valorisation options for sargassum, with a focus placed on co-composting.

A small-scale vermicomposting project is also being carried out in Guadeloupe by the 'Association pour une Agriculture Paysanne et Écologique dans la Caraïbe' (APECA) group using sargassum. Further research is needed, however, 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 not been any large-scale industrial production of algal-based fertilizers, particularly because of 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, which 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 will likely 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 the examples given here.

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

Country	Arsenic	Cadmium
New Zealand[6]	75 ppm	280 ppm in phosphorus fertilizers
USA-California (California department of food and agriculture)	2 ppm for each percent available phosphate	4 ppm for each percent available phosphate
Canada (Canadian Food Inspection Agency 2018)	75 ppm product (based on 4400kg/ha/yr application rate of product.	20 ppm product (based on 4400kg/ha/yr application rate of product)

Biostimulants, also called 'metabolic enhancers', are products used to: reduce the amount of fertilizer needed; enhance plant and root growth; promote early germination; and increase resistance to biotic and abiotic stresses (Feitosa de Vasconcelos and Garófalo Chaves 2019, Khan *et al*. 2009). 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 (Thomas *et al*. 2013b, Khan *et al*. 2009).

Although biostimulants are often used as a foliar-application (spraying 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, period at which the seaweed was collected, additives used to produce the end product and production method employed. Here are some examples of biostimulants made using brown seaweed extracts:

[6] https://ballance.co.nz/medias/Fertiliser-Association-Metals-Dec-Version-1-6-Oct-2014-2-.pdf?context=bWFzdGVyfERvY3VtZW50c3w1NDQyODV8YXBwbGljYXRpb24vcGRmfGgwYS9oMGIvODgwMzAzMDY2MzE5OC5wZGZ8MDFmMDdiNmM1ZjA0NGFiOTJiODY2Mjk4ZmQyOTdiZDc1YzBiN2ZjNzY3YzVkNTYwNjQ1NmM4YzY2M2I1MDA4Yw

- 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*. 2013b, Thomas *et al*. 2013a).
- 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 commercialised 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, root development, nutrient uptake, resistance to drought and to stimulate soil microorganisms[7].

As indicated in the orange box, there are several companies that have commercialised pelagic sargassum biostimulants across the Caribbean. In addition, several farmers have reported using sargassum to fertilize coconut trees (Antigua and Barbuda) and citrus trees (Dominica) (JICA and CRFM 2019). In Barbados, there has been some consideration given to using sargassum as a fertilizer in the sugarcane industry, where it was estimated that it could potentially increase yields by 20 percent (JICA and CRFM 2019).

Examples of sargassum-based fertilizers commercialised in St. Lucia (left), Mexico (centre), and Barbados (righthand images).

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. Properties such as antifungal, antibacterial, antiviral, antimicrobial and antiprotozoal have been widely studied (Perez, Falque, and Dominguez 2016, Vera *et al*. 2011). 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 defense 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 phytoelicitor 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 which have explored the bio-elicitor effects of various compounds in brown macroalgae include:

[7] http://www.agrilife.in/biostimulants_somzyme_sl.htm

- 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 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)
  - Powdery mildew on strawberries (Bajpai *et al*. 2019).
- β-1,3-glucan laminarin derived from *Laminaria digitata* showed an efficient elicitor defense response in grapevines to reduce the development of *Botrytis cinera* and *Plasmopara viticola*, two pathogens that have significant negative impacts in 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 there have not been many research projects looking at sargassum's bio-elicitor properties and potential crop protection applications, it is anticipated that the ongoing SARGOOD project will provide more information on this potential use.

2.3.3 Growth substrate

SBI
Sargassum-based growth substrate

- 13 kg mushrooms/m^3 fresh sargassum
- 114 kg mushrooms/mt fresh sargassum

Agricultural products like 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 ligno-cellulosic materials as growth substrate for mushrooms (Kaaya *et al*. 2012, Molloy *et al*. 2003, 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 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.

Experimenting with sargassum-based growth substrates for mushroom culture by CICY in Mexico

In Mexico, research on the potential of pelagic sargassum for use as mushroom growth substrate is being undertaken by the

Crop production applications of pelagic sargassum in the Caribbean

Research:

- **Amadéite Group:** offer solutions based on algae, clays and trace elements for improving plant, animal and human health. 6-month project to calibrate sargassum treatment process and optimization of extract of compounds (see Section 4);
- **Centro de Investigación Científica de Yucatán (CICY), Colegio Postgraduados**, Puebla Campus **& Universidad Popular Autó noma del Estado de Puebla (UPAEP)** (Mexico): ongoing research on the use of sargassum as growth substrate for mushroom cultivation (see Section 4);
- **ECO$_3$SAR project** (France & Guadeloupe): valorisation of sargassum, with a focus on composting (see Section 4);
- **INRA-Université des Antilles** (Guadeloupe): sargassum analysis of pollutants, composting and direct spreading (see Section 4);
- **Institut Technique Tropical - IT2** (Martinique): agronomic and toxicological analyses of effects resulting from application of pelagic sargassum compost and direct field spreading (see Section 4);
- **PYROSAR project** (Guadeloupe & collaborators): valorisation of sargassum by pyrolysis and application for food safety. Use of biochar for soil amendment (see Section 3.2.4);
- **SARGOOD project** (Guadeloupe & collaborators): holistic approach to sargassum valorisation including developing bioelicitors, biostimulants and other agricultural products (see Section 3.2.4);
- **SAVE project** (France & Martinique): sargassum agricultural valorisation including digestates (see Section 5.2.4);
- **SAVE-C project** (France, Martinique & collaborators): valorisation of sargassum including biopesticides (see Section 3.2.4);
- **Several municipal co-composting projects financed by ADEME** (Guadeloupe & Martinique);
- **University of the West Indies**: Researchers at the three campuses have been working on various projects for agricultural uses (see Section 3.2.2).

Commercialisation:

- **Algas Organics** (St. Lucia): is a pioneer in the development of sargassum-based plant-tonics in the Caribbean (see Section 4);
- **AlgeaNova** (Dominican Republic): are using sargassum for co-composting with other organic wastes and are also producing 100% sargassum mulch (see Section 3.1.3);
- **Alquimar** (Mexico): is commercialising a biofertilizer called Alquifert (see Section 4);
- **Dianco México** (Mexico): are in the process of developing a sargassum-based fertilizer (see Section 4);
- **Holdex** (Martinique): have been using sargassum in co-composting with other organic wastes and have an interest in producing sargassum biochar (see Section 4);
- **Moon Palace Resort** (Mexico): they have been producing sargassum-based compost and using it on the hotel compound.
- **Red Diamond Compost** (Barbados): have been commercialising a sargassum-based biostimulant called Super Seaweed (see Section 3.1.4);
- **Salgax** (Mexico): are commercialising a range of sargassum-based fertilizer and mulch (see Section 3.1.7);
- **Sargasso Organics** (Barbados): have commercialised a sargassum-based fertilizer in stores across Barbados (see Section 4);
- **Suez** (Guadeloupe): sargassum co-composting (see Section 4).

'Centro de Investigación Científica de Yucatán' (CICY), in collaboration with the 'Colegio de Postgraduados' (Campus Puebla) and the 'Universidad Popular Autónoma del Estado de Puebla' (UPAEP)[8,9].

Summary of uses in agriculture

Extensive research over the last 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, biostimulant, soil amendments, etc.) to improve soil properties and fertility, for better resistance against certain pests, and for increasing 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 other components detected in several pelagic sargassum samples can also damage soils over the long-term and 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 commercialisation 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 agri-businesses from a number of countries in the region are currently commercialising sargassum-based fertilizers and biostimulants.

[8] https://www.cicy.mx/noticias-y-eventos/boletin-15-cicy-propone-estrategia-integral-para-el-aprovechamiento-del-sargazo?fbclid=IwAR3zikHq73a5m617E_3jy6lN-TYup2GIRMa48AmuX7rn_cSdGdDe6bU4EDI

[9] http://colpospuebla.mx/sargazo/sargazo

Antifouling

2.4 Antifouling

Marine biofouling presents a number of challenges for marine vessels and for industries with marine installations (e.g. those using piped seawater for cooling, mariculture operations, desalination plants, etc.). When aquatic organisms settle and grow on vessel hulls and propellers (see image), it decreases hull efficiency and vessel speed, resulting in additional fuel usage and increased emissions of air pollutants and greenhouse gases[10]. Biofouling is also a source of invasive alien species when vessels travel to different places or even through different oceans. Biofouling can also decrease the efficiency or even block pipes, and stop moving parts from functioning (e.g. pumps), and weigh-down mariculture infrastructure (e.g. cages, nets, floats) (Amara *et al*. 2018). As such there is high demand for antifouling treatments globally.


Photo credit: Yachting-pages

Yacht hull showing extensive marine fouling.

However, some of the most effective antifouling paints contain chemical compounds that are highly toxic to a broad range of marine organisms even at very low concentrations, such tributyltin (TBT). 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, and 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 defense 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 (*Ulva fasciata* and *Codium tomentosum*) and red (*Corallina mediterranea*) seaweeds are very 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' had good antifouling capabilities and no cytotoxicity, and thus shows promise for use in environmentally-friendly antifoulants (Li *et al*. 2018). Secondary metabolites accumulated by macroalgae are assumed to play a role in their

[10] International Maritime Organization Website: http://www.imo.org/en/OurWork/Environment/Biofouling/Pages/default.aspx

defense 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 defense 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).

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%), polyunsaturated fatty acids (29%), mono-unsaturated fatty acids (19%) and unidentified fatty acids (15%), as described in the Composition Section. Palmitic acid was the predominant fatty acid, followed by oleic acid.

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 (see Section 3.2.4).

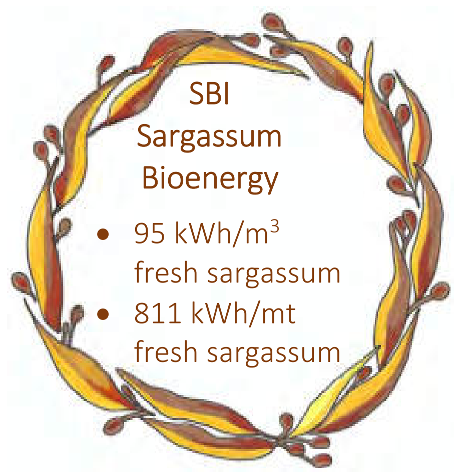
The orange box indicates the only on-going project in the Caribbean, to our knowledge, regarding pelagic sargassum and its potential antifouling applications.

Summary of uses for antifouling

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

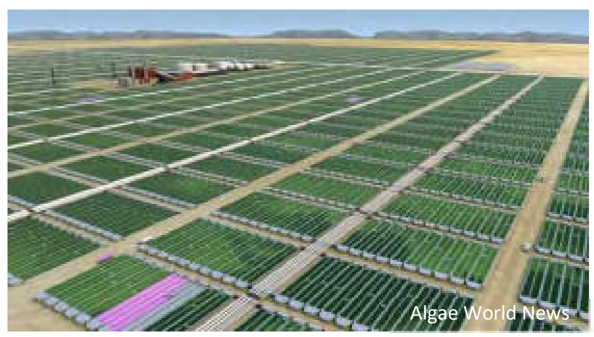
Bioenergy

2.5 Bioenergy



Bioenergy is a term used to describe the use of organic material derivatives to produce energy, which can take the form of liquids (e.g. biofuels), gas (e.g. biogas) or solid (e.g. 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, sugarcane and oil seed (Chaker Ncibi, Menyar Ben Hamissa, and Gaspard 2014). Use of algae as feedstock to produce bioenergy/biofuels, referred to as 'third-generation biofuels', is very 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). In this section, we review four potential renewable energy options using algae: (1) bioethanol, (2) biodiesel, (3) biomethane, and (4) biopellets.

2.5.1 Bioethanol



Example of commercial scale microalgae hydrothermal processing to produce bioethanol

Bioethanol, used as a transport fuel, can be produced from algae by converting the carbohydrates to ethanol using a multi-step process including: pretreatment; hydrolysis; and fermentation. Pretreatment converts the algal biomass to complex carbohydrates (complex sugars), and is an important and generally costly step of the process (Li *et al*. 2018). Pretreatments 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 (i.e. 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 pretreatments, hydrolysis and microorganisms required for fermentation to produce the highest bioethanol yield. Some examples include:

- 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 pretreatment (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 fermentor 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 very 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 pretreatment, hydrolyzing 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 good 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 six 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 production of renewable biofuels, their commercialisation in bioethanol production remains challenging. This is primarily due to the cost of pretreatments 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, Milledge, Nielsen and Harvey 2018).

As indicated in the orange box at the end of this section, 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

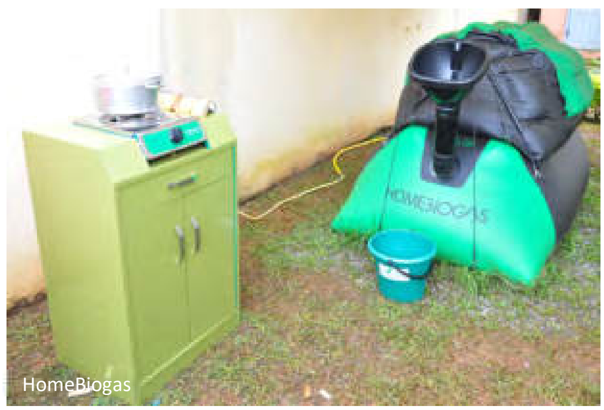
Biodiesel is a renewable and highly versatile transport fuel that is derived from natural oil sources including vegetable oil and animal fats, and is considered as a better option than petroleum diesel in terms of environmental impacts because it is carbon neutral (i.e. its production and use does not add carbon dioxide to the atmosphere) (Chaker Ncibi, Menyar Ben Hamissa, and Gaspard 2014). Feedstock that are used in different countries depend on what raw biomass is available, such as rapeseed or soybeans in the United States 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, we will not delve further into microalgae-based biodiesels.

Not surprisingly, there are no research projects in the Caribbean, to our knowledge, that are exploring biodiesel production using pelagic sargassum.

2.5.3 Biogas (biomethane)

Biogas can be produced from a wide range of feedstocks when compared to bioethanol that requires high sugar content, or biodiesel that 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.



Examples of anaerobic biogas digesters. *Top*: shows a medium-scale operation. *Bottom*: shows a small-scale domestic unit.

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, however 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 looking at 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). Additionally, 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 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 etc. (Chen *et al*. 2015, Paul, Melville, and Sulu 2016). In addition, 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 (e.g. milling); physical (e.g. thermal, pressure, microwave, ultrasound); chemical (e.g. acid, alkali); and use of enzymes. The effectiveness of pre-treatments depends on several variables including the type of algae used (Paul, Melville, and Sulu 2016, Montingelli *et al*. 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, which include 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 investigations are 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 is associated with several elements 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 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 (i.e. use of sargassum as the sole feedstock) is unsuitable for methane production, co-digestion with other organic waste material can increase the amount of energy recovered by as much as five times (Thompson, Young, and Baroutian 2020). A pilot project carried out in St. 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 pretreatment increased methane yield by 20 percent (Tapia-Tussell *et al*. 2018). This effective pretreatment could allow for scaling 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 the orange box at the end of this section.

2.5.4 Biopellets

Biopellets are made of biodegradable materials such as agricultural waste (e.g. crop stalks, husks, shells, bagasse), forest residues (e.g. sawmill residues, branches, leaves) and solid waste (e.g. paper). They are used to heat buildings and in cooking and can be used at industrial scales to reduce energy costs of large-scale operations. Biopellets are considered as a sustainable alternative to petroleum-based fuel because they are made from renewable materials, they are efficient, clean, economical, environmentally friendly and responsible[11].

Example of the appearance of standard biopellets

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

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 learnt from the few studies to date. One study examined the potential for production of biobriquettes[12] from carbonized brown macrolagae, but found it 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 were suitable for use directly in boilers. However, it was determined that they could be used for other industrial purposes or for animal feed.

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

As indicated in the orange box below, despite a lack of successful application of macroalgae in biopellet production from published literature to date, promising results have been obtained by 'Energryn' in Mexico, mixing sargassum with other organic waste to produce biopellets for use in local hotel boilers.

Bioenergy production using pelagic sargassum in the Caribbean

Research:

- **Centro de Investigación Científica de Yucatán (CICY)** (Mexico): Dr. 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 (see Section 4);
- **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 (see Section 4);
- **Innovation Développement** (Guadeloupe): Recipient of Ademe grant in 2016 for a pilot sargassum methanization trial (see Section 4);
- **SAVE** (France/Guadeloupe/Martinique): On-going study on anaerobic digestion of sargassum and factors affecting methane production (see Section 3.2.4);
- **University of the West Indies** (Barbados & Trinidad): Researchers at both Cave Hill & St. Augustine campuses are investigating the potential use of sargassum to produce biogas and bioethanol (see Section 3.2.2);

Commercialisation:

- **Biogen** (Barbados): This company is investigating anaerobic co-digestion of sargassum (see Section 4);
- **Damen / Maris Group** (Netherlands): This group has been investigating further use of sargassum in biofuel applications (see Section 4);
- **Energryn** (Mexico): investigating the use of sargassum blended with other organic wastes to produce biopellets for use in local hotels (see Section 4);
- **EnergyAlgae** (Israel & Dominican Republic): This collaborative project between YA MAOF, UNAPEC and AlgeaNova has implemented a pilot in Punta Cana (DR) to determine the use of sargassum in anaerobic biogas co-digestion units (see Section 3.1.3);
- **Hotels in Cancun and neighboring 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): The company is investigating the potential use of sargassum as feedstock in the patented dry methanization mobile technology Hemer (see Section 4);
- **Num SMO Technologies** (Guadeloupe): pyrolysis of sargassum to produce electricity and activated carbon (see Section 3.1.8);
- **SARA** (French Guiana & Guadeloupe): 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 (e.g. pyrolysis) to produce biofuel (see Section 4);
- **The Pelikan System** (St. Barts): The company Green Engineering S.A.S. proposes a complete 'autocombustore' system fed with bio-sargassum pellets to generate electricity through an electric turbine generator (see Section 4).

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 of *Sargassum* spp. to produce reasonable yields of bioethanol through fermentation by micro-organisms has been demonstrated. However, commercialisation of the process remains challenging, largely due to the high cost of pre-treatment needed to make the seaweed suitable for fermentation, and the need to identify suitable salt-tolerant microorganisms. Sargassum (and seaweeds in general) are 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 that interfere with the digestion process such as sulphur and heavy metals) 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 in the use of brown seaweeds to produce biopellets as a sustainable solid fuel reported in the literature.

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 commercialise biomethane for small and medium to large-scale production. There have also been some promising results 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.

Bioplastics

2.6 Bioplastics

Plastic pollution is a worldwide concern, with many plastics taking 1000 years to decompose (Kale *et al*. 2015). Over 300 million tons 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, with as much 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. Over 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 (e.g. corn starch), cellulose-based (e.g. woodchips and sawdust), protein-based (e.g. wheat gluten, casein and milk), organic polyethylene (e.g. fermented agricultural waste) and aliphatic polyesters (e.g. polylactic acid (PLA), polyglycolide (PGA) and polyhydroxyvalerate (PHV)).

There are different end-of-life options for bioplastics, including recycling, composting, incineration, anaerobic digestion or 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[13]. These criteria are mainly related to time, environmental conditions and quality of compost produced[14]. 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, biodegradability tests and ensure access to adequate facilities to dispose of or recycle material 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 sugarcane. However, these are not fully in accordance with the UN's Sustainable Development Goals (SDGs) because they need arable land and fresh water, 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 ensure compatibility with scaling circular bioeconomies (Karan *et al*. 2019). However, microalgae are not easily harvested compared with macroalgae.

Research supporting the commercialisation 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). Their polysaccharide composition 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

[13] http://www.bioplastics.guide/ref/bioplastics/standards-and-certifications/
[14] https://bpiworld.org/page-190422

also be used directly as compressed biomass in the manufacture of materials suitable as alternatives for single-used 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 the 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 EU funded project called SEABIOPLAS studied the production of seaweeds as feedstock in sustainable Integrated Multi-Trophic Aquaculture (IMTA) systems for the development of bioplastics[15]. 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 in dairy farms. Results revealed two bioplastic supply chains from two distinct seaweed species: PLA from *Ulva lactuca* and polysaccharide films from *Gracilaria vermiculophylla*.

The French Brittany-based Algopack company, founded in 2010, is the first manufacturer of bioplastics made from cultivated brown algae[16]. After the seaweed is harvested, it is turned into granules using a patented process and used in two different bioplastics: Algoblend (50% seaweed and 50% oil-based plastic) and Algopack (100% seaweed). Algoblend is considered more versatile and is used for more permanent items such as office equipment, construction material, toys, etc. Algoblend is also suitable for industrial extrusion, thermoforming and injection processes without needing any technical adjustments, and even improves the energy output of presses (25% energy savings due to reduced manufacturing temperature). Algopack is used for single-use items such as disposable packaging. Algopack granules are completely biocompostable and biodegrade within 12 weeks in soil, and 5 hours in water.

Examples of 'Algopack' bioplastic end products made from 100% seaweed: flowerpots, USB flash drive and disposable food packaging.

Several studies have investigated the use of sargassum species as feedstock and as a source of extracts to produce

[15] https://cordis.europa.eu/project/id/606032/reporting
[16] http://www.algopack.com

Bioplastics made from pelagic sargassum in the Caribbean

Research:

- **Clemson University & Rochester Institute of Technology** (USA): nanocomposite films with *Sargassum natans* (see Section 4);
- **NOVUNDI Environnement & AlgoPack** (France & Guadeloupe): Recipient of a grant from Ademe in 2016 to evaluate the feasibility of producing sargassum-based bioplastics (see Section 4);
- **University of the West Indies** (Barbados & Trinidad): Researchers at both Cave Hill and St. Augustine campuses are exploring sargassum for use in the manufacture of bioplastic (see Section 3.2.2);

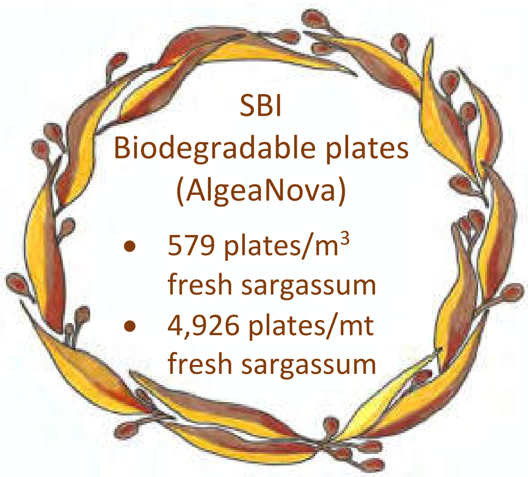
Commercialisation:

- **Abaplas** (Mexico): Currently testing production of a bioplastic made of 30% sargassum and 70% plastic for use in different applications, including ecological housing (see Section 4);
- **AlgeaNova/EnergyAlgae** (Dominican Republic): The team has started to produce single use plates made with 50% sargassum and 50% cassava (see Section 3.1.3);
- **Algopack** (France): With their knowledge using brown seaweed in France, they are exploring the possibilities of using sargassum to produce bioplastic (see Section 4);
- **EnerGryn** (Mexico): Currently testing production of two types of bioplastics: biodegradable pellets and recyclable bioplastic for use in making water heaters, cups and plates (see Section 4);
- **Groupe CAÏALI** (Martinique): an industrial consortium of three companies, is investigating the valorisation potential of sargassum to bioplastics under the GARAS project (see Section 4);
- **Le Floch Depollution** (France): Currently testing development of two different types of bioplastics made with (1) 30% sargassum and 70% thermoplastic resins (2) 40% sargassum and 60% polylactic acid (see Section 4).

bioplastics. *Sargassum* sp. was reported to be a promising feedstock for the bacterium *Cupriavidus necator* to produce polyhydroxybutyarte (PHB) bioplastic (Azizi, Najafpour, and Younesi 2017). Another study showed that alginates extracted from *Sargassum siliquosum* have promise for the synthesis of bioplastic film (Lim *et al*. 2018).

A recent study carried out in the US determined that novel seaweed nanocomposite biopolymer films can be made from *Sargassum natans* and *Laminaria japonica* extracts (Doh, Dunno, and Whiteside 2020). These have great 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 the orange box, several companies in the Caribbean region are looking to commercialise sargassum-based bioplastic.



Sargassum and cassava single-use plates from AlgeaNova

Seaweed bioplastic granules by Algopack

Sargassum-based water heater, plates and glasses from EnerGryn

Summary of uses for bioplastics

Bioplastics are typically made from plant-based material, especially agricultural crops (such as corn, sugarcane and sugar beet). However, manufacture of bioplastics is now possible from seaweeds, which has an added advantage of not competing for land space used 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 many examples of ongoing research and commercialisation ventures across the Caribbean region that are experimenting with pelagic sargassum to manufacture a variety of bioplastics.

Bioremediation & purification

2.7 Bioremediation and purification

2.7.1 Water and wastewater treatment

A recent review of literature on the use of seaweeds for wastewater treatment indicates that they have good biosorption properties and show promising results in removing pollutants such as dyes, heavy metals and other compounds such as 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 blue box) can be produced from different types of seaweeds, including brown seaweeds (Altenor *et al*. 2012, Salima *et al*. 2013). Activated carbons are well known to be very effective at removing metal ions, dyes and chlorinated compounds from drinking water and wastewater.

Activated Carbon (AC)

- Characterized by 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 early 20th Century.
- Traditional materials used as precursors for AC include coal, coke, wood, bamboo, sugarcane 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 & beverage processing, and the automotive industry.
- Global market value of AC is estimated at US$4.72 billion (2018).
- Large market opportunity in the Caribbean (Dominican Republic alone imports > 1,700 mt per year of granular AC).

The adsorption capacity of activated carbons varies according to the botanical composition of the precursors, 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, and indicate 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%.

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

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

Examples of research and commercialisation of sargassum for bioremediation and purification in the Caribbean are given in the orange box.

Bioremediation and purification applications of pelagic sargassum in the Caribbean

Research:

- **Center for Applied Physics and Advanced Technology (CFATA), Autonomous University of Mexico (UNAM)** (Mexico): Developing sargassum filters for bioremediation, removing contaminants such as metals, sulphates and pigments from water (see Section 3.2.6);
- **COVACHIM-M2E laboratory** (University of Antilles in Guadeloupe & French Guiana): Creating sargassum AC for soil remediation, pesticide sequestration in animals and water treatment applications (see Section 3.2.1);
- **Instituto Tecnológico de Santo Domingo (INTEC)** (Dominican Republic): Testing sargassum-based AC for water treatment and other applications (see Section 4);
- **PYROSAR project** (Guadeloupe/Martinique): Optimizing the production of sargassum AC and biochar to adsorb the pesticide chlordecone in contaminated areas to allow for safe food production (see Section 3.2.4);
- **SARtrib project** (Guadeloupe): Examining potential of sargassum nano-carbon and nano-oxide for use in filtering pollution gases (see Section 3.2.4);
- **University of the West Indies** (Trinidad): Extracting sargassum polymers to create membranes for use as biofilters in the remediation of heavy metals in wastewaters (see Section 3.2.2).

Commercialisation:

- **Grupo TMM** (Mexico): Implementation of an industrial plant to produce gas, electricity and AC through sublimation using sargassum and organic waste (municipal & cruise ships) (see Section 4);
- **NBC & Tecmalab** (French Guiana & Dominican Republic): Commercialisation potential of sargassum-based AC for water and air treatment applications (see Section 4);
- **Num-Smo Technologies (NST)** (Guadeloupe): Using solar pyrolyzer to transform biomass (including sargassum) into gas, electricity and AC (see Section 4).

Summary of uses for bioremediation & purification

Living pelagic sargassum (like most seaweeds) has excellent biosorption properties meaning that it is capable of removing a variety of contaminants (e.g. 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 a 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 commercialisation ventures involving the use of sargassum in environmental bioremediation and purification systems.

Clothing, footwear & accessories

2.8 Clothing, footwear and accessories

SBI
Sargassum shoe soles
(Renovare)

- 261 pairs of shoes/m^3 fresh sargassum
- 2,220 pairs of shoes/mt fresh sargassum

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, here are a few 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, Smartfiber AG). SeaCell has gained popularity in sportswear, yoga wear, sheets, towels, blankets and baby clothing[17] (Rana *et al*. 2014).

Al-life.com

Comparison of resources used to make a conventional T-shirt versus one using the Algalife technology.

- The Israeli and German-based Algalife company created the brand 'Algae Apparel', using algae bio-fibre 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[18].
- The Swiss-based Beyond Surface Technologies company 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[19].
- The Hong Kong-based Fabric Workshop company, in collaboration with Chaintex, have developed an algae-based fibre called ‘Celp’, using cellulose and algae yarn. Celp fibres have anti-bacterial properties and generate negative ions which are said to be beneficial to humans[20].

[17] smartfiber.de/en/fibers/seacelltm/
[18] alga-life.com
[19] checkerspot.com/Matthias-foessel/
[20] thefabricworkshop.net/celp

- The Mississippi-based Algix company is commercialising Bloom Algae Foam, a microalgae-based foam used in footwear, yoga mats, backpacks, surfboard traction pads and other applications[21]. They teamed up with a Taiwanese supplier and have been producing the algae foam for five years in 70 factories, for 63 brands.
- AlgiKnit, a Brooklyn-based biomaterials company, 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[22].

Slater Designs Traction pad for surfboards made with algae

Example of AlgiKnit's yarn made from kelp seaweed

Clothing & footwear from pelagic sargassum in the Caribbean

Commercialisation:

- **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 (see Section 3.1.5).

Sodium alginates extracted from brown seaweed are often used in the textile printing industry. They are used to thicken dye containing 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, hence the reason 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 considered as a good candidate for use as a natural dye for textile applications (Rani *et al*. 2020).

Summary of uses for clothing, footware & 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 more expensive than the widely used starch.

The only known use of pelagic sargassum in Caribbean fashion industry to date is as a component of shoe soles.

[21] algix.com/#bloom
[22] algiknit.com

Construction materials

2.9 Construction materials

SBI
Sargassum bricks
(Sargablocks)

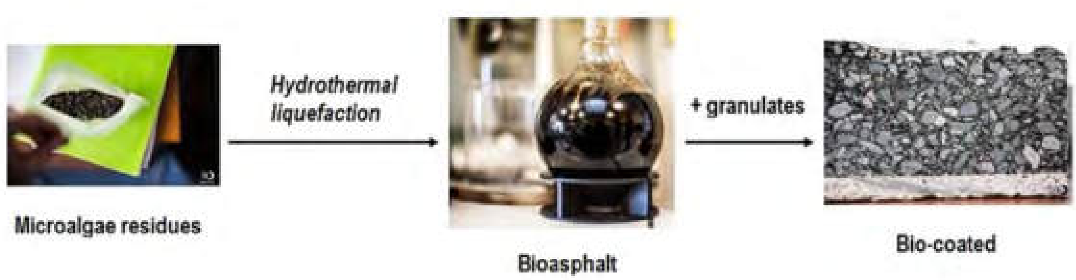
- 13 building blocks/m^3 fresh sargassum
- 108 building blocks/mt fresh sargassum

Biomaterials are attracting more interest and commercial attention for use as 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 use of innovative 'SolarLeaf' technology has been piloted on the four-story Bio Intelligent Quotient House in Hamburg, Germany by Arup design, Colt International and Strategic Science Consult. It is the world's first bio-reactive integrated façade system, which cultivates microalgae to generate heat and biomass as a source of renewable energy. The algal biomass and heat generated by the 129 algae filled tanks on the façade are transported to the building's energy management centre via a closed loop system, where the biomass is harvested by floatation and the heat by a heat exchanger. This zero-energy loss system is flexible, as it can be used for power and heat generation[23].

Bio Intelligent Quotient House in Hamburg, Germany with its 'SolarLeaf' façade of flat panel glass bioreactors containing microalgae that produce bioenergy and heat for the building.

- The Algix company 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 sound proofing and temperature control for houses, to cover pipes and other applications.
- Microalgae residues have also been used in the production of bio-asphalt (Audo *et al*. 2015).



[23] arup.com/projects/solar-leaf

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

- The Las Vegas-based Tamarisk Technologies Alginix company uses an alginate extracted from the brown seaweed, 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 with 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 incorporation of marine bio-fillers improved moisture resistance 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 architecture; cabinetry; furniture; acoustic and insulating panels; division panels and screens; architectural linings; and ceiling panels (Echeverria *et al*. 2017).

Insideflows

Chair and lampshade made from seaweed and paper by designers Jonas Edvard and Nokolaj Steenfatt

- Biopolymers extracted from brown seaweed have shown good properties 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). Highest strength was seen with the use of soil with low clay content, combined with medium viscosity alginate from the brown seaweed *Laminaria hyperborean* stem.

Demonstration by University of New South Wales (UNSW) researchers showing various particleboards made from brown seaweed and mollusc waste.

As shown in the orange box, there are a few ongoing projects in the Caribbean region using pelagic sargassum to develop different building materials including eco-panels, resin-board, construction blocks and bio-asphalt.

SargaBlocks produced in Mexico
by Omar Vazquez

Construction materials from pelagic sargassum in the Caribbean

Research:

- **SarGood project** (Guadeloupe): research and development on innovative eco-materials and panels (see Section 3.2.4).

Commercialisation:

- **Biogen** (Barbados): The company has carried out trials to make a sargassum-based resin board for industrial development (see Section 4);
- **Sargablock** (Mexico): since 2015 Omar Vázquez Sánchez has been making sargassum-based construction blocks to build housing for low-income families (see Section 3.1.1);
- **The Marine Box** (Martinique): this start-up company is looking to add sargassum to bioasphalt for use in paving roads (see Section 4).

Summary of uses for construction materials

Seaweeds are being used in the production of composite material for use in a variety of construction material, such as resins, foam boards, plastic sheeting, particleboards, slabs, bricks, bio-asphalt and even in 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 paneling, and as an additive in bio-asphalt. Furthermore, one company in the region has already successfully developed and commercialised a pelagic sargassum-based brick now being used in the construction of low-cost housing and other applications in Mexico.

Cosmetics

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, antibacterial, anti-inflammatory and anti-aging properties as well as high moisture retention ability, which are all beneficial properties for skin care products.

A recent review of cosmeceutical (both cosmetic and pharmaceutical) uses of seaweed bioactive compounds for skin care indicates that they have excellent skin protection ability, particularly for use as anti-acne, anti-bacterial, anti-microbial, antioxidant and anti-aging products (Jesumani *et al*. 2019). Bioactive compounds in seaweeds can absorb 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.

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 its 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 food and beverages, pharmaceuticals, agricultural, biomedical, cosmetics, paper, ceramics and welding industries.
- 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 (PGA) is widely used as a food additive. For example, it is used to stabilize beer foam, and to increase shelf life, preserve 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 aging and UV exposure (Shanura Fernando *et al*. 2018). Brown seaweeds also synthesize phlorotannins, a diverse set of polyphenolic polymers, well known for their potential for use in anti-melanogenesis and anti-aging (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 good 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 good potential for sargassum-derived activated carbon (AC) in the cosmetics industry, where demand has been increasing for skincare and personal care products using activated carbon and charcoal in scrubs, facewash, masks, soaps, pore strips, toothpastes and toothbrushes.

Examples of skin care and personal care products using charcoal.

As presented in the orange box, there are a number of examples in the Caribbean region related to research and commercialisation of pelagic sargassum for several cosmetic applications. The company 'Oasis Laboratory' in Barbados makes soap bars and uses sargassum as one of its ingredients. Seaweed soaps are said to provide moisturizing and regenerating effect to the skin.

Sargassum bath bars produced by Oasis Laboratory in Barbados

Cosmetics made from pelagic sargassum in the Caribbean

Research:

- **Nexo project, Tecnológico de Monterrey** (Mexico): A group of students are extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses in bath gels, creams and other cosmetics (see Section 4);
- **University of the West Indies** (Barbados, Jamaica, Trinidad & Tobago): researchers are working on alginate extract from pelagic sargassum for use in cosmetics and other products (see Section 3.2.2).

Commercialisation:

- **Alquimar & Grupo Metco** (Mexico): Extracting alginate from pelagic sargassum for use in several sectors including cosmetics (see Section 4);
- **Oasis Laboratory** (Barbados): Producing a sargassum skincare line, including bath bars (see Section 3.1.6);
- **Salgax** (Mexico): Looking to commercialise a sargassum hair treatment (see Section 3.1.7).

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 skin and hair care. 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, and has already been commercialised by one cosmetics company. There is also good potential for use of sargassum-based activated carbon in this industry which uses activated carbon from other sources in many cosmetic products.

Electrochemical industry

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 (Seok *et al*. 2019, Ji *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 more attention during the last 15 years because of 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. Using only metal oxides for electrodes can reduce the performance of a battery due to its lower electrical conductivity and unstable structure while cycling, however, 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-capacitors 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). This is the reason 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, stable in different types of solutions and at different temperatures as well as available in a wide range of materials (e.g. activated carbon, graphite, coke, mesocarbon microbeads, aerogel, carbon black, carbon nanotubes and nanofibers, etc.) (Gogotsi and Presser 2014, Inagaki *et al*. 2014).

As strange as it sounds, seaweeds are considered a great 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 ionic electrolytes (Taberna and Gaspard 2014). Key characteristics when selecting a material for nanotextured carbons are accessibility, affordability, processability, adaptability (form, porosity and surface functionality) (Gogotsi and Presser 2014).

Different types of seaweeds, 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 (Raymundo-Piñero *et al*. 2011, Pintor *et al*. 2013, Bichat, Raymundo-Piñero, and Béguin 2010, Perez-Salcedo *et al*. 2020).

As presented in the orange box, there is on-going research in the Caribbean region examining the efficacy of using activated carbon produced from pelagic sargassum biomass in electrochemical applications.

Electrochemical applications using pelagic sargassum in the Caribbean

Research:

- **SARtrib project** (Guadeloupe)**:** This project is Investigating the potential for valorisation of vacuum pyrolysis by-products of sargassum for use as lithium battery electrodes and super-capacitors (see section 3.2.4);
- **COVACHIM-M2E laboratory** (University of Antilles in Guadeloupe & French Guiana): The team is investigating the valorisation of sargassum biomass for energy storage purposes (see section 3.2.1).

Summary of uses in the electrochemical industry

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

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

Environmental restoration

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 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 and thus 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 well known and considered by 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[24].

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

- 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

Environmental restoration applications using pelagic sargassum in the Caribbean

- **Moon Palace Resort** (Mexico): They have been using sargassum-based compost to enhance coastal vegetation growth to reduce erosion and protect their beach and hotel structures (see Section 4);
- **PYROSAR project** (Guadeloupe / Martinique): Optimizing the production of sargassum AC and biochar (see Section 3.2.4);
- **SOScarbon** (Dominican Republic): Developing technology to sink pelagic sargassum and potentially sequester blue carbon in the deep ocean (see Section 3.2.3);
- **Texas A&M University** (USA): Extensive research carried out using sargassum bales to protect dunes from erosion and promote plant growth (see Section 4);
- **WIRRED** (Barbados): Using sargassum to help regenerate dune vegetation in Walker's reserve (see Section 4).

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

Pelagic sargassum 'Seabale' project for dune restoration on Galveston Island, conducted by Texas A&M University. Source: Figlus *et al*. (2015).

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 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 an 800-foot 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). They concluded that 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 adversities such as drought and erosion. Further studies have focused on the optimization of dune plants for ecosystem restoration to maximize coastal dunes’ resiliency to erosion caused by wave and storm surges, looking particularly at the addition of sargassum and arbuscular mycorrhizal fungi inoculum (Sigren, Figlus, and Armitage 2014).

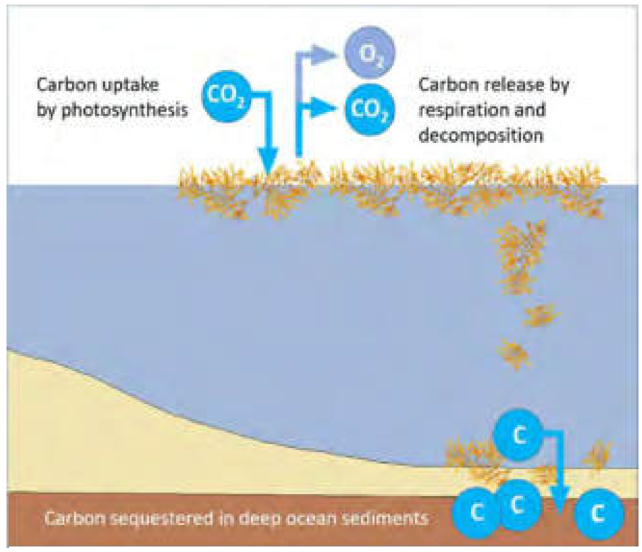
- Walkers Institute for Regeneration Research, Education and Design (WIRRED), located on the east coast of Barbados is restoring the natural dune ecosystem damaged by years of commercial sand quarrying at the site. They are conducting research on the efficacy of using sargassum to enhance the growth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

Aerial view of Walkers Reserve showing dune restoration at Walkers sand quarry

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 today in mitigating climate change through atmospheric reduction of carbon dioxide, 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, whilst oxygen is released back into the atmosphere. Forests, in particular, hold (sequester) a significant stock of carbon in the 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'. 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). On the other hand, 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 timeframe.



Conceptual diagram to illustrate how pelagic sargassum captures, transports and sequesters blue carbon in the deep ocean (adapted from: Gouvêa *et al*. 2020).

However, 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 now reported as being particularly important in sequestering blue carbon (Orr 2014, Krause-Jensen and Duarte 2016, Paraguay-Delgado *et al*. 2020, Gouvêa *et al*. 2020). Paraguay-Delgado *et al*. (2020) report that pelagic sargassum can capture carbon dioxide through photosynthesis and plant growth.

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

The carbon currently held as biomass of pelagic sargassum in the Atlantic (an estimated 7.52 Pg C[25]) (Gouvêa *et al*. 2020) has emerged as globally significant. The dying tissues of sargassum, when exported to areas with soft anoxic marine sediments, are stored over long periods (from decades to hundreds or thousands of years, in the case of deep water sediments), thereby contributing to global carbon sequestration. 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, commercialising blue carbon credits of sargassum currently has 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 perhaps be leveraged to assist with costs (e.g. through Nationally Appropriate Mitigation Actions (NAMAs) and the Green Climate Fund) (He 2016). Examples of blue carbon projects with funding from 'voluntary carbon markets' in Kenya, India, Vietnam and Madagascar reveal the strengths and challenges of implementation and policy implications (Wylie, Sutton-Grier, and Moore 2016).

It is important to note however that part of the organic carbon sequestration may be offset by the production of calcium carbonate by sargassum epibionts 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 (e.g. 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 mt 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 emision of 11.6 million mt CO_2 into the atmosphere. Thus, more studies are clearly needed to determine the net contribution of the new sargassum biomass to global carbon sequestration.

There is one Caribbean initiative, the SOScarbon project, pursuing the idea of sinking sargassum as shown in the orange box. The potential benefits of such a scheme would include: (1) prevention of negative impacts of mass strandings of sargassum along Caribbean coastlines; and (2) contribution to ocean-based climate change mitigation through sequestering blue carbon in the deep ocean; although much caution is needed, as further studies are required to avoid enormous biomass accumulations on the seafloor in oxygen minimum zones in the oceans (usually inbetween the surface photic zone and ~1000 m depth) that may potentially create dead zones.

Biochar is another example considered as sequestering carbon in the soil. Since biochar is made in large part of carbon, it can contribute a significantly to increase carbon to the soil when applied for agricultural purposes. Much research is ongoing related to biochar and its potential for carbon sequestration (Matovic 2011).

[25] 1 Pg = 1 billion metric tonnes

Summary of uses in environmental restoration

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

Another application is to use sargassum to sequester carbon and thus help to mitigate climate change effects by reducing carbon dioxide emissions to the atmosphere. A promising use of sargassum for this application 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.

Food and Beverages

BEWARE

2.13 Food and beverages

SBI
Food & beverages
Information not available

Algae have been consumed by humans for thousands of years worldwide. The most widely consumed macroalgae are brown seaweeds (66.5%), followed by red seaweeds (33%) and to a much lesser extent, green seaweeds (5%) (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 for wild species are Chile, China and Norway (FAO 2018). Approximately 221 species of algae have been recognized to have commercial value as food, of these 10 genera are widely cultivated (FAO 2018):

- Brown seaweed: *Saccharina japonica*, *Undaria pinnatifid* and *Sargassum fusiforme*;
- Red seaweed: *Porphyra* spp., *Eucheuma* spp., *Kappaphycus alvarezii* and *Gracilaria* spp.;
- 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 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.

Seamoss cultivation in Grenada and Mayreau for consumption in drinks.

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).
- Concentrations of certain minerals (e.g. 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 benefits and potential adverse effects (e.g. excess intake of toxic metals, allergenicity, cyanotoxins, secondary metabolites, etc.). Further discussion on challenges related to pollutants is included in Section 5.2 of this guide.

The consumption of seaweed differs from country to country in terms of quantity and specific culinary use. Seaweed consumption in South-East Asia is traditional, while in non-Asian European and North American markets, they 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 are 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).

Kombu (a mixture of *Laminaria* species), wakame (*Undaria pinnatifida*) and hiziki (*Hizikia fusiforme*) are three examples of commonly consumed brown seaweeds 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) when compared to 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 therefore methods have been elaborated and patented to remove this toxic component from dried seaweed products (Yamashita 2014). The method consists of boiling the dried raw seaweed in seawater up to four times (reducing total arsenic levels by 86-92%), then soaking in distilled water at 20˚C for 30 minutes (Yamashita 2014). Care must be taken for the disposal of remaining water containing high levels of arsenic to avoid further environmental impact.

2.13.2 Alcoholic beverages

Beers made with seaweed are also gaining popularity. Although, seaweed-based beers are not new (seaweeds were traditionally used in breweries in Scotland, Ireland and Germany), several breweries have a renewed interest in this ingredient and have begun to introduce different types of seaweed in their beer making process[26]. For example, Great Lakes Brewing in Cleveland Ohio brewed a special St. Patrick's

Seaweed-based beers

[26] http://www.montereybayseaweeds.com/the-seaweed-source/2019/3/13/seaweed-beers-are-gaining-in-popularity

Day Irish stout made with the red algae *Palmaria palmata*, also known as dulse or dillisk. In Australia, Brisbane's Newstead Brewing Company introduced a beer made with the green algae *Ulva* species (sea lettuce). Portsmouth Brewery in New Hampshire has also introduced a kelp-based craft beer called 'Selkie', whilst the Williams Brothers Brewing Company in Scotland make a seaweed beer named 'Kelpie'.

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 Alginate blue box in Section 2.9) (FAO 2018).

2.13.4 Activated carbon

Another potential use of seaweed biomass in food and beverage processing is as activated carbon (see Activated Carbon blue box 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 sugarcane processing, edible oil purification and flavour modification in alcoholic beverages and food additives[27]. Black pizzas made with activated charcoal infused crusts are gaining in popularity[28].

Black pizza with activated charcoal added to the pizza dough.

As indicated in the orange box, there are several initiatives in the Caribbean region using pelagic sargassum in food and beverages, mostly as extracts.

Food and beverage applications using pelagic sargassum in the Caribbean

Research:

- **Texas A&M University** (USA): In 2015, students and researchers, in collaboration with Galveston Island Brewery, made and tested a sargassum craft beer (see section 4);
- **University of the West Indies** (Barbados, Jamaica and Trinidad & Tobago): Researchers at all three campuses have been working on alginate extract for different uses (see section 3.2.2).

Commercialisation:

- **Alquimar & Grupo Metco** (Mexico): alginate extracts for use in several sectors (see section 4);
- **Mixologist Bruno Lardelli** (Mexico): has created the cocktail drink 'pineapple gift' using sargassum (see section 4);
- **Tomfoodery Kitchen** (Cayman Islands): Chef Thomas Tennant has been experimenting with sargassum as an ingredient in different dishes (see section 4).

[27] www.puragen.com/markets/food-and-beverage
[28] https://food.ndtv.com/food-drinks/no-this-pizza-isnt-burnt-its-black-pizza-made-with-activated-charcoal-2050982

Summary of uses in food and beverages

Although seaweeds are consumed in many parts of the world and also 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 which may be toxic.

Extracts of pelagic sargassum could have potential for use in food and beverages as additives, however thorough composition analysis must be done prior. 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. There are several Caribbean initiatives examining 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.

Lubricants, surfactants & adhesives

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, causing pollution issues. 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). There is a wide range of biolubricants used in food, pharmaceuticals, cosmetics, agriculture, textile and biofuels. The following are a few examples of advances using algae for biolubricants:

- The Solazyme company uses 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, they are 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 that release lubricant only when needed[29].
- Algae-based biolubricants have great 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[30].

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

2.14.2 Surfactants

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. Viable production, however, requires access to large volumes of low-cost renewable biomass. As such, marine algae are considered good candidates, especially given that

[29] solazymeindustrials.com
[30] https://beerandbrewing.com/a-guide-to-the-use-of-food-grade-lubricants-in-the-brewing-industry/

the lipids produced by algae are a source of naturally occurring surfactants. Examples of their use as surfactants are given here:

- In 2015, BASF and Solazyme launched Dehyton AO45, the first commercial microalgae-derived betaine surfactant used to produce foam in personal care products such as soap and shampoo[31].
- Foley *et al*. (2012) report that brown algae are a good source for naturally occurring glycinebetaine, used to derive several classes of surfactants.
- Benvegnu and Sassi (2010) indicate that brown seaweeds are considered attractive as renewable raw material which could be used in different biosurfactant applications such as cosmetics, agrochemistry and health.

2.14.3 Adhesives

One of the biggest challenges of the adhesives industry is the development of substances capable of gluing surfaces under an aqueous environment (Bitton 2015). Extensive research has been focusing on marine organisms such as algae to better understand their submerged adhesive abilities and how to mimic their biochemical process (biomimetic) into 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 with the brown algae wakame (*Undaria pinnatifida*) determined that the phosphate groups and monoester-sulphated polysaccharides were key components responsible for the 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 with the secretion of polyphenols and that after algae germination, phenolic polymers and 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 great potential for bio-adhesive and eco-resin applications. Based on these results, Sealantis developed a commercial alga-biomimetic adhesive which has great adherence capabilities, even in wet conditions[32]. 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 the sections pertaining to clothing and footwear as well as paper products, sodium alginate is used in the textile and paper industries to increase the adhesive properties of materials.

[31] https://www.basf.com/us/en/media/news-releases/2015/07/P-US-15-137.html
[32] www.sealantis.co.il

The production of adhesive properties has been studied for a wide range of macroalgae species with structurally different spores and 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 the orange box, there is only one ongoing project, to our knowledge, taking place in the Caribbean to examine the potential of sargassum for use as lubricants, surfactants and adhesives.

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

Research:

- **SARtrib project** (Guadeloupe)**:** Investigating the potential for valorisation of vacuum pyrolysis by-products of sargassum for use in new generation lubricants, solvents and adhesives (see section 3.2.4).

Summary of use in lubricants, surfactants & adhesives

Third generation bio-lubricants used for industrial applications such as drilling, are now being made with microalgae, whilst the potential to use 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 also.

Brown seaweeds are also being studied for their suitability in production of adhesives 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 bio-lubricants, surfactants, solvents and adhesives.

Paper products

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 to 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 limited mainly 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 with green algae. Here are a few examples:

SBI
Paper products
(Sargánico)

- 59 notebooks/m^3 fresh sargassum
- 500 notebooks/mt fresh sargassum
- 587 coasters/m^3 fresh sargassum
- 5,000 coasters/mt fresh sargassum

- 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, where significantly less energy and chemicals are required. Since most algae do not have any lignin, but only cellulose and hemicellulose, no chemicals are required, only heated water. However, in order to produce at commercial scale, algae is being mass cultivated to ensure clean raw material without impurities (Seo *et al*. 2010).

Algae Research Lab team, Universiti Kuala Lumpur

- In the '90s the Italian company Favini created the Shiro Alga Carta paper, using algae blooms invading the Venice lagoon and was able to commercially produce this specialty paper and distribute it on a small-scale, mostly in Europe. However, it is unclear which species of algae is used in the algae paper, since Venice lagoon's algal proliferations seem 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 with 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 fibers (López *et al*. 2014).

- In Chile, collaboration between researchers from the Concepción University along with 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 ensures additional preservation of fruit during export. They estimate that approximately 60 percent less fruit loss occurs due to oxidation and decomposition when their algal-based protection paper is used (CNN Chile 2019).

Algal-based paper for fruit protection and preservation during export, Concepción University, Chile

Although it is not impossible to produce paper made from 100 percent algae fibre, its overall strength (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°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, a UK start-up company by the name of 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. They are currently working on creating biodegradable, recyclable, waterproof and heat-resistant paper cups and other single use food packaging using brown seaweed. Their aim is to obtain a product that can fully decompose within four to six weeks[33].

In addition, alginates are used in the paper industry for surface sizing (see Alginate blue box in Section 2.9). This process consists of adding alginate to the 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 indicate that *Sargassum*

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

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 the orange box, innovators are already making a wide range of paper and cardboard products, which are not only aesthetically pleasing, but also very useful and environmentally sustainable.

Variety of sargassum-based paper products by Sargánico

Sargassum paper by Sargasse project

Prototype coffin made by The Marine Box out of sargassum-based cardboard

Sargassum paper for specialized art, Golden Tide project

Papermaking with pelagic sargassum in the Caribbean

Commercialisation:

- **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 (see Section 4);
- **Salgax** (Mexico): Although mainly focused on sargassum-based fertilizers, the team is also developing sargassum paper products (see Section 3.1.7);
- **Sargánico** (Mexico): producing high quality notebooks, folders, drink coasters, business cards, and much more (see Section 3.1.2);
- **Sargasse Project** (St. Barths): Making 100% sargassum-based paper and cardboard products (see Section 4);
- **Sargazbox** (Mexico): Developing cardboard boxes with sargassum cellulose (see Section 4);
- **The Marine Box** (Martinique): Developing various paper and cardboard products made with sargassum. This even includes coffins using cardboard made with sargassum (see Section 4).

Summary of use for paper products

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

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

Pharmaceutical & biomedical

BEWARE

2.16 Pharmaceutical & 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 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).
- 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

Alginates, fucoidans, 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 used mainly 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, whilst magnesium alginate has medicinal properties and is used mainly to treat ulcers and reflux disease (Baldassarre *et al*. 2019). Another research study indicates

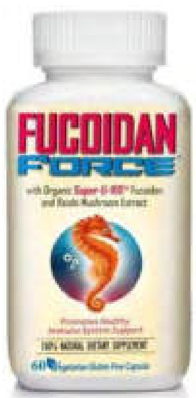
SBI
Sargassum
pharmaceutical
extracts

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

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).

Examples of products using alginates. Left: wound dressing. Right: controlled release medication.

There is much interest in the use of fucoidans because of 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, anti-tumor, antiviral, antithrombotic, anticoagulant, and immuno-regulatory; and have also been used in cognitive protection and as an anti-hyperglycemic agent (Citkowska, Szekalska, and Winnicka 2019, Luthuli *et al*. 2019).



Algae fucoidan in dietary supplement

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 anti-tumor 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: anti-diabetic, anti-cancer, anti-hypertension, anti-photoaging, anti-oxidation, anti-viral, 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 different abiotic and biotic factors and the extraction procedure employed (Generalić Mekinić *et al*. 2019).

Terpenoids from brown seaweed are also very useful for the pharmaceutical industry due to their anti-fungal, cytotoxic, anti-inflammatory and anti-viral activity (Campos de Paula, Vallim, and Laneuville Teixeira 2011). Likewise, the carotenoid pigment, fucoxanthin has potential anti-oxidant, anti-inflammatory, anti-obesity, anti-tumor 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 exhibiting promising pharmaceutical applications include: plastoquinones (significant anti-oxidant 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 anti-oxidant, anti-diabetic and anti-

Examples of sargassum seaweed being used in dietary supplements

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 therapeutic potential and health benefits of sargassum species indicates that some of the main health-related properties include: anti-oxidant, cholinesterase inhibition, neuroprotection, anti-pyretic (fever reducer), analgesic, anti-tumor, anti-inflammatory, hepatoprotection (liver protection), immunomodulatory, anti-viral and anti-coagulant (Yende, Harle, and Chaugule 2014).

Algae-based lubricants are also used for the preparation of root canal treatment in dentistry applications, 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 the 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 anti-coagulant, anti-microbial, anti-inflammatory and anti-oxidant properties (D'Amelio 1999).

There are a number of on-going projects in the Caribbean region to determine pharmaceutical and biomedical potential of pelagic sargassum, as shown in the orange box below.

Pharmaceutical & biomedical projects using pelagic sargassum in the Caribbean

Research:

- **Nexo project**, **Tecnológico de Monterrey** (Mexico): a group of students are extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses (see section 4);
- **SARSCREEN project** (Guadeloupe): to determine pharmacological potentials of sargassum extracts against non-communicable diseases common and widespread across the Caribbean (see section 3.2.4);
- **University of the West Indies** (Barbados, Jamaica and Trinidad & Tobago): Different researchers at the three campuses have been working on polysaccharide and secondary metabolite extracts for different uses (see section 3.2.2).

Commercialisation:

- **Alquimar & Grupo Metco** (Mexico): both companies have been working on alginate extracts for use in several sectors. Alquimar has also been commercialising fucoidans nationally (see section 4).

Summary of pharmaceutical & biomedical uses

Brown seaweeds contain unique polysaccharides (e.g. alginates, fucoidans 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 commercialisation 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.

Summary of uses and scalability

2.17 Summary of uses and scalability

2.17.1 Product-specific challenges

Based on the detailed review presented in this section of potential uses of pelagic sargassum, we provide in Table 4, a summary of the key potential uses, and the product-specific issues that represent current challenges to successful product commercialisation. Note that in Section 5 we take this further by looking in greater detail at the general over-arching challenges and constraints faced by researchers, entrepreneurs and businesses developing commercially viable uses for sargassum, and the implications of these for policy makers, managers and funding agencies.

Table 4. Summary of potential applications for pelagic sargassum, showing current potential challenges and ongoing research (Res.), commercial development (Com. Dev.) and full commercialisation (Full Com.) in the Wider Caribbean

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 salinisation if no pre-treatment) • No reported benefits to crops	✓	✗	✗
	Mulch	• High salt content (risk of soil salinisation 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 salinisation 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	✓	✓	✓

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. Dev.	Full Com.
	Biochar	• High salt content (risk of soil salinisation if no pre-treatment)	✓	✗	✗
	Fertilizer/biostimulant/ digestate	• High salt content (risk of soil salinisation 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/bioelicitor	• High salt content (risk of soil salinisation 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 bioelicitor properties	✓	✗	✗
	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	✓	✗	✗
Anti-fouling	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 micro-organisms for fermentation due to high salt content • High investment needed for specialized equipment	✓	✗	✗
	Biodiesel - Not currently feasible	• Insufficient lipid (fat) content • Limited research available; macroalgae do not seem suitable for this use	✗	✗	✗
	Biopellets	• Limited research using macroalgae (variable results); limited research with pelagic sargassum • Need to mix with other organic material • High investment needed for equipment	✓	✓	✗

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. Dev.	Full Com.
	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	✓	✓	✗
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 with pelagic sargassum to determine if it needs to be blended with other materials and recommended amounts • High investment needed for equipment	✓	✓	✗
Bioremediation and purification	Water and wastewater treatment (activated carbon, live floating seaweed)	• High salt content may reduce biosorption capacity – more research needed with 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 with 100% sargassum bricks is ongoing (need to test stability and durability) • Need for specialized equipment	✓	✓	✓
	Resin/particleboard and panels	• Insufficient research with pelagic sargassum • Need for specialized equipment	✗	✓	✗
	Bio-asphalt	• Insufficient research with pelagic sargassum	✓	✗	✗
	Furniture	• Insufficient research with pelagic sargassum	✗	✗	✗

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. Dev.	Full Com.
Cosmetics	Skin and hair care 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 needed 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.	✓	✗	✗
	Carbon sequestration (potential application to earn blue carbon credits e.g. biochar, deep ocean sinking)	• High investment costs needed 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 beverages	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 needed for pyrolysis equipment	✓	✗	✗
Lubricants/ surfactants/adhesives	Bio-lubricant (sargassum extracts)	• Insufficient research using pelagic sargassum	✓	✗	✗
	Bio-surfactant (sargassum extracts)	• Brown seaweeds have potential to be used in the production of surfactants, however there is insufficient research using pelagic sargassum	✓	✗	✗
	Bio-adhesive (sargassum extracts)	• Brown seaweeds are being studied for their suitability, however 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	✗	✗	✗

Use	Potential applications	Potential challenges	Caribbean initiatives		
			Res.	Com. Dev.	Full Com.
Pharmaceutical & biomedical	Pharmaceutical and biomedical drugs and applications	• Research has been focused on the potential of brown seaweeds with limited research using pelagic sargassum • Therapeutic effectiveness and safety of pelagic sargassum extracts remain unknown	✓	✗	✗

2.17.2 Amount of sargassum needed

Based on case studies from around the region where we have been able to apply our 'Sargassum Biomass Index', we can see that one metric tonne (1000 kg) of fresh sargassum can potentially be used to create a large range of valuable products as illustrated in Figure 4.

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 4. Diagram showing our crude Sargassum Biomass Index to illustrate the relative product yields that could potentially be produced from one metric tonne (1000 kg) of fresh sargassum

Section 3
Using sargassum: Regional case studies

Photo credit: Hazel A. Oxenford

3 Using sargassum: Regional case studies

Many entrepreneurs and research teams across the wider Caribbean region have been working arduously over the last few years to raise funds and develop innovative businesses and projects to use sargassum seaweed. In this section we present a wide variety of case studies that we have been fortunate enough to learn about, to visit, or to communicate with, and who were willing to share their information and findings for the benefit or others wishing to take up opportunities presented by the new pelagic sargassum influxes to provide an income and/or to defray the current costs of 'clean-up' of sargassum stranded along coastlines.

3.1 A closer look at local entrepreneurs

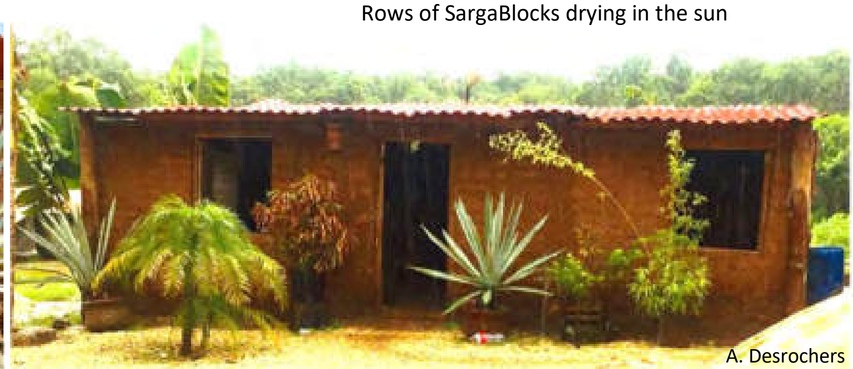
There are many inspiring innovators across the region that have become leaders in this emerging industry, including young businessmen and businesswomen who have taken up the challenge of finding beneficial uses for sargassum. This section is dedicated to their stories. Through their experience, they share their successes and challenges so that we can learn about their inspiring achievements. Most of the selected case studies have already begun commercialising their products, and have great potential to scale-up and replicate in other countries.

3.1.1 **SARGABLOCK**: Sargassum construction blocks [Mexico]

The vision

Omar Vázquez Sánchez started making sargassum construction blocks in 2015. He had a vision one night which led him on a mission to reproduce his grandparents' traditional adobe farmhouse where he grew up. With the enormous arrivals of sargassum off the coast of Quintana Roo, in Mexico, Omar had the idea to try making construction blocks with the seaweed. It was from there that the innovative 'SargaBlocks' were born. With a total of 2,150 SargaBlocks, he was able to complete his mission of building a reproduction of his grandparents' farmhouse, which he named *Casa Angelita*. The now famous *Casa Angelita* is located in Puerto Morelos, Mexico, at Omar's BlueGreen plant nursery business. The house has received regional and

Rows of SargaBlocks drying in the sun



Omar Vázquez Sánchez and his first sargassum house *Casa Angelita* built with SargaBlocks.

international attention and many travellers and reporters have come by to catch a glimpse of the first sargassum house.

The process

About 20 tons of fresh sargassum is used to make a house like the *Casa Angelita*. After five years experimenting with the production of SargaBlocks, looking for the ideal technique and mixture of ingredients to make the high-quality blocks, Omar is already on his fourth improved version. Each ecological block is made with 100% natural local materials, including up to 40% sargassum. Complying with federal regulations, his blocks can be used in standard construction of buildings. The blocks come in two standard sizes: 30 x 15 x 12 cm and 40 x 15 x 12 cm, and cost between 10 to 12 pesos per block (USD 0.42 to 0.51). Not only have the SargaBlocks gone through a series of tests to ensure their durability and resistance, they are also highly aesthetic and have great acoustic and insulating capacity. The resistance of walls built with SargaBlocks varies between 75 and 110 kg/cm^2

Employee showing a SargaBlock with the industrial press in the background

Initially, Omar was making SargaBlocks manually in Puerto Morelos and his production rate was about 3,500 SargaBlocks per week. However, with demand for sargassum as a raw material rising in the area and after some disagreements regarding the handling of the seaweed, he decided to distance himself and establish the production of SargaBlocks further away, about 320 kilometers south of Puerto Morelos, in an area where there are no issues with sargassum availability or handling. Omar was able to increase his production rate to 2,000 SargaBlocks per day with the purchase of a customised industrial press. The blocks need to dry for a period of about four hours before they are ready to use or can be stored for later use.

Solidarity

Omar did not have an easy upbringing and knows what it is like to struggle financially. As a young boy, he crossed the border to the US with his mother, a probing journey in harsh conditions, in search of a better life. For many years, he worked in the wine region of California, where he learned about agriculture and crop production. He always had the dream to one day, come back to live in Mexico and contribute in a significant manner to the development of his country and his community. Omar has a strong sense of respect and belonging with his family and his community. He is committed to assisting families and schools that have the least resources by building and donating affordable housing. Omar is also working collaboratively to build SargaBlocks condos in Tulum and houses in San Pedro and Ambergris Caye in Belize.

Poster highlighting the innovative SargaBlock

3.1.2 **SARGÁNICO:** Sargassum paper [Mexico]

Sargánico, established in March 2019, is a company located in Cancun, Mexico, that specializes in the development of paper and cardboard based products using sargassum. The young entrepreneur Victoria Morfín, 19 years old, is the CEO and the visionary behind Sargánico.

After the frustration of seeing hundreds of notebooks and booklets thrown away at the end of each school year in Cozumel, Victoria and her mother started a small company called 'Chibi Book'. They created and promoted recycled, artisanal and personalized notebooks. They noticed that their artisanal paper needed more cellulose and in 2018, after seeing the quantities of sargassum piling up on beaches, Victoria decided to try it as part of her ingredients, and she realized that it was a good source of cellulose. After months of testing and experimenting with different mixes and designs, she was able to develop a good formula to process the seaweed and transform it to practical, useful and aesthetically pleasing paper products. She also tested using discarded cigarette butts to add texture to the paper and at the same time clean the beautiful beaches of the island of Cozumel.

Example of some of Sargánico's artisanal paper products

Solid partnership

It was after being featured in a TV interview, that Grupo Regio, a multi-million marketing and printing company with offices in Cancun, Miami and Punta Cana, took an interest in Chibi Book and Victoria's sargassum-based paper and offered to become partners. That's how Sárganico was born, where Victoria began her new operation within Grupo Regio, continuing to develop her artisanal and environmentally friendly products, while exploring new opportunities and scaling-up her business.

Sargánico and Grupo Regio team up

Innovative and ecological

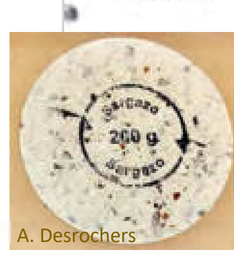
Victoria has developed a wide range of paper-based products such as notebooks, agendas, folders, coasters, menu holders, business cards, boxes, and many more. Sargánico's entire product line is ecofriendly and contributes to removing sargassum seaweed from beaches and processing it in an innovative and sustainable way. They are proud to report that within one year, they have processed over 7 tons of sargassum and recycled over 6 tons of paper. Most of their notebooks have cardboard on the outside (made with 20% recycled paper and 80% sargassum), and sheets of 100% recycled paper on the inside. When considering that approximately 17 trees are needed to produce one ton of paper, Sargánico is proud to have saved over 100 trees during their first year in business. Furthermore, while paper making usually requires a large amount of water for the process (100-150 litres), it is nonetheless Sargánico's main aim to be environmentally responsible and therefore, they reuse the water up to four times. For coloured notebooks, they use recycled coloured paper or natural plant-based dyes. Sargánico's mission is to offer products with low impact on the environment, giving their clients the option of a sustainable choice.

Victoria Morfín, founder and CEO of Sargánico

Process

sargassum is harvested by hand one day per week by three persons. After the sargassum is collected manually, it is cleaned of all sand and then processed to produce the paper manually. The sand that is removed from the seaweed is later carried back to the beach. Sargánico currently has a production rate of 200 notebooks weekly, which corresponds to 500 sheets of paper per day, using approximately 100 kg of dried sargassum daily. On average, 200 g of seaweed is used for each coaster and up to 2 kg for larger notebooks. In order to raise awareness on the use of sargassum, Sargánico indicates the amount of seaweed used on each product.

Victoria making sargassum paper



Sargánico indicates on each product the amount of sargassum used to make it.

3.1.3 **EnergyAlgae**: Multi-sectoral and multi-national initiative developing sustainable sargassum uses [Dominican Republic]

Partners: AlgeaNova, Grupo Puntacana, University APEC (UNAPEC) of the Dominican Republic and Y.A. MAOF Holdings & Management Ltd. of Isreal

EnergyAlgae's team

According to the Dominican Republic Ministry of Tourism, the popular tourist destination of Punta Cana received over 6.5 million tourists in 2018 and is home to over 100 hotels. While vacationing in Punta Cana with his family in 2018, Ygdal Ach, founder and CEO of Y.A. MAOF was stunned by the amount of seaweed on local beaches and the lack of local initiatives to turn this problem into an opportunity. The Israeli company approached the private Grupo Puntacana, which includes 10 businesses (hotels, airport, commercial village, school, etc.), to develop a partnership with the multi-national AlgeaNova company and a private university in Santo Domingo, University APEC. The project EnergyAlgae was created from this partnership. With the increasing amount of sargassum seaweed piling up on Punta Cana's pristine beaches and cancellation of reservations by tourists, Grupo Puntacana accepted the proposal to embark on a collaborative journey and use some of their own funds in an attempt to combat sargassum beaching and build a more resilient coastal community and company. Thanks to the efforts of all partners, this is the first innovative multi-national and multi-sectoral project of its kind, offering a holistic approach to sargassum management. Although still in its initial stages for the processing of sargassum, this project has great potential to be scaled-up and replicated in other countries, while adapting to local conditions and communities.

Collection and processing

AlgeaNova is a partner of the multi-national HoldiNova Group, which has a wide range of entities in several countries (UK, United Arab Emirates, Morocco and Dominican Republic). The company AlgeaNova, located in Punta Cana, Dominican Republic, specializes in anti-sargassum floating barriers and has been developing innovative solutions for collecting sargassum at sea, maintenance, processing, valorisation and marine protection since 2018. In collaboration with the hotel group Grupo Puntacana, AlgeaNova installed a 4.2 km long anti-sargassum floating barrier in December 2018. Their barrier guarantees sargassum-free beaches and coastlines, which helps to preserve not only the hotels and tourism sectors, but also helps preserve the fragile beach ecosystem and traditional fisheries. For several years, the group has invested nearly a million euros in research and development in order to find a suitable

AlgeaNova's floating barrier in Punta Cana holding sargassum off the beach ready for collection response to the sargassum problem and according to the company, developed the most efficient all-in-one solution for sargassum, from collection and harvesting to processing. Their floating barrier system has the advantage of being easily and quickly disassembled in case of hurricanes or extreme weather conditions. AlgeaNova's success has allowed the team to offer their services across the Caribbean, and in November 2019 they started the process of installing a 2.2 km long floating barrier at Moon Palace Resort in Cancun, Mexico and entered into a one-year contract, with a guarantee of a sargassum-free beach, including collection from sea using specialized boats. All partners of EnergyAlgae have signed an agreement for joint coordination of their activities not only in the Dominican Republic, but also for future projects in other locations across the Caribbean.

An underwater view of AlgeaNova's floating barrier with captured sargassum

AlgeaNova's boats have the capacity to harvest 100 to 130 tons of sargassum at sea per day, and they are looking to upgrade to a new boat with the capacity of harvesting up to 500 tons/day in the near future. AlgeaNova has a service contract with Grupo Puntacana hotels whereby they maintain the floating barrier, harvest, transport and process the seaweed. This preventative measure operating a short distance from shore ensures little to no beaching of sargassum at hotel beaches and other popular beaches. Although the seaweed is now effectively removed from the nearshore area with the help of the floating barriers and boat harvesters, the team has gone on to develop partnerships and collaborations with other international actors to find innovative and sustainable solutions for the valorisation of the collected sargassum.

AlgeaNova's sargassum harvesting boat working along the outside of the sargassum barrier.

Biogas

In October 2019, a pilot experimental biogas project was developed on Grupo Puntacana's transformation site. The collaborative project EnergyAlgae, is led by the Israeli company Y.A. MAOF and its specialists in solid waste management. A system of five small units of anaerobic biogas digesters (HomeBiogas) was installed for testing different formulations of blended sargassum and organic waste from local hotels to optimize the output of biogas. Experimentation, monitoring, logistics, coordination and business development for this project are carried out in collaboration with the University APEC. Sargassum is

Biogas pilot project in Punta Cana in partnership with University APEC.

collected and supplied by Grupo Puntacana and AlgeaNova, organic waste is provided, collected and separated by Grupo Puntacana and Eco Services.

Informative poster about the sargassum to energy pilot project of EnergyAlgae

This pilot project will serve as a basis for the implementation of a larger 1 MW co-digestion model biogas facility in Punta Cana using sargassum and hotel food waste as feedstock which could be replicable across the Caribbean. The facility intends to receive approximately 28,000 tons per year of sargassum and 32,000 tons per year of organic food waste input in order to generate 1 MW of power. The electricity and heat that will be generated will be fed back into the grid for use in the entire concession area. The electricity within the concession area is provided by the company 'Corporación Turística de Servicios Punta Cana' (CTSPC), which is an electricity subsidiary owned by Grupo Puntacana. To avoid any reductions in generated energy output, there are several elements that need to be taken into consideration and solutions identified before implementing the larger electricity plant. These include sand and salt content in the sargassum and plastic contamination in the digestate cake. Large quantities of salt can reduce the amount of methane yield. The digestate produced from the system will be treated and used locally as compost, where demand is very high.

Although the Y.A. MAOF Holdings & Management team has their own expertise in biogas research and development, engineering, control, process and feedstock management, they have partnered with other experts such as MADEI TAAS and ANAERGIA. The cumulative experience of the team of experts from Y.A. MAOF will ensure the success and sustainability of this first biogas project in Punta Cana:

- ✓ Y.A. MAOF provides high-quality environmental services, specializing in waste management, recycling and supervision over environmental projects. MAOF collaborates with a wide range of stakeholders including municipal and governmental authorities, private companies and NGOs. Its unique position makes it a major player in the Israeli environmental ecosystem where the elements of waste treatment, innovative technologies and environmental protection are integrated.

Some of MOAF's expert team members explaining the pilot biogas system.

- ✓ Based on its extensive experience in environmental entrepreneurship, MAOF is continuously initiating and taking part in a variety of projects and regulatory processes in Israel. The company has been key in influencing statutory and policy-making processes that promote environmental standardization and the removal of bureaucratic and economic barriers.

- ✓ The company has extensive experience and knowhow in developing, promoting and implementing supportive regulatory systems which are built into all of the company's projects.
- ✓ The founder and CEO has over 20 years' experience in environmental services, specializing in waste treatment, waste management, recycling, rehabilitation of landscapes, hazardous land, contaminated soils, etc.
- ✓ The project manager is the former Senior Deputy Director General of the Ministry of Environmental Protection in Israel and Head of MASHAV extension at the Arava Institute and was the principal investigator for an extensive small-scale biogas systems project to assist off-grid Bedouin communities.
- ✓ The key engineer expert has experience in small, medium and large-scale biogas, gasification and several different waste to energy projects around the world.
- ✓ The two key water and marine experts hold unique and extensive experience, one is the former president of the Israel Water Association and the other is a Marine Environment specialist, former senior officer in the United Nations Environment Programme (UNEP).

Some of MOAF's expert team members

Soil amendments

In March 2019, AlgeaNova signed an agreement with Grogenics, a Canadian biotech company, for the development and installation of a mobile model processing plant to transform sargassum into organic compost, which can easily be replicated in other Caribbean countries. Processing of sargassum initiated in June 2019 with a compost formulation developed by Grogenics with a composition of 60% sargassum and 40% garden trimmings, inoculated with vermicompost leachate. AlgeaNova has also developed a garden mulch made of 100% sargassum.

Sargassum composting site in Punta Cana

Bioplastics

AlgeaNova has also signed an agreement with Biotrem, a Polish company, to develop and produce single-use plates made with 100% biodegradable materials, composed of a blend of 50% sargassum and 50% cassava. Each plate contains approximately 45 g of dried seaweed. Their patented machinery has the capacity to produce 2,000 plates per day.

Sargassum-cassava biodegradable single-use plates made in Punta Cana

3.1.4 **Red Diamond Compost**: Sargassum-based plant biostimulant [Barbados]

Joshua Forte promoting Red Diamond Compost's organic products

Joshua Forte is a young environmental management practitioner exploring innovative solutions to the region's environmental crisis. Based in Barbados, Joshua expanded his knowledge base and experience beyond agriculture to include exploration on removing pollutants from the environment. He has served in various capacities with the Caribbean Centre of Excellence for Sustainable Livelihoods and was awarded a business development grant by the Caribbean Climate Innovation Centre for his environmental outcomes with the launch of Red Diamond Compost, a biotech business established in 2014. Red Diamond Compost has been featured at several regional and international entrepreneurship and cleantech competitions and summits. Joshua believes every person has a right to access clean nutrient-rich foods and as such Red Diamond's mission is to bring new life and vitality to the soils across the Caribbean, by providing the highest quality organic and biological soil treatment and crop protection solutions.

Red Diamond's products are made primarily from organic waste residuals and other organic environmental hazards such as the sargassum seaweed. Due to the huge influx of sargassum, Joshua decided to postpone further product development plans and address the challenge. After two years of product development trial and error, Red Diamond Compost had its first product ready for market testing. Now known as the 'Super Seaweed Biostimulant'; a liquid organic concentrate that not only super charges plant and root growth but also boosts the plants' natural immune system, improves colour and overall appearance, increases nutrient uptake, and stimulates soil microbial activity. This results in tastier produce and plants that are more resilient to stresses, pests and diseases.

Red Diamond Compost's sargassum-based Super Seaweed biostimulant

Managing the process from environmentally friendly collection of sargassum has been a key quality control measure to ensure the efficacy of the end-product. Initially using a low-temperature extraction method and the addition of organic inputs to improve plant uptake and shelf-life, Joshua has since designed a new manufacturing process that uses fewer resources, is faster, produces a high quality and concentrated product with the aid of automation processes. To date he is utilizing 90 kg of dried sargassum for the production of approximately 300 litres of biostimulant, a third of which has been sold to small farmers and home gardeners. The small-scale development and production has been enough to garner interest from managers of sports fields and grounds managers in Barbados' most prestigious resorts, and great interest from home gardeners as well. Challenges in scaling-up manufacturing capacity to utilize 50 wet tons of sargassum per day, initially included harvesting and transport costs to the processing facility. Additionally, managing the environmental risk inherent to seaweeds as bioaccumulators, proactive formulation measures have been taken to safeguard against potential excessive heavy metal content or other undesirable contaminants in the end-product. Though there is still a need for more extensive testing in this area, Red Diamond Compost is committed to continually ensure human and animal safety of Super Seaweed and all its end-products. Identifying suitable solutions to these, meant the primary challenge was access to financing required for machinery. Financiers are less than eager to support a venture in new uncharted territory. Even with strong interest coming from regions in Africa through their Agribusiness Incubator Network, there is still a local financial hurdle to overcome. With sargassum negatively impacting the coasts of the Caribbean, Mexico and West Africa, Red Diamond Compost's plans include exporting the production model to these regions, which will also include the production of an animal feed by-product.

Joshua with large amounts of sargassum pilling up on beaches in Barbados

3.1.5 **Renovare Ocean Shoes**: A successful sargassum marketing strategy [Mexico]

Displaying a Renovare Ocean Shoe manufactured with recycled materials including sargassum seaweed in the sole

Established in 2014 and based in León, Mexico, Renovare specializes in the use of recycled materials to create unique footwear while promoting environmental and ecological footprint awareness. Founders Jorge Castro and Mario López are young entrepreneurs who are passionate about environmental protection, recycling, reducing consumables and reusing materials. A third-generation shoemaker, Jorge has been involved in the business since early childhood. With backgrounds in business administration and marketing, Jorge and Mario make up a perfect team to help prosper the family business.

Environmental awareness

Concerned with pollution and climate change, they decided to create eco-friendly shoes by using recycled PET plastic bottles and organic waste. After 10 years of trial and error, they successfully created a line of ecological footwear. Renovare's objective is to raise awareness about the potential of using recycled and renewable products in our everyday life and promoting sustainable living. Renovare wants to raise awareness among the public about the fact that only 25% of the 480 billion plastic bottles produced annually are recycled and, as a result of the discarded plastic, millions of marine species are affected and often die. In addition, with the huge quantities of sargassum seaweed arriving on the Caribbean Mexican coasts, Renovare wanted to play an active part in finding solutions to this serious problem and after 8 months of testing, created and presented in March 2019 the first shoe made with sargassum and plastic bottles. Through their Renovare Foundation, the company launched a blue ocean campaign and have vowed to donate 10 percent of their profits to support groups involved in cleaning the ocean, such as Plastic Ocean, as well as support the creation of a centre for young entrepreneurs.

Renovare Ocean team (Benjamín López, Mario López and Jorge Castro)

Process and partnerships

For the development of their line of footwear, Renovare uses processed natural skins, vegetal-based products, plastic bottles, sargassum and water-based adhesives. The company has carried out over 50 resistance trials to ensure high quality and durability of the shoe. Each pair of shoes is made with five plastic bottles and 100 g of dried sargassum to make the soles. With a current monthly production rate of over 20,000 pairs of shoes, they are using approximately two tons of fresh sargassum per month. The company currently has 60 employees and is looking to double and even triple their production in the near future. Since Renovare is located in León, approximately 2,000 kilometres from Cancun, they have partnered with Moon Palace Resort to obtain shipments of dried sargassum. When the dried seaweed arrives at Renovare, they need to clean it and remove sand, coral, plastic and other impurities. After crushing, the seaweed is mixed with injected or moulded polymers to make the shoe soles.

However, with the high costs of transportation at approximately US$1,300 per ton to reach León, Renovare was successful in securing a partnership with FedEx, that will cover the cost for transporting 10,000 tons of sargassum. The company expanded and joined forces with Benjamín López, who contributed to the company's success.

The ecofriendly Renovare Ocean Shoe made with recycled plastic bottles and sargassum

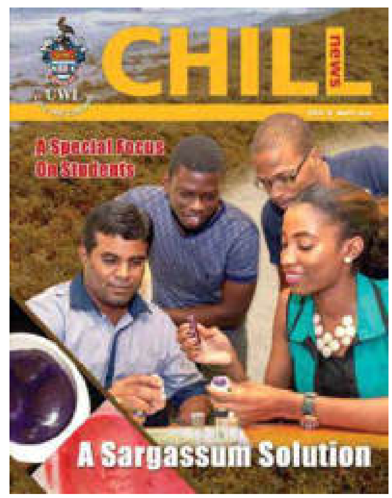
The strategy

Although Renovare did not identify any structural benefit to shoes or soles from adding sargassum, they nonetheless decided to use the seaweed as a two-fold approach: 1) a marketing strategy to gain popularity for their company and shoe brand to increase sales and profit, and 2) promote awareness related to the increasing environmental issues related to both sargassum stranding and the use of plastic bottles.

3.1.6 **OASIS Laboratory**: Sargassum beauty care products [Barbados]

Oasis Laboratory's soap bars containing sargassum seaweed.

Oasis Laboratory is a Barbados-based company established in March 2018, specializing in high quality natural eco-friendly personal care products. The two young founders are chemists Kemar Codrington and Mikhail Eversley, both graduates of the University of the West Indies. The idea came about in 2015 when large influxes of sargassum were washing up on Barbados shores. While studying at the university, Kemar and Mikhail assisted fellow chemist Tiffany Husbands on her undergraduate project supervised by Dr. Popuri of the Chemistry Department, in finding solutions to this problem affecting the entire region. For their project, they extracted sodium alginate from sargassum, to determine its chemical properties and potential uses, such as emulsifiers, stabilizers, thickening agents and many more. They have also worked with other local plants to determine their properties for cosmetics, such as breadfruit, tamarind, aloe vera, coconut, purslane, lemongrass, okra, etc. According to Kemar and Mikhail, sargassum is a gold mine for skin care, as the seaweed has many excellent properties such as anti-aging, anti-inflammatory, anti-bacterial, ultra-hydrating, exfoliant, toning and many more.



CHILL magazine (University of the West Indies, Cave Hill Campus) featuring Dr. Popuri and his team working on sargassum

It was in 2018, when the seaweed returned in large masses to Barbados coastlines that the team joined their knowledge and willingness together to put into action a potential solution to the sargassum invasion; they created Oasis Laboratory. They wanted to put their skills and abilities to good use and to encourage other young scientists to pursue an entrepreneurial path. The two young entrepreneurs have created two different flagship brands: 1) Ocean by Oasis, with ocean-themed and environmental-based products, particularly sargassum and 2) Nature's Melanin, promoting local plants, self-love and Barbadian heritage. Oasis Laboratory has developed different types of soaps, detoxifying masks, lip balms, creams, body butter,

Kemar Codrington and Mikhail Eversley, founders and CEOs of OASIS Laboratory serums, toothpowder, hair products, scrubs, deodorant, sargassum jewelry, handbags and several other items. All their products are natural and safe for use, where the sargassum undergoes treatment before it is processed. Each product that contains sargassum may have different amounts, however on average, their soap bars contain approximately 5 g of dry seaweed.

Mikhail and Kemar presenting their products to the Honourable Prime Minister of Barbados, Mia Amor Motley.

Oasis Laboratory's four main pillars are: Barbados heritage, innovation, nature and sustainability. They seek to offer their clients better options for personal care products and promote, educate and sensitize people to treat their skin with natural local products without harming our environment. It is Oasis Laboratory's aim to utilize locally grown plants and other local materials to make their environmentally friendly and sustainable products. To promote Barbadian heritage, they named their products to highlight different beaches of Barbados. In the near future, they would like Oasis Laboratory to become a modern analytical and research facility and a regional hub for science and technology.

3.1.7 **SALGAX**: Applied marine biotechnology [Mexico]

Sargassum-based fertilizers developed and commercialised by SALGAX

SALGAX is a company established in 2015, located in Mérida, Mexico, specializing in marine biotechnology and processing of sargassum. This Yucatán based company is dedicated to research and development of innovative biotechnological products derived from the marine environment. Products that they have been developed include natural fertilizers, mulch, cosmetics (hair treatment), paper, varnishes and others. The visionaries and CEO behind SALGAX are Mauricio Gómez, a 30-year-old marine biologist who is responsible for processing, research and development of products and 26-year-old Dayre Catzim, the administrative director responsible for sales and acquisitions. Mauricio's curiosity and willingness to experiment and develop marine-based products led him to further investigate potential uses for the large quantities of sargassum and other types of macroalgae piling up on beaches. In January 2015, after a few months experimenting, Mauricio came up

100% sargassum paper under development by SALGAX.

Mauricio Gómez, founder and CEO of SALGAX

with a first prototype for a foliar fertilizer made with the seaweed, which he presented at ExpoCampo Yucatán with great success. After many trials and errors, SALGAX improved their products and in October 2017 participated in the Reto Emprendedor (Entrepreneurial Challenge) programme, where they won first place.

In 2019, SALGAX received much-needed support from a businessman with a solid trajectory and experience, who strongly believes in the two young entrepreneurs, their ideas and the company. Through this partnership, they have developed a 100% sargassum paper, which will soon be commercialised.

SALGAX has been commercialising their foliar organic fertilizers since 2015 and currently has over 20 distributors selling their products across Mexico, using 20 mt of fresh sargassum each month. Products are sold directly to plant nurseries, home gardeners and farmers (particularly for corn, lemon and cocoa production). Seaweed collection is done manually from nearby beaches and processed in Mérida using environmentally friendly techniques. Salgax ensures that their final product is tested regularly for its nutritional composition and heavy metals content in order to avoid any harmful elements such as inorganic arsenic.

3.1.8 **NUM SMO Technologies (NST):** An environmentally friendly mobile unit to process sargassum [Guadeloupe]

The industrial-sized solar microwave oven (SMO) for valorisation of organic biomass and organic waste

The company NUM SMO Technologies has turned to crowd funding to raise enough capital to install a solar microwave oven (SMO) operational site at Anse-Bertrand in Guadeloupe in 2020, to process sargassum and other biomasses. The patented Active Solar Microwave Process (Active-SMO) is considered as an ecologically friendly process for the valorisation of waste. Solar energy is used to transform biomass and organic waste into high value end products such as carbon powder, activated carbon, biochar and biogas, while absorbing carbon dioxide. This innovation was developed to find a sustainable solution to producing high quality activated carbon with adapted 'lower cost' technologies using different sources of biomass, while reducing the amount of greenhouse gases emitted during the process.

The Active-SMO process consists of four transformation steps: granulation, solar pyrolysis, gasification and conditioning. NST partnered with a Moroccan company to establish Peps (Pour Et Par le Soleil) and since February 2014, this innovation is being tested in Marrakech, Morocco. They have been able to effectively valorise 27 mt of household waste per day. NST was established in Guadeloupe in 2009 by partners with complementary background expertise in science, energy and civil engineering. NST expertise combines a synergistic approach to CO_2 sequestration, waste treatment, energy production and storage, in line with current climate mitigation strategies.

With the implementation of NST's first pilot site in the Caribbean (Guadeloupe), sargassum and other biomass will be used as feedstock to produce activated carbon, carbon powder and biochar. The company is expecting to produce 11,000 mt of activated carbon, and 22,000 mt of carbon powder and biochar on an annual basis. These products will potentially be sold to municipalities, for wastewater treatment.

NST's Active-SMO system is an excellent solution to manage sargassum biomass, for its positive environmental balance, mobility, adaptability and versatility in terms of inputs (waste and biomass) and outputs (electricity, activated carbon, biochar). The company estimates that with 108 mt of sargassum per day, their system could produce 50 MWH of electricity and 22 mt of activated carbon per day.

3.1.9 **Holdex Environnement**: Composting with sargassum [Martinique]

Holdex Environnement is a company based in Martinique that specializes in organic waste management. Since 2007, they have been producing a wide range of organic amendments for use in agriculture and horticulture. They have been collaborating with various French-funded projects and several researchers, namely ECO_3SAR, ADEME (2015 grant) and Université des Antilles. A comprehensive study has been ongoing for several years in collaboration with the Holdex company for large-scale co-composting of sargassum and commercialisation of controlled-quality end products. Very promising results have been obtained, and in fact, Holdex is already commercialising a sargassum-based compost in Martinique (approximately 10% sargassum content) via the product line 'L'idée Verte'. 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 ADEME and the Direction de l'Environnement, de l'Aménagement et du Logement (DEAL), where the composition of each batch of compost produced is analyzed to determine salt and heavy metal levels and product composition.

Holdex specializes in the production of composts made with green organic wastes such as sugarcane bagasse, chicken manure, eggshells and other materials. They have been researching co-composting of sargassum for over seven years, which has led them to adapt and resolve several issues related to composting this raw material (e.g. sand, salt, pesticide and heavy metals content). Products that Holdex manufacture need to be analyzed and results communicated to authorities, based on strict regulations for the rights to process and commercialise:

Mike Bernus showing the compost produced by Holdex

- Standard NFU 44-051: maximum concentration of compounds in organic amendments, including arsenic at 18 mg/kg dry matter;
- Standard NFU 44-551: composition of growth substrate.

Holdex uses sargassum seaweed as a component in their compost, mainly for its important source of trace elements and microorganism enhancing ability. The company holds several patents related to their processing methods to obtain high quality compost and soil amendments. They are planning to process a total of 30,000 mt of sargassum yearly.

3.2 On-going research

There are currently many on-going research initiatives across the region, exploring ways to use sargassum. This emerging field of research is highly dynamic, and many new projects are now coming on stream. Here we present a selection of research case studies covering different types of uses, including some that have been awarded research funding very recently.

3.2.1 **Activated Carbon:** Successful multi-lateral and multi-national research project

Collaborating universities & institutes:

- Université des Antilles (Guadeloupe) (COVACHIMM2E laboratory)
- Instituto Tecnológico de Santo Domingo (INTEC) (Dominican Republic)
- Institut National de la Recherche Agronomique (INRA) (Guadeloupe & Nancy, France)
- Queen Mary University (UK)
- Instituto Superior de Tecnologías y Ciencias Aplicadas (InSTEC) (Cuba)
- Centre Inter-universitaire de Recherche et d'Ingénierie des Matériaux (CIRIMAT) (Toulouse, France)
- Université d'État d'Haïti (Haiti)
- Université Quisqueya (Haiti)

Collaborating private businesses:

- NBC (French Guiana), TECMALAB (Dominican Republic)
- NUM SMO Technologies (NST) and Phytobokaz (Guadeloupe)

Several ongoing projects about synthesis of activated carbons from sargassum are led by Prof. Sarra Gaspard from

Dr. Ulises Jáuregui-Haza (INTEC-InSTEC) and Prof. Sarra Gaspard (Université des Antilles) receiving the Cuban Academy of Sciences Award, for their research on the use of sugarcane bagasse activated carbons for chlorinated pesticide removal from water.

the Université des Antilles and supported by multi-lateral and multi-national collaborative teams from both the private and public sectors. The team has been working with pelagic sargassum since 2015, to explore the valorisation of its biomass for remediation and energy storage. More particularly, their research is looking at the potential of using sargassum biomass to produce activated carbon (AC) for use as pesticide sequestration in animal husbandry systems and water treatment. The chemical composition of seaweeds lends them to have great electrochemical properties for the production of nanotextured carbons. Oxygen enriched carbons with high porosity can be produced depending on the pyrolysis conditions.

This research project is looking at the different activation methods and different pyrolysis temperatures (600-900˚C) to obtain activated carbon:

a) Physical activation
b) Chemical activation
c) Hydrothermal carbonization

For this research study, after preparation, carbon samples are characterized based on their:

a) <u>Chemical composition:</u> surface chemistry (x-ray photo-electron spectroscopy, elemental analysis, surface functional groups) and adsorption (kinetic and isotherm)
b) <u>Textural characteristics:</u> nitrogen adsorption, BET (Brunauer-Emmett-Teller) surface area, porous volume
c) <u>Electrochemical properties:</u> cyclic voltammetry and galvanometry measurement

Promising preliminary results indicate that sargassum-based activated carbon has great potential for the treatment of micropollutant contaminants (caffeine, chromium and diazepam) in water and wastewater and the development of filters, membranes and electrodes for use in water and wastewater treatment and capacitive deionization units (Francoeur *et al*. 2019, Alvarez *et al*. 2019, Gaspard 2019).

Prof. Gaspard's team is one of the twelve recipients of a research grant from the 'Sargassum Call for Projects', issued by the European Interreg funds and the local governmental agencies of the Guadeloupe Region in 2019. Their research project, PYROSAR, will look at the valorisation of sargassum by pyrolysis and potential application for food safety. This research is based on the need to develop innovative strategies to establish safe food production and safe livestock rearing systems in chlordecone-contaminated areas such as Guadeloupe and Martinique. This project will assess the retention of chlordecone during the digestive processes of piglets after amendment of soils with biochar or AC. *In vitro* assays of soil amendment strategies by sorption assessment of chlordecone will be performed using activated carbons and biochars. *Ex vivo* assays of chlordecone transfer

Activated carbon made with sargassum displayed alongside a commercial sample of activated carbon (centre) between soil to plant and innocuity will then be tested, and finally *in vivo* relative bioavailability assays of chlordecone transfer will be carried out.

The study aims to:

- Optimize the production of biochar and activated carbon from sargassum at laboratory to industrial scale using the solar microwave process (SMO) of NST
- Characterize the raw sargassum and carbon materials produced
- Assess the ability of the produced biochar and activated carbon to adsorb organic micropollutants and avoid the transfer of organochlorine pesticides into the food chain (6 different biochars and ACs will be produced)
- Evaluate the macroeconomic impact of biochar and AC applications
- Evaluate the driving effect of a biochar/AC sector (including collection activity) on the local economy

3.2.2 **The University of the West Indies (UWI)**: Developing sargassum uses through research and promoting entrepreneurial initiatives

Research on the potential of using sargassum for a wide range of applications is being undertaken at the three UWI campuses. Examples from each campus are presented here.

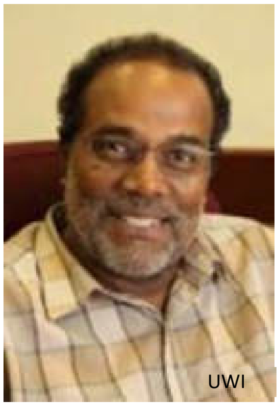
UWI Cave Hill Campus, Barbados

Dr. Srinivasa Popuri – Department of Biological and Chemical Sciences

Dr. Popuri's main research interests focus on membrane and adsorption technologies, particularly the development of biopolymers and biodegradable adsorbents. Even though they have numerous potential applications in our daily life, these are often overlooked. Since 2015, Dr. Popuri has been involved in the development of commercial sargassum-based products such as alginate for use in cosmetics, food and agricultural products. He has sparked students' curiosity and interest in finding innovative solutions for the use of the 'nuisance' sargassum seaweed by looking closely at its chemical composition and properties. He has also been encouraging students to look beyond the laboratory analyses to determine the potential of developing entrepreneurial ventures. In fact, two of his past students established the company Oasis Laboratory in 2018, having great success developing various beauty care products with sargassum. He continues to carry out controlled laboratory trials to further elaborate different cosmetic products using sargassum seaweed and improve their quality control and shelf life.

In addition, Dr. Popuri is conducting other sargassum related research including:

- A biocorrosion study to determine the chemical impact of the seaweed's decomposition and microorganisms' role in material degradation
- An adsorption study to determine the seaweed's wastewater treatment potential
- A bioplastics study to determine the seaweed's potential and commercialisation opportunities
- A bioethanol project using sargassum seaweed



Dr. Francis Lopez - Department of Biological and Chemical Sciences

Dr. Lopez is a research agronomist specializing in crop ecology, horticulture, crop physiology, biometry and turfgrass management. Dr. Lopez has been researching the potential of using sargassum seaweed in agriculture, as fertilizer and mulch. Several trials have been carried out since 2015 to generate evidence that seaweed can be used in the agricultural sector. Trials included testing of the seaweed at different decomposition stages (fresh, 3-months old and 8-months old) both in small field plots and potted plants. Possible interactive effects of sargassum mulch and extract with inorganic fertilizers were also examined. His team has concluded that although fresh sargassum (washed and unwashed) can have potential benefits on soil properties and plant growth, possible adverse effects due to soil salinisation must be considered. Best results were obtained with the 3-month old mulch (increased soil moisture content, soil biological activity and plant growth).

Sargassum mulch field trials conducted by Dr Lopez.

Dr. Bidyut Mohapatra – Department of Biological and Chemical Sciences

Dr. Mohapatra is a microbiologist. His research primarily focuses on (1) Exploring novel nanobiocatalysts for sustainable utilization of seaweed wastes using molecular microbiological approaches, and (2) Assessing the impact of Sargassum blooming on microbial community structure and enzyme-mediated biogeochemical cycles via culture-dependent and integrated metaomic (metagenomics and metaproteomics) techniques. To date, he has isolated several novel alginate lyase, cellulase and mannanase-producing bacteria from decomposed sargassum, which indicate potential industrial applications in pharmaceutical, food, agriculture, bioenergy and medical sectors. Obtaining microbial isolates from sargassum is an important step towards effective production of microbial enzymes, as a cheap feedstock for propagation.

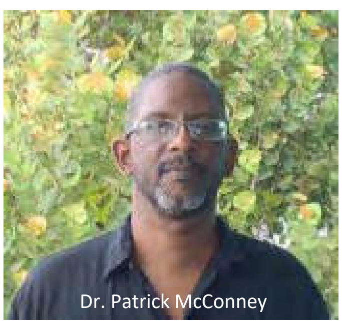
Dr. Legena Henry – Department of Computer Science, Mathematics and Physics

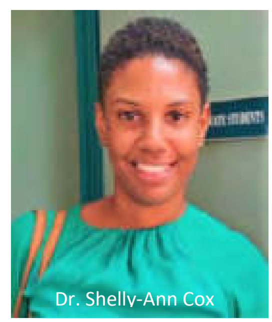
Dr. Henry is a professional mechanical engineer specializing in renewable energy, ocean engineering analysis, ocean wave statistics, marine hydrodynamics and applied mechanics. Dr. Henry is currently carrying out research focusing on using natural resources such as ocean waves, seaweed and agricultural processing waste to generate electric power.

Dr. Henry presented the Best Initiative in the 2019 call for Solutions Initiatives by the Sustainable Development Solutions Network Caribbean (SDSN Caribbean). With the support of the Blue Chip Foundation, Dr. Henry has recently commenced a 22-month biogas project using sargassum seaweed and rum distillery waste as feedstock. This project is being carried out in collaboration with Dr. Renique Murray of the Department of Mechanical and Manufacturing Engineering at the St. Augustine Campus of the UWI, Dr. Nikolai Holder of the UWI (Cave Hill) and the company HomeBiogas. This pilot project includes setting up four biogas systems, two of which will be located at the West Indies Rum Distillery Ltd. and two others at the Foursquare Rum Distillery. The pilot project will consist in producing biomethane and testing it on cars converted to compressed natural gas (CNG) engines.

Centre for Resource Management and Environmental Studies (CERMES) - Sargassum research team

Dr. Patrick McConney (Director), Prof. Hazel Oxenford, Dr. Janice Cumberbatch, Dr. Shelly-Ann Cox, Dr. Lisa Soares, Maria Pena, Anne Desrochers, Karima Degia, Kristie Alleyne





The CERMES sargassum team has been involved with sargassum research, communication, co-ordination and management initiatives since the first inundations in 2011. They have hosted two regional sargassum Symposia, in 2015 and 2018, bringing together researchers, members of the public and private sectors, and key stakeholders from the fishing and tourism industries to share information on good practices for managing sargassum influxes, including innovative uses. They continue to lead and/or work in partnership with regional and international organisations on a number of sargassum-focused projects that are helping to realize the opportunities provided by sargassum influxes, including:

- The GEF-funded FAO Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) project. As a subcomponent of this project, CERMES has undertaken this review of current and potential uses of sargassum to produce this 'Sargassum Uses Guide'.
- The Caribbean Biodiversity Fund's (CBF) Ecosystem-based Adaptation (EbA) Facility, German Development Bank (KfW)-funded project Adapting to a new reality: managing responses to

influxes of sargassum seaweed in the Eastern Caribbean as ecosystem hazards and opportunities (SargAdapt). This project is aimed at enhancing knowledge, improving technical and institutional capacity, and developing innovative practical applications for sargassum use.

- The University of Southampton's Economic and Social Research Council (ESRC) Global Challenges Research Fund (GCRF)-funded project Teleconnected sargassum risks across the Atlantic: building capacity for transformational adaptation in the Caribbean and West Africa (SARTRAC). This project is striving to (1) identify opportunities for transformational adaptation that can be generated through the management and use of sargassum seaweed, and (2) build capacity to support use of the seaweed by vulnerable coastal communities.

UWI Mona Campus, Jamaica

Prof. Mona Webber, Director of the Centre for Marine Sciences - Department of Life Sciences

Prof. Webber is a marine biologist and ecologist and her main research interests have focused on zooplankton (production, community structure and distribution and their use as water quality indicators), mangrove habitats (biodiversity, water quality indices and coastline protection), micro-plastics, mangrove forest rehabilitation, seagrass assessment among others. She is also the chair of the Faculty of Science and Technology's Sargassum Research Group and a Co-Principal Investigator in the University of Southampton ESRC GCRF-funded project 'Teleconnected sargassum risks across the Atlantic: building capacity for transformational adaptation in the Caribbean and West Africa (SARTRAC)'. She has been working on identification of the different species and morphotypes of pelagic sargassum and developing efficient field methods for distinguishing them and recording their relative abundance. Through partnerships with local and international stakeholders, the Centre for Marine Sciences has been studying methods of composting sargassum for use in agriculture and mangrove nurseries as well as other methods of 'storage' (e.g. ensilage, drying, etc.) appropriate for beached sargassum.

Other members of the Sargassum Research Group include:

- Prof. Rupika Delgoda, Director - Natural Products Institute: assessment of anticancer properties of sargassum extracts and trials on breast cancer cell lines.
- Dr. Winklet Gallimore - Department of Chemistry: identification of commercially viable natural marine products based on their chemistry and bioactive compounds.
- Dr. Frederick Boyd - Department of Life Sciences: research on medicinal botany and assessment of sargassum antimicrobial properties.
- Dr. Howard Reid - Mona Institute of Applied Science: chemical profile and product development based on sargassum alginates.
- Dr. Ava Maxam - Mona GeoInformatics Institute: Impact of surface currents on sargassum movement, shoreline and nearshore data for hydrodynamic model mesh development and the provision and refinement of downscaling data towards sargassum early-warning system development and implementation for Jamaica.

- Dr. Tannecia Stephenson - Department of Physics: development of methodology for integrating satellite and drone data and analysis for forecasting sargassum beaching and assisting with the development of the sargassum early-warning system functional specifications and requirements.

UWI St. Augustine Campus, Trinidad and Tobago

Dr. Ward and members of his research team in 2017.

Dr. Keeran Ward - Department of Chemical Engineering

Dr. Ward and his team are working on projects to determine the supply chain demand of alginate extracted from seaweed. Dr. Ward is investigating the polymer's use to create membranes that can be used as a biofilter for remediation of heavy metals in wastewater and as a bioplastic substitute. These potential applications contribute to the sustainable development and management of seaweed, from a material that is considered a nuisance, such as the stranded pelagic sargassum, to an environmentally friendly and viable substitute. In keeping with the project's key objective to fully utilize the seaweed material, Dr. Ward and his team are also considering the valorisation of the residual biomass for the generation of clean energy solutions.

Dr. Ward has been working since 2017, on developing a biodegradable water container made of sargassum; this new bioplastic prototype seeks to optimize the famous edible Ooho water bottle designed by Skipping Rocks Lab in the UK, by upgrading the membrane to a harder consistency. As such, the potential of Thin Film Composite (TFC) technique with calcium alginate membranes is being investigated for its durability. The improved, more rigid prototype being developed will be able to hold any type of liquid, including water, juice, wine, etc.

The team is also researching the effects of adding other biomaterials such as starch, clay, cellulose, pectin, etc. to increase the TFC alginate membrane' ability to adsorb harmful toxins like heavy metals from industrial wastewater facilities.

Dr. Renique Murray - Department of Mechanical and Manufacturing Engineering

Dr. Renique Murry is collaborating on a biogas project with Dr. Legena Henry (see description above).

Prof. Jayaraj Jayaraman - Department of Life Sciences

Prof. Jayaraman is a professor of biotechnology and plant microbiology at UWI-St. Augustine, and his main research interests include:

- Plant-microbe interactions, induced resistance, elicitor-biomolecules, nanopesticides, bioremediation, biological control and integrated pest management
- Genetic engineering of plants for disease resistance and stress tolerance

- Metabolic engineering, biopharming of therapeutic proteins and industrially valuable compounds
- Phyto-nutraceuticals, Natural products for human health and therapy
- Seaweed biomolecules and products for agriculture and human health
- Antimicrobial resistance of pathogens

Prof. Jayaraman has been working on several research projects related to seaweeds, to find ways to recover some of the seaweeds' valuable components which could be of potential commercial value. His group demonstrated for the first time the elicitor action of seaweed extracts at the molecular level in plants, happening through induced resistance, and has published several research papers on the elicitor activity of seaweed products. His research team has developed several methods for extracting elicitors and biomolecules from Caribbean seaweeds including pelagic sargassum. The seaweed products developed are being tested for phytostimulatory action in plants, antimicrobial and therapeutic activities. His team has also developed a few stable formulations from sargassum extracts which are now being investigated for plant-promotive effects. His research on seaweeds is focused towards developing circular economy methods for complete and sustainable valorisation of seaweeds. Prof. Jayaraman is one of the key researchers of the globally recognised seaweed research network. He is a key partner in the SARGOOD project – a Caribbean initiative which envisages finding sustainable ways for managing the sargassum problem.

3.2.3 **SOS Carbon**: A multi-national public-private research venture [USA]

The Sargassum Ocean Sequestration of Carbon project, also known as SOS Carbon, stems from Luke Gray's Masters' research project at the Massachusetts Institute of Technology (MIT), supervised by Prof. Alexander Slocum of MIT's Precision Engineering Research Group. The Boston-based engineering team has been working on a specialized machine to be used as an alternative way to manage pelagic sargassum stranding, affecting the entire Caribbean region. Pelagic sargassum floats at the surface thanks to its small gas bladders. However, based on Luke's discovery that when sargassum is pumped to a critical depth (approximately 150 to 200 m), it becomes negatively buoyant and sinks to the ocean floor. The MIT team developed a close partnership with fellow engineer and collaborator Andrés Bisonó León, a native of the Dominican Republic who is based in Philadelphia.

Luke and Andrés have been working in close collaboration on the SOS Carbon project both in the United States and in the Dominican Republic and have presented initial findings of their proof of concept experimental testing and highlighted the pilot project at different meetings and conferences in the Caribbean (Jamaica, Guadeloupe, Dominican Republic and Florida). They are drawing much attention in all sectors, from private investors, to researchers and even various Caribbean governments, due to the fact that their proposed solution is quite different from all others presented to date. Most other solutions involve several stages and large investments in order to remove and dispose of the seaweed, from the installation of floating barriers, boats for maintenance and harvesting, transportation, storage and processing of the seaweed. Not to mention the high costs associated with equipment and negative impacts related to beach compaction with the use of heavy equipment on shore, health effects and potential accumulation of heavy metals. Andrés has been the driving force behind the logistics, ensuring smooth completion of this multi-national and multi-lateral project, developing close ties with several key public and private stakeholders, and Luke has been driving the technical, design and research-focus of this project.

SOS Carbon's equipment for field trials in the Dominican Republic

SOS Carbon has developed close partnerships with several key stakeholders, including the Dominican Republic navy and Fundación Cap Cana, an environmental protection group that is part of Cap Cana (an exclusive real estate, marina, hotel, golf course, equestrian centre, schools, parks and village centres located in Punta Cana). In collaboration with key stakeholders, SOS Carbon has been carrying out field testing of their patented machinery and system as well as proof of concept testing for the research project. Several tons of specially designed and built machinery including an industrial-size pump were shipped to the Dominican Republic. Field testing of the equipment began in November 2019, however up to the time of writing, there had been insufficient quantities of sargassum to allow the team to carry out real-time field testing and confirm the successful offshore interception and effective sinking of the seaweed before it impacts the coastlines. For those interested in processing the seaweed, SOS Carbon's team is also considering the option of pumping the seaweed biomass into barges far offshore and delivering it to processing facilities. Conversely, sargassum collected from shore could also be placed on a barge and SOS Carbon could haul it offshore and pump it down into the deep ocean.

SOS Carbon team with members of the Dominican Republic navy

SOS Carbon's equipment for field trials in the Dominican Republic

Another interesting and innovative aspect of this project is that SOS Carbon is exploring the possibility of offering an option for practicing entities to earn carbon credit income or carbon trading opportunities by sequestering and storing substantial amounts of carbon locked in the enormous sargassum biomass and reducing the greenhouse gas (GHG) emissions in the atmosphere. According to the researchers, SOS Carbon is comparable to industry-wide measures for carbon reduction, and therefore, the Caribbean could be a leader and a model in terms of carbon sequestration. According to Luke's research, pumping-to-depth is a simple and energy-efficient process that could generate carbon offsets, representing more than 0.25 mt of carbon dioxide per mt of fresh sargassum. The proposed project contributes to the development of a system that is low-cost and effective in the long-term management of sargassum.

Although the team believes that their solution is not only sustainable but will also help to alleviate some of the negative impacts on the nearshore environment and the tourism sector, they are aware of the need to further study the environmental implications of seaweed biomass sinking to the deep sea floor. In addition, SOS Carbon is researching and collaborating with other Caribbean governments, such as Jamaica, to determine how best to implement their services and technology in each country, area or hotel resort and build a solid business model to meet the needs of the entire Caribbean community.

SOS Carbon is now working to bring their collection and sequestration technology to the Caribbean at large, using a simpler more inclusive system, that will be deployed in collaboration with local fishermen. By partnering with local fishermen and the use if their boats, this will allow the collection device to operate continuously at the lowest marginal cost, while promoting economic activity and increasing the benefits of reducing the impact of sargassum influxes. The system was designed to operate in areas with or without barriers, where sargassum is collected, placed in barges and pumped into the deep ocean floor.

3.2.4 **Sargassum Call for Projects (2019):** Twelve selected research projects

A Joint Call for "Sargassum Research, Development and Innovation" projects was officially launched in late 2018 and open from February to June 2019 to receive project proposals from any researchers from public research establishments or private companies based in French overseas territories, mainland France and Brazil. The Agence nationale de la recherche (ANR) was responsible for the Call for Projects, jointly with the Agence de l'environnement et de la maîtrise de l'énergie (ADEME), the French Territorial Overseas Collectivities of Guadeloupe, Martinique and French Guiana, and Brazil's Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Fundação do Amparo a Ciência e Tecnologia (FACEPE).

The aim of this Call for Projects was to select and fund projects that would cover and meticulously document all aspects related to sargassum issues, including scientific, economic, environmental and health issues, and provide pragmatic solutions to the stranding of sargassum affecting many areas. The call was focused on four main themes:

1. Characterization of sargassum: physiology, genetics, biochemistry, morphology and demography
2. Forecasting sargassum events and their trajectory in open ocean and close to shore
3. Collection (offshore and onshore) and valorisation of sargassum strandings by innovative techniques
4. Economic, healthcare and environmental impacts of strandings and coping strategies

In October 2019, a total of twelve research projects were selected to receive support in the form of research grants totalling 13 million Euros. Local governmental agencies of the Guadeloupe Region (including French overseas territories) and the European Interreg funds are co-financing the implementation of this multifaceted programme.

The selected projects, many of them representing collaborative initiatives, are considered as a starting point for the development of a long-term action plan based on a better understanding of the issues related to the pelagic sargassum phenomenon, and a better alignment of projects at the regional level.

Here we present a summary of the twelve selected projects:

CESAR: Coastal environment under sargassum crisis

Coordinator: J-R Gros-Desormeaux (Laboratoire Caribéen de sciences sociales (LC2S)).
Collaborators: Franck Dolique (Laboratoire biologie des organismes et écosystèmes aquatique (BOREA)), Philippe Palany (Météo France-Antilles), Solange Teles da Silva (Universidade Presbiteriana Mackenzie, Brazil), Marion Sutton (Collecte localisation satellites) and Hubert Mazurek (Institut de recherche pour le développement (IRD) in Aix-Marseille, France).
Aims:

- To provide knowledge and propose orientation for tools and methods development to manage sargassum influxes in the Caribbean, particularly in the French West Indies
- To provide a better knowledge on sargassum as well as inputs for improvement of our forecast capabilities to predict sargassum stranding events at the islands scale
- To contribute to the policy decision chain processes and develop guidelines for strategic sargassum action plans through policy brief

CORSAIR: Atmospheric and marine corrosions

Coordinator: Christophe Roos (Université des antilles (UA), Laboratoire des matériaux et molécules en milieu agressif (L3MA)).
Collaborators: Carole Boullanger (Madininair), Jean Marel (ECO MOBIL), Srinivasa Popuri (University of the West Indies (UWI), Cave Hill), Claire Hellio (Université de Bretagne Occidentale (UBO)-Laboratoire des sciences de l'environnement marin (LSEM)), Karine Vallee-Rehel (Université Bretagne Sud (UBS)-Laboratoire de biotechnologique et chimie marines (LBCM)), Benoit Lescop (UBO-Laboratoire des sciences et technologies de l'information, de la communication et de la connaissance (STICC)), Dominique Thierry (Institut de la corrosion) and Aude Farinetti (Université Paris-Sud-Institut d'études de droit public (IEDP)).

Aims:

- Understanding the corrosion rate of exposure sites and modelling the phenomenon of corrosion and its natural inhibitory solution

- Characterization of biofilms (sulphate-reducing microorganisms): corrosion rate, development of a new generation of sensors, electro active potential of microorganisms and natural molecules with antifouling performance
- Compilation of legal tools: proposals for improvements from the private, public and international perspectives.

FORESEA: Forecasting of sargassum strandings in the Tropical Atlantic

Coordinator: Julien Jouanno (IRD-Unité mixte de recherche (UMR) in Legos, France).

Collaborators: Léo Berline (Mediterranean Institute of Oceanography (MIO)), Rudy Calif (Laboratoire de recherche en géosciences et énergies), Christophe Lett (IRD), Franck Dolique (BOREA-UA in Martinique), Yann Drillet (Mercator Ocean), Audrey Minghelli (Laboratoire d'informatique et systèmes (LIS)), Pascal Zongo (L3MA), Julio Sheinbaum (Centro de Investigación Científica y de Educación Serior de Ensenada (CICESE) in Baja California, Mexico).

PYROSAR: Valorisation of sargassum by pyrolysis - application for food safety

Coordinator: Sarra Gaspard (UA).

Collaborators: Guido Rychen (Université de Lorraine (UL), Unité de recherche animal et fonctionnalité des produits animaux (UR AFPA), Marie Ugolin (NST), Ted Soubdhan (UA-Laboratoire de recherche en géoscience et énergies), Gérard Thamensi (Agence régionale de santé, Martinique), Antoine Richard (Unité de recherche sur les agrosystèmes tropicaux, Institut national de la recherche agronomique (INRA)), Olivier Gros (UA-Institut de systématique, évolution, biodiversité (ISYEB)), Sébastien Mathouraparsad (UA-Centre de recherche en économie et en droit sur le développement insulaire CREDDI) and Maguy Dulormne (UA-Joint Research Unit of Guianan Forests (EcoFoG)).

Aims:

- Optimize the production of biochar and activated carbon (AC) from sargassum at laboratory and industrial scale using the solar microwave oven process (SMO) of NST
- Characterize raw sargassum and the carbon materials produced
- Assess the ability of the produced biochar and AC with the aim to avoid organochlorine pesticides transfer either to vegetables entering the food chain or food producing animals (6 different biochars and ACs will be produced and evaluated)
- Soil amendment in organochlorine pesticide contaminated areas, in close collaboration with landowners, with the best biochar and AC candidates
- Evaluate the macroeconomic impact
- Evaluate the driving effect of a biochar/AC sector (including collection activity) on the rest of the economy.

Background:

There is an urgent need to develop innovative strategies to establish safe livestock rearing systems in chlordecone-contaminated areas. The field plot will use six gardens of two soil types in Guadeloupe and Martinique. This project will assess the retention of chlordecone during the digestive processes of piglets after amendment of soils with biochar or AC. Three raw materials will be tested: *Sargassum fluitans*, *Cocos nucifera* (coconut) and *Quercus ilex* (holm oak). This project will perform *in vitro* assays of soil amendment strategies by sorption assessment of chlordecone by activated carbons and biochars. *Ex vivo* assays of chlordecone transfer between soil to plant and innocuity will then be tested and finally *in vivo* relative bioavailability assays of chlordecone transfer will be carried out.

Sarg As Cld: Environmental impacts of sargassum leachate due to arsenic and chlordecone: quantification, mitigation and social perception

Coordinator: Christophe Mouvet (Bureau de recherche géologiques et minières).

Collaborators: Fabienne Séby (Association pour le développement de l'enseignement et de la recherche en Aquitaine (ADERA)-Laboratoire ultra traces analyses Aquitaine (UT2A)), Benoît Cagnon (Centre national de la recherche scientifique (CNRS)-Interfaces, confinement, matériaux et nanostructures (ICMN)), David Hala (Texas A&M University at Galveston), Soazig Lemoine (UA), Thierry Nicolas (Université de Guyane-Migration interculturalité et éducation en Amazonie (MINEA)).

Aims:

- Improve knowledge on sargassum contamination by arsenic (marine origin) and chlordecone (terrestrial origin)
- Assess the eco-toxicity of sargassum leachates, with a focus on arsenic and chlordecone, to a range of representative test organisms (eco-toxicity to freshwater and marine organisms)
- Develop durable remediation processes for arsenic and chlordecone leachates
- Assess the social acceptability of sargassum stockpiling
- Dissemination of results and dialogue with stakeholders.

Background:

This project is looking to do a characterization of sargassum and leachates through microscopy observations of sargassum, speciation and analysis of arsenic in sargassum (inorganic and organic) and leachates and analyses of chlordecone. The project will also study the environmental impacts of sargassum leachates through three bioassays on crustaceans, oysters and zebra fish. Mitigation measures of leachate impacts will be evaluated and the social acceptability of sargassum stockpiling will be addressed through this project.

SARGACARE: Human health effects of chronic exposure to gaseous fumes from decomposing brown algae in the French West Indies

Coordinator: Rémi Neviere (Centre hospitalier universitaire (CHU) of Martinique).

Collaborators: Dabor Resiere (CHU of Martinique), Sylvie Merle (Observatoire de la santé de la Martinique), Rachel Nadif (Institut national de la santé et de la recherche médicale (INSERM)-Aging and chronic diseases, epidemiologic and public health approaches, France), Michel Carles (CHU of Guadeloupe) and Mariana Veras (Laboratório de Poluição Atmosférica Experimental (LIM05)-Hospital das Clínicas da Facultade de Medicina da Universidade de São Paulo (HCFMUSP) of Brazil).

Goal: Conduct a detailed study of the clinical, biological, functional and socio-anthropological consequences of gaseous emissions produced by decomposing sargassum in the Caribbean.

Aims:

- Characterize the toxicological syndrome induced by decomposing sargassum gaseous emissions
- Investigate the associations between exposure levels to gaseous emissions and the toxicological syndrome

- Assess, through an anthropo-sociological approach, the knowledge, belief and practices of populations confronted with the problem of sargassum influxes in Guadeloupe and Martinique.

Background:
In the past two years, over 200 patients have been seen at the CHU in Martinique for clinical symptoms potentially associated with exposure to gaseous emissions from sargassum decomposition. Most frequent clinical signs and symptoms include reddening and irritation of skin, eyes, mucous membrane and respiratory tract, coughing, wheezing, headache, abdominal pain and intestinal transit disorders. Acute exposure to high doses of hydrogen sulphide (H_2S) is known to be lethal, however the effects of repeated exposures to low doses of H_2S and a combination of other gases is unknown.

SARGASSUM ORIGINS: Identity and origins of pelagic sargassum

Coordinator: Thierry Thibaut (IRD-MIO).
Collaborators: Florence Rousseau (ISYEB), Solène Connan (UBO-LSEM), Frédérique Viard (CNRS-Adaptation et diversité en milieu marin), Jerome Llido (IRD in Legos, France), Etienne Bezault (UA-BOREA), Fabrice Javel (SUEZ Consulting), Amy Siuda (Eckerd College in USA), Kerry Whittaker (Sea Education Association in USA) and Karl Kaiser (Texas A&M University at Galveston in USA).

Aims:
- Identify sargassum species growing in the North Atlantic (co-occurrence)
- Study the connectivity of sargassum at the Atlantic scale (fluxes and exchanges, comparison with historical Sargasso Sea and the new area of proliferation)
- Trace the carbon and nitrogen pathway within the sargassum.

SARGOOD: Holistic approach to sargassum valorisation

Coordinator: Marie-Ange Arsene (Connaissance et valorisation: chimie des matériaux, environnement, énergie (COVACHIM-M2E)).
Collaborators: Valerie Simon (École nationale supérieure des ingénieurs en arts chimiques et technologiques (ENSIACET)-Laboratoire de chimie agro-industrielle (LCA)), Cédric Coco-Viloin (SMART-ISLAND), Joao Adriano Rossignolo (Universidade de São Paulo), Hugues Occibrun (100% Zeb), Anne Becker (Ross University, School of Veterinary Medicine in St Kitts & Nevis), Jayaraj Jayaraman (UWI, Trinidad & Tobago).

Aims:
- Assessment of sargassum life cycle
- Optimization of harvesting and processing techniques
- Development of extraction processes and analytical methods
- Valorisation of products and by-products by bio refinery
- Developing innovative materials and technologies (eco-materials and panels from ashes and particles, porous carbon for water treatment, gelling agents, anticorrosive dyes, bioelicitors and biostimulants, agricultural products).

Background:
This project will address several important aspects to be considered for the valorisation of sargassum, such as:

- The biological impact of sargassum harvest on associated native fauna
- The phytochemical, metabolomics and physico-chemical study of non-extractable sargassum material
- The pozzolanicity and geopolymer precursor potential
- The morphology of sargassum carbon for water treatment
- The biological and anticorrosive activity of sargassum gelling agent
- The stability, viability, validity and environmental impact of proposed processes of valorised products.

SARGSCREEN: Pharmaco-toxicological screening of molecules extracted from Caribbean sargassum: highlighting their impact on certain pathologies widespread in the Caribbean

Coordinator: Azaria Remon (Association pour la valorisation des ressources naturelles de la Martinique).
Collaborators: Juliette Smith-Ravin (Association de recherche en épidémiologie et en biodiversité (AREBio) in Martinique) and Lionel Massi (Université Nice Sophia Antipolis, Institut de chimie de Nice).

Aim:
To detect pharmacological potential of sargassum extracts against pathologies spread over the Caribbean.

Background:
Sargassum has great pharmaceutical potential due to its biologically active compounds (tannins, terpenoids, flavonoids, sterols, sulphated polysaccharides, polyphenols, sargaquinoic acids, sargachromenol, pheophytin, etc.) and its pharmacological activities (analgesic, anti-inflammatory, antioxidant, neuroprotective, antimicrobial, fibrinolytic, immunomodulatory, anticoagulant, hepatoprotective, etc.

SARtrib: Tribological and electrochemical valorisation of sargassum

Coordinator: Thierry Cesaire (Groupe de technologie des surfaces et interfaces (GTSI)).
Collaborators: Sébastien Mathouraparsad (CREDDI-Laboratory of Economics Applied to Development (LEAD)), Christine Cecutti (Toulouse Institut national polytechnique (INP)-ENSIACET-LCA) and Marc Dubois (Institut de chimie de Clermont-Ferrand (ICCF)).

Aims:
Valorisation of vacuum pyrolysis by-products of sargassum: electrodes for lithium batteries and new generation of lubricant.

Background from the project's consortium:

- GTSI will study the tribology, nano-mechanics and physico-chemical characterization of sargassum. The tribology characterization uses friction reduction and anti-wear mechanisms, based on carbon friction reducers derived from local biomass. GTSI will be responsible for the characterization of the biomass before pyrolysis (along with LCA), of the pyrolyzed solid phase and the tribology.
- ICCF will study the fluoridation and fluorinated materials for energy and surface engineering. Nanocarbons and nano-oxide materials will be tested as filters or material sensitive to pollution gases. Carbide-derived carbons from fluorination will be tested for use in supercapacitors. Fluorides and oxyfluorides of transition metals will be tested as electrode materials for secondary batteries, whereas (nano) fluorinated carbons as electrode for primary batteries. Surface treatment of

polymers will be tested to obtain one or more properties (hydrophobicity, CO_2, O_2 and water gas barrier, antibacterial, etc.). Incorporation of fluorinated nanocarbons will be tested in polymers and fluoridation of grapheme, nanotubes, nanofibers and carbon nanodiscs will be tested. ICCF will be responsible for the fluorination and electrochemistry aspects of the project.

- LCA will study the fractionation of different biomass, including waste from agriculture, agro-industries, forest, food waste, microalgae and algae and their chemical reactivity for potential uses (bio products, agro-materials, solvents, pigments, surfactants, adhesives, aromas, additives and lubricants). LCA will be responsible of characterization of the biomass before pyrolysis (along with GTSI) and the pyrolyzed liquid phase.
- CREDDI-LEAD will study the development of models applied to the outermost regions, preparation of various financing plan contracts, structural funds, surveys and econometric modelling. CREDDI will be responsible for the economic model.

SAVE: Sargassum agricultural valorisation and energy production

Coordinator: Stéphane Pacaud (École nationale supérieure d'agronomie et des industries alimentaires).

Collaborators: Harry Archimede (INRA-Unité de recherche zootechnique (URZ)), Séverine Piutti (Laboratoire agronomie environnement) and Jean Pierre Porry (Société maritime de remorquage et d'assistance (SOMARA) in Martinique).

Aims:

- Identify non-destructive sargassum harvesting methods
- Identify methods of sargassum stocking and sanitary measures
- Effects of salt impact on anaerobic digestion
- Effects of adding bio wastes on anaerobic digestion
- Identify the agronomic quality of digestates and their functions in soils
- Develop sanitary management measures (physico-chemical and microbiological) of digestates
- Develop a social and environmental approach to integrating the treatment of sargassum and local bio wastes.

SAVE-C: Study of holopelagic sargassum responsible of massive beachings: valorisation and ecology on Caribbean coasts

Coordinator: Valérie Stiger (UBO-LSEM).

Collaborators: Valérie Michotey (IRD-MIO), Béatrice Rhino (Centre de coopération internationale en recherche agronomique pour le développement (CIRAD)), Nathalie Bourgougnon (Laboratoire de biotechnologie et chimie marines), Jean-Louis Lanoiselle (Institut de recherche Duy de Lôme (IRDL)), Isabelle Mussio (UMR BOREA), Maud Benoit (ALGAIA), Ivan Janeau (EFINOR), Henri Vallès (UWI, Cave Hill, Barbados), Charlotte Dromard (UA-UMR BOREA), Maxime Chevalier (UA-L3MA in Martinique), Jean-Pierre Allenou (Institut français de recherche pour l'exploitation de la mer (IFREMER) in Martinique), Daniel Reobledo (Centro de Investigación y de Estudios Avanzados (CINVESTAV) in Merida, Mexico), Ralph Siniamin (Siniamin Funeraire Sasu & The Marine Box).

Aims:

- To better understand the diversity and the functioning of pelagic sargassum, from the drifting rafts until their beaching

- To understand the capacity of sargassum to live in pelagic conditions, how it concentrates particular contaminants and the degradation process in beached sargassum
- To collect and valorise sargassum in two sectors: agriculture (biopesticides) and biomaterial (cardboard).

Background:
This project is based on three main themes: 1) Characterization, 2) Collection and valorisation, and 3) Impacts. The characterization will focus on studying the diversity associated with sargassum rafts and the influence of environmental conditions on the lifecycle, such as contaminants and degradation. The collection and valorisation will focus on studying the stabilization of raw material and different types of valorisation. Finally, the impacts theme will look at the trophic and chemical interactions of organisms within sargassum rafts.

3.2.5 **Polytechnic University of Quintana Roo**: Developing a sustainable sargassum value chain

Since 2019, the Polytechnic University of Quintana Roo (UPQRoo), located in Cancun, Mexico, has been working on a research project to identify sustainable business opportunities utilizing sargassum seaweed that could lead to the development of a sustainable sargassum value chain, easy to replicate and scaled-up in other areas or countries. This two-year project is funded by the government of Mexico's Science and Technology Council (Consejo Nacional de Ciencia y Tecnología (CONACyT)), and is being carried out by a research team, led by Dr. Jorge Cantó and ten other researchers. In order to better identify potential economic uses for sargassum, the research team planned out their activities so that a comprehensive approach would be followed:

1. Organize discussion forums with other researchers to identify potential uses
2. Sargassum sampling and analysis
3. Sample characterization
4. Assess technical possibilities and challenges
5. Assess social and ecological impacts
6. Assess market demand.

Dr. Jorge Cantó, team leader

Laboratory analyses carried out include: reverse phase High Performance Liquid Chromatography (HPLC), hydraulic magnetic resonance of hydrogen (200 MHz), separation by column chromatography for spots of interest, infrared spectroscopy of the extracts, calorific value with calorimetric pump and composition (compounds, energy, fibre, ash, metals, alginate, triglyceride, polyphenol, etc.). After analysis, both fractions of liquid and solid samples were characterized and subdivided into potential application streams. Potential applications based on components of interest include those shown in the following Table.

Potential applications of sargassum extracts, according to UPQRoo

Component	Potential Applications
Polyphenols	Pharmaceuticals, food, cosmetics
Alginates	Pharmaceuticals, food, cosmetics, textile, dentistry products and veterinary products
Triglycerides	Materials development, surfactants, corrosion inhibitors, biofuels and medical products and drugs
Sargassum bagasse	Agricultural (fertilizers, animal feed supplement), paper products

UPQRoo's research team developed a tool to quantitatively evaluate the feasibility and potential impacts related to the development of each potential sargassum use identified. This impact indicator could be a valuable tool to determine and prioritize the best suited and most promising uses for sargassum development based on different locations and contexts. To do so, an indicator was created to assign a value and weigh the success probability, in terms of benefits generated to society, financial profitability, acceptability, market demand and technical viability. Seven different impact elements were evaluated based on a set of predetermined criteria and an associated value as shown in the following Table.

Impact Factor Table showing criteria for assessing the likely potential for different sargassum uses

Impact Indicator	Criteria	Value
Type of algae used for research	Technical development carried out with *Sargassum fluitans* and/or *S. natans*	5
	Technical development carried out with other species of algae	0
Social	The application generates direct social benefits	5
	The application generates indirect social benefits	3
	The application does not generate any social benefit	1
Technical	The level of technical development is found at the industrial level in the world	5
	The level of technical development is found at the industrial level in the country	4
	The level of technical development is found at a pilot plant level	3
	The level of technical development is found at the research laboratory level	2
	The level of technical development is found at the theoretical research level	1
Financial	Technical development carried out at the industrial level and is considered as economically viable	5
	Technical development carried out at the pilot plant level and is considered as very likely to be economically viable	3
	Technical development is only at the research level and the economically viability is unknown	1
	Not considered as economically viable	0
Institutional	Development of inter-institutional collaborations between various actors (public, private or a combination of both)	5
	Inter-institutional collaboration is not required	3
	Unknown if inter-institutional collaborations are required	0
Environmental	Favourable environmental impact resulting from development of the use	5
	No environmental impact resulting from development of the use	3
	Adverse environmental impact resulting from development of the use, however there is a prevention and/or mitigation plan in place	1
	Unknown if the development of the use will have any environmental impact	0
Market demand	Proven market demand in a solid market	5
	No proven market demand	3
	No data available on the existence of a market	1

Based on results obtained from the impact indicator tool, the team identified three main industries for which sargassum has potential commercial value in the Mexican context:

1. <u>Pharmaceutical</u>

Sodium alginate extracted from sargassum seaweed can have many different applications such as thickening and emulsifying agents, commonly used in pharmaceutical products, cosmetics, food preparation, paper products, textile, etc. Global market demand for sodium alginate is expected to reach over US $923 million by 2025 (Grand View Research 2017). According to Dr. Cantó, "*If Mexico could secure 20 percent of the global market share of sodium alginate, that would use 35 percent of the entire amount of sargassum that arrived on the coasts of Mexico in 2019, so that's a third of the problem solved by just this one product"* (Edwards 2020).

2. <u>Agricultural</u>

The development of biofertilizers for Mexico's agricultural industry is also a potential sustainable business for use of sargassum. Most Mexican farms are located in the central and northern parts of the country partly because farmers rely heavily on imported fertilizers from the US. According to Dr. Cantó, producing local fertilizers could increase agricultural production in the region. UPQRoo's team has partnered with the agricultural biotechnology company Tierra de Monte to lead the project's research on sargassum-based fertilizers. Preliminary results indicate three distinct agricultural products that can be produced from a simple heating and filtering process of the seaweed:

- Concentrate liquid extracted can be used as a plant biostimulant
- Remaining solid residues can be used as a substrate for mushroom production
- After use, this substrate can be composted and applied to agricultural fields as a soil amendment.

3. <u>Oil and gas</u>

Another interesting potential business identified for sargassum seaweed is for use as a corrosion inhibitor for oil and gas pipelines. Sargassum has compounds that could be used in steel pipelines to prevent these from corroding. Although this use is for a very specific market and would probably require smaller amounts of sargassum than the agricultural option, it would nevertheless have an important economic impact.

Dr. Jorge Cantó and Lorenzo Martínez

UPQRoo has partnered with Lorenzo Martínez (Harvard Business School graduate), who is leading the commercialisation and market research part of the project. By creating a market value chain for sargassum and implementing central processing plants, this will incentivize more harvesting of the seaweed and more entrepreneurs getting involved and creating businesses. However, when developing sustainable business models, it will be crucial to consider the variability in supply, since large sargassum arrivals are not constant and do not occur on a regular basis. Entrepreneurs are not inclined to invest in a business that is likely to have shortages of the primary material and no guarantee that sargassum will continue to bloom at the rate that it has since 2015. According to Lorenzo, even if there is a decrease in sargassum arrivals, the amount would be sufficient to develop a sustainable value chain and a number of viable businesses. In addition, the team will also evaluate economic projections of certain end-use products of interest.

Another element being investigated by the UPQRoo team is the development of a satellite imagery and artificial intelligence detection system to predict sargassum movement. This system will assist the Mexican navy to pinpoint offshore areas with large sargassum blooms so that specialized harvesting boats used by the navy could navigate directly to these hotspots and harvest drifting sargassum rafts before they reach Mexican coastlines.

3.2.6 **Center for Applied Physics and Advanced Technology (CFATA), Autonomous University of Mexico (UNAM)**, Queretaro Juriquilla Campus: Sargassum biofilters for bioremediation

Collaborators:

- Dr. Miriam Rocío Estévez González (CFATA, UNAM)
- Dr. José Luis López Miranda (CFATA, UNAM)
- Dr. Rodrigo Alonso Esparza Muñoz (CFATA, UNAM)
- Dr. Ángel Ramón Hernández Martínez (CFATA, UNAM)
- Dr. Rodolfo Silva Casarín (Inst. de Ingeniería UNAM)
- Dr. Brigitta I. Van Tussenbroek (Inst. De Ciencias del Mar y Limnología, UNAM)

Dr. Miriam Rocío Estévez González is a Chemical Engineer and the Head of the Applied Biomaterials Laboratory. Her main research interests are: 1) Synthesis and characterization of new composite materials with biomedical applications, 2) Green synthesis of metallic nanoparticles, and 3) Green synthesis of polymers for different bio applications and treatment of sewage water.

Since 2019, she has been working to develop filters (membranes) of sargassum for use in bioremediation applications, removing contaminants such as metals, sulphates and pigments (phenolic compounds). She has also done trials with these filters with promising results to treat the lixiviates of sargassum, which are extremely acid and full of sulphur compounds.

Sargassum-based biofilters are an excellent proposal for the removal of contaminants dissolved in water. This type of device aims to treat contaminated water, taking advantage of the properties of sargassum. In previous studies, the ability of sargassum to absorb various substances and elements has been evaluated and reported for static systems with a fixed water volume under a stirring system. However, no attempt has been made to exploit this removal capacity in the implementation of a filter with continuous water flow. These biofilters have been designed and manufactured by the research group led by Dr. Estevez. The biofilters consist of a vessel containing sargassum through which contaminated water is circulated. Various factors such as inflow rate, contaminant concentration, mass and distribution of sargassum within the container have been evaluated to determine the optimal conditions and characteristics of the biofilters. Substances successfully removed using these biofilters are organic dyes (methylene blue, methyl orange and methyl red) and ionic species (lead, copper and sulphate ions). These dyes are widely used in paper and cosmetics industries, and the effluents are often disposed of in rivers or lakes. Removal efficiency depends on the contaminant dissolved in the water. In the case of methylene blue, close to 100% efficiency has been obtained, with the complete absorption of this substance. In the case of lead ions more than 85 percent absorption has been achieved. For other substances evaluated the efficiency was greater than 65 percent. These biofilters can be applied in two different ways: (1) for the remediation and treatment of water that has already been contaminated; and (2) for cleaning wastewater from industries so that it can be released safely into the environment.

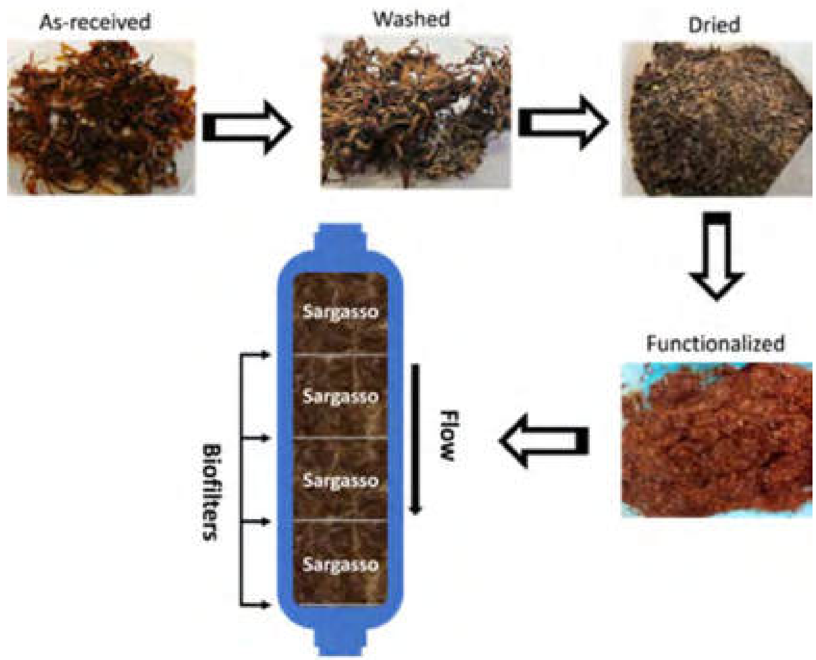


Diagram showing the process for constructing a sargassum biofilter for removal of contaminants dissolved in water

One of the advantages of using sargassum as a biofilter is the limited processing that is required. Sargassum is washed with tap water to remove impurities such as sand, and is subsequently dried at room temperature to eliminate moisture, in order to avoid decomposition. Sargassum is finally loaded into the filter, distributing it in several layers, ready to filter the contaminated water.

Sargassum appearance before and after the removal process

It is important to note that one of the most important factors in obtaining a high removal efficiency is the residence time of the contaminated water inside the filter. This is achieved by controlling the inlet flow of the fluid, by means of a regulating valve. In this way, only 3.5 kg of sargassum is required to treat 1 m^3 of contaminated water. Another advantage of this type of biofilter is that it can be reused. Studies have shown that the contaminants removed by sargassum can be desorbed through chemical treatment. In such a way that sargassum can be used several times for the same purpose.

Sargassum biofilters represent a viable, economical and environmentally friendly alternative for solving major problems and challenges faced in Mexico. Firstly, by reducing sargassum biomass accumulating on the Mexican coasts, and giving it a useful purpose. Secondly, by treating contaminated water at several levels (domestic, agricultural or industrial). Finally, by promoting the recovery of aquatic flora and fauna that have been affected by pollutants released into natural water bodies for several years.

Section 4

Directory of entrepreneurs and researchers

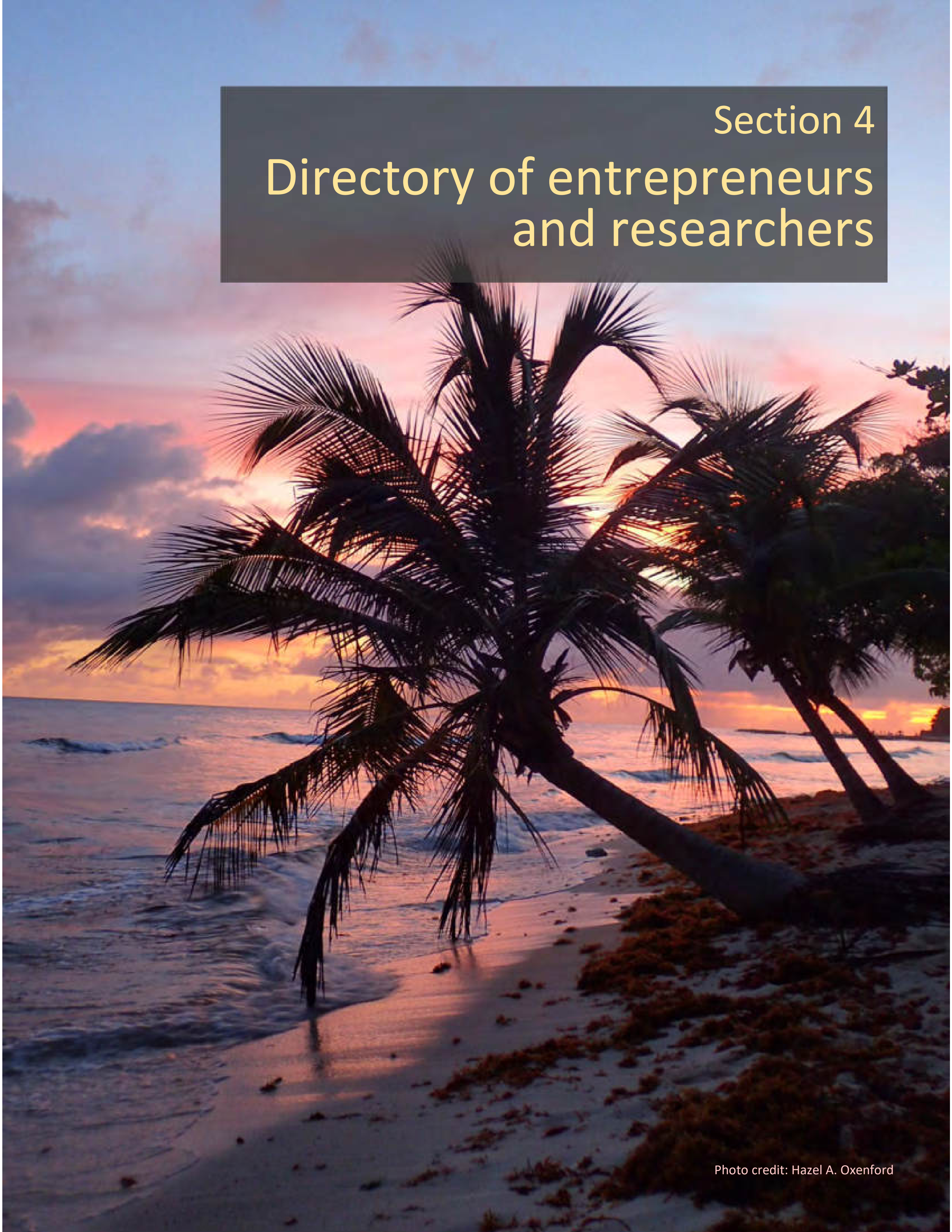
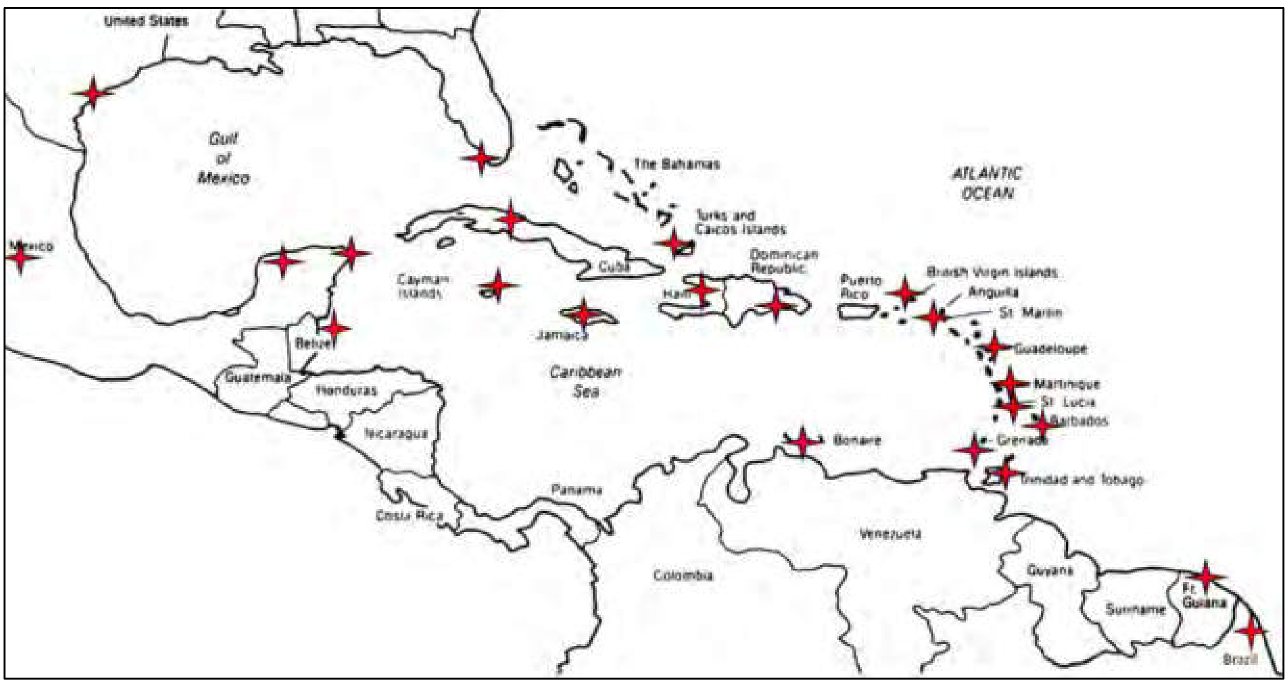


Photo credit: Hazel A. Oxenford

4 Directory of entrepreneurs and researchers developing sargassum uses

To assist with networking among the many actors involved in developing viable and sustainable uses for pelagic sargassum biomass located in many countries across the Wider Caribbean (see map), and to help prevent the possibility of unnecessary repetition of effort and wastage of research and development funds, resources and time, we provide here a directory of sargassum entrepreneurs and researchers by category of sargassum use applications.

We recognize that this directory will be very dynamic and it is our hope that this will be a starting point for initiation of a continually up-dated online resource.



Map showing the wide spread of sargassum entrepreneurs and researchers across the Wider Caribbean

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
Agricultural – Animal husbandry	Animal feed supplement for goats & sargassum-based charcoal	Awganic Inputs / Integral Recyclers Limited	Jamaica	Daveian Morrison, Founder & CEO 876 383 5286 / 876 323 8682 awganicinputs@gmail.com	This young entrepreneur is developing innovative sargassum-based products such as a blended goat feed and charcoal. His feed is made from a mix of sargassum (up to 30%) and locally available organic agro-processing wastes (feed has a 30% protein content). In collaboration with local goat farmers, he has been testing the feed as to whether goats' would accept the scent of this new feed. Since the feed has been well received by the goats, he is now starting clinical trials. - https://www.facebook.com/awganic/ - https://www.facebook.com/integralrecyclers/ - http://jamaica-gleaner.com/article/news/20191001/growth-jobs-daveian-morrison-transforms-seaweed-goat-feed
	Research - AC & biochar	PYROSAR project	France (Guadeloupe, Martinique) & collaborators	Prof. Sarra Gaspard, project coordinator sarra.gaspard@univ-antilles.fr	Valorisation of sargassum by pyrolysis and application for food safety.
	Research - Compost & animal feed	SARGWA Consortium, INRA & Université des Antilles	France (Guadeloupe)		Physicochemical analysis of sargassum composition (heavy metals, pesticides, hydrocarbons, biochemicals and biocides) for valorisation in agriculture (direct spreading, compost and animal feed). http://saas971.com/index.php/2018/07/22/consortium-sargwa/
	Research - Animal feed	Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán (INCMNSZ), Department of Animal Nutrition	Mexico	Silvia Carrillo Domínguez silvia.carrillod@incmnsz.mx	Research on use of natural non-traditional ingredients, including sargassum, for animal feeds (chicken and small ruminants), compositional analysis of eggs and meat to see impact of feed and evaluation of nutritional feed strategies to reduce the risk of fatty liver disease in animals. https://www.incmnsz.mx/Investigacion/investigador.jsp?id=83&idep=3
Agricultural Crop production	Biostimulant - Super Seaweed	Red Diamond Compost	Barbados	Joshua Forte, Founder & CEO 246 549 1594 info@reddiammondcompost.com	This company is developing several organic agricultural amendments including plant biostimulants made with different plant-based materials, including sargassum. http://www.reddiamondcompost.com/en/
	Biostimulant - Total Plant Tonic	Algas Organics	St. Lucia	Johanan Dujon, Founder & CEO 758 461 5019 johanan@algasorganics.com	This young entrepreneur is a pioneer in developing sargassum-based plant biostimulant and is well-known for his innovative project throughout the Caribbean. https://www.algasorganics.com/
	Compost	Holdex Environnement	France (Martinique)	Mike Bernus, Director 0596 50 36 58 mb@holdexenvironnement.com	The company has commercialised several organic-based products for agriculture (soil amendments - mulch, fertilizers, biochar), including a sargassum-based compost (co-composting).

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
					https://www.martinique2030.com/non-classe/holdex-environnement-une-solution-de-valorisation-des-sargasses-100-martiniquaise
Agricultural - Crop production	Fertilizer, mulch, cosmetics & paper	Salgax Biotecnología Marina Aplicada	Mexico	Mauricio Gómez 52 999 285 4541 / 52 999 374 3214 / 52 999 371 5107 salgaxventas@salgax.com	The team of young entrepreneurs are developing several sargassum-based products such as fertilizers, mulch, cosmetics and paper. - https://salgax.com - https ://www.efe.com/efe/english/technology/mexican-young-entrepreneurs-turning-seaweed-into-eco-friendly-products/50000267-3709834
	Compost, mulch & bioplastic	AlgaeNova	Dominican Republic	Manolo Despradel, General Manager 809 959 2070 algeanovard@gmail.com	The team is producing a compost made of 60% sargassum and 40% river tamarind, which takes approximately 70 days to mature and also a 100% sargassum mulch. In collaboration with Bionova, they have developed single-use plates made with 50% sargassum and 50% cassava, which is fully compostable (no industrial composting required) within 30 days - www.algeanova.com - https ://www.facebook.com/algeanovard/
	Compost (in development)	SUEZ	France (Guadeloupe)	Stéphane Dupuy, General Director for Sita Espérance Stephane.dupuy@suez.com	SUEZ is a long-standing company specialized in water and waste management, where they place a focus on innovative, intelligent and sustainable management of resources. They promote circular economies that ensure recycling and valorisation of materials. https://www.suez.fr/fr-fr/notre-offre/succes-commerciaux/nos-references/valorisation-des-sargasses
	Fertilizer	Sargasso Organics	Barbados	Roett's Garage 246 426 0547 roettsgarage@gmail.com	This recent company is commercialising sargassum-based fertilizer, available island wide.
	Fertilizer (Alquifert), alginate & fucoidans	Alquimar	Mexico	Luis Masía Nebot, Founder 998 310 1231 info@alquimar.com.mx	This active company is developing several seaweed-based products, including sargassum. They are commercialising fertilizers and fucoidan extract, and will soon add alginate extracts to their end products. https://alquimar.com.mx/nosotros/
	Fertilizer & paper products	Dianco México	Mexico	Hector Romero 55 2731 3841 hromero@medialectica.com	Dianco is in the process of establishing a sargassum processing plant to produce a sargassum-based fertilizer and paper products. - www.diancomexico.com - https://www.facebook.com/DiancoMexico/ - https://www.elfinanciero.com.mx/tv/la-nota-dura/sargazo-no-dejara-de-llegar-es-consecuencia-del-cambio-climatico-dianco

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
Agricultural - Crop production	Compost	Beacon Farms & University College of the Cayman Islands (UCCI)	Cayman Islands	Granger Haugh, Chairman / Sasha Appleby, Agricultural Production Unit 345 326 4426 / 345 324 2991 grangerhaugh@gmail.com	Beacon Farms is a nonprofit organization, offering housing and employment for people in recovery from drug and alcohol use. In collaboration with researchers at the University College of the Cayman Islands, they are exploring the potential of sargassum for use as a compostable soil additive. - www.beaconfarmscayman.org - https://cen.acs.org/environment/sustainability/Sargassum-strangling-tourism-Caribbean-scientists/97/i34
	Compost & coastal restoration	Moon Palace Resort	Mexico	Antonio Ortiz, Environmental Manager Info@palaceresorts.com	Moon Palace resort has been collecting sargassum from their 2-km long beach for several years and have been processing it into compost and used on the hotel grounds. They have been actively involved in restoring their coastal area and enhancing the growth of plants to prevent further beach erosion, using sargassum.
	Research - Mulch, fertilizer, bioelicitor	University of the West Indies	Barbados, Trinidad & Tobago	- Dr. Francis Lopez, Dept. of Biological and Chemical Sciences, Barbados (mulch & fertilizer) francis.lopez@cavehill.uwi.edu - Prof. Jayaraj Jayaraman, Dept. of Life Sciences, Trinidad (bio-elicitors, nanopesticides & biocontrol) Jayaraj.Jayaraman@sta.uwi.edu	Several ongoing projects to research the potential of using sargassum in agricultural applications.
	Research - Practical field application	Institut Technique Tropical (IT2)	France (Guadeloupe & Martinique)	David Dural, Director 0596 42 43 54 d.dural@it2.fr	Agronomic and toxicological analyses of effects resulting from application of pelagic sargassum compost and direct field spreading. http://www.it2.fr/
	Research - AC & biochar	PYROSAR project	France (Guadeloupe, Martinique) & collaborators	Prof. Sarra Gaspard, project coordinator sarra.gaspard@univ-antilles.fr	Valorisation of sargassum by pyrolysis and application for food safety.
	Research - Bioelicitor, biostimulant	SARGOOD project	France (Guadeloupe) & collaborators	Marie-Ange Arsène, project coordinator maarsene@univ-ag.fr	Holistic approach to sargassum valorisation including developing bioelicitors, biostimulants and other agricultural products, products and by-products by bio refinery, eco-materials and panels from ashes and particles, activated carbon, gelling agents, anticorrosive dyes
	Research - Agriculture	SAVE project	France (Martinique) & collaborators	Stéphane Pacaud, project coordinator stephane.pacaud@univ-lorraine.fr	Sargassum agricultural valorisation and energy production.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
	Research - Biopesticides	SAVE-C project	France (Martinique) & collaborators	Valérie Stiger, project coordinator Valerie.Stiger@univ-brest.fr	Valorisation of sargassum in agriculture (biopesticides) and as a biomaterial (cardboard).
Agricultural - Crop production	Research - Compost & analysis	ECO$_3$SAR project	France (Guadeloupe)	Dr. Pascal Jean Lopez, project coordinator 33 1 40 79 37 02 Pascal-jean.lopez@mchn.fr	Compositional analysis of sargassum and through co-composting (project in collaboration with Holdex Environnement). http://www.cnrs.fr/fr/un-projet-de-recherche-aux-antilles-francaises-pour-valoriser-les-sargasses
	Research - Fertilizer, animal feed & analysis	Amadéite Group	France (Guadeloupe)		Pilot project in collaboration with ADEME, to determine the potential of sargassum for improving plant, animal and human health through the optimization of compound extraction.
	Research - Mushroom substrate	Centro de Investigación Científica de Yucatán (CICY), Colegio Postgraduados, Puebla Campus & Universidad Popular Autónoma del Estado de Puebla (UPAEP)	Mexico	Dr. Alfonso Larqué Saavedra, CICY larque@cicy.mx Dr. Daniel Claudio Martínez Carrera, UPAEP dcarrera@colpos.mx	Ongoing research on the use of sargassum as growth substrate for mushroom cultivation. https://www.cicy.mx/noticias-y-eventos/boletin-06-cicy-y-colpos-proponen-aprovechar-sargazo-para-la-produccion-de-hongos-comestibles https://www.foroconsultivo.org.mx/eventos_realizados/RP_hongos_14_01_2019/1_hongos_comestibles.pdf
Alginates	Alginates	Grupo Metco	Mexico	Hector Alvarez clientes@metco.com.mx	Grupo Metco has over 25 years working in the development of food supplements and sweeteners. They are currently researching the extraction of alginates from sargassum and other seaweeds. They are also elaborating construction blocks made with sugarcane bagasse and sargassum.
	Alginate, fucoidans & fertilizer (Alquifert)	Alquimar	Mexico	Luis Masía Nebot, Founder 998 310 1231 info@alquimar.com.mx	This active company is developing several seaweed-based products, including sargassum. They are commercialising fertilizers and fucoidan extract, and will soon add alginate extracts to their end products. https://alquimar.com.mx/nosotros/
	Alginate extracts	University of the West Indies	Barbados, Trinidad & Jamaica	Dr. Srinivasa Popuri, Dept. of Biological and Chemical Sciences, Barbados (bioethanol) srinivasa.popuri@cavehill.uwi.edu Dr. Bidyut Mohapatra, Dept. of Biological and Chemical Sciences, Barbados (nanobiocatalytic alginate lyase) bidyut.mohapatra@cavehill.uwi.edu	Several researchers across the three campuses in the Caribbean are working on different studies to evaluate the potential use of sargassum alginate extracts for several applications.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
				Prof. Jayaraj Jayaraman, Dept. of Life Sciences, Trinidad (bio-elicitors, nanopesticides & biocontrol) Jayaraj.Jayaraman@sta.uwi.edu Dr. Dr. Keeran Ward, Dept. of Chemical Engineering, Trinidad (thin film composite - biodegradable water container) keeran.ward@sta.uwi.edu Dr. Howard Reid, Mona Institute of Applied Science mias@uwimona.edu.jm	
	Alginate extracts	Nexo project, Tecnológico de Monterrey	Mexico	Dr. Jesús Antonio Jáuregui Jáuregui, Bioengineering jesusjauregui@tec.mx	A group of students are extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses in bath gels, creams and other cosmetics. https://guiauniversitaria.mx/estudiantes-transforman-el-sargazo-en-cosmeticos/
Antifouling	Research - Antifouling properties	CORSAIR project	Guadeloupe	Christophe Roos, project coordinator christophe.roos@univ-antilles.fr	Research on the impact of chemical products extracted from sargassum and the characterization of natural molecules with antifouling properties.
	Research - Anticorrosive dyes	SARGOOD project	Guadeloupe & collaborators	Marie-Ange Arsène, project coordinator maarsene@univ-ag.fr	Holistic approach to sargassum valorisation including developing bioelicitors, biostimulants and other agricultural products, products and by-products by bio refinery, eco-materials and panels from ashes and particles, activated carbon, gelling agents, anticorrosive dyes
Biofuels	Biogas & digestate	EnergyAlgae	Dominican Republic	Ygdal Ach, CEO, Y.A. MAOF Holding Management Ltd. 972 3 7798825 / 972 50 2626749 ygdal@yamaof.co.il Dr. Shmuel Brenner, Project Manager shmuel4212@gmail.com Franklyn Holguin Hache, Universidad APEC fholguinhache@adm.unapec.edu.do	Pilot Project in Punta Cana to experiment five small-scale anaerobic digestors, using sargassum and organic waste as feedstock. Results will be used as a basis to develop a of a larger 1 MW co-digestion model biogas facility. https://www.energy-algae.com/
	Biogas & digestate	Fickert & Winterling Maschinenbau (FWM) - BiogasTiger	Germany	Karen Guerrero, Regional Manager 593 998 038 333 Karen.guerrero@fwe.energy	Will be installing anaerobic digestors at hotel facilities in Mexico shortly, using sargassum in co-digestion with other hotel wastes.
	Biogas & digestate	Mécaméto	France	Guillaume Brillat, Manager 06 22 53 23 02 Contact@mecameto.com	Dry methanation technology. Methanization container using a dry process, continuous, modular and portable.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
	Biogas	BJP Renov	France (Guadeloupe)		Pilot project to determine the potential of sargassum for biogas production.
	Biogas, Bioenergy & digestate	Blue Caribbean Energy Solutions (Damen & Maris Group)	Netherlands	Lennart Koning, Business Development, Damen 31 0630 30 46 41 Lennart.koning@damen.com Ruben van Maris, Managing Director, Maris Group 31 06 515 09 430 ruben@maris-projects.nl	Consortium of both companies is looking to branch out in the Caribbean to implement their holistic solution including harvesting, preprocessing, transport and anaerobic digestion (two-step process) of sargassum. Production of biogas via (1) low temperature anaerobic digestion and (2) high temperature anaerobic thermal reactor. https://www.damen.com/en/news/2019/10/damen_partners_with_maris_to_consider_seaweed_solution
Biofuels	Bioenergy, activated carbon, biochar	Num SMO Technologies (NST)	France (Guadeloupe)	Franck Saint-Martin info@smo-process.com contact@smo-process.com	Active-SMO is a Solar microwave procedure, based on solar pyrolysis and gasification. The mobile and versatile unit can generate electricity, activated carbon, carbon powder and biochar. https://feedelios.com/Investir-startup/buuyers https://www.youtube.com/watch?v=L7zUqutlubc
	Bioenergy	Microsystemfuel Srl / Green Engineering S.A.S. / Garbage Service Srl / The Pelikan System	France (St. Barts) & Italy	Maurizio Coni, General Director Green Engineering S.A.S. +590 690 290956 greenengineering@gmail.com	This collaboration has developed a prototype based on low CO_2 emission auto-combustor to transform biomass into electrical energy, where bio-seaweed pellets are treated with spontaneous combustion. This open circuit gasification allows the production of syngas, the synthesis gas generated by the combustion of biomass.
	Biogas	Biogen Biotechnologies Inc.	Barbados	Mark Hill, Director biogengas.barbados@gmail.com markhill@thinkdesignbarbados.org	Biogen produces bio-methane and bioCNG for transport fuel in Barbados. The team has been exploring the potential of sargassum for anaerobic co-digestion to produce bio-methane. https://www.facebook.com/biogengas/
	Biopellets & bioplastic	Energryn / Solesyto	Mexico	Andres Muñoz, Founder & CEO info@energryn.com	The team is investigating the use of sargassum to produce blended bio-pellets used in boilers at local hotels and bioplastic products, including water heaters, plates and cups. - https://www.energryn.com/nosotros.html - http://veracidadchannel.com/_site/crean-calentador-de-agua-hecho-a-base-de-sargazo/
	Bioenergy, bioplastic, compost & soil amendments	GARAS project (Groupe CAïALI, La SARA & Holdex Environnement)	France (French Guiana, Guadeloupe, Martinique)	La SARA: information.comrse@sara.mq Groupe CAÏALI: 0596 57 10 23 Holdex: Mike Bernus, Director 0596 50 36 58 mb@holdexenvironnement.com	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 (e.g. pyrolysis) to produce biofuel, CAÏALI Group is looking at the potential of sargassum for bioplastic (extrusion tests with composite materials from PVC/PE and

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
					sargassum powder), and Holdex Environnement will focus on the valorisation of sargassum through composting. https://www.sara-antilles-guyane.com/le-projet/garas/ https://www.caiali.fr/ https://www.martinique2030.com/non-classe/holdex-environnement-une-solution-de-valorisation-des-sargasses-100-martiniquaise
Biofuels	Bioenergy & activated carbon	Transporte Maritima Mexicana (TMM)	Mexico	Jesus Davis businessdevelopment@tmm.com.mx	This very expansive company offering services of maritime transport, logistics, and storage, is researching the possibilities of producing electricity and activated carbon with sargassum and other organic waste (municipal & cruise ships) using a sublimation process. https://www.elfinanciero.com.mx/peninsula/estas-cuatro-empresas-quieren-hacer-negocio-con-el-sargazo-de-quintana-roo
	Research - Biogas, bioethanol	University of the West Indies	Barbados & Trinidad	Dr. Legena Henry, Dept. of Computer Science, Math & Physics, Barbados & Dr. Renique Murray, Dept. of Mechanical and Manufacturing Eng. (anaerobic digestion - biogas) legena.henry@cavehill.uwi.edu Dr. Srinivasa Popuri, Dept. of Biological and Chemical Sciences, Barbados (bioethanol) srinivasa.popuri@cavehill.uwi.edu Dr. Nikolai Holder, Barbados (Biogas) nikolai.holder@gmail.com	Researchers at Cave Hill & St. Augustine campuses are investigating the potential use of sargassum to produce biogas and ethanol.
	Research - Effect of salt on anaerobic digestion, digestate	SAVE project	France, Martinique & collaborators	Stéphane Pacaud, project coordinator stephane.pacaud@univ-lorraine.fr	Sargassum agricultural valorisation and energy production (anaerobic digestion).
	Research - Biogas pre-treatment	Centro de Investigación Científica de Yucatán (CICY)	Mexico	Dr. Raúl Tapia Tussell rtapia@cicy.mx	The team has developed a prototype methodology (patent pending) that involves mixing sargassum with a locally sourced fungus, able to degrade lignin, and a bacterial inoculum as a pre-treatment to produce methane. - https://www.cienciamx.com/index.php/centros-de-investigacion/centros-publicos-de-investigacion/23708-cientificos-del-cicy-producen-biogas-a-partir-de-sargazo

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
					- http://www.ngvjournal.com/s1-news/c1-markets/mexico-yucatan-scientists-produce-biogas-from-algae/
	Research - Biogas	ESETA, Greenaffair & INRA	France (Guadeloupe)		Recipient of Ademe grant in 2016 for a pilot sargassum methanization trial.
	Research - Bio-pellets	Ecodec	France (Guadeloupe)		Recipient of Ademe grant in 2016 for a pilot trial to evaluate sargassum's potential as a fuel to power a biomass boiler.
	Research - Bio-oil	University Exeter & University of Bath	UK	Dr. Mike Allen, Plymouth Marine Laboratory mije@pml.ac.uk	This team has been developing a method to pre-process sargassum on an industrial scale by fractionation, which can then go through a hydrothermal liquefaction to produce liquid bio-oil. This end-product can be further processed into fuel and fertilizer precursor. https://www.theguardian.com/environment/2020/jun/30/how-do-you-deal-with-9m-tonnes-of-suffocating-seaweed-aoe?fbclid=IwAR1W2QumIExNs5QmjVkvpN31fPcCUmJZDyjH9VAxKry0U1-WIDG-US5e1_8
Bioplastics	Bioplastics - Microcapsules	Algopack	France & collaborators in Guadeloupe/ Martinique	David Coti, Founder contact@algopack.com	Experts developing bioplastics with brown algae in France. They are collaborating with researchers and businesses in Guadeloupe and Martinique to develop a sargassum-based bioplastic. Recipient of a grant from Ademe in 2016 to evaluate the feasibility of producing sargassum-based bioplastics in collaboration with Novundi Group. https://www.ouest-france.fr/bretagne/ille-et-vilaine/saint-malo-algopack-transforme-les-sargasses-en-plastique-6078218
	Bioplastics, compost & mulch	AlgaeNova	Dominican Republic	Manolo Despradel, General Manager 809 959 2070 algeanovard@gmail.com	The team is producing a compost made of 60% sargassum and 40% river tamarind, which takes approximately 70 days to mature and also a 100% sargassum mulch. In collaboration with Bionova, they have developed single-use plates made with 50% sargassum and 50% cassava, which is fully compostable (no industrial composting required) within 30 days - www.algeanova.com - https://www.facebook.com/algeanovard/
	Bioplastics & biopellets	Energryn / Solesyto	Mexico	Andres Muñoz, Founder & CEO info@energryn.com	The team is investigating the use of sargassum to produce blended bio-pellets used in boilers at local hotels and bioplastic products, including water heaters, plates and cups. - https://www.energryn.com/nosotros.html - http://veracidadchannel.com/_site/crean-calentador-de-agua-hecho-a-base-de-sargazo/

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
	Bioplastics	Le Floch Depollution	France	Pauline Morvan contact@leflochdepollution.com	The team is currently testing to develop two different grades of bioplastics: (1) 30% sargassum and 70% thermoplastic resins and (2) 40% sargassum and 60% polylactic acid. http://leflochdepollution.com
Bioplastics	Bioplastics	Abaplas	Mexico	Marco Moreno Sandoval, CEO 33 35 77 22 11 marco@abaplas.com	This company has been producing plastic and bioplastic products for 15 years. Currently testing to produce a bioplastic made of 30% sargassum and 70% plastic for use in different applications, including ecological housing and train tracks. http://abaplas.com/
	Research - Bioplastics	University of the West Indies	Barbados & Trinidad	Dr. Srinivasa Popuri, Dept. of Biological and Chemical Sciences, Barbados srinivasa.popuri@cavehill.uwi.edu Kerri-Ann Bovell, UWI Cave Hill student kerri-ann.bovell@mycavehill.uwi.edu Dr. Keeran Ward, Dept. of Chemical Engineering, Trinidad (thin film composite - biodegradable water container) keeran.ward@sta.uwi.edu	Researchers at both Cave Hill and St. Augustine campuses are exploring sargassum for use in the manufacture of bioplastics. https://www.bb.undp.org/content/barbados/en/home/presscenter/blog/2020/actioning-the-blue-economy-for-green-islands.html https://www.bb.undp.org/content/barbados/en/home/presscenter/pressreleases/20191/eight-pitch-innovative-solutions-to-blue-economy-challenges.html
	Research bioplastics	Clemson University & Rochester Institute of Technology	USA	William Scott Whiteside, Dept. of Food, Nutrition and Packaging Sciences, Clemson University wwhtsd@clemson.edu	Researchers at both institutes working together on development of nanocomposite films using *Sargassum natans*
	Bioplastic, bioenergy compost & soil amendments	GARAS project (Groupe CAïALI, La SARA & Holdex Environnement)	France (French Guiana, Guadeloupe, Martinique)	La SARA: information.comrse@sara.mq Groupe CAÏALI: 0596 57 10 23 Holdex: Mike Bernus, Director 0596 50 36 58 mb@holdexenvironnement.com	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 (e.g. pyrolysis) to produce biofuel, CAÏALI Group is looking at the potential of sargassum for bioplastic (extrusion tests with composite materials from PVC/PE and sargassum powder), and Holdex Environnement will focus on the valorisation of sargassum through composting. https://www.sara-antilles-guyane.com/le-projet/garas/ https://www.caiali.fr/ https://www.martinique2030.com/non-classe/holdex-environnement-une-solution-de-valorisation-des-sargasses-100-martiniquaise

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
Bioremediation & purification	Activated carbon	NBC / TECMALAB	France (French Guiana) & Dominican Republic	Nicolas Brehm, Founder & Director 594 05 94 29 07 70 / 809 817 7764 06 94 43 36 00 Nicolas.brehm@nbcsarl.com	In collaboration with research teams in French Guiana, Guadeloupe and Dominican Republic, NBC and TECMALAB are working to develop and commercialise a sargassum-based activated carbon for use in water and wastewater treatment and air purification applications. www.nbcsarl.com www.tecmalab.com
	Activated Carbon & biochar	Num SMO Technologies (NST)	France (Guadeloupe)	Franck Saint-Martin info@smo-process.com contact@smo-process.com	Active-SMO is a Solar microwave procedure, based on solar pyrolysis and gasification. The mobile and versatile unit can generate electricity, activated carbon, carbon powder and biochar. https://feedelios.com/Investir-startup/buuyers https://www.youtube.com/watch?v=L7zUqutlubc
	Activated carbon	Transporte Maritima Mexicana (TMM)	Mexico	Jesus Davis businessdevelopment@tmm.com.mx	This very expansive company offering services of maritime transport, logistics, and storage, is researching the possibilities of producing electricity and activated carbon with sargassum and other organic waste (municipal & cruise ships) using a sublimation process. https://www.elfinanciero.com.mx/peninsula/estas-cuatro-empresas-quieren-hacer-negocio-con-el-sargazo-de-quintana-roo
	Research - Activated Carbon & biochar	PYROSAR project	France (Guadeloupe, Martinique) & collaborators	Prof. Sarra Gaspard, project coordinator sarra.gaspard@univ-antilles.fr	Valorisation of sargassum by pyrolysis and application for food safety.
	Research - Activated carbon, biochar & energy storage	University des Antilles, COVACHIM-M2E laboratory	France (Guadeloupe, Martinique) & collaborators	Prof. Sarra Gaspard sarra.gaspard@univ-antilles.fr	The team is researching the potential of sargassum to produce activated carbon for soil remediation, pesticide sequestration in animals, water treatment and energy storage (electrodes for supercapacitors) applications. http://www.univ-ag.fr/recherche/structures-de-recherche/covachim-m2e-connaissance-valorisation-chimie-des-materiaux
	Research - Activated Carbon	Instituto Tecnológico de Santo Domingo (INTEC)	Dominican Republic	Dr. Ulises Jauregui ulises.jauregui@intec.edu.do	Sargassum-based activated carbon for water treatment and other applications.
	Research - Purification & bioremediation, biofilters	Center for Applied Physics and Advanced Technology (CFATA), Autonomous	Mexico	Dr. Miriam Rocio Esteves Gonzalez miries@fata.unam.mx www.fata.unam.mx/Academicos/DraMiriamEsteves	Has developed filters using sargassum for bioremediation, removing contaminants such as metals, sulphates and pigments (phenolic compounds) from water. Also promising results in trials to treat the acidic, sulphur-rich lixiviates of sargassum.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
		University of Mexico (UNAM)			
	Research - Purification & bioremediation, biofilters/ membranes	University of the West Indies	Trinidad, Barbados	Dr. Keeran Ward, Dept. of Chemical Engineering, Trinidad (biofilter membranes) keeran.ward@sta.uwi.edu Dr. Srinivasa Popuri, Dept. of Biological and Chemical Sciences, Barbados (wastewater treatment) srinivasa.popuri@cavehill.uwi.edu	Sargassum polymers to create membranes for use as biofilters in the remediation of heavy metals in wastewaters.
	Research - Activated carbon	SARGOOD project	Guadeloupe & collaborators	Marie-Ange Arsène, project coordinator maarsene@univ-ag.fr	Holistic approach to sargassum valorisation including developing bioelicitors, biostimulants and other agricultural products, products and by-products by bio refinery, eco-materials and panels from ashes and particles, activated carbon, gelling agents, anticorrosive dyes
Clothing, footwear & accessories	Shoes	Renovare Ocean	Mexico	Jorge Castro Ramos, CEO Renovare.r@gmail.com	Third generation shoemaker, this company is making eco-friendly shoes using recycled plastic bottles, biodegradable resins and sargassum seaweed in their 'Ocean Ova' shoe line. https://www.renovareco.com https://www.entrepreneur.com/article/336680 https://eldiariodefinanzas.com/jorge-castro-y-mario-lopez-los-creadores-de-los-tenis-hechos-de-sargazo/
Construction material	Bricks	Blue Green	Mexico	Omar Vázquez Sánchez, Founder, CEO Blue Green +52 984 175 0536	Omar built the first sargassum house in 2015, when he invented SargaBlocks, which are construction blocks made of sargassum and organic waste. Since then, he has been making thousands of blocks and improved his production method and equipment. Innovation and success at its best. https://www.facebook.com/bluegreenmx/ https://ecologica.jornada.com.mx/2019/08/25/omar-vazquez-el-mexicano-que-construye-casas-con-algas-marinas-5492.html
	Particleboard	Diseño y Decorativos del Caribe Maya	Mexico	Saúl Duarte Méndez, Director 0152 331 980 4711 caribemayadiseno@gmail.com	The industrial designer has developed a sargassum-based conglomerate board that can be used in several construction and furniture applications. https://noticias.canal10.tv/nota/municipios/disenador-industrial-desarrolla-un-conglomerado-a-base-de-sargazo-2018-08-21 https://noticaribe.com.mx/2018/08/28/patentan-proyecto-para-usar-sargazo-en-la-elaboracion-de-muebles-a-nivel-industrial/

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
Construction material	Particleboard, biogas	Biogen Biotechnologies Inc.	Barbados	Mark Hill, Director biogengas.barbados@gmail.com markhill@thinkdesignbarbados.org	Biogen has been exploring the potential of sargassum for the development of particleboards. https://www.facebook.com/biogengas/
	Bioasphalt, paper products	The Marine Box	France (Martinique)	Christophe Germé & Priscilla Lambert, Founders Jérôme Siniamin, CEO 596 696 17 93 70 / 569 696 30 47 07 j.siniamin@themarinebox.com c.germe@themarinebox.com	These young entrepreneurs are leading a French start-up and researching the possibility of using sargassum for different biomaterials, including paper and cardboard products, such as coffins, and bioasphalt. http://themarinebox.com/
	Research - Eco-materials	SARGOOD project	France (Guadeloupe) & collaborators	Marie-Ange Arsène, project coordinator maarsene@univ-ag.fr	Holistic approach to sargassum valorisation including developing bioelicitors, biostimulants and other agricultural products, products and by-products by bio refinery, eco-materials and panels from ashes and particles, activated carbon, gelling agents, anticorrosive dyes.
Cosmetics	Soaps	Oasis Laboratory	Barbados	Kemar Codrington & Mikhail Eversley, Founders, CEOs 246 264 9543 sustainable@oasislaboratory.com	These two young entrepreneurs have been developing a sargassum skincare line. - https://www.facebook.com/OasisLaboratory/ - https://www.loopnewsbarbados.com/content/bajan-chemists-tap-beauty-industry-sargassum-skincare-line-3
	Hair care products, fertilizers, mulch & paper	Salgax Biotecnología Marina Aplicada	Mexico	Mauricio Gómez 52 999 285 4541 / 52 999 374 3214 / 52 999 371 5107 salgaxventas@salgax.com	The team of young entrepreneurs are developing several sargassum-based products such as fertilizers, mulch, cosmetics and paper. - https://salgax.com - https ://www.efe.com/efe/english/technology/mexican-young-entrepreneurs-turning-seaweed-into-eco-friendly-products/50000267-3709834
Electrochemical industry	Research - Electrodes	SARtrib project	Guadeloupe & collaborators	Thierry Cesaire, project coordinator thierry.cesaire@univ-antilles.fr	Valorisation of vacuum pyrolysis by-products of sargassum for use as lithium battery electrodes, supercapacitors, new generation lubricants, solvents and adhesives.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
	Research - Energy storage, activated carbon & biochar	University des Antilles, COVACHIM-M2E laboratory	France (Guadeloupe, Martinique) & collaborators	Prof. Sarra Gaspard sarra.gaspard@univ-antilles.fr	The team is researching the potential of sargassum activated carbon for soil remediation, pesticide sequestration in animals, water treatment and energy storage (electrodes for supercapacitors) applications. http://www.univ-ag.fr/recherche/structures-de-recherche/covachim-m2e-connaissance-valorisation-chimie-des-materiaux
Environmental restoration	Dune restoration	Texas A&M University	USA	Dr. Jens Figlus, Dept. of Ocean Engineering 409 741 4317 figlusj@tamu.edu	Extensive research carried out by Texas A&M University, to determine the use of sargassum in coastal erosion prevention and restoration of sand dune ecosystems. Sargassum bales were tested to protect dunes from erosion and promote plant growth.
	Dune restoration	Walkers Institute for Regenerative Research Education and Design (WIRRED)	Barbados	Kiesha Farnum, Managing Director 246 622 4097 info@wirred.org	WIRRED is a not-for-profit think tank, research centre and consultancy dedicated to the study of climate-smart agricultural practices. Amongst their several ongoing projects, they are researching potential techniques for dune restoration and enhancing coastal plant growth. - http://walkersreserve.com/wirred1/ - https://www.facebook.com/wirredbarbados/
	Coastal restoration & compost	Moon Palace Resort	Mexico	Antonio Ortiz, Environmental Manager Info@palaceresorts.com	Moon Palace resort has been collecting sargassum from their 2-km long beach for several years and have been processing it into compost and used on the hotel grounds. They have been actively involved in restoring their coastal area and enhancing the growth of plants to prevent further beach erosion, using sargassum.
	Carbon sequestration	Sargassum Ocean Sequestration of Carbon project (SOS Carbon)	Dominican Republic	Andrés Bisonó León & Luke Gray 833 767 2726 (SOS CRBN) Sales@soscarbon.com	This Boston-based engineering team and partners in Dominican Republic have developed a system to pump and effectively sink sargassum into the deep ocean before it impacts the coastlines. https://soscarbon.com/
Food & Beverage	Cocktail drinks	Bruno Lardelli	Mexico		Mixologist in Mexico has explored the potential use of sargassum in drinks. https://www.villapalmarcancun.com/blog/destination/practical-and-creative-uses-of-*Sargassum*-seaweed-in-the-caribbean
	Food	Tomfoodery Kitchen	Cayman Islands	Thomas Tennant, Chef	A chef in the Cayman Islands has experimented with the use of sargassum as an ingredient in different dishes. https://www.caymancompass.com/2019/10/20/eat-it-to-beat-it-sargassum-seaweed-baked-boiled-and-fried/

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
	Beer	Texas A&M University & Galveston Island Brewery	USA		In 2015, students and researchers from Texas A&M University, in collaboration with Galveston Island Brewery, have tested producing a craft beer using sargassum. https://www.houstonpublicmedia.org/articles/news/2015/04/02/58969/how-galveston-researchers-are-putting-seaweed-to-use/
Lubricants, surfactants & adhesives	Research	SARtrib project	France (Guadeloupe) & collaborators	Thierry Cesaire, project coordinator thierry.cesaire@univ-antilles.fr	Valorisation of vacuum pyrolysis by-products of sargassum for use as lithium battery electrodes, supercapacitors, new generation lubricants, solvents and adhesives.
Paper and cardboard products	Paper products	Sargánico	Mexico	Victoria Morfin, Founder & CEO 998 296 9700 ext 112 hola@sarganico.mx	This young entrepreneur has developed several high quality sargassum-based paper products such as notebooks, agendas, folders, business cards and many more. https://sarganico.mx/
	Paper products & bioasphalt	The Marine Box	France (Martinique)	Christophe Germé & Priscilla Lambert, Founders Jérôme Siniamin, CEO 596 696 17 93 70 / 569 696 30 47 07 j.siniamin@themarinebox.com c.germe@themarinebox.com	These young entrepreneurs are leading a French start-up and researching the possibility of using sargassum for different biomaterials, including paper and cardboard products, such as coffins, and bioasphalt. http://themarinebox.com/
	Paper products	Sargasse Project	France (St. Barts)	Pierre-Antoine Guibout, Founder & CEO sargassesproject@gmail.com	Sargasse Project has been developing paper products made with 100% sargassum and is looking to scale-up the business. http://sargasseproject.com/
	Paper products	Golden Tide Project	Curaçao	Wouter Osterholt	This artist started the project Golden Tide, which consisted in making sargassum-based paper for use as painting canvas. Paintings skeletal remains were depicted, representing fauna killed by sargassum influx. Proceeds of sales were donated to Amazon Watch. http://www.wouterosterholt.com/golden-tide/golden-tide
	Cardboard boxes	Sargazbox	Mexico	sargazbox@gmail.com	Developing cardboard boxes with sargassum cellulose. https://www.facebook.com/Sargazbox/
	Paper, fertilizer, mulch & cosmetics	Salgax Biotecnología Marina Aplicada	Mexico	Mauricio Gómez 52 999 285 4541 / 52 999 374 3214 / 52 999 371 5107	The team of young entrepreneurs are developing several sargassum-based products such as fertilizers, mulch, cosmetics and paper.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
				salgaxventas@salgax.com	- https://salgax.com - https ://www.efe.com/efe/english/technology/mexican-young-entrepreneurs-turning-seaweed-into-eco-friendly-products/50000267-3709834
	Research - Cardboard	SAVE-C project	France (Martinique) & collaborators	Valérie Stiger, project coordinator Valerie.Stiger@univ-brest.fr	Valorisation of sargassum in agriculture (biopesticides) and as a biomaterial (cardboard).
	Fertilizer & paper products	Dianco México	Mexico	Hector Romero 55 2731 3841 hromero@medialectica.com	Dianco is in the process of establishing a sargassum processing plant to produce a sargassum-based fertilizer and paper products. - www.diancomexico.com - https://www.facebook.com/DiancoMexico/ - https://www.elfinanciero.com.mx/tv/la-nota-dura/sargazo-no-dejara-de-llegar-es-consecuencia-del-cambio-climatico-dianco
Pharmaceuticals & biomedical	Research	SARGSCREEN project	France (Martinique) & collaborators	Azaria Remion, project coordinator azaria.remion@gmail.com	Determining pharmacological potentials of sargassum extracts against non-communicable diseases common and widespread across the Caribbean.
	Research	University of the West Indies	Jamaica & Trinidad	Prof. Rupika Delgoda, Natural Research Institute (anticancer properties of sargassum extracts) npi@uwimona.edu.jm Dr. Winklet Gallimore, Dept. of Chemistry (bioactive compounds) Winklet.gallimore@uwimona.edu.jm Dr. Frederick Boyd, Dept. of Life Sciences (medical botany & antimicrobial properties) Frederick.boyd@uwimona.edu.jm Dr. Jayaraj Jayaraman (Dept. of Life Sciences) Jayaraj.Jayaraman@sta.uwi.edu	Several ongoing projects at UWI researching the potential of sargassum in pharmaceutical and biomedical applications.
Health impacts	Research - Arsenic & chlordecone	Sarg As Cld	France & collaborators	Christophe Mouvet, project coordinator c.mouvet@brgm.fr	Assess the eco-toxicity of sargassum leachates, with a focus on arsenic and chlordecone.
	Research - Human health effects	SARGACARE	Martinique & collaborators	Rémi Neviere, project coordinator Remi.neviere@chu-martinique.fr	Human health effects of chronic exposure to gaseous fumes of decomposing sargassum.

Use	End product / service	Name of business / organization / institution / project	Country	Contact links	Additional Information
General research	Research - Commercial value	Polytechnic University of Quintana Roo (UPQRoo)	Mexico	Jorge Cantó, Lead Researcher canto@corrosionyproteccion.com	Funded by the Consejo Nacional de Ciencia y Tecnología (CONACYT) of Mexico, this research project focuses on determining potential commercial value of sargassum through interviews with local stakeholders, analysis of compounds and determining the impact indicator value for each potential use. https://www.raconteur.net/sustainability/sustainable-business-2020/sargassum-seaweed-business
	Research	Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de Mexico	Mexico	Dr. Brigitta van Tussenbroek vantuss@cmarl.unam.mx	Assessment of eco-toxological impact of sargassum leachates and particulate organic matter (POM) on marine organisms and ecosystems https://www.icmyl.unam.mx/puerto_morelos/en/node/24
	Research	University of Greenwich	UK	Dr. John Milledge jj.milledge@gre.ac.uk	Renown algae biotechnology researcher with interest in macroalgae value chains for hydrocarbon fuel, energy balance of bioenergy and algal production processes and many more. Dr. Milledge has published on these topics with regards to sargassum.
	Primary processing	Thalasso As	Mexico & Norway	Paulina Zanela & Frode Stolen Sønstebø 52 55 22 20 6751 paulinazanela@gmail.com frodesonstebo@gmail.com	This project is supported by Norway's Foreign Affairs in Mexico. The team is currently carrying out research for coastal harvesting and containment and offshore harvesting and primary processing of sargassum.
	Research	Fearless Fund	USA	Alyson Myers 202 297 9743 Alysonmyers1@gmail.com	Fearless Fund is a non-profit dedicated to healthy ocean ecosystems, is supported by the US DOE ARPA-E to produce macroalgae at energy scale. They are looking to efficiently intercept the biomass before it beaches to repurpose the carbon for long term sequestration or conversion to carbon neutral energy. This includes building products, cement and various forms of energy. www.fearlessfund.org
	Research - Biomass (sargassum + organic waste), nanocarbons and extracts	Tecnológico Nacional de México /IT de Cancún	México	Prof. J. Ysmael Verde Gómez, Graduate Studies and Research Department, TecNM/ITdeCancun jose.vg@cancun.tecnm.mx Dr. Ana María Valenzuela-Muñiz, Graduate Studies and Research Department, TecNM/ITdeCancun ana.vm@cancun.tecnm.mx	The research group is performing fundamental studies on the properties of sargassum to generate new knowledge towards future sustainable applications such as: biofuels, nanocarbons for energy and environmental applications, and extracts.

Section 5
Challenges and Implications

Photo credit: Hazel A. Oxenford

5. 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. However, as we have learnt, exploring these opportunities has been met with many challenges that present barriers to starting up, expanding, and scaling-up existing sargassum-related ventures. Here we highlight the major constraints that have been shared with us 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 sub-sections. We also offer guidance, of particular relevance to policy makers and funders, on what needs to be done to move forwards with addressing these challenges and to promote an enabling environment that fosters innovation and creativity. This will allow the region to obtain benefits from sargassum influx events through creation of industry, employment, cost recovery from beach clean-ups and disposal of sargassum, and improved adaptive capacity to sargassum influxes.

5.1 Unpredictable supply

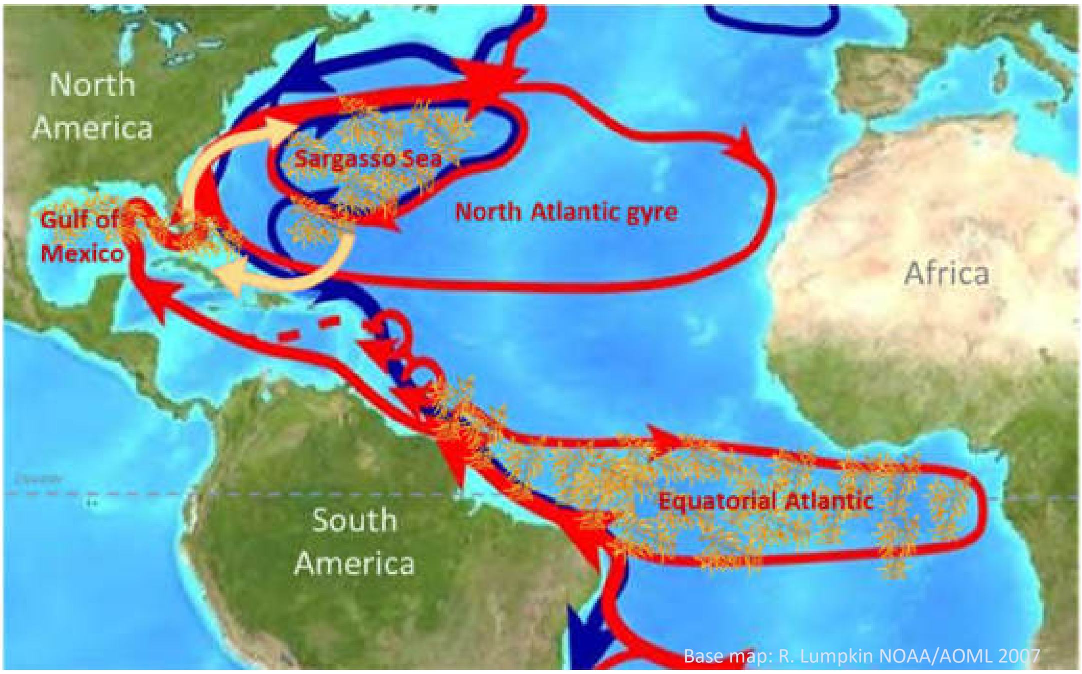
Key Challenges

- Major uncertainty regarding sargassum influx timing, quantity and location
- Insufficient monitoring of volume and location of sargassum strandings
- Variability in relative abundance of different sargassum species and morphological forms

5.1.1 When, how much and where?

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

A key issue is the ‘newness’ of the sargassum influx phenomenon and the large 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). 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, likely taking different routes in different months (depending on the highly variable and complex surface currents transporting it), and possibly coming from different source sub-regions within the Equatorial Atlantic (Johnson *et al*. *forthcoming*).



Diagramatic map of the Atlantic showing the sargassum accumulation areas (source regions). 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 (deep water currents are shown in blue).

There have been many important advances in sargassum detection, monitoring and prediction over the last decade which have begun to address some of these uncertainties (e.g. Wang and Hu 2016, Brooks *et al*. 2018, Putman *et al*. 2018, Wang *et al*. 2018, Wang *et al*. 2019, Johns *et al*. 2020, Wang and Hu 2017, Hu *et al*. 2016). 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 greater than three months. These challenges include:

- The limited optical satellite coverage in the cloud-covered sargassum source regions which means that sargassum presence cannot be detected in places that could ultimately deliver sargassum to the Caribbean.
- The relatively low satellite image resolution and optical noise (e.g. 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.
- High precision satellite imagery and radar that could help in observing movements of sargassum nearshore and thus local predictions of strandings are generally costly.
- The 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.
- The lack of consistent national and site-level monitoring of sargassum strandings, especially the quantity (as volume or weight) and the location, constrains the ability to validate predictive models and/or provide ball-park figures of what could be expected in the future, based on past occurrences.

5.1.2 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 (García-Sánchez *et al*. 2020, Schell, Goodwin, and Siuda 2015).

In the Caribbean the relative proportions of the different forms have changed over time, since the first inundations of 2011, and continue to show inter-annual 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.

5.1.3 Implications

The highly variable supply and lack of reliable forecasts of sargassum influx events, exacerbated by a general lack of monitoring at the national or site level has several important implications for valorising sargassum. Not knowing the approximate volumes of sargassum arriving at any given location over time makes it very difficult to determine appropriate potential uses for the sargassum 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 5.3.

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

5.1.4 Moving forwards

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

- Continuing 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 (e.g. through growth and mortality, natural subduction in Langmuir cells or during storms).
- Develop oceanographic models that aid in the prediction of sargassum strandings.
- Promote comprehensive ground truthing initiatives to validate presence of sargassum at sea, and accuracy of forecasts.
- Develop simple harmonized monitoring protocols using remote sensing technology (e.g. drones, satellite imagery) and citizen science to improve the ease and geographical scale of monitoring the volume and location of sargassum strandings.
- Develop simple rapid assessment methodology to monitor the relative composition of pelagic sargassum forms (species and morphotypes) over space and time.
- Develop easily accessible platforms to make the sightings and predictions of the sargassum influxes at oceanic, regional and local scale available to the public

5.2 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
- Limited research on chemical composition, and difficulty accessing the existing knowledge and results

5.2.1 High salt and ash content

Seaweeds are typically known for their high salt and high ash (inorganic residue) content. This holds true for sargassum that has a high concentration of saline elements (e.g. Na, K, Ca, Mg and Cl) (See Table in Section 1.4.2: Minerals and nutritional compounds) and high percentage of ash (see Table in Section 1.4.1: Maine components).

5.2.2 Uncertainty and variation in chemical composition

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

Furthermore, there is a large variation in the reported concentrations or relative proportions of most components (as summarized in the Tables 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 (e.g. species, stage of life cycle, age), but also with abiotic factors (e.g. pH, salinity, water motion, temperature, light availability, mineral content of seawater, and environmental pollutants) (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, likely taking different routes over time, and possibly coming from different source sub-regions 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 eight widely spaced sites over a period of 11 months, showed considerable variation not only among species and morphotypes, but also among locations, and over time, although there was no apparent seasonal pattern (Rodríguez-Martínez *et al*. 2020). They suggested that much of the observed variation in element concentration was likely dependent on the route travelled by the floating sargassum and whether or not it passed through contaminated areas, given that 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 last three decades (Lapointe *et al*. 2014). They reported higher C:N ratios in the 1980s compared to pelagic sargassum sampled in the 2010s, and lower C:P and N:P ratios in the 1980s compared with 2010s, suggesting that this reflected changing ocean conditions.

5.2.3 Heavy metals and other toxins

The biosorption of certain heavy metals and other potential toxins (e.g. 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 across the Caribbean to date have been found to contain concentrations of arsenic that exceed most countries' permitted concentrations for certain agricultural and nutritional uses (Section 1.4.3: Heavy metals, and Tables in Sections 2.2 and 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 micro and macro nutrients (e.g. iodine) can be toxic for humans, animals and plants.

In general, there has been a relative 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 region.

5.2.4 Implications

High salt content presents a challenge for agricultural uses (including soil salinisation, 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, 2.3 Crop Production, 2.5 Bioenergy and 2.7 Bioremediation). Attempts at applying seaweed in the raw or composted form have resulted in soil salinisation in some cases. Removing excess salt is not only costly and time consuming but also requires large amounts of fresh water.

Insufficient testing to date, and lack of standard methods means that there is still considerable uncertainty in the chemical composition of sargassum. This constrains the assessment of potential valorisation.

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 uses (e.g. fertilizers and animal feed), it could be problematic for production of bioenergy, particularly for direct combustion and gasification because the high ash content means a lower gross calorific value (also refered to as 'higher heating value'[HHV]) resulting a lower energy yield than is typical for most terrestrial plant biomass (Milledge 2014, Milledge 2016).

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

5.2.5 Moving forwards

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

- More extensive (over space and time) sampling and compositional analysis of pelagic sargassum from across the region to improve our understanding of the geographic, seasonal and annual variation in chemical composition.
- More comprehensive compositional analyses (performed separately by species and morphotypes) using standardised 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.
- Engage 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.
- Undertake frequent testing of pelagic sargassum and/or sargassum-based end products and waste for 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.
- Examine whether toxins such as arsenic transfer to crops and enter the food chain.
- Develop 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.
- 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.

5.3 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
- Ease of causing environmental damage if inappropriate equipment and methods are used for collection
- Lack of policy and mechanism for issuing harvesting permits in most places

5.3.1 Harvesting and transport

Sargassum arrives ‘free of charge’, but as we have learnt over the last decade, requires specialized machinery and equipment for effective large-scale shoreline or in-water collection to minimize environmental damage, and this tends to be very costly to purchase and to 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, among others.

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 to provide a suitable raw material for many industries. Separating sand from sargassum collected on the beach, associated fauna (e.g. sea turtle hatchlings) and marine debris (e.g. plastics) from harvested sargassum is tedious and requires significant manpower or specialized separation equipment to automate this process that 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 also 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 by the development of new purpose-built equipment that has significantly increased efficiency and decreased environmental impacts of sargassum collection and cleaning. There are also continuing significant efforts to gather information, assess sargassum collection methods, and develop informative materials and best practice guides, that 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) and 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); Puerto Morelos Protocol, and the 'Monitoring and evaluation of Sargassum collection operations' (see blue box) (Chereau 2019).

Sargassum collection options

- Offshore barriers to concentrate sargassum
- Mechanised offshore collection (boat harvesters)
- Manual onshore collection
- Mechanised onshore collection
- Accessory equipment to move sargassum.

These 5 categories of sargassum collection methods and equipment are described in detail and assessed in a report by Chereau (2019).

The document can be downloaded here: http://bit.ly/ADEMESarg

There are also ongoing efforts to improve communication of new knowledge through symposia and exhibitions dedicated to sargassum, formal networks, and knowledge hubs that are sharing information, improving access to documentation and allowing exchange of ideas and questions. Examples include:

SPAW-RAC basecamp, SargNet Listserv and Slack Workspace, Guadeloupe Sarg'Expo, and the Sargassum Information Hub (https://sargassumhub.org).

Challenges that still remain include:

- 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 framework in most countries for issuing harvesting permits.

5.3.2 Storage

Relying on a raw material with a highly variable availability, will require stockpiling and preservation of sargassum to ensure a constant supply for industry in times of low sargassum influx. 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 which present a health hazard for nearby communities (ANSES 2017). A further challenge is that preservation methods for extending storage time of sargassum are still being explored.

5.3.3 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 (e.g. 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 a legal framework for permitting sargassum harvest presents an additional challenge that is considered in Section 5.4.

5.3.4 Moving forwards

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, biodiversity studies of floating sargassum at different distances from shore are needed to inform the most appropriate location for in-water harvest to 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 (e.g. 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 best/lowest costs, including process, transactional and handling costs for the entire supply chain.
- Improve access to knowledge and communication to share lessons learnt and promote best practices for on-shore and in-water collection methods.
- Consider the local context, potential impact on the environment and types of uses to be developed before investing in a specific type of harvesting equipment.
- Consider ways of reducing the cost of importing specialized sargassum harvesting equipment.
- Develop protocols and standards for safe harvesting, transport and storage of sargassum.

5.4 Management and regulation

Key Challenges

- Mass influxes of sargassum is a relatively new phenomenon for this region and its arrival, collection and potential uses are characterised 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 (process and end products)

5.4.1 Uncertainty

Mass influxes and stranding of pelagic sargassum in the Caribbean is a relatively new phenomenon (unprecedented prior to 2011) and is characterized by many uncertainties with regard to arrival (timing, amount, location), composition (chemical and species), appropriate collection, transport and storage methodologies and 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 harvest and use of sargassum.

5.4.2 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 great uncertainty with whether or not this would be a recurring phenomenon discouraged the development of an appropriate governance mechanism for several years. The initial focus was on treating sargassum as a hazard and removing it from critical coastlines as rapidly as possible. There was, and still is, relatively little attention paid to the potential opportunities for valorising 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 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 valorisation of sargassum are lagging behind (Cox, Oxenford, and McConney 2019).

Regional policies and statements that support the valorisation and commercialisation 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'[34].

5.4.3 Implications

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

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

The lack of a regional policy that speaks to the harvesting of sargassum as a shared resource is a hindrance for 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.

5.4.4 Moving forwards

Management and regulation to support commercialisation 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.

5.5 Funding and support

Key Challenges

- Availability of funding for valorising sargassum
- Difficulty accessing funding
- Low level of support for new ventures
- Lack of industrial infrastructure

5.5.1 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 education.

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

Specific current challenges include:

- 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 many times loans to develop businesses based on an unpredictable supply of raw material could further complicate access to funds).
- Donor funding is generally very difficult to access, and the application process and reporting requirements can be daunting and time consuming.
- Government budgets are generally not adaptive enough to support new ventures especially those with high uncertainty.

5.5.2 Support for innovation and business enterprises

The region is typically characterized by cumbersome bureaucratic procedures for setting up, operating and growing a business, that provide 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 (e.g. fisheries) and coastal (e.g. tourism) resources and lack industrial infrastructure.

5.5.3 Implications

The current difficulties in accessing funding to support the development and commercialisation of sargassum businesses, and the lack of a supporting environment to encourage entrepreneurship and new ventures is a significant constraint to the growth of a sargassum industry. This is exacerbated by the general lack of industrial infrastructure in many countries. This is also hindering the development of industry that has the potential to help solve the enormous cost of current clean-up efforts currently sustained by governments and the private sector.

5.5.4 Moving forwards

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.

- There are opportunities for sargassum innovations to be considered as blue growth initiatives which can be integrated into blue economy strategic frameworks and road maps. This can support economic diversification and resilience to reduce economic vulnerability and reliance on a small number of sectors. Increase the number of public-private partnerships in the domain of applied research and product development. This would allow spreading the risk of investment while maximizing innovation.
- Create a national policy framework for the development of micro-, small- and medium-sized enterprises (MSMEs) to support sustainable sargassum businesses.
- Build the capacity of small- and medium-scale entrepreneurs in the areas of business development, accessing grant funding, marketing, financial and human resources management.
- Create the enabling environment for affected stakeholders (fisherfolk and coastal community residents) to pursue sargassum uses as an alternative livelihood.
- Provide incentives for businesses that contribute to governments' cost recovery arrangements for cleaning beaches of sargassum.
- Create a 'sargassum tax' through tourism or other initiatives (such as the one in Quintana Roo, $1 per day per visiting tourist).
- Foster creativity through innovation hubs, hackathons and pitch competitions.

Section 6
References

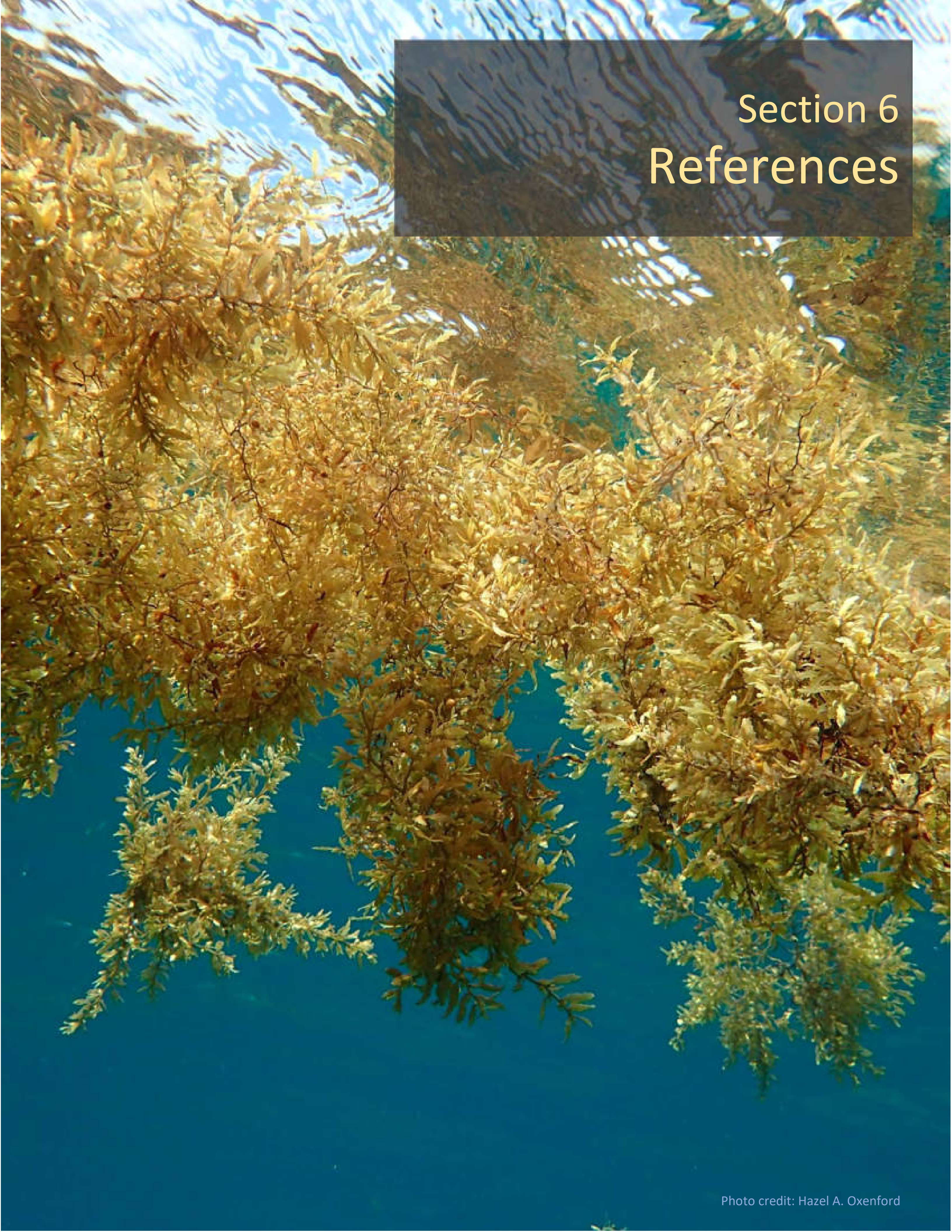


Photo credit: Hazel A. Oxenford

6. References

Abdel-Raouf, N., A. A. Al-Homaidan & I. B. M. Ibraheem. 2012. Agricultural importance of algae. *African Journal of Biotechnology* 11:11648-11658.

Abdul Khalil, H. P. S., E. W. N. Chong, F. A. T. Owolabi, M. Asniza, Y. Y. Tye, H. A. Tajarudin, M. T. Paridah & S. Rizal. 2018. Microbial-induced CaCO3 filled seaweed-based film for green plasticulture application. *Journal of Cleaner Production* 199:150-163. doi: 10.1016/j.jclepro.2018.07.111.

Abou El-Ezz, S. S. & F. E. Younis. 2010. Salt and trace minerals for livestock and other animals -A review. Eighth Scientific Conference of Society of Physiological Sciences and their Applications, Sharm El-Sheik, Egypt.

Adamse, P., H. J. Van der Fels-Klerx & J. de Jong. 2017. Cadmium, lead, mercury and arsenic in animal feed and feed materials – trend analysis of monitoring results. *Food Additives & Contaminants: Part A* 34 (8):1298-1311. doi: 10.1080/19440049.2017.1300686.

Addico, G. N. D. & K. A. A. deGraft-Johnson. 2016. Preliminary investigation into the chemical composition of the invasive brown seaweed Sargassum along the West Coast of Ghana. *African Journal of Biotechnology* 15 (39):2184-2191. doi: DOI: 10.5897/AJB2015.15177

Afonso, N. C., M. D. Catarino, A. M. S. Silva & S. M. Cardoso. 2019. Brown macroalgae as valuable food ingredients. *Antioxidants (Basel, Switzerland)* 8 (9):365. doi: 10.3390/antiox8090365.

Al-Harthi, M. A. & A. A. El-Deek. 2012. Effect of different dietary concentrations of brown marine algae (*Sargassum dentifebium*) prepared by different methods on plasma and yolk lipid profiles, yolk total carotene and lutein plus zeaxanthin of laying hens. *Italian Journal of Animal Science* 11 (4):e64. doi: 10.4081/ijas.2012.e64.

Ali, O., A. Ramsubhag & J. Jayaraman. 2019. Biostimulatory activities of *Ascophyllum nodosum* extract in tomato and sweet pepper crops in a tropical environment. *PLoS One* 14 (5):e0216710. doi: 10.1371/journal.pone.0216710.

Allen, V. G., K. R. Pond, K. E. Saker, J. P. Fontenot, C. P. Bagley, R. L. Ivy, R. R. Evans *et al*. 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.

Altenor, S., M. C. Ncibi, E. Emmanuel & S. Gaspard. 2012. Textural characteristics, physiochemical properties and adsorption efficiencies of Caribbean alga *Turbinaria turbinata* and its derived carbonaceous materials for water treatment application. *Biochemical Engineering Journal* 67:35-44. doi: https://doi.org/10.1016/j.bej.2012.05.008.

Alvarez, Y., C. Yacou, J. Louis-Thèrése, R. Liranzo-Gómez, N. Brehm, U. Jáuregui-Haza & S. Gaspard. 2019. Adsorption of hexavalent chromium from water using acidic activated carbons from Sargassum seaweed. Caribbean Science and Innovation Meeting, Pointe-à-Pitre, Guadeloupe, 2019-10-21.

Amara, I., W. Miled, R. B. Slama & N. Ladhari. 2018. Antifouling processes and toxicity effects of antifouling paints on marine environment. A review. *Environmental Toxicology and Pharmacology* 57:115-130. doi: https://doi.org/10.1016/j.etap.2017.12.001.

Angell, A. R., L. Mata, R. de Nys & N. A. Paul. 2016. The protein content of seaweeds: A universal nitrogen-to-protein conversion factor of five. *Journal of Applied Phycology* 28 (1):511-524. doi: 10.1007/s10811-015-0650-1.

ANR (Agence Nationale de la Recherche). 2019. Joint call for research, development and innovation on sargassum.

ANSES (Agence nationale de sécurité sanitaire de l'alimentation, d l'environnement et du travail). 2017. Expositions aux émanations d'algues sargasses en décomposition aux Antilles et en Guyane. 135 pp.

Arumugam, N., S. Chelliapan, H. Kamyab, S. Thirugnana, N. Othman & N. S. Nasri. 2018. Treatment of wastewater using seaweed: A review. *International Journal of Environmental Research and Public Health* 15 (12). doi:10.3390/ijerph15122851.

Audo, A., M. Paraschiv, C. Queffélec, I. Louvet, J. Hémez, F. Fayon, O. Lépine *et al*. 2015. Subcritical hydrothermal liquefaction of microalgae residues as a green route to alternative road binders. *ACS Sustainable Chemistry & Engineering* 3 (4): 583–590. Doi:10.1021/acssuschemeng.5b00088.

Aziz, A., B. Poinssot, X. Daire, M. Adrian, A. Bézier, B. Lambert, J.-M. Joubert & A. Pugin. 2003. Laminarin elicits defense responses in grapevine and induces protection against *Botrytis cinerea* and *Plasmopara viticola*. *Molecular Plant-Microbe Interactions* 16 (12):1118-1128. doi: 10.1094/MPMI.2003.16.12.1118.

Azizi, N., G. Najafpour & H. Younesi. 2017. Acid pretreatment and enzymatic saccharification of brown seaweed for polyhydroxybutyrate (PHB) production using *Cupriavidus necator*. *International Journal of Biological Macromolecules* 101:1029-1040. doi: https://doi.org/10.1016/j.ijbiomac.2017.03.184.

Bach, S. J., Y. Wang & T. A. McAllister. 2008. Effect of feeding sun-dried seaweed (*Ascophyllum nodosum*) on fecal shedding of *Escherichia coli* O157:H7 by feedlot cattle and on growth performance of lambs. *Animal Feed Science and Technology* 142 (1):17-32. doi: https://doi.org/10.1016/j.anifeedsci.2007.05.033.

Bajpai, S., P. S. Shukla, S. Asiedu, K. Pruski & B. Prithiviraj. 2019. A biostimulant preparation of brown seaweed *Ascophyllum nodosum* suppresses powdery mildew of strawberry. *Plant Pathol J* 35 (5):406-416. doi: 10.5423/PPJ.OA.03.2019.0066.

Balat, M. 2011. Potential alternatives to edible oils for biodiesel production - A review of current work. *Energy Conversion and Management* 52 (2):1479-1492. doi: 10.1016/j.enconman.2010.10.011.

Balboa, E., E. Conde, A. Constenla, E. Falqué & H. Domínguez. 2017. Sensory evaluation and oxidative stability of a suncream formulated with thermal spring waters from Ourense (NW Spain) and Sargassum muticum extracts. *Cosmetics* 4 (2):19.

Baldassarre, M. E., A. Di Mauro, M. C. Pignatelli, M. Fanelli, S. Salvatore, G. Di Nardo, A. Chiaro, L. Pensabene & N. Laforgia. 2019. Magnesium alginate in gastro-esophageal reflux: A randomized multicenter cross-over study in infants. *Int J Environ Res Public Health* 17 (1). doi: 10.3390/ijerph17010083.

Bazes, A., A. Silkina, P. Douzenel, F. Faÿ, N. Kervarec, D. Morin, J. - P. Berge & N. Bourgougnon. 2009. Investigation of the antifouling constituents from the brown alga *Sargassum muticum* (Yendo) Fensholt. *Journal of Applied Phycology* 21 (4):395-403. doi: 10.1007/s10811-008-9382-9.

Béguin, F. 2010. *Carbons for electrochemical energy storage and conversion systems*. Edited by F. Béguin and E. Frackowiak. Boca Raton: CRC Press. 529 pp.

Ben Salah, I., S. Aghrouss, A. Douira, S. Aissam, Z. El Alaoui-Talibi, A. Filali-Maltouf & C. El Modafar. 2018. Seaweed polysaccharides as bio-elicitors of natural defenses in olive trees against verticillium wilt of olive. *Journal of Plant Interactions* 13 (1):248-255. doi: 10.1080/17429145.2018.1471528.

Benvegnu, T. & J. - F. Sassi. 2010. Oligomannuronates from seaweeds as renewable sources for the development of green surfactants. *Topics in current chemistry* 294:143-64. doi: 10.1007/128_2010_48.

Berger, L. L. 2006. *Salt and trace minerals for livestock, poultry and other animals*: Salt Institute. 52 pp.

Bichat, M. P., E. Raymundo-Piñero & F. Béguin. 2010. High voltage supercapacitor built with seaweed carbons in neutral aqueous electrolyte. *Carbon* 48 (15):4351-4361. doi: 10.1016/j.carbon.2010.07.049.

Bird, M. I., C. M. Wurster, P. H. de Paula Silva, A. M. Bass & R. de Nys. 2011. Algal biochar - production and properties. *Bioresource Technology* 102 (2):1886-91. doi: 10.1016/j.biortech.2010.07.106.

Bitton, R. 2015. Chapter 7: Algal glue mimetics. In *Bioadhesion and Biomimetics from Nature to Applications*, edited by H. Bianco-Peled and M. Davidovich-Pinhas, 314 pp. New York: Jenny Stanford Publishing.

Blunden, G. & R. T. Jones. 1973. Toxic effects of *Ascophyllum nodosum* as a rabbit food additive. Food-Drugs from the Sea. Proceedings 1972.

Borines, M. G., R. L. de Leon & J. L. Cuello. 2013. Bioethanol production from the macroalgae *Sargassum* spp. *Bioresource Technology* 138:22-29. doi: https://doi.org/10.1016/j.biortech.2013.03.108.

Bowen, R. 2015. Literature research and review on Sargassum use in animal husbandry. Barbados: Barbados Ministry of Agriculture, Food Fisheries and Water Resource Management; The Animal Nutrition Unit. 25 pp.

Braden, K. W., J. R. Blanton, V. G. Allen, K. R. Pond & M. F. Miller. 2004. *Ascophyllum nodosum* supplementation: A preharvest intervention for reducing *Escherichia coli* O157:H7 and *Salmonella* spp. in feedlot steers. *Journal of Food Protection* 67 (9):1824-1828. doi: 10.4315/0362-028X-67.9.1824.

Braden, K. W., J. R. Blanton, Jr., J. L. Montgomery, E. van Santen, V. G. Allen & M. F. Miller. 2007. Tasco supplementation: Effects on carcass characteristics, sensory attributes, and retail display shelf-life. *Journal of Animal Science* 85 (3):754-768. doi: 10.2527/jas.2006-294.

Brooks, M. T., V. J. Coles, R. R. Hood & J. F. R. Gower. 2018. Factors controlling the seasonal distribution of pelagic Sargassum. *Marine Ecology Progress Series* 599:1-18.

Buschmann, A. H., C. Camus, J. Infante, A. Neori, Á. Israel, M. C. Hernández-González, S. V. Pereda *et al*. 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *European Journal of Phycology* 52 (4):391-406. doi: 10.1080/09670262.2017.1365175.

California department of food and agriculture. (undated). Proposed regulations title 3. Food and agriculture division 4. Plant industry Chapter 1. Chemistry subchapter 1. Fertilizing materials. https://www.cdfa.ca.gov/is/ffldrs/pdfs/AdoptedText.pdf

Campos de Paula, J., M. A. Vallim & V. Laneuville Teixeira. 2011. What are and where are the bioactive terpenoids metabolites from Dictyotaceae (Phaeophyceae). *Revista Brasileira de Farmacognosia* 21:216-228.

Canadian Food Inspection Agency. 2018. Guide to submitting spplications for registration under the fertilizers act. 48 pp.

Carrillo, S., A. Bahena, M. Casas, M .E. Carranco, C .C. Calvo, E. Ávila & F. Pérez-Gil. 2012. The alga Sargassum spp. as alternative to reduce egg cholesterol content. *Cuban Journal of Agricultural Science* 46 (2):181-186.

Carrillo, S., E. López, M. M. Casas, E. Avila, R. M. Castillo, M. E. Carranco, C. Calvo & F. Pérez-Gil. 2008. Potential use of seaweeds in the laying hen ration to improve the quality of n-3 fatty acid enriched eggs. *Journal of Applied Phycology* 20 (5):721-728. doi: 10.1007/s10811-008-9334-4.

Carrillo, S., V. H. Ríos, C. Calvo, M. E. Carranco, M. Casas & F. Pérez-Gil. 2012. n-3 Fatty acid content in eggs laid by hens fed with marine algae and sardine oil and stored at different times and temperatures. *Journal of Applied Phycology* 24 (3):593-599. doi: 10.1007/s10811-011-9777-x.

Casas-Valdez, M. , H. Hernández-Contreras, A. Marín-Álvarez, R. N. Aguila-Ramírez, C. J. Hernández-Guerrero, I. Sánchez-Rodríguez & S. Carrillo-Domínguez. 2006. El alga marina *Sargassum* (Sargassaceae): una alternativa tropical para la alimentación de ganado caprino. *Revista de Biología Tropical* 54 (1):83-92.

Casas-Valdez, M., G. Portillo-Clark, N. Aguila-Ramírez, S. Rodríguez-Astudillo, I. Sánchez-Rodríguez & S. Carrillo-Domínguez. 2006. Efecto del alga marina *Sargassum* spp. sobre las variables productivas y la concentración de colesterol en el camarón café, *Farfantepenaeus californiensis* (Holmes, 1900). *Revista de biología marina y oceanografía* 41:97-105.

Chaker Ncibi, M., A. Menyar Ben Hamissa & S. Gaspard. 2014. Chapter 7: Plantae and marine biomass. In *Biomass for sustainable applications: Pollution remediation and energy*, edited by S. Gaspard and M. Chaker Ncibi, 290-334. The Royal Society of Chemistry.

Chambers, L. D., K. R. Stokes, F. C. Walsh & R. J. K. Wood. 2006. Modern approaches to marine antifouling coatings. *Surface and Coatings Technology* 201 (6):3642-3652. doi: https://doi.org/10.1016/j.surfcoat.2006.08.129.

Chapman, V. J. & D. J. Chapman. 1980. *Seaweeds and their uses*. 3rd ed. ed. London: Chapman & Hall. 334 pp.

Chaves Lopez, C., A. Serio, C. Rossi, G. Mazzarrino, S. Marchetti, F. Castellani, Lisa Grotta, F. P. Fiorentino, A. Paparella & G. Martino. 2016. Effect of diet supplementation with Ascophyllum nodosum on cow milk composition and microbiota. *Journal of Dairy Science* 99 (8):6285-6297. doi: https://doi.org/10.3168/jds.2015-10837.

Chen, H., D. Zhou, G. Luo, S. Zhang & J. Chen. 2015. Macroalgae for biofuels production: Progress and perspectives. *Renewable and Sustainable Energy Reviews* 47:427-437. doi: 10.1016/j.rser.2015.03.086.

Chereau, E. 2019. Monitoring and evaluation of *Sargassum* collection operations - Summary report. 15MAG007. ADEME, SAFEGE and SUEZ. 227 pp.

Choi, B. W., G. Ryu, S. H. Park, E. S. Kim, J. Shin, S. S. Roh, H. C. Shin & B. H. Lee. 2007. Anticholinesterase activity of plastoquinones from Sargassum sagamianum: lead compounds for alzheimer's disease therapy. *Phytotherapy Research* 21 (5):423-426. doi: 10.1002/ptr.2090.

Citkowska, A., M. Szekalska & K. Winnicka. 2019. Possibilities of fucoidan utilization in the development of pharmaceutical dosage forms. *Marine drugs* 17 (8):458. doi: 10.3390/md17080458.

CNN Chile. 2019. Papel alga: innovación forestal "made in Chile". May 26, 2019. https://www.youtube.com/watch?v=jsCbBYDJj1U

Cox, S.-A., H. A. Oxenford & P. McConney. 2019. Summary report on the review of draft national sargassum plans for four countries in the Eastern Caribbean. Report (D20) prepared for the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector (CC4FISH) Project of the Food and Agriculture Organization (FAO) and the Global Environment Facility (GEF). Centre for Resource Management and Environmental Studies, University of the West Indies, Cave Hill, Barbados. 20 pp.

Creis, E., E. A. Gall & P. Potin. 2018. Chapter 3: Ubiquitous phlorotannins prospects and perspectives. In *Blue Biotechnology: Production and Use of Marine Molecules*, edited by S. La Barre and S. S. Bates, 67-116. Wiley-VCH Verlag GnbH & Co. KGaA

D'Amelio, F. S. 1999. Botanicals : a phytocosmetic desk reference. In. Boca Raton: CRC Press. 361 pp.

de Vrije, T. & A. M. López-Contreras. 2016. Chemical analysis of *Sargassum* biomas. Unpublished: Food and Biobased Products, Wageningen UR & Technical center for algae promotion (CEVA).

Deemy, M. & L. Benjamin. 2019. CVM CY15-17 Report on Heavy Metals in Animal Food. Center for Veterinary Medicine. 4 pp.

Déléris, P., H. Nazih & J. M. Bard. 2016. Chapter 10 - Seaweeds in human health. In *Seaweed in Health and Disease Prevention*, edited by Joël Fleurence and Ira Levine, 319-367. San Diego: Academic Press.

Diez, S., P. Patil, J. Morton, D. Rodriguez, A. Vanzella, D. Robin, T. Maes & C. Corbin. 2019. *Marine pollution in the Caribbean: Not a minute to waste*. Washington, DC: World Bank Group. 100 pp.

Doh, H., K. D. Dunno & W. S. Whiteside. 2020. Preparation of novel seaweed nanocomposite film from brown seaweeds *Laminaria japonica* and *Sargassum natans*. *Food Hydrocolloids* 105. doi: 10.1016/j.foodhyd.2020.105744.

Dove, C. A., F. F. Bradley & S. V. Patwardhan. 2016. Seaweed biopolymers as additives for unfired clay bricks. *Materials and Structures* 49 (11):4463-4482. doi: 10.1617/s11527-016-0801-0.

Doyle, E. & J. Franks. 2015. Sargassum fact sheet. Gulf and Caribbean Fisheries Institute. 3 pp.

Dutch Caribbean Nature Alliance. 2019. Prevention and clean-up of Sargassum in the Dutch Caribbean. 30 pp.

Echeverria, C., F. Pahlevani, V. Gaikwad & V. Sahajwalla. 2017. The effect of microstructure, filler load and surface adhesion of marine bio-fillers, in the performance of Hybrid Wood-Polypropylene Particulate Bio-composite. *Journal of Cleaner Production* 154:284-294. doi: https://doi.org/10.1016/j.jclepro.2017.04.020.

Edwards, B. 2020. Turning seaweed into big business. *Sustainable Business*, 06/03/2020, 26-27.

El-Banna, S. G., A. A. Hassan, A. B. Okab, A. A. Koriem & M. A. Ayoub. 2005. Effect of feeding diets supplemented with seaweed on growth performance andsome blood hematological and biochemical characteristics of male Baladi rabbits. 4th International Conference on Rabbit Production in Hot Climates, Sharm El-Sheikh,Egypt.

El-Deek, A. A & A. Mervat Brikaa. 2009. Effect of different levels of seaweed in starter and finisher diets in pellet and mash form on performance and carcass quality of ducks. *International Journal of Poultry Science* 8 (10):1014-1021. doi: 10.3923/ijps.2009.1014.1021.

Elad, Y., D. R. David, Y. M. Harel, M. Borenshtein, H. B. Kalifa, A. Silber & E. R. Graber. 2010. Induction of systemic resistance in plants by biochar, a soil-applied carbon sequestering agent. *Phytopathology* 100 (9):913-21. doi: 10.1094/PHYTO-100-9-0913.

Erickson, P. S., S. P. Marston, M. Gemmel, J. Deming, R. G. Cabral, M. R. Murphy & J. I. Marden. 2012. Short communication: Kelp taste preferences by dairy calves. *Journal Of Dairy Science* 95 (2):856-858. doi: 10.3168/jds.2011-4826.

Evans, F. D. & A. T. Critchley. 2014. Seaweeds for animal production use. *Journal of Applied Phycology* 26 (2):891-899. doi: 10.1007/s10811-013-0162-9.

Eyras, M. C., C. M. Rostagno & G. E. Defossé. 1998. Biological evaluation of seaweed composting. *Compost Science & Utilization* 6 (4):74-81. doi: 10.1080/1065657x.1998.10701943.

FAO. 2018. The global status of seaweed production, trade and utilization. *Globefish Research Programme*. Volume 124. edited by F. Ferdouse, Z. Yang, S. Løvstad Holdt, P. Murúa and R. Smith. Rome, Italy. 115 pp.

FAO and WHO. 2011. Discussion paper on arsenic in rice. edited by 5th Session Joint FAO/WHO Food Standards Programme Codex Committee on Contaminants in Foods. The Hague, The Netherlands, 21-25 March 2011. 28 pp.

Feitosa de Vasconcelos, A. C. & L. H. Garófalo Chaves. 2019. Biostimulants and their role in improving plant growth under abiotic stresses, biostimulants in plant science. In *Biostimulants in plant sciencesea*, edited by S. M. Mirmajlessi and R. Radhakrishnan. IntechOpen. 14 pp.

Fernández, F., C. J. Boluda, J. Olivera, L. A. Guillermo, B. Gómez, E. Echavarría & A. M. Gómez. 2017. Análisis elemental prospectivo de la biomasa algal acumulada en las costas de la República Dominicana durante 2015. *Centro Azúcar* 44:11-22.

Figlus, J., J. Sigren, R. Webster & T. Linton. 2015. Innovative technology seaweed prototype: Dunes demonstration project. Final technical report. Texas A&M University. 46 pp.

Fike, J. H., V. G. Allen, R. E. Schmidt, X. Zhang, J. P. Fontenot, C. P. Bagley, R. L. Ivy, R. R. Evans, R. W. Coelho & D. B. Wester. 2001. Tasco-Forage: I. Influence of a seaweed extract on antioxidant activity in tall fescue and in ruminants. *Journal of Animal Science* 79 (4):1011-1021. doi: 10.2527/2001.7941011x.

FitzGerald, A. 2008. Final report for SEAFISH: Abalone feed requirements. South West Abalone Growers Association. 34 pp.

Fletcher, R. L. & M. E. Callow. 1992. The settlement, attachment and establishment of marine algal spores. *British Phycological Journal* 27 (3):303-329. doi: 10.1080/00071619200650281.

Foley, P., E. S. Beach & J. B. Zimmerman. 2012. Derivation and synthesis of renewable surfactants. *Chemical Society Reviews* 41 (4):1499-1518. doi: 10.1039/C1CS15217C.

Francoeur, M., A. Ferino-Perez, C. Yacou, C. Jean-Marius, E. Emmanuel, Y. Chérémond, U. J. Jauregui-Haza & S. Gaspard. 2019. Valorisation of *Sargassum* sp. and modelling of adsorption of emerging micropollutants on activated carbon. Caribbean Science and Innovation Meeting, Pointe-à-Pitre, Guadeloupe, October 2019.

Franks, J., D. Johnson & D. Ko. 2016. Pelagic Sargassum in the Tropical North Atlantic. *Gulf and Caribbean Research* 27:SC6-SC11. doi: 10.18785/gcr.2701.08.

García-Sánchez, M., C. Graham, E. Vera, E. Escalante-Mancera, L. Álvarez-Filip & B. I. van Tussenbroek. 2020. Temporal changes in the composition and biomass of beached pelagic Sargassum species in the Mexican Caribbean. *Aquatic Botany* 167. doi: 10.1016/j.aquabot.2020.103275.

Gaspard, S. 2019. Sargassum valorization by pyrolysis - Application for food safety. International Sargassum Conference, Guadeloupe, 24 October 2019.

Gaspard, S., N. Passé-Coutrin, A. Durimel, T. Cesaire & V. Jeanne-Rose. 2014. Activated carbon from biomass for water treatment. In *Biomass for Sustainable Applications: Pollution Remediation and Energy*, edited by S. Gaspard and M. Chaker Ncibi, 46-105. The Royal Society of Chemistry.

GCFI. 2018. Sargassum best practices poster - Responding to a sargassum influx.

Generalić Mekinić, I., D. Skroza, V. Šimat, I. Hamed, M. Čagalj & Z. Popović Perković. 2019. Phenolic content of brown algae (Pheophyceae) species: extraction, identification, and quantification. *Biomolecules* 9 (6):244. doi: 10.3390/biom9060244.

Gerber, P.J. , H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci & G. Tempio. 2013. Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities. edited by Food and Agriculture Organization of the United Nations (FAO). Rome. 116 pp.

Ghosh, S., R. Gnaim, S. Greiserman, L. Fadeev, M. Gozin & A. Golberg. 2019. Macroalgal biomass subcritical hydrolysates for the production of polyhydroxyalkanoate (PHA) by Haloferax mediterranei. *Bioresource technology* 271:166-173. doi: 10.1016/j.biortech.2018.09.108.

Gogotsi, Y. & V. Presser. 2014. Carbon nanomaterials. In. Boca Raton: CRC Press. 529 pp.

Gourmelon, G. 2018. Problematic plastic. *USA Today Magazine* 147 (2878):69-69.

Gouvêa, L. P., J. Assis, C. F. D. Gurgel, E. A. Serrão, T. C. L. Silveira, C. M. Duarte, L. M. C. Peres *et al*. 2020. Golden carbon of *Sargassum* forests revealed as an opportunity for climate change mitigation. *Science of The Total Environment* 729. doi: https://doi.org/10.1016/j.scitotenv.2020.138745.

Government of Canada. 2017. Proposal - Maximum Chemical Contaminant Levels in Livestock Feeds. accessed January 30, 2020. https://www.inspection.gc.ca/animal-health/livestock-feeds/consultations/maximum-chemical-contaminant-levels-in-livestock-f/eng/1501175158139/1501175158765.

Govindarajan, A. F., L. Cooney, K. Whittaker, D. Bloch, R. M. Burdorf, S. Canning, C. Carter *et al*. 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. doi: 10.7717/peerj.7814.

Grand View Research. 2017. Alginate Market Analysis by Type (High G, High M), by Product (Sodium Alginate, Calcium Alginate, Potassium Alginate, Propylene Glycol Alginate), by Application, and Segment Forecasts, 2014 - 2025.

Han, W., W. Clarke & S. Pratt. 2014. Composting of waste algae: a review. *Waste Manag* 34 (7):1148-55. doi: 10.1016/j.wasman.2014.01.019.

Hanisak, M. D. & M. A. Samuel. 1987. Growth rates in culture of several species of Sargassum from Florida, USA. *Hydrobiologia* 151/152:399-404. doi: doi:10.1007/BF00046159.

Hasan, M., E. W. N. Chong, S. Jafarzadeh, M. T. Paridah, D. A. Gopakumar, H. A. Tajarudin, S. Thomas & H. P. S. Abdul Khalil. 2019. Enhancement in the physico-mechanical functions of seaweed biopolymer film via embedding fillers for plasticulture application-A comparison with conventional biodegradable mulch film. *Polymers (Basel)* 11 (2). doi: 10.3390/polym11020210.

Haykiri-Acma, H., S. Yaman & S. Kucukbayrak. 2013. Production of biobriquettes from carbonized brown seaweed. *Fuel Processing Technology* 106:33-40. doi: 10.1016/j.fuproc.2012.06.014.

Hazelton, P. & B. Murphy. 2016. *Interpreting soil test results: What do all the numbers mean?* 3rd edition ed. Victoria, Australia: CSIRO Publishing. 186 pp.

He, E. X. 2016. How carbon trading can help preserve coastal ecosystems. Washington DC, USA: Climate Institute. 7 pp.

Henry, J. 2016. Sea Potential - Scientists Seek Opportunity in Sargassum Threat. *The Pelican*, January-June 2016, 18-23.

Hill, R., A. Bellgrove, P. I. Macreadie, K. Petrou, J. Beardall, A. Steven & P. J. Ralph. 2015. Can macroalgae contribute to blue carbon? An Australian perspective. *Limnology and Oceanography* 60 (5):1689-1706. doi: 10.1002/lno.10128.

Hinds, C., H. A. Oxenford, J. Cumberbatch, F. Fardin, E. Doyle & A. Cashman. 2016. Sargassum management brief - Golden tides: Management best practices for influxes of Sargassum in the Caribbean with a focus on clean-up. Centre for Resource Management and Environmental Management (CERMES), University of the West Indies; Regional Activity Centre for Specially Protected Area and Wildlife (SPAW-RAC), Parc National de la Guadeloupe; Gulf and Caribbean Fisheries Institute (GCFI). 17 pp.

Hu, C., B. Murch, B. B. Barnes, M. Wang, J.-P. Maréchal, J. Franks, D. Johnson *et al*. 2016. *Sargassum* watch warns of incoming seaweed. *EOC* 97. doi: https://doi.org/10.1029/2016EO058355.

Ibrahim, A. E., M. N. Moawad, H. R. Z. Tadros, A. M. Attia & M. M. A. El-Naggar. 2019. Production of antifouling paints' using environmentally safe algal extracts on laboratory scale. *Egyptian Journal of Aquatic Biology and Fisheries* 23 (3):171-184. doi: 10.21608/ejabf.2019.41237.

Immirzi, B., G. Santagata, G. Vox & E. Schettini. 2009. Preparation, characterisation and field-testing of a biodegradable sodium alginate-based spray mulch. *Biosystems Engineering* 102 (4):461-472. doi: 10.1016/j.biosystemseng.2008.12.008.

Inagaki, M., F. Kang, M. Toyoda & H. Konno. 2014. Chapter 11 - Carbon materials for electrochemical capacitors. In *Advanced Materials Science and Engineering of Carbon*, edited by Michio Inagaki, Feiyu Kang, Masahiro Toyoda and Hidetaka Konno, 237-265. Boston: Butterworth-Heinemann.

Indergaard, M. & J. Minsaas. 1991. Animal and human nutrition. In *Seaweed resources in Europe : uses and potential*, edited by M. D. Guiry and G. Blunden, 432 pp. Chichester: John Wiley & Sons Ltd.

IT2 & ADEME. 2015. Unpublished data.

Janarthanan, M. & M. Senthil Kumar. 2018. Extraction of alginate from brown seaweeds and evolution of bioactive alginate film coated textile fabrics for wound healing application. *Journal of Industrial Textiles* 49 (3):328-351. doi: 10.1177/1528083718783331.

Jayaraj, J., A. Wan, M. Rahman & Z. K. Punja. 2008. Seaweed extract reduces foliar fungal diseases on carrot. *Crop Protection* 27 (10):1360-1366. doi: 10.1016/j.cropro.2008.05.005.

Jayaraman, J., J. Norrie & Z. K. Punja. 2010. Commercial extract from the brown seaweed *Ascophyllum nodosum* reduces fungal diseases in greenhouse cucumber. *Journal of Applied Phycology* 23 (3):353-361. doi: 10.1007/s10811-010-9547-1.

Jeffery, S., T. M. Bezemer, G. Cornelissen, T. W. Kuyper, J. Lehmann, L. Mommer, S. P. Sohi *et al*. 2015. The way forward in biochar research: targeting trade-offs between the potential wins. *GCB Bioenergy* 7 (1):1-13. doi: 10.1111/gcbb.12132.

Jesumani, V., H. Du, M. Aslam, P. Pei & N. Huang. 2019. Potential use of seaweed bioactive compounds in skincare-A review. *Marine drugs* 17 (12):688. doi: 10.3390/md17120688.

Ji, Y., Y. Ma, R. Liu, Y. Ma, K. Cao, U. Kaiser, A. Varzi, Y.-F. Song, S. Passerini & C. Streb. 2019. Modular development of metal oxide/carbon composites for electrochemical energy conversion and storage. *Journal of Materials Chemistry A* 7 (21):13096-13102. doi: 10.1039/C9TA03498F.

JICA & CRFM. 2019. Final Report: Fact-finding survey regarding the influx and impacts of Sargassum seaweed in the Caribbean region. 83 pp.

Johns, E. M., R. Lumpkin, N. F. Putman, R. H. Smith, F. E. Muller-Karger, D. T. Rueda-Roa, C. Hu *et al*. 2020. The establishment of a pelagic Sargassum population in the tropical Atlantic: Biological consequences of a basin-scale long distance dispersal event. *Progress in Oceanography* 182:102269. doi: https://doi.org/10.1016/j.pocean.2020.102269.

Johnson, D. L. & R. S. Braman. 1975. The speciation of arsenic and the content of germanium and mercury in members of the pelagic Sargassum community. *Deep Sea Research and Oceanographic Abstracts* 22 (7):503-507. doi: 10.1016/0011-7471(75)90023-6.

Johnson, D. R., J. S. Franks, H. A. Oxenford & S.-A. Cox. Forthcoming. Pelagic sargassum prediction and marine connectivity in the Tropical Atlantic.

Kaaya, G. P., P. N. Kadhila-Muandingi, H. R. Lofty & K. E. Mshigeni. 2012. Determination of optimum seaweed concentration for mushroom cultivation and the ability of mushrooms to absorb iodine. *African Journal of Agricultural Research* 7 (25):3673-3676. doi: 10.5897//AJAR11.897.

Kaladharan, P. 2006. Animal feed from seaweeds. National Training Workshop on Seaweed Farming and Processing for Food, Kilakarai, India, 3-5 August 2006.

Kale, S. K., A. G. Deshmukh, M. S. Dudhare & V. B. Patil. 2015. Microbial degradation of plastic: a review. *Journal of Biochemical Technology* 6 (2):952-961.

Kang, J.-I., E.-S. Yoo, J.-W. Hyun, Y.-S. Koh, N. H. Lee, M.-H. Ko, C.-S. Ko & H.-K. Kang. 2016. Promotion effect of apo-9′-fucoxanthinone from *Sargassum muticum* on hair growth *via* the activation of wnt/β-catenin and VEGF-R2. *Biological and Pharmaceutical Bulletin* 39 (8):1273-1283. doi: 10.1248/bpb.b16-00024.

Karan, H., C. Funk, M. Grabert, M. Oey & B. Hankamer. 2019. Green bioplastics as part of a circular bioeconomy. *Trends in Plant Science* 24 (3):237-249. doi: https://doi.org/10.1016/j.tplants.2018.11.010.

Khan, W., U. P. Rayirath, S. Subramanian, M. N. Jithesh, P. Rayorath, D. M. Hodges, A. T. Critchley, J. S. Craigie, J. Norrie & B. Prithiviraj. 2009. Seaweed extracts as biostimulants of plant growth and development. *Journal of Plant Growth Regulation* 28 (4):386-399. doi: 10.1007/s00344-009-9103-x.

Kim, N.-J., H. Li, K. Jung, H. N. Chang & P. C. Lee. 2011. Ethanol production from marine algal hydrolysates using *Escherichia coli* KO11. *Bioresource Technology* 102 (16):7466-7469. doi: https://doi.org/10.1016/j.biortech.2011.04.071.

Koul, B. & P. Taak. 2018. Soil remediation through algae, plants and animals. In *Biotechnological strategies for effective remediation of polluted soils*, edited by B. Koul and P. Taak, 129-195. Singapore: Springer Nature Singapore Pte Ltd.

Krause-Jensen, D. & C. M. Duarte. 2016. Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience* 9 (10):737-742. doi: 10.1038/ngeo2790.

Laffoley, D. d'A. & G. Grimsditch (eds). 2009. *The management of natural coastal carbon sinks*. Gland, Switzerland: IUCN. 53 pp.

Lapointe, B. E. 1986. Phosphorus-limited photosynthesis and growth of *Sargassum natans* and *Sargassum fluitans* (Phaeophyceae) in the western North Atlantic. *Deep-Sea Research* 33 (3):391-399. doi: 10.1016/0198-0149(86)90099-3.

Lapointe, B., L. West, T. Sutton & C. Hu. 2014. Ryther revisited: Nutrient excretions by fishes enhance productivity of pelagic Sargassum in the western North Atlantic Ocean. *Journal of Experimental Marine Biology and Ecology* 458:46–56. doi: 10.1016/j.jembe.2014.05.002.

Lee, J. Y., P. Li, J. Lee, H. J. Ryu & K. K. Oh. 2013. Ethanol production from *Saccharina japonica* using an optimized extremely low acid pretreatment followed by simultaneous saccharification and fermentation. *Bioresource Technology* 127:119-125. doi: 10.1016/j.biortech.2012.09.122.

Leupp, J. L., J. S. Caton, S. A. Soto-Navarro & G. P. Lardy. 2005. Effects of cooked molasses blocks and fermentation extract or brown seaweed meal inclusion on intake, digestion, and microbial efficiency in steers fed low-quality hay. *Journal of Animal Science* 83 (12):2938-2945. doi: 10.2527/2005.83122938x.

Li, K., S. Liu & X. Liu. 2014. An overview of algae bioethanol production. *International Journal of Energy Research* 38 (8):965-977. doi: 10.1002/er.3164.

Li, X., F. Li, H. Jian & R. Su. 2018. Exploration of antifouling potential of the brown algae *Laminaria* 'Sanhai'. *Journal of Ocean University of China* 17 (5):1135-1141. doi: 10.1007/s11802-018-3524-8.

Lim, J.-Y., S.-L. Hii, S.-Y. Chee & C.-L. Wong. 2018. *Sargassum siliquosum* J. Agardh extract as potential material for synthesis of bioplastic film. *Journal of Applied Phycology* 30 (6):3285-3297. doi: 10.1007/s10811-018-1603-2.

Liu, L., M. Heinrich, S. Myers & S. A. Dworjanyn. 2012. Towards a better understanding of medicinal uses of the brown seaweed Sargassum in Traditional Chinese Medicine: A phytochemical and pharmacological review. *Journal of Ethnopharmacology* 142 (3):591-619. doi: https://doi.org/10.1016/j.jep.2012.05.046.

Liu, Z., Y. G. Adewuyi, S. Shi, H. Chen, Y. Li, D. Liu & Y. Liu. 2019. Removal of gaseous Hg^0 using novel seaweed biomass-based activated carbon. *Chemical Engineering Journal* 366:41-49. doi: https://doi.org/10.1016/j.cej.2019.02.025.

Lopes, G., C. Sousa, P. Valentão & P. Andrade. 2013. Chapter 9 - Sterols in algae and health. In *Bioactive compounds from marine foods: Plant and animal sources*, edited by B. Hernández-Ledesma and M. Herrero, 173-191. John Wiley & Sons.

López, M., A. Moral, R. Aguado, L. Campaña & A. Tijero. 2014. Evaluation of bloom algae as raw material for papermaking. 13th European Workshop on Lignocellulosics and Pulp, Seville, Spain, June 24-27, 2014.

Lüning, K. & S. Pang. 2003. Mass cultivation of seaweeds: current aspects and approaches. *Journal of Applied Phycology* 15 (2):115-119. doi: 10.1023/A:1023807503255.

Luthuli, S., S. Wu, Y. Cheng, X. Zheng, M. Wu & H. Tong. 2019. Therapeutic effects of fucoidan: a review on recent studies. *Marine drugs* 17 (9):487.

Maceiras, R., L. Ortiz, A. Cancela & A. Sanchez. 2015. Analysis of combustion products of seaweeds residue pellets. *Environmental Progress and Sustainable Energy* 34 (4):1187-1190. doi: 10.1002/ep.12080.

Machmud, M. N., F. Fadi, Z. Fuadi & C. Kokarkin. 2013. Alternative fiber sources from *Gracilaria* Sp and *Eucheuma Cottonii* for papermaking. *International journal of science and engineering (edisi elektronik)* 6 (1):1-10. doi: 10.12777/ijse.6.1.1-10.

Macreadie, P. I., A. Anton, J. A. Raven, N. Beaumont, R. M. Connolly, D. A. Friess, J. J. Kelleway *et al*. The future of Blue Carbon science. *Nat Commun* 10 (1):3998. doi: 10.1038/s41467-019-11693-w.

Maehre, H. K., L. Dalheim, G. K. Edvinsen, E. O. Elvevoll & I. J. Jensen. 2018. Protein determination-method matters. *Foods* 7 (1). doi: 10.3390/foods7010005.

Makkar, H. P. S. , G. Tran, V. Heuzé, S. Giger-Reverdin, M. Lessire, F. Lebas & P. Ankers. 2016. Seaweeds for livestock diets: A review. *Animal Feed Science and Technology* 212:1-17.

Maneein, S., J. J. Milledge, B. V. Nielsen & P. J. Harvey. 2018. A review of seaweed pre-treatment methods for enhanced biofuel production by anaerobic digestion or fermentation. *Fermentation* 4 (100):1-31. doi:10.3390/fermentation4040100.

Mansauda, K. L. R., E. Anwar & T. Nurhayati. 2018. Antioxidant and anti-collagenase activity of *Sargassum Plagyophyllum* extract as an anti-wrinkle cosmetic ingredient. *Pharmacognosy Journal* 10 (5):932-936. doi: 10.5530/pj.2018.5.157.

Marín, A., M. Casas-Valdez, S. Carrillo, H. Hernández, A. Monroy, L. Sanginés & F. Pérez-Gil. 2009. The marine algae *Sargassum* spp. (Sargassaceae) as feed for sheep in tropical and subtropical regions. *Revista de Biología Tropical* 57:1271-1281.

Marín, A., M. Casas, S. Carrillo, H. Hernández & A. Monroy. 2003. Performance of sheep fed rations with Sargassum spp. sea algae. *Cuban J. Agric. Sci.* 37 (2):119-123.

Marinho, G. S., S. L. Holdt, M. J. Birkeland & I. Angelidaki. 2015. Commercial cultivation and bioremediation potential of sugar kelp, Saccharina latissima, in Danish waters. *Journal of Applied Phycology* 27 (5):1963-1973. doi: 10.1007/s10811-014-0519-8.

Matovic, D. 2011. Biochar as a viable carbon sequestration option: Global and Canadian perspective. *Energy* 36 (4):2011-2016. doi: https://doi.org/10.1016/j.energy.2010.09.031.

Mazé, J., P. Morand & P. Potoky. 1993. Stabilisation of "Green tides" Ulva by a method of composting with a view to pollution limitation. *Journal of Applied Phycology* 5:183-190.

McDonnell, P., S. Figat & J. V. O'Doherty. 2010. The effect of dietary laminarin and fucoidan in the diet of the weanling piglet on performance, selected faecal microbial populations and volatile fatty acid concentrations. *Animal* 4 (4):579-585. doi: 10.1017/S1751731109991376.

McHugh, D. 2003. A Guide to the Seaweed Industry. In *FAO Fisheries Technical Paper*. Rome, Italy: FAO. 106 pp.

Milledge, J. J. & J. P. Harvey. 2016. Golden tides: problem or golden opportunity? The valorisation of sargassum from beach inundations. *Journal of Marine Science and Engineering* 4 (3). doi: 10.3390/jmse4030060.

Milledge, J. J., S. Maneein, E. Arribas López & D. Bartlett. 2020. Sargassum inundations in Turks and Caicos: methane potential and proximate, ultimate, lipid, amino acid, metal and metalloid analyses. *Energies* 13 (1523):1-27.

Milledge, J. J., B. V. Nielsen, S. Maneein & P. J. Harvey. 2019. A brief review of anaerobic digestion of algae for bioenergy. *Energies* 12 (6). doi:10.3390/en12061166.

Milledge, J. J., B. Smith, P. W. Dyer & P. Harvey. 2014. Macro-algae-derived biofuel: A review of methods of energy extraction from seaweed biomass. *Energies* 7:7194-7222. doi: 10.3390/en7117194

Mišurcová, L., L. Machů & J. Orsavová. 2011. Chapter 29 - Seaweed minerals as nutraceuticals. In *Advances in Food and Nutrition Research*, edited by Se-Kwon Kim, 371-390. Academic Press.

Molloy, F. J., A. T. Critchley, L. Kandjengo & K. E. Mshigeni. 2003. The use of the valuable oyster mushroom, Pleurotus sajor-caju, for conversion of waste materials produced from seaweed and brewing industries: preliminary investigations. *Ambio* 32 (1):76-8. doi: 10.1579/0044-7447-32.1.76.

Montingelli, M. E., K. Y. Benyounis, J. Stokes & A. G. Olabi. 2016. Pretreatment of macroalgal biomass for biogas production. *Energy Conversion and Management* 108:202-209. doi: 10.1016/j.enconman.2015.11.008.

Mora Castro, N., M. Casas Valdez, A. Marín Álvarez, R. N. Águila Ramírez, I. Sánchez Rodríguez, H. Hernández Contreras & L. Sanginés García. 2009. The kelp *macrocystis pyrifera* as nutritional supplement for goats. *Revista Científica* 19:63-70.

Morrison, M. & D. Gray. 2017. Anaerobic digestion economic feasibility study: Generating energy from waste, sewage and sargassum seaweed in the OECS. Centre for Process Innovation (CPI), The Caribbean Council. England. 79 pp.

Mouritsen, O. G., M. Johansen & J. D. Mouritsen. 2013. *Seaweeds : Edible, Available, and Sustainable*. Chicago, USA: University of Chicago Press. 306 pp.

Moutinho, S., F. Linares, J. L. Rodríguez, V. Sousa & L. M. P. Valente. 2018. Inclusion of 10% seaweed meal in diets for juvenile and on-growing life stages of Senegalese sole (*Solea senegalensis*). *Journal of Applied Phycology* 30 (6):3589-3601. doi: 10.1007/s10811-018-1482-6.

Mshandete, A. M. 2014. Utilization of brown seaweeds *Sargassum* species organic supplements in grass basal substrate to enhance yield of edible *Coprinus cinereus* (Schaeff) S. Gray S. Lato. mushroom in Tanzania. *International Journal of Basic and Applied Sciences* 3 (4):177-186.

Mukherjee, P. &J. P. Keshri. 2018. Present status and development of algal pulp for hand-made paper making technology: a review. *Advances in Plants & Agriculture Research* 8 (1):10-18.

Nawaim, A., R. Aydi Ben Abdallah, H. Jabnoun-Khiareddine, A. Nefzi, R. Safa & M. Daami-Remadi. 2017. *Sargassum vulgare* extracts as an alternative to chemical fungicide for the management of fusarium dry rot in potato. *Journal of Agricultural Science and Food Research* 8:197.

Neori, A., T. Chopin, M. Troell, A. H. Buschmann, G. P. Kraemer, C. Halling, M. Shpigel & C. Yarish. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231 (1):361-391. doi: 10.1016/j.aquaculture.2003.11.015.

Neveux, N., J. Bolton, A. Bruhn, D. Roberts & M. Ras. 2018. The bioremediation potential of seaweeds: recycling nitrogen, phosphorus, and other waste products. In *Blue biotechnology - Production and use of marine molecules*, 217-239. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA.

Nkemka, V. N. & M. Murto. 2010. Evaluation of biogas production from seaweed in batch tests and in UASB reactors combined with the removal of heavy metals. *J Environ Manage* 91 (7):1573-9. doi: 10.1016/j.jenvman.2010.03.004.

Ocean Harvest Technology. 2016. Preliminary results of biochemical composition of Sargassum collected from beach in BVI in March 2016.

Ody, A., T. Thibaut, L. Berline, T. Changeux, J.-M. André, C. Chevalier, A. Blanfuné, J. Blanchot *et al*. 2019. From In Situ to satellite observations of pelagic Sargassum distribution and aggregation in the Tropical North Atlantic Ocean. *PLOS ONE* 14 (9):e0222584. doi: 10.1371/journal.pone.0222584.

Okab, A. B., E. M. Samara, K. A. Abdoun, J. Rafay, L. Ondruska, V. Parkanyi, J. Pivko *et al*. 2013. Effects of dietary seaweed (*Ulva lactuca*) supplementation on the reproductive performance of buck and doe rabbits. *Journal of Applied Animal Research* 41 (3):347-355. doi: 10.1080/09712119.2013.783479.

Orr, K. K. 2014. Floating seaweed (Sargassum) – at a glance. In *The significance and management of natural carbon stores in the open ocean. A summary.*, edited by D. Laffoley, J. M. Baxter, F. Thevenon and J. Oliver, p.10. Gland, Switzerland: IUCN.

Oxenford, H. A., P. McConney & K. Sabir. 2019. Challenges of managing sargassum influxes: A way forward. 39th AMLC Scientific Meeting: Environmental variability in the wider Caribbean and the ecological, social and economic consequences, Punta Cana, Dominican Republic, 20-24 May 2019.

Oyesiku, O. & A. Egunyomi. 2014. Identification and chemical studies of pelagic masses of *Sargassum natans* (Linnaeus) Gaillon and *S. fluitans* (Borgessen) Borgesen (brown algae), found offshore in Ondo State, Nigeria. *African Journal of Biotechnology* 13 (10):1188-1193. doi: 10.5897/AJB2013.12335.

Panchal, T. M., A. Patel, D. D. Chauhan, M. Thomas & J. V. Patel. 2017. A methodological review on bio-lubricants from vegetable oil based resources. *Renewable and Sustainable Energy Reviews* 70:65-70. doi: https://doi.org/10.1016/j.rser.2016.11.105.

Paraguay-Delgado, F., C. Carreno-Gallardo, I. Estrada-Guel, A. Zabala-Arceo, H. A. Martinez-Rodriguez & D. Lardizabal-Gutierrez. 2020. Pelagic *Sargassum* spp. capture CO_2 and produce calcite. *Environ Sci Pollut Res Int* 27 (20):25794-25800. doi: 10.1007/s11356-020-08969-w.

Patrón-Prado, M., B. Acosta-Vargas, E. Serviere-Zaragoza & L. C. Méndez-Rodríguez. 2010. Copper and cadmium biosorption by dried seaweed *Sargassum sinicola* in saline wastewater. *Water Air Soil Pollut* 210 (1-4):187-202.

Paul, R., L. Melville & M. Sulu. 2016. Anaerobic digestion of micro and macro algae, pre-treatment and co-digestion-biomass — A review for a better practice. *International Journal of Environmental Science and Development* 7 (9):646-650.

Peng, Y., J. Hu, B. Yang, X.-P. Lin, X.-F. Zhou, X.-W. Yang & Y. Liu. 2015. Chapter 5: Chemical composition of seaweeds. In *Seaweed sustainability : Food and non-food applications*, edited by D. J. Troy and B. K. Tiwari, 79-118 p. London: Academic Press.

Penn State. 2019. Seaweed feed additive cuts livestock methane but poses questions. In *ScienceDaily*. 17 June 2019. www.sciencedaily.com/releases/2019/06/190617164642.htm

Pereira, L. & J. Cotas. 2020. Introductory chapter: alginates - A general overview. In *Alginates - Recent uses of this natural polymer*, edited by L. Pereira. IntechOpen. 16 pp.

Perelo, L. W. 2010. Review: In situ and bioremediation of organic pollutants in aquatic sediments. *Journal of Hazardous Materials* 177 (1-3):81-89. doi: 10.1016/j.jhazmat.2009.12.090.

Perez-Salcedo, K. Y., S. Ruan, J. Su, X. Shi, A. M. Kannan & B. Escobar. 2020. Seaweed-derived KOH activated biocarbon for electrocatalytic oxygen reduction and supercapacitor applications. *Journal of Porous Materials*. doi: 10.1007/s10934-020-00871-7.

Perez, M. J., E. Falque & H. Dominguez. 2016. Antimicrobial action of compounds from marine seaweed. *Mar Drugs* 14 (3). doi: 10.3390/md14030052.

Petrone, L., R. Easingwood, M. F. Barker & A. J. McQuillan. 2011. In situ ATR-IR spectroscopic and electron microscopic analyses of settlement secretions of Undaria pinnatifida kelp spores. *Journal of the Royal Society, Interface* 8 (56):410-422. doi: 10.1098/rsif.2010.0316.

Pintor, M.-J., C. Jean-Marius, V. Jeanne-Rose, P.-L. Taberna, P. Simon, J. Gamby, R. Gadiou & S. Gaspard. 2013. Preparation of activated carbon from *Turbinaria turbinata* seaweeds and its use as supercapacitor electrode materials. *Comptes rendus - Chimie* 16 (1):73-79. doi: 10.1016/j.crci.2012.12.016.

Plouguerné, E., K. Le Lann, S. Connan, G. Jechoux, E. Deslandes & V. Stiger-Pouvreau. 2006. Spatial and seasonal variation in density, reproductive status, length and phenolic content of the invasive brown macroalga *Sargassum muticum* (Yendo) Fensholt along the coast of Western Brittany (France). *Aquatic Botany* 85 (4):337-344. doi: 10.1016/j.aquabot.2006.06.011.

Putman, N. F., G. J. Goni, L. J. Gramer, C. Hu, E. M. Johns, J. Trinanes & M. Wang. 2018. Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea. *Progress in Oceanography* 165:205-214. doi: 10.1016/j.pocean.2018.06.009.

Radulovich, R., S. Umanzor, R. Cabrera & R. Mata. 2015. Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. *Aquaculture* 436:40-46. doi: 10.1016/j.aquaculture.2014.10.032.

Rajauria, G. 2015. Chapter 15 - Seaweeds: a sustainable feed source for livestock and aquaculture. In *Seaweed Sustainability*, edited by B. K. Tiwari and D. J. Troy, 389-420. San Diego: Academic Press.

Rajendran, N., P. Sharanya, M. S. Raj, B. R. Angeeleena & C. Rajam. 2012. Seaweeds can be a new source for bioplastics. *Journal of Pharmacy Research* 5 (3):1476-1479.

Ramlogan, N. R., P. McConney & H. A. Oxenford. 2017. Socio-economic impacts of Sargassum influx events on the fishery sector of Barbados. CERMES Technical Report No. 81. Centre for Resource Management and Environmental Studies (CERMES), The University of the West Indies, Cave Hill Campus, Barbados. 86 pp.

Ramos, M. V., A. C. O. Monteiro, R. A. Moreira & A. Carvalho. 2000. Amino acid composition of some Brazilan seaweed species. *Journal of Food Biochemistry* 24 (1):33-39. doi: 10.1111/j.1745-4514.2000.tb00041.x.

Rana, S., S. Pichandi, S. Parveen & R. Fangueiro. 2014. Regenerated cellulosic fibers and their implications on sustainability. In *Roadmap to Sustainable Textiles and Clothing - Eco-friendly Raw Materials, Technologies, and Processing Methods*, edited by S. S. Muthu, 239-276. Singapore: Springer.

Rani, K., M. K. Pervez, A. Rehman, S. Perven, N. Akhtar & F. Ahmad. 2020. A potential benefit of brown seaweed (*Stoechospermum marginatum*) using for sustainable fabric dyeing. *Journal of Research in Weed Science* 3 (2):120-132. doi: 10.26655/JRWEEDSCI.2020.2.1.

Raymundo-Piñero, E., M. Cadek, M. Wachtler & F. Béguin. 2011. Carbon nanotubes as nanotexturing agents for high power supercapacitors based on seaweed carbons. *ChemSusChem* 4 (7):943-949. doi: 10.1002/cssc.201000376.

Reimann, C., J. Matschullat, M. Birke & R. Salminen. 2009. Arsenic distribution in the environment: The effects of scale. *Applied Geochemistry* 24 (7):1147-1167. doi: https://doi.org/10.1016/j.apgeochem.2009.03.013.

Roberts, D. A., N. A. Paul, S. A. Dworjanyn, M. I. Bird & R. de Nys. 2015. Biochar from commercially cultivated seaweed for soil amelioration. *Scientific Reports* 5 (1):9665. doi: 10.1038/srep09665.

Rodríguez-Martínez, R. E., P. D. Roy, N. Torrescano-Valle, N. Cabanillas-Terán, S. Carrillo-Domínguez, L. Collado-Vides, M. García-Sánchez & B. I. van Tussenbroek. 2020. Element concentrations in pelagic Sargassum along the Mexican Caribbean coast in 2018-2019. *PeerJ* 8:e8667. doi: 10.7717/peerj.8667.

Rodriguez Cuevas, A., E. Rivera & J. A. Gil. 2020. Estudio de caso: Transformación de sargazo y desechos orgánicos en energía limpia. Latin American and Caribbean Consortium of Engineering Institutions (LACCEI), 27-30 July 2020. 13 pp.

Ron, E. Z. & E. Rosenberg. 2014. Enhanced bioremediation of oil spills in the sea. *Current Opinion in Biotechnology* 27:191-194. doi: https://doi.org/10.1016/j.copbio.2014.02.004.

Ruslin, M., A. F. Husain, H. Y. As & S. Subehan. 2018. Analysis of total flavonoid levels in brown algae (*Sargassum* sp. and *Padina* sp.) as analgesic drug therapy. *Asian Journal of Pharmaceutical and Clinical Research* 11 (7). doi: 10.22159/ajpcr.2018.v11i7.25657.

Saderne, V., N. R. Geraldi, P. I. Macreadie, D. T. Maher, J. J. Middelburg, O. Serrano, H. Almahasheer *et al*. 2019. Role of carbonate burial in Blue Carbon budgets. *Nature Communications* 10 (1):1106. doi: 10.1038/s41467-019-08842-6.

Saha, B. C. & F. M. Racine. 2011. Biotechnological production of mannitol and its applications. *Applied Microbiology and Biotechnology* 89 (4):879-891. doi: 10.1007/s00253-010-2979-3.

Saker, K. E., V. G. Allen, J. P. Fontenot, C. P. Bagley, R. L. Ivy, R. R. Evans & D. B. Wester. 2001. Tasco-Forage: II. Monocyte immune cell response and performance of beef steers grazing tall fescue treated with a seaweed extract. *Journal of Animal Science* 79 (4):1022-1031. doi: 10.2527/2001.7941022x.

Salima, A., B. Benaouda, B. Noureddine & L. Duclaux. 2013. Application of *Ulva lactuca* and *Systoceira stricta* algae-based activated carbons to hazardous cationic dyes removal from industrial effluents. *Water Research* 47 (10):3375-3388. doi: 10.1016/j.watres.2013.03.038.

Schell, J. M. , D. S. Goodwin & A. N. S Siuda. 2015. Recent sargassum inundation events in the Caribbean: shipboard observations reveal dominance of a previously rare form. *Oceanography* 28 (3):8-10.

Sembera, J. A., E. J. Meier & T. M. Waliczek. 2018. Composting as an alternative management strategy for Sargassum srifts on coastlines. *HortTechnology* 28 (1):80-84. doi: 10.21273/horttech03836-17.

Seo, Y., Y.-W. Lee, C.-H. Lee & H.-C. You. 2010. Red algae and their use in papermaking. *Bioresource technology* 101:2549-53. doi: 10.1016/j.biortech.2009.11.088.

Seok, D., Y. Jeong, K. Han, D. Yoon & H. Sohn. 2019. Recent progress of electrochemical energy devices: Metal oxide–carbon nanocomposites as materials for next-generation chemical storage for renewable energy. *Sustainability* 11:3694. doi: 10.3390/su11133694.

Shanura Fernando, I. P., K. K. Asanka Sanjeewa, K. W. Samarakoon, H.-S. Kim, U. K. D. S. S. Gunasekara, Y.-J. Park, D. T. U. Abeytunga, W. W. Lee & Y.-J. Jeon. 2018. The potential of fucoidans from *Chnoospora minima* and *Sargassum polycystum* in cosmetics: antioxidant, anti-inflammatory, skin-whitening, and antiwrinkle activities. *Journal of Applied Phycology* 30 (6):3223-3232. doi: 10.1007/s10811-018-1415-4.

Shukla, P. S., E. G. Mantin, M. Adil, S. Bajpai, A. T. Critchley & B. Prithiviraj. 2019. *Ascophyllum nodosum*-based biostimulants: Sustainable applications in agriculture for the stimulation of plant growth, stress tolerance, and disease management. *Front Plant Sci* 10:655. doi: 10.3389/fpls.2019.00655.

Siddhanta, A. K., M. U. Chhatbar, G. K. Mehta, N. D. Sanandiya, S. Kumar, M. D. Oza, K. Prasad & R. Meena. 2011. The cellulose contents of Indian seaweeds. *Journal of Applied Phycology* 23 (5):919-923. doi: 10.1007/s10811-010-9599-2.

Siddhanta, A. K., K. Prasad, R. Meena, G. Prasad, G. K. Mehta, M. U. Chhatbar, M. D. Oza, S. Kumar & N. D. Sanandiya. 2009. Profiling of cellulose content in Indian seaweed species. *Bioresource technology* 100 (24):6669-73. doi: 10.1016/j.biortech.2009.07.047.

Sigren, J., J. Figlus & A. Armitage. 2014. Coastal sand dunes and dune vegetation: Restoration, erosion, and storm protection. *Shore and Beach* 82:5-12.

Singh, B., R. Chopra, S. Rai, M. Verma & R. Mohanta. 2015. Nutritional evaluation of seaweed on nutrient digestibility, nitrogen balance, milk production and composition in Sahiwal cows. *Proceedings of the National Academy of Sciences, India - Section B: Biological Sciences* 87. doi: 10.1007/s40011-015-0616-8.

Sissini, M. N., M. B. Barbosa de Barros Barreto, M. T. Menezes Széchy, M. Bouças de Lucena, M. Cabral Oliveira, J. Gower, G. Liu *et al*. 2017. The floating Sargassum (Phaeophyceae) of the South Atlantic Ocean - likely scenarios. *Phycologia* 56 (3):321-328.

Smartfiber AG. SeaCell: The power of seaweed in a fiber. accessed July 4th, 2020. https://www.smartfiber.de/en/fibers/seacelltm/.

Solarin, B. B., D. A. Bolaji, O. S. Fakayode & R. O. Akinnigbagbe. 2014. Impacts of an invasive seaweed *Sargassum hystrix var. fluitans* (Børgesen 1914) on the fisheries and other economic implications for the Nigerian coastal waters. *IOSR Journal of Agriculture and Veterinary Science* 7 (7):1-6.

Sudaryono, A., P. Sukardi, E. Yudiarti, E. H. Hardi, S. Hastuti & T. Susilowati. 2018. Potential of using tropical brown macroalgae *sargassum cristaefolium* meal in the diets for juvenile white shrimp (*litopenaeus vannamei*). *IOP Conf. Ser.: Earth and Environ. Sci*. 144:012049

Sun, N., Z. Li, X. Zhang, W. Qin, C. Zhao, H. Zhang, D. H. L. Ng, S. Kang, H. Zhao & G. Wang. 2019. Hierarchical porous carbon materials derived from kelp for superior capacitive applications. *ACS Sustainable Chemistry & Engineering* 7 (9):8735-8743. doi: 10.1021/acssuschemeng.9b00635.

Sustainable Fashion Earth. 2020. Textile produced from algae. accessed July 4th 2020. https://www.sustainablefashion.earth/type/waste/is-digital-clothing-the-future-of-fashion/.

Szekalska, M., A. Puciłowska, E. Szymańska, P. Ciosek & K. Winnicka. 2016. Alginate: Current use and future perspectives in pharmaceutical and biomedical applications. *International Journal of Polymer Science* 2016:1-17. doi: 10.1155/2016/7697031.

Tabassum, M. R., A. Xia & J. D. Murphy. 2017. Potential of seaweed as a feedstock for renewable gaseous fuel production in Ireland. *Renewable and Sustainable Energy Reviews* 68 (Part 1):136-146. doi: 10.1016/j.rser.2016.09.111.

Taberna, P.-L. & S. Gaspard. 2014. Nanoporous carbons for high energy density supercapacitors. In *Biomass for Sustainable Applications: Pollution Remediation and Energy*, edited by Sarra Gaspard and Mohamed Chaker Ncibi, 366-399. The Royal Society of Chemistry.

Tang, J., M. Wang, Q. Zhou & S. Nagata. 2011. Improved composting of Undaria pinnatifida seaweed by inoculation with Halomonas and Gracilibacillus sp. isolated from marine environments. *Bioresour Technol* 102 (3):2925-30. doi: 10.1016/j.biortech.2010.11.064.

Tapia-Tussell, R., J. Avila-Arias, J. Domínguez Maldonado, D. Valero, E. Olguin-Maciel, D. Pérez-Brito & L. Alzate-Gaviria. 2018. Biological pretreatment of Mexican Caribbean macroalgae consortiums using

Bm-2 Strain (*Trametes hirsuta*) and its enzymatic broth to improve biomethane potential. *Energies* 11 (3). doi: 10.3390/en11030494.

Tarvainen, T., S. Albanese, M. Birke, M. Poňavič & C. Reimann. 2013. Arsenic in agricultural and grazing land soils of Europe. *Applied Geochemistry* 28:2-10. doi: 10.1016/j.apgeochem.2012.10.005.

Teas, J., S. Pino, A. Critchley & L. E. Braverman. 2004. Variability of iodine content in common commercially available edible seaweeds. *Thyroid : official journal of the American Thyroid Association* 14 (10):836-41.

Thomas, M., D. Chauhan, J. Patel & T. Panchal. 2013a. Bioassay of biostimulants extracted from brown seaweed using various solvents and their comparison with extracts of terrestrial plants. *International Journal of Current Research* 2 (1):405-407.

Thomas, M., D. Chauhan, J. Patel & T. M. Panchal. 2013b. Analysis of biostimulants made by fermentation of Sargassum tenerimum seaweed. *International Journal for current trends in Research* 2:405-407.

Thompson, T. M., B. R. Young & S. Baroutian. 2020. Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados. *Renewable and Sustainable Energy Reviews* 118:109564. doi: https://doi.org/10.1016/j.rser.2019.109564.

Tirolien, J. 2019. Presentation: Valorisation agronomique des algues sargasses. International Conference on Sargassum, Guadeloupe, France, 25 October 2019.

Trilaksana, A. C., I. Kirana & Arisandi. 2020. Effectiveness of brown algae extract (*Sargassum* sp) 15% in dissolving root canal smear layer (a SEM study). *Medicina Clínica Práctica* 3:100095. doi: https://doi.org/10.1016/j.mcpsp.2020.100095.

Turner, J. P. & J. R. Rooker. 2006. Fatty acid composition of flora and fauna associated with Sargassum mats in the Gulf of Mexico. *Marine Biology* 149 (5):1025-1036. doi: 10.1007/s00227-006-0269-5.

Tye, A., M. Fullen & T. Hocking. 2001. Mode of action of calcified seaweed on grassland. *Communications in Soil Science and Plant Analysis* 32 (3-4):311-329. doi: 10.1081/CSS-100103010.

UNEP. 2018. Sargassum white paper - Sargassum outbreak in the Caribbean: Challenges, opportunities and regional situation. UNEP(DEPI)/CAR WG.40/ INF8. Adopted at 8th Meeting of the Scientific and Technical Advisory Committee (STAC) to the Protocol Concerning Specially Protected Areas and Wildlife (SPAW) in the Wider Caribbean Region, Panama City, Panama, 5-7 December 2018. 14 pp.

Vallini, G., A. Pera, F. Cecchi, M. M. Valdrighi & M. A. Sicurani. 1993. Compost stabilization of algal biomass drawn in eutrophic lagoon ecosystems. *Compost Science & Utilization* 1 (2):49-53. doi: 10.1080/1065657X.1993.10757872.

van Ginneken, V. J. T., J. P. F. G. Helpsper, W. de Visser, H. van Keulen & W. A. Brandenburg. 2011. Polyunsaturated fatty acids in various macroalgal species from north Atlantic and tropical seas. *Lipids in Health and Disease* 10 (1).

van Tussenbroek, B. I., H. A. Hernández Arana, R. E. Rodríguez-Martínez, J. Espinoza-Avalos, H. M. Canizales-Flores, C. E. González-Godoy, M. G. Barba-Santos, A. Vega-Zepeda &L. Collado-Vides. 2017. Severe impacts of brown tides caused by *Sargassum* spp. on near-shore Caribbean seagrass communities. *Marine Pollution Bulletin* 122 (1-2):272-281. doi: 10.1016/j.marpolbul.2017.06.057.

Veira, A. K. & F. B. Lopez. 2016. Potential for use of Sargassum mulch in sweet potato production. Caribbean Food Crops Society, 52nd Annual Meeting, Le Gosier, Guadeloupe, July 10-16 2016.

Vera, J., J. Castro, A. Gonzalez & A. Moenne. 2011. Seaweed polysaccharides and derived oligosaccharides stimulate defense responses and protection against pathogens in plants. *Mar Drugs* 9 (12):2514-25. doi: 10.3390/md9122514.

Vergara-Fernández, A., G. Vargas, N. Alarcón & A. Velasco. 2008. Evaluation of marine algae as a source of biogas in a two-stage anaerobic reactor system. *Biomass and Bioenergy* 32 (4):338-344. doi: 10.1016/j.biombioe.2007.10.005.

Vreeland, V., J. H. Waite & L. Epstein. 1998. Minireview—Polyphenols and oxidases in substratum adhesion by marine algae and mussels. *Journal of Phycology* 34 (1):1-8. doi: 10.1046/j.1529-8817.1998.340001.x.

Walsh, K. T. 2019. Examining the quality of a compost product derived from *Sargassum* (*Sargassum fluitans* and *Sargassum natans*). Master of Education with a Major in Agricultural Education, Texas State University. 48 pp.

Wang, M. & C. Hu. 2016. Mapping and quantifying Sargassum distribution and coverage in the Central West Atlantic using MODIS observations. *Remote Sensing of Environment* 183:350-367. doi: https://doi.org/10.1016/j.rse.2016.04.019.

Wang, M. & C. Hu. 2017. Predicting *Sargassum* blooms in the Caribbean Sea from MODIS observations. *Geophysical Research Letters* 44 (7):3265-3273. doi: 10.1002/2017gl072932.

Wang, M., C. Hu, B. B. Barnes, G. Mitchum, B. Lapointe & J. P. Montoya. 2019. The great Atlantic *Sargassum* belt. *Science* 365 (6448):83. doi: 10.1126/science.aaw7912.

Wang, M., C. Hu, J. Cannizzaro, D. English, X. Han, D. Naar, B. Lapointe, R. Brewton & F. Hernandez. 2018. "Remote sensing of Sargassum biomass, nutrients, and pigments." *Geophysical Research Letters* 45 (22):12,359-12,367. doi: 10.1029/2018gl078858.

Wang, S.-B., Y.-H. Jia, L.-H. Wang, F.-H. Zhu & Y.-T. Lin. 2013. *Enteromorpha prolifera* supplemental level: effects on laying performance, egg quality, immune function and microflora in feces of laying hens. *Chinese Journal of Animal Nutrition* 25 (6):1346-1352.

Wang, S., X. Shi, C. Zhou & Y. Lin. 2013. *Entermorpha prolifera*: Effects on performance, carcass quality and small intestinal digestive enzyme activities of broilers. *Chinese Journal of Animal Nutrition* 25 (6):1332-1337.

Wardani, A. K. & R. Herrani. 2019. Bioethanol from sargassum sp using acid hydrolysis and fermentation method using microbial association. *Journal of Physics: Conference Series* 1241 (1). doi: 10.1088/1742-6596/1241/1/012008.

Webber, M., H. Reid, R. Delgoda, W. Gallimore, F. Boyd, T. Stephenson, A. Maxam, O. Campbell, D. Davis & J. Freeman. 2019. Sargassum update from Jamaica 2: The UWI response. Kingston, Jamaica (workshop document): IAEA Interregional Workshop on the use of nuclear techniques for Sargassum control. 5 pp.

Wells, M. L., P. Potin, J. S. Craigie, J. A. Raven, S. S. Merchant, K. E. Helliwell, A. G. Smith, M. E. Camire & S. H. Brawley. 2017. Algae as nutritional and functional food sources: revisiting our understanding. *Journal of applied phycology* 29 (2):949-982. doi: 10.1007/s10811-016-0974-5.

Wijesinghe, W. A. J. P., and Y.-J. Jeon. 2011. Biological activities and potential cosmeceutical applications of bioactive components from brown seaweeds: a review. *Phytochemistry Reviews* 10 (3):431-443.

Williams, A. & R. Feagin. 2010. Sargassum as a natural solution to enhance dune plant growth. *Environmental management* 46 (5):738-747. doi: 10.1007/s00267-010-9558-3.

Williams, J. E., D. E. Spiers, L. Thompson-Golden, T. J. Hackman, M. R. Ellersieck, L. Wax, D. P. Colling, J. B. Corners & P. A. Lancaster. 2009. Effects of Tasco in alleviation of heat stress in beef cattle. *Professional Animal Scientist* 25 (2):109-117.

Wilson-Howard, M. 2015. Potential for the use of Sargassum seaweed in Barbados. *Unpublished*.

Wiseman, M. 2012. Evaluation of Tasco as a candidate prebiotic in broiler chickens. Master of Science, Department of Plant and Animal Science, Dalhousie University. 234 pp.

Wylie, L., A. E. Sutton-Grier & A. Moore. 2016. Keys to successful blue carbon projects: Lessons learned from global case studies. *Marine Policy* 65:76-84. doi: 10.1016/j.marpol.2015.12.020.

Xu, W., J. Pan, B. Fan & Y. Liu. 2019. Removal of gaseous elemental mercury using seaweed chars impregnated by NH4Cl and NH4Br. *Journal of Cleaner Production* 216:277-287. doi: https://doi.org/10.1016/j.jclepro.2019.01.195.

Yamashita, Y. 2014. Method of removing inorganic arsenic from dried hijiki seaweed products. *NIPPON SUISAN GAKKAISHI* 80 (6):973-978. doi: 10.2331/suisan.80.973.

Yang, E.-J., Y. M. Ham, K.-W. Yang, N. H. Lee & C.-G. Hyun. 2013. Sargachromenol from Sargassum micracanthum inhibits the lipopolysaccharide-induced production of inflammatory mediators in RAW 264.7 macrophages. *Scientific World Journal*:1-6. doi: 10.1155/2013/712303.

Yangthong, M., S. Oncharoen & J. Sripanomyom. 2014. Effect of Sargassum meal supplementation on growth performance of sex-reversed tilapia (*Oreochromis niloticus* Linn.). Proceedings Kasetsart University Annual Conference, Chatuchak, Bangkok: Kasetsart University.

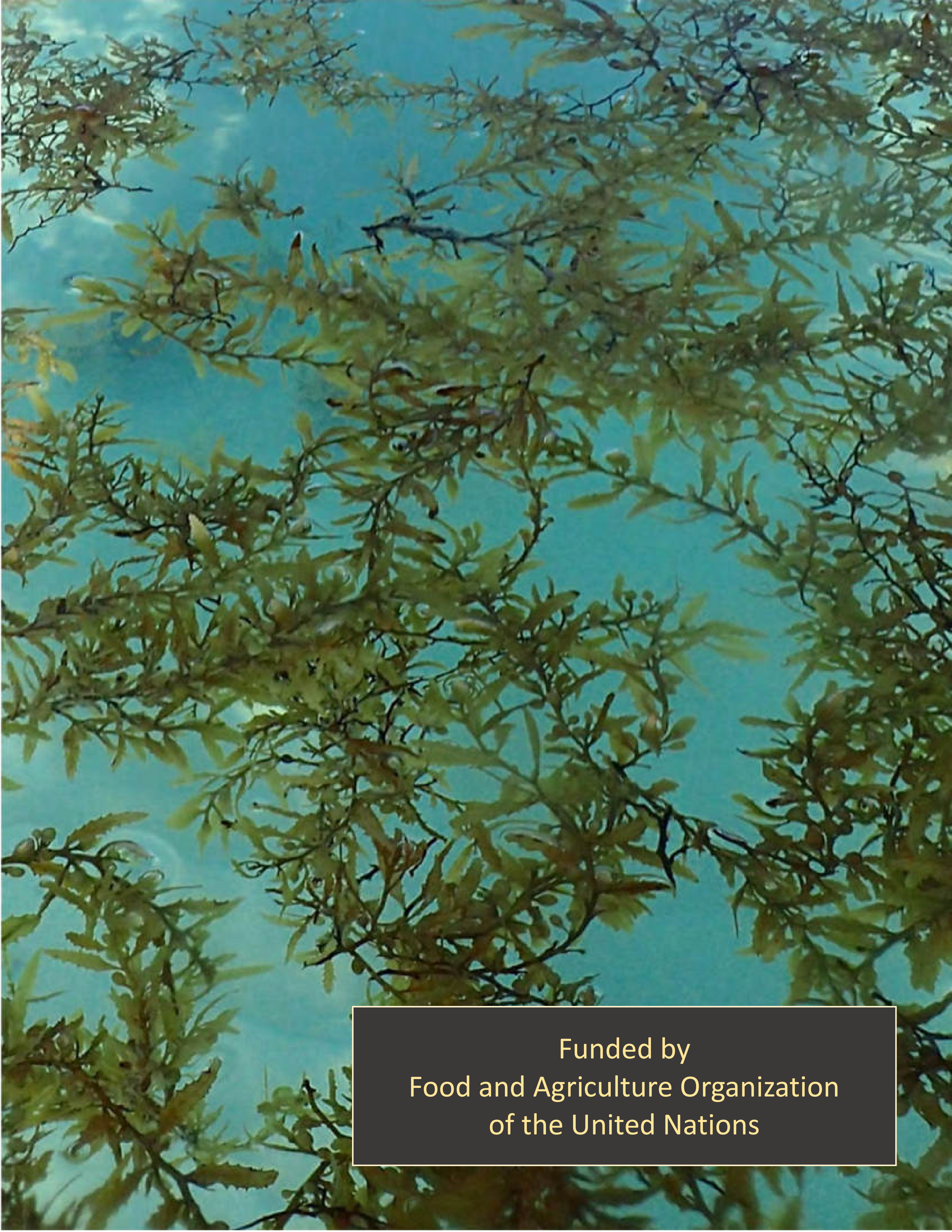
Yende, S. R., U. N. Harle & B. B. Chaugule. 2014. Therapeutic potential and health benefits of Sargassum species. *Pharmacognosy Reviews* 8 (15):1-7. doi: 10.4103/0973-7847.125514.

Yeon, J.-H., S.-E. Lee, W. Y. Choi, D. H. Kang & H.-Y. Lee. 2011. Repeated-batch operation of surface-aerated fermentor for bioethanol production from the hydrolysate of seaweed *Sargassum sagamianum*. *Journal of Microbiology and Biotechnology* 21 (3):323-331. doi: 10.4014/jmb.1010.10057.

Yu, Z., X. Zhu, Y. Jiang, P. Luo & C. Hu. 2014. Bioremediation and fodder potentials of two Sargassum spp. in coastal waters of Shenzhen, South China. *Marine Pollution Bulletin* 85 (2):797-802. doi: https://doi.org/10.1016/j.marpolbul.2013.11.018.

Zahid, P. B., A. Ali & M. J. Zahid. 2001. Brown seaweed as supplement for broiler feed. *Hamdard medicus* 154 (2):98-101.

Zhao, W., P. Yuan, X. She, Y. Xia, S. Komarneni, K. Xi, Y. Che, X. Yao & D. Yang. 2015. Sustainable seaweed-based one-dimensional (1D) nanofibers as high-performance electrocatalysts for fuel cells. *Journal of Materials Chemistry A* 3 (27):14188-14194. doi: 10.1039/C5TA03199K.



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