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Perspective

Tracking and Utilizing Sargassum, an Abundant Resource from the Caribbean Sea

Meng-Chou Lee [1,2], Han-Yang Yeh [1], Chun-Ming Chang [3], Yu-Fu Liou [3], Fan-Hua Nan [1] and Jane Wungen-Sani [1,*]

1 Department of Aquaculture, National Taiwan Ocean University, Keelung City 20224, Taiwan; mengchoulee@email.ntou.edu.tw (M.-C.L.); 20833001@mail.ntou.edu.tw (H.-Y.Y.)
2 Center of Excellence for the Ocean, National Taiwan Ocean University, Keelung City 20224, Taiwan
3 Advanced Research Center for Earth Sciences, National Central University, Taoyuan City 328003, Taiwan; glazejimmy@gmail.com (C.-M.C.); liouyufu@g.ncu.edu.tw (Y.-F.L.)
* Correspondence: 21133009@mail.ntou.edu.tw; Tel.: +886-2-246222192 (ext. 5239)

Abstract: Due to climate change and its associated factors, there has been an increased influx of pelagic brown algae biomass drifting freely in the Caribbean Sea in recent years. Its use as an industrial recyclable material is feasible, although pelagic Sargassum species have Arsenic (As) heavy metal content; among 531 tested pesticide residues applied to vegetables, fruit, infant food, herbs, and spices, zero were found in Sargassum. Sargassum also contains sulfated polysaccharides and oligosaccharides, which are known to be beneficial immunomodulators. Our results thus suggest Sargassum to be a functionally useful organic material in small quantities as an additive in animal feed. With improved chemical extraction methods, it could also be highly effective in adjusted proportions in cosmetics and for other industrial uses. A viable solution for predicting and tracking the large-scale movements of algal masses is provided. Furthermore, a method for addressing increasing Sargassum influx is proposed via its use as an industrial recyclable material following composition analysis, evaluation and safety assessments for cosmetic use, and research and design of new beauty products and other functional cosmetics.

Keywords: *Sargassum*; Sargasso Sea; algal bloom; arsenic; satellite; numerical simulation

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1. Introduction

Climate change and its associated factors has resulted in the abundant growth and dispersal of brown algae drifting in great masses across the Atlantic Ocean. These occurrences have been progressively increasing since 2011 [1]. The influx of *Sargassum sp.* in the Caribbean Sea is influenced by climate-induced fluctuations in sea surface currents and increasing sea surface temperatures, which are associated with anthropogenic factors, such as deforestation in the Amazon, as well as leaching and runoff from agricultural sources [2]. The ocean thus acts as a reservoir for human-induced carbon, which in turn impacts ecosystems and resources that have important societal functions [3–5]. Climate variations can have direct and indirect influences on water environments through different pathways, such as by affecting pollutant quantities in flowing water or changing their toxicity in different circumstances [6–8].

Heightened amounts of algae can cause numerous environmental and ecological problems, and interdisciplinary collaboration may help provide solutions to effectively manage this issue and avoid more detrimental effects on coastal environments in the Caribbean. Primarily made up of water, organic components, and trace toxic material, the composition of *Sargassum* sp. can vary depending on lifespan, environmental factors, and geographic distribution [1,9–11]. Of the three groups of macroalgae that are distinguished by their pigments (i.e., Phaeophyta, brown; Rhodophyta, red; and Chlorophyta, green), brown algae, in particular, has been widely researched as a plausible heavy metal bioindicator species [12].

Phaeophyta is also known to accumulate the most arsenic compared to Rhodophyta and Chlorophyta [6]. In addition, only when toxic component concentrations are excessively increased are *Sargassum* considered hazardous [13]. Some known disadvantages created by the influx and mass accumulation of *Sargassum* along coastal areas, aside from its offensive odor, is that it is conducive to the proliferation of sandflies, which in turn negatively impact recreational beach activities and the navigation of fishing vessels. Harmful pesticide residues are known to be quite toxic for some algal species and other aquatic fauna and flora, so frequent monitoring of these environments is fundamental for controlling pesticide concentrations within all biota [14].

Algae are low-energy foods containing a wide variety of compounds with multi-functional potential for use in nutrition and technology. *Sargassum* species are known to contain sulfated polysaccharides and oligosaccharides, which are highly recognized immunomodulators that have positive effects on human and animal health and well-being [15–17]. With widespread availability, *Sargassum* can also offer abundant biomass for use in biogas plants [18,19]. The bioactive compounds of the genus *Sargassum*, including fucoxanthin, fucoidan, and alginates, are all highly valued commercially and are rich in essential minerals; with potassium and low nitrogen-phosphorous content, it can furthermore be used as a complimentary ingredient in fertilizer [13,20–22].

We aim to provide an effective solution for predicting and tracking the large-scale movements of algal biomass, and to also propose a method of addressing *Sargassum* influx through its use as an industrial recyclable material following composition analysis, evaluation and safety assessments for cosmetic use, and research and design of new beauty products and functional cosmetics.

2. Materials and Methods

The authors collected *Sargassum* samples in late October 2022 from the eastern coasts of four countries in the Caribbean Sea: Saint Lucia, Saint Vincent and the Grenadines, Saint Kitts and Nevis, and Belize. The samples were air-dried and ground into a powder, then sent to the Algal Cultivation and Biotech Laboratory at The National Taiwan Ocean University. The Traceability Certification and Inspection Center at The National Taiwan Ocean University analyzed the samples for four heavy metals: lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As). Additionally, the samples were analyzed for 531 pesticides by Eurofins Scientific Taiwan, a division of the Eurofins Scientific Group, in their food testing laboratory. All measured data in this study is outlined and shown in Table 1b. By detecting the heavy metal content present, we sought to determine the functional usability of pelagic *Sargassum*, establish limits of detection (LOD) for values presently not determined by renowned regulations such as the European Union (EU) and the United States (US), and to confirm suitability for use according to the standard limitations presently regulated. Determining *Sargassum* sp. suitability for industrial applications and investigating processing techniques helps allow for the recycling and use of this existing highly abundant resource.

Table 1. (**a**) Algal sample analysis (LOD) of heavy metal content. (**b**) Standard LOD heavy metal content (mg kg^{-1}, dry weight).

(**a**)

Items		Heavy Metal (mg kg^{-1}, Dry Weight)				
Country	**Species**	**Pb (Lead)**	**Cd (Cadmium)**	**Hg (Mercury)**	**Total Arsenic**	**Inorganic Arsenic**
St. Lucia	*Sargassum* sp.	0.03	0.38	N.D.	109.18	6.26
St. Vincent	*Sargassum* sp.	0.08	0.35	N.D.	111.29	8.79
St. Kitts	*Sargassum* sp.	N.D.	0.29	N.D.	106.11	6.15
Belize	*Sargassum* sp.	0.05	0.39	N.D.	84.09	5.13
St. Kitts	*Eucheuma* sp.	0.07	0.18	N.D.	3.67	N.D.
Method detection limit		0.01	0.01	0.001	0.02	0.05

Table 1. *Cont.*

(b)					
Categories	**Heavy Metal (mg kg^{-1}, Dry Weight)**				
	Pb (Lead)	**Cd (Cadmium)**	**Hg (Mercury)**	**Total Arsenic**	**Inorganic Arsenic**
EU food rule	3	3	0.1	N.D.	N.D.
USA food rule	0.01	3	1	-	3
Taiwan food rule	1	1	0.5	-	1.0
Taiwan cosmetic Products rule	10	5	1	3	-
Taiwan animal Feed rule	5	1 (cows, goats, excluding young animals); 0.5 others	0.1	2	-
Taiwan aquafeed rule	5	3 (marine fish and shrimps); 1 other	0	10	-
Taiwan soil rule	500	5	5	60	-

Notes: N.D.: Not Determined. Source: EU and USA Standards for heavy metal data: report of the expert meeting on food safety for seaweed: current status and future perspectives, Rome, 28–29 October 2021, MDL: the traceability certification and inspection center at the National Taiwan Ocean University Taiwan, October 2022 [23,24].

3. Results

3.1. Heavy Metal Accumulation in Sargassum and Its Ecological Implications

Hazardous heavy metal pollutants are widespread throughout the marine environment, with macroalgae known to be efficient bio-indicator species for heavy metal accumulation [12,25]. Ecologically, certain metals are essential for macroalgal growth, including iron, manganese, zinc, and copper. However, other naturally occurring metals like mercury and lead are non-essential elements, and are not required for growth or other physiological functions; when found in excess, these may become highly toxic [26]. Although certain heavy metals such as cadmium, lead, mercury, and arsenic do occur naturally in the environment, their concentrations vary in different locations of the ocean; macroalgae are known to uptake these elements through the process of biosorption, which reduces their toxic effects and lowers the numbers of free ions present [18,25,26]. These heavy metals are also known food safety hazards, and present safety concerns for seafood products. Concentrations of these metals in seaweeds have been used to test metal pollution along ocean coastlines [23].

Various human-induced activities play a major role in the availability of heavy metals in the open ocean. According to Clark (2001), $HAsO_4^{-2}$ concentrations in the Atlantic Ocean range from 1.27 to 2.10 µg L^{-1} in aerated water at a salinity level of 35% [26,27]. With a confirmed absorption concentration almost 180 times more than seawater, it is assumed that macroalgae absorb arsenic as a phosphorus substitute for growth and other physiological requirements [18,25–29]. As a biosorbent species, *Sargassum* can eliminate heavy metals like lead, mercury, zinc, and copper ions in the ocean through physisorption, microprecipitation exchange, and chemisorption [13,27]. Internally, concentrations of heavy metals have a significant impact on most algal species' ability to fluoresce depending on metal speciation [26,30].

Sargassum samples obtained from four locations in the Caribbean were tested for heavy metal content. Our analysis indicates that arsenic absorption is dependent on seawater pollution sources, which influence the bioavailability and speciation of other heavy metals (Table 1). For instance, bivalves are also found to accumulate chemical contaminants, including As, and can serve as an indicator species of climate variability [6,31]. A significant rise in temperature influences enzyme activity, and may promote cell wall enlargement through accelerated metabolic processes during adsorption [6,32].

Bioaccumulation of harmful pesticides has been widely researched, and climate change-influenced scenarios are proving to be of greater and greater relevance [2]. Our results show that no pesticide residue was detected in *Sargassum* among the 531 tested pesticides that are known to be applied to vegetables, fruit, infant food, spices, and herbs. Although pelagic algae may be susceptible to anthropogenic activities such as agricultural runoff, deforestation, and other associated events, the bioaccumulation of pesticide residue was negligible [6,33]. This suggests that various uses of *Sargassum* could be highly feasible with efficient chemical extraction of the heavy metal content, including as an animal feed additive or for use within the cosmetic industry [2].

The European Union (EU) legislation Commission Regulation (EC) No. 1881/2006 outlines the acceptable standards for inorganic and total arsenic, cadmium, lead, and mercury for seaweed (macroalgae) use in food products for animals, but no legislation has been developed for human consumption [23,24]. Similarly, the Food and Drug Association (FDA) of the United States (US) establishes the following acceptable limits: "Heavy metals as lead (Pb) not more than 10 parts per million, Arsenic (As) not more than 3 parts per million, Mercury (Hg) not more than 1 part per million." However, the list does not include cadmium, the limit for which has yet to be determined [20,23,34]. Similarly, standard limits for products other than food and supplements remain to be determined and documented. Accordingly, EU legislation Commission Regulation (EC) No. 396/2005 also states an applicable default maximum residue limit (MRL) for pesticide residue of 0.01 mg/kg for most seaweeds [23,24]. Our LOD testing and analysis show that other than arsenic, the heavy metal and pesticide content in *Sargassum* fall within these established requirements. Our findings, therefore, support the functional utilization of pelagic *Sargassum*. With effective extraction methods and processing techniques, it is highly suitable for a wide variety of applications.

Although human-induced, climate change-related activities can influence algal growth, abundance, and distribution, residual chemicals from pesticides have not been found to accumulate in the cell structure of *Sargassum* [26]. Moreover, bioactive compounds of the *Sargassum* genus, including fucoxanthin, fucoidan, and alginates, are considered to be of high value commercially [20,22]. Advanced extraction processes can effectively remove heavy metal substances from the algal biomass, thereby enhancing the commercial value of *Sargassum* as an organic material for industrial applications [21,22]. *Sargassum* inundation is known to inflict damage on nearshore ecosystems and beaches, and, when left to decompose, produces a highly unpleasant odor that poses safety risks to human health through the release of toxic gases, such as sulfuric acid and ammonia [29,35].

The heavy metal content of *Sargassum* sp. was analyzed (Table 1a) at four specific locations: St. Lucia, St. Vincent, St. Kitts and Nevis, and Belize, in comparison to *Eucheuma* sp. Analysis showed higher levels of arsenic content than the recognized standards. Algal cells can bind to heavy metals and are subject to increased pH levels in the environment [6,36]. Effective measures to extract the arsenic content are thus needed to adhere to EU and USA stipulated heavy metal content standard requirements (Table 1b) for full usage of the algae in industrial applications such as consumable food, cosmetic products, or animal and aquaculture feed. Pretreatment methods should be determined by algal species type and the intended product use.

3.2. Sargassum Distribution and Predictive Measures via Ocean Climate Circulation

Sargassum sp. biomass' presence and timing are dependent on sea surface currents and wind direction. These large, widely distributed biomasses are further subject to Stokes drift, a confined variation of Langmuir circulation, that may influence the responses of *Sargassum* to temperature and nutrient availability [37,38]. Essentially all living components within an ecosystem are influenced by climatic conditions and the combined action of sea surface currents, wind, and wave action; all of these also determine the spatial coverage of pelagic *Sargassum* sp. [18,38]. Due to wider distribution and more frequent occurrences of algal biomass, a part of the Atlantic Ocean between North America and the west of Africa has been named the Sargasso Sea. The *Sargassum* that occur in the Sargasso Sea are holopelagic and can effectively reproduce on the high seas [39]. Periodically, these brown algal mats drift along the coastlines of most Caribbean Island nations—it has become a frequent phenomenon each winter due to stronger trade winds, which drive great amounts of drift toward coastlines [40,41]. These floating mats provide an ecologically important niche that many different marine species depend on, although they can also transport non-native species.

Ideally, offshore collection of *Sargassum* is preferable, because once it has arrived at the beach, even if it is collected within one day, damage has already been inflicted [2,13]. Studies have shown a great variation in the species of *Sargassum* within locations, so predictions can be made by measuring the drift of the *Sargassum* biomass with respect to ocean flux through satellite observation [39,40,42]. Predictive measurements and forecasting can be derived from current ocean circulation modeling systems, including SMA Tools (*Sargassum* Monitoring Tool), which can provide a five-day predictive forecast of drifting *Sargassum* [39,40]. In general, there are discrepancies even in the best solutions for predicting influx or tracking movement by satellite.

The dominant pelagic species of *Sargassum*, *S. natans* and *S. fluitans*, comprise much of the drifting seaweed biomass and have a widespread distribution within the North Atlantic Ocean, starting from the Gulf of Mexico to the Sargasso Sea [43,44]. These prolific algal blooms are highly detrimental to local economies and surrounding environments [2]. Solutions for the management of *Sargassum* require spatial and temporal predictive management measures; remote sensing techniques provide a cost-effective solution by delivering important information on the locality of algal accumulation for collection and removal [2,40]. Similar techniques can also be useful on a wider scale for information on the spatial distribution of frequent *Sargassum* landings [31,40]. The affected communities are required to anticipate surges in beach landings and implement strategies for their collection to effectively manage the *Sargassum* influx [44]. The uncertainty and limited availability of precise forecasting models pose challenges to the adequate management of *Sargassum* incursions each year.

In a related scenario, floating populations of *S. horneri*, a large marine brown alga of the Korean strait, have drifted in larger quantities towards the north of Taiwan via the cold current flowing south along the coast of China [45]. Drifting *S. horneri* biomass is speculated to be caused by stronger Kuroshio currents that create an Ekman drift, thus transporting massive amounts of algae toward Taiwan [46,47]. Similarly, the canary current flows from the North to the West in the Atlantic Ocean, where it meets the south equatorial current. In doing so, it pushes the algal mass towards the east coast of Mexico and the Caribbean Sea. Larger aggregations of *Sargassum* have been found frequently in the central part of the coast during times of increased influx from March to October [13,48].

Anthropogenic activities, such as the uncharacteristic nutrient enrichment related to deforestation in the Amazon and changes in African dust deposition patterns in the Sahara Desert, are inferred to encourage an increase in the nutrient flow from terrestrial sources specific to the Caribbean Sea [1,47]. These contribute to the overgrowth of *Sargassum* blooms, and their prolific nature suggests that changes in ocean temperature alongside stronger monsoon periods can influence the growth, distribution, and sightings of floating algae, similar to *S. horneri* biomass movements in northern Taiwan [45]. It is, therefore, essential to be able to predict spatial distribution patterns induced by temporal variations due to climate change. Studies have also determined that surface currents, altered by wind patterns, cause a redistribution of pelagic *Sargassum*, with the major currents found in the Atlantic Ocean influencing distribution in the Great Atlantic *Sargassum* Belt [13]. Predictive six-month forecasts are highly viable through the use of various drift observations and data obtained from ocean models, which are dependent on satellite imagery detecting *Sargassum* across a wider area of the Atlantic Ocean and the Caribbean Sea [40].

In situ applications use remote sensing to develop predictions based on maps obtained by high spatial resolution satellite imagery [40,49]. Satellite images with manual recognition (Figure 1) are comparable to assessments of forest biomass, which has proven effective for forest management and monitoring in the context of carbon budgeting and reduced emissions [50]. Similarly, using map-making or ground truth masks validates maps of land and sea and provides a method for classification and prediction. Segmentation masks, which are generated automatically in real-time, can also enhance the input layers with extra information to predict future frames, thereby presenting opportunities to create knowledge under uncertain conditions [51,52].

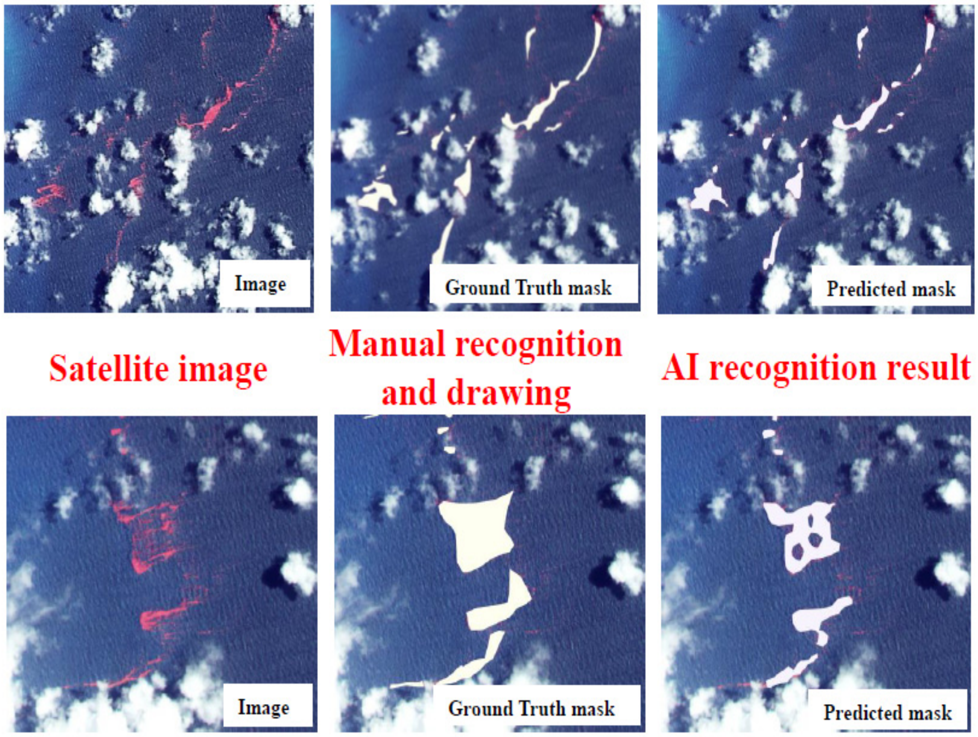

Figure 1. AI satellite images of floating algae on the eastern coast of St. Lucia, captured by Optical satellite Sentinel-2 on 22 August 2022.

4. Discussion

Cost-Effective Management and Opportunities for Functional Utilization of Sargassum

Marine macroalgae occur in highly complex and diverse ecosystems, which can offer ideal conditions for new active molecules to be developed and allows for a variety of applications [26]. Macroalgae are eukaryotic organisms comprised of chlorophyll and carbohydrates; 80% of seaweed harvested is consumed by humans, and these algae contribute quality proteins with high amounts of vitamins and minerals, dietary fiber, and essential unsaturated fatty acids, which altogether provide nutrition that is beneficial to human health. [18,53–55]. The *Sargassum* genus has several important components in the thallus, and with advances in extraction processes to effectively remove heavy metal substances from the algal biomass, the commercial value of *Sargassum* can be further enhanced. The specific content and characteristics of the constituents in *Sargassum* may vary depending on species and growth conditions.

Important constituents of the genus *Sargassum*:

1. Fucoxanthin is a natural pigment belonging to the class of carotenoids called fucoxanthins. It imparts a deep brown color to the genus *Sargassum* and possesses antioxidant and anti-inflammatory properties. Fucoxanthin has been studied as a potential anticancer and antiobesity compound;
2. Fucoidan is one of the most significant bioactive compounds found in *Sargassum*. It is a sulfated polysaccharide with various biological activities, including anti-inflammatory, anticoagulant, antioxidant, antitumor, and immune-modulating properties. Fucoidan has been extensively researched and is considered to have potential applications in pharmaceuticals and functional foods;
3. Alginates are polysaccharides composed primarily of α-L-guluronic acid and β-D-mannuronic acid. They are widely present in the cell walls of *Sargassum*. Alginates

have gel-forming abilities, and find extensive applications in food, pharmaceutical, and cosmetic industries as thickeners, stabilizers, and emulsifiers [20–22].

Sourcing *Sargassum* from the ocean surface through sustainable collection methods facilitated by floating nets lessens the negative ecological impacts of beach landings [31]. Initially, processing includes washing with fresh water, drying, grinding, and vacuum sealing and packaging for storage or transport. The development and production of biodegradable materials and functional textile materials and feed for both aquaculture and agricultural uses remain important, and recently seaweed has been found to be a highly useful raw material. In addition to playing an important role in diets, it can also be functionally useful for creating value-added goods, in energy production methods, and in several fields, such as cosmetics, agriculture, and construction [18,56–58]. Developing new materials from seaweed, such as textiles, can also help create environmentally friendly alternatives to reduce the negative impacts of non-degradable materials, such as single-use plastics that pollute bodies of water. Using *Sargassum* could therefore help reduce fossil fuel usage, the production of plastic waste, logging, and pulp production, which can, in turn, reduce the accidental ingestion of non-degradable materials by marine organisms. *Sargassum* biomass landings onshore present larger problems, with higher costs associated with recurrent blooms [19,47]. U-shaped barriers can provide a suitable recovery method with the least detriment to beaches, and allow for an efficient offshore capture method [31]. *Sargassum* collection is dependent on the oceanographic and geomorphological attributes of the location, and the accumulated *Sargassum* in these barriers are likely to decompose or sink within 24–48 h [13,31].

As discussed, alternative uses for this abundant biomass can provide countless benefits both for communities and the environment [44,58]. With a high nutritional content, *Sargassum* can be used as fertilizer for soil and plants as well as food for consumption, while extracting their phytochemicals has the potential for medicinal use [16,55]. The main regulation categories listed in Table 1b outline utilization rules for human consumption, and there has been an increased interest in marine algae recently as a bioactive source useful for many applications in processing and developing healthier functional food groups [59]. Algae can enrich the nutritional properties of food; cereal-based food products, such as pasta, are low in protein and essential amino acids, so incorporating algae could greatly enhance its nutritional properties [18]. Studies have shown that eating algae-based pasta resulted in improved amino acid and fatty acid profiles, with better total phenolic content, antioxidant activity, and a higher fucoxanthin and fucosterol content [18,59]. Similar benefits of algae-enriched bread and noodle products can also be expected [18]. Furthermore, there is a higher feasibility of *Sargassum* sp. producing compounds that can enhance food flavors, such as carbonyls, alcohols esters, aldehydes, and esters, because these compounds occur naturally with less toxic waste under minimal production conditions [60].

Composition analysis has confirmed seaweed to be suitable for energy production, such as a biofuel, due to its high sugar content; even so, pretreatment is recommended for exploring *Sargassum* use for anaerobic biogas production [16,18,36,57,58]. Although bioenergy production from *Sargassum* has great potential and utilizes an abundant resource, economic viability also depends on the production of higher-value products, similar to bioethanol production [59,61]. Other commercially viable solutions aside from algae-based functional foods, nutraceuticals, and cosmeceuticals can include environmentally friendly solutions such as biodegradable materials, plant fiber panels for buildings, textiles, and toiletries, although these possibilities depend on creating sustainable and innovative technologies and products with specific product markets [61,62]. With an eco-friendly decomposition rate of over 150 years, macroalgae can be used as a building material: it has the potential to provide quality insulation, and offers good acoustics, humidity control, and visual comfort while being non-toxic and fireproof with less associated CO_2 emissions [62].

Pretreatments are generally required to release the usable organic matter through the breakdown of the cell walls, and *S. natans* and *S. fluitans* have been found to produce small quantities of lignin compounds in response to stressors related to climate change, such as heat and light [1,13,61]. *Sargassum*, with its low to zero lignin content and good nutrient properties, can be beneficial as feed for anaerobic digestion; for instance, the polyphenols found in brown algae are found to have an influence on methanogen activity in ruminant animals, mitigating the effects of methane (CH_4) production and thus reducing problematic greenhouse gas emissions in livestock supply chains [13,63,64]. Interestingly, a previous study determined that the usage of brown algae as livestock feed can supply greater energy content compared to other seaweed varieties due to its low ash content [63]. Extracts from *Sargassum* have also been used in crop production as seed treatments, in foliar applications, and for the purpose of soil drenching [13,65]. Similarly, there are viable possibilities for *Sargassum* filtration systems due to their high biosorption potential to effectively remove organic dyes and heavy metal ions [13]. The alginates and fucoidans derived from algae can benefit the pharmaceutical, cosmetic, and food industries [35]. Moreover, other practical uses include sodium alginate production for eco-friendly bioplastics; use as an emulsifier and stabilizer; and use for its antioxidant, anti-inflammatory, and anticoagulant properties, all of which can help treat or protect against viruses, cancer, and many other diseases [17,31,59].

The implications of large-scale utilization of *Sargassum* have not been fully determined; however, ecologically, the prolific nature of increasing pelagic *Sargassum* influx to coastal shores requires solutions and alternative approaches to alleviate the negative impacts on coastal environments, essential ecosystems, and people's livelihoods and tourism, which are important concerns for the Caribbean Island nations [2,31]. Furthermore, large-scale cultivation is promising for increasing the supply of usable material in the event that it is not available or accessible in nature; this cultivation can be achieved with long lines near coastal areas of the open ocean, and would have the twofold benefit of not only keeping up with an abundant supply of resources for food and non-food applications, but also mitigating issues such as eutrophication and nutrient enrichment from anthropogenic activities, which are highly problematic in coastal ecosystems [66–68].

5. Conclusions

There have been numerous studies undertaken on the functional uses of *Sargassum*, and management methods using satellite data and numerical simulations can provide solutions for forecasting and tracking large amounts of algae, allowing for effective collection and recovery of large quantities of algal biomass, which is a valuable organic resource and offers great potential for industrial applications. Developing more advanced processing techniques can open further avenues for industries in various uses of *Sargassum*.

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References

1. Orozco-González, J.G.; Amador-Castro, F.; Gordillo-Sierra, A.R.; García-Cayuela, T.; Alper, H.S.; Carrillo-Nieves, D. Opportunities Surrounding the Use of *Sargassum* Biomass as Precursor of Biogas, Bioethanol, and Biodiesel Production. *Front. Mar. Sci.* **2022**, *8*, 791054. [CrossRef]
2. Lee, M.-C. Situations and Solutions of *Sargassum* Influxes—Saint Lucia, Saint Vincent and the Grenadines, Saint Kitts and Nevis, and Belize. Unpublished Work. 2022.
3. Fox-Kemper, B.; Adcroft, A.; Böning, C.W.; Chassignet, E.P.; Curchitser, E.; Danabasoglu, G.; Eden, C.; England, M.H.; Gerdes, R.; Greatbatch, R.J.; et al. Challenges and Prospects in Ocean Circulation Models. *Front. Mar. Sci.* **2019**, *6*, 65. [CrossRef]
4. Khatiwala, S.; Primeau, F.; Hall, T. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* **2009**, *462*, 346–349. [CrossRef]
5. Khatiwala, S.; Tanhua, T.; Mikaloff Fletcher, S.; Gerber, M.; Doney, S.C.; Graven, H.D.; Gruber, N.; McKinley, G.A.; Murata, A.; Ríos, A.F.; et al. Global ocean storage of anthropogenic carbon. *Biogeosciences* **2013**, *10*, 2169–2191. [CrossRef]
6. Lee, M.-C.; Libatique, M.J.H.; Yeh, H.-Y.; Chloe Lung, W.Q. Increasing arsenic accumulation as an implication of climate change: A case study using red algae. *Bull. Environ. Contam. Toxicol.* **2022**, *108*, 839–847. [CrossRef]
7. Wu, Q.; Qi, J.; Xia, X. Long-term variations in sediment heavy metals of a reservoir with changing trophic states: Implications for the impact of climate change. *Sci. Total Environ.* **2017**, *609*, 242–250. [CrossRef]
8. Yuan, Y.; Zhang, C.; Zeng, G.; Liang, J.; Guo, S.; Huang, L.; Wu, H.; Hua, S. Quantitative assessment of the contribution of climate variability and human activity to streamflow alteration in Dongting Lake, China. *Hydrol. Process.* **2016**, *30*, 1929–1939. [CrossRef]
9. Davis, D.; Simister, R.; Campbell, S.; Marston, M.; Bose, S.; McQueen-Mason, S.J.; Gomez, L.D.; Gallimore, W.A.; Tonon, T. Biomass composition of the golden tide pelagic seaweeds *Sargassum fluitans* and *S. natans* (morphotypes I and VIII) to inform valorisation pathways. *Sci. Total Environ.* **2021**, *762*, 143134. [CrossRef]
10. Kordjazi, M.; Etemadian, Y.; Shabanpour, B.; Pourashouri, P. Chemical composition antioxidant and antimicrobial activities of fucoidan extracted from two species of brown seaweeds(*Sargassum ilicifolium* and *S. angustifolium*) around Qeshm Island. *Iran. J. Fish. Sci.* **2018**, *18*, 457–475. [CrossRef]
11. Yaich, H.; Garna, H.; Besbes, S.; Paquot, M.; Blecker, C.; Attia, H. Chemical composition and functional properties of Ulva lactuca seaweed collected in Tunisia. *Food Chem.* **2011**, *128*, 895–901. [CrossRef]
12. Al-Homaidan, A.A.; Al-Ghanayem, A.A.; Al-Qahtani, H.S.; Al-Abbad, A.F.; Alabdullatif, J.A.; Alwakeel, S.S.; Ameen, F. Effect of sampling time on the heavy metal concentrations of brown algae: A bioindicator study on the Arabian Gulf coast. *Chemosphere* **2021**, *263*, 127998. [CrossRef]
13. López Miranda, J.L.; Celis, L.B.; Estévez, M.; Chávez, V.; van Tussenbroek, B.I.; Uribe-Martínez, A.; Cuevas, E.; Rosillo Pantoja, I.; Masia, L.; Cauich-Kantun, C.; et al. Commercial Potential of Pelagic *Sargassum* spp. in Mexico. *Front. Mar. Sci.* **2021**, *8*, 768470. [CrossRef]
14. Polat, A.; Polat, S.; Simsek, A.; Kurt, T.T.; Ozyurt, G. Pesticide residues in muscles of some marine fish species and seaweeds of Iskenderun Bay (Northeastern Mediterranean), Turkey. *Environ. Sci. Pollut. Res.* **2018**, *25*, 3756–3764. [CrossRef]
15. Sanjeewa, K.K.A.; Kang, N.; Ahn, G.; Jee, Y.; Kim, Y.-T.; Jeon, Y.-J. Bioactive potentials of sulfated polysaccharides isolated from brown seaweed *Sargassum* spp in related to human health applications: A review. *Food Hydrocoll.* **2018**, *81*, 200–208. [CrossRef]
16. Leandro, A.; Pacheco, D.; Cotas, J.; Marques, J.C.; Pereira, L.; Gonçalves, A.M.M. Seaweed's Bioactive Candidate Compounds to Food Industry and Global Food Security. *Life* **2020**, *10*, 140. [CrossRef]
17. Hwang, J.; Yadav, D.; Lee, P.C.; Jin, J.-O. Immunomodulatory effects of polysaccharides from marine algae for treating cancer, infectious disease, and inflammation. *Phytother. Res.* **2022**, *36*, 761–777. [CrossRef]
18. Zhao, Y.; Bourgougnon, N.; Lanoisellé, J.-L.; Lendormi, T. Biofuel Production from Seaweeds: A Comprehensive Review. *Energies* **2022**, *15*, 9395. [CrossRef]
19. Milledge, J.J.; Maneein, S.; Arribas López, E.; Bartlett, D. *Sargassum* Inundations in Turks and Caicos: Methane Potential and Proximate, Ultimate, Lipid, Amino Acid, Metal and Metalloid Analyses. *Energies* **2020**, *13*, 1523. [CrossRef]
20. Holdt, S.L.; Kraan, S. Bioactive compounds in seaweed: Functional food applications and legislation. *J. Appl. Phycol.* **2011**, *23*, 543–597. [CrossRef]
21. Plaza, M.; Cifuentes, A.; Ibáñez, E. In the search of new functional food ingredients from algae. *Trends Food Sci. Technol.* **2008**, *19*, 31–39. [CrossRef]
22. Zhang, R.; Zhang, X.; Tang, Y.; Mao, J. Composition, isolation, purification and biological activities of *Sargassum fusiforme* polysaccharides: A review. *Carbohydr. Polym.* **2020**, *228*, 115381. [CrossRef]
23. Publication, F. *Report of the Expert Meeting on Food Safety for Seaweed—Current Status and Future Perspectives*; FAO: Rome, Italy, 2022.
24. Publication, E. Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. *Off. J. Eur. Union* **2006**, *364*, 5–24.
25. Libatique, M.J.H.; Lee, M.-C.; Yeh, H.-Y.; Jhang, F.-J. Total and inorganic arsenic biosorption by *Sarcodia suiae* (Rhodophyta), as affected by controlled environmental conditions. *Chemosphere* **2020**, *248*, 126084. [CrossRef]
26. Hurd, C.L.; Harrison, P.J.; Bischof, K.; Lobban, C.S. *Seaweed Ecology and Physiology*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2014.
27. Clark, R.B. Marine Pollution and Sea Life: (ed. M. Ruivo). Fishing News (Books) Ltd., London, by arrangement with the Food and Agriculture Organization of the UN (1972). xxiv + 624 pp. £17.75. *Mar. Pollut. Bull.* **1973**, *4*, 112. [CrossRef]

28. Nischwitz, V.; Pergantis, S.A. First report on the detection and quantification of arsenobetaine in extracts of marine algae using HPLC-ES-MS/MS. *Analyst* **2005**, *130*, 1348–1350. [CrossRef]
29. Robalds, A.; Naja, G.M.; Klavins, M. Highlighting inconsistencies regarding metal biosorption. *J. Hazard. Mater.* **2016**, *304*, 553–556. [CrossRef]
30. Baumann, H.A.; Morrison, L.; Stengel, D.B. Metal accumulation and toxicity measured by PAM—Chlorophyll fluorescence in seven species of marine macroalgae. *Ecotoxicol. Environ. Saf.* **2009**, *72*, 1063–1075. [CrossRef]
31. Chávez, V.; Uribe-Martínez, A.; Cuevas, E.; Rodríguez-Martínez, R.E.; van Tussenbroek, B.I.; Francisco, V.; Estévez, M.; Celis, L.B.; Monroy-Velázquez, L.V.; Leal-Bautista, R.; et al. Massive Influx of Pelagic *Sargassum* spp. on the Coasts of the Mexican Caribbean 2014–2020: Challenges and Opportunities. *Water* **2020**, *12*, 2908. [CrossRef]
32. Ramelow, G.; Fralick, D.; Zhao, Y.-f. Factors affecting the uptake of aqueous metal ions by dried seaweed biomass. *Microbios* **1992**, *72*, 81–93.
33. Maulvault, A.L.; Camacho, C.; Barbosa, V.; Alves, R.; Anacleto, P.; Fogaça, F.; Kwadijk, C.; Kotterman, M.; Cunha, S.C.; Fernandes, J.O.; et al. Assessing the effects of seawater temperature and pH on the bioaccumulation of emerging chemical contaminants in marine bivalves. *Environ. Res.* **2018**, *161*, 236–247. [CrossRef]
34. U.S. Food and Drug Administration. *FDA Total Diet Study TDS*; U.S. Food and Drug Administration: Silver Spring, MD, USA, 2022.
35. Libatique, M.J.H.; Yeh, H.-Y.; Nan, F.-H.; Lee, M.-C. Phosphate affects susceptivity of *Sarcodia suae* to arsenate. *Eur. J. Phycol.* **2023**, *58*, 45–57. [CrossRef]
36. Resiere, D.; Mehdaoui, H.; Névière, R.; Mégarbane, B. *Sargassum invasion* in the Caribbean: The role of medical and scientific cooperation. *Rev. Panam. Salud Pública* **2019**, *43*, e52. [CrossRef]
37. Sulaymon, A.H.; Mohammed, A.A.; Al-Musawi, T.J. Competitive biosorption of lead, cadmium, copper, and arsenic ions using algae. *Environ. Sci. Pollut. Res.* **2013**, *20*, 3011–3023. [CrossRef]
38. Freitas, R.; Salamanca, L.; Velez, C.; Wrona, F.J.; Soares, A.M.V.M.; Figueira, E. Multiple stressors in estuarine waters: Effects of arsenic and salinity on *Ruditapes philippinarum*. *Sci. Total Environ.* **2016**, *541*, 1106–1114. [CrossRef]
39. Jouanno, J.; Benshila, R.; Berline, L.; Soulié, A.; Radenac, M.H.; Morvan, G.; Diaz, F.; Sheinbaum, J.; Chevalier, C.; Thibaut, T.; et al. A NEMO-based model of *Sargassum* distribution in the tropical Atlantic: Description of the model and sensitivity analysis (NEMO-Sarg1.0). *Geosci. Model Dev.* **2021**, *14*, 4069–4086. [CrossRef]
40. Marsh, R.; Oxenford, H.A.; Cox, S.-A.L.; Johnson, D.R.; Bellamy, J. Forecasting seasonal *Sargassum* events across the tropical Atlantic: Overview and challenges. *Front. Mar. Sci.* **2022**, *9*, 914501. [CrossRef]
41. NOAA. *What is Eutrophication*; NOAA: Washington, DC, USA, 2023.
42. Berline, L.; Ody, A.; Jouanno, J.; Chevalier, C.; André, J.-M.; Thibaut, T.; Ménard, F. Hindcasting the 2017 dispersal of *Sargassum* algae in the Tropical North Atlantic. *Mar. Pollut. Bull.* **2020**, *158*, 111431. [CrossRef]
43. Gavio, B.; Rincón-Díaz, M.N.; Santos-Martínez, A. Massive quantities of pelagic *Sargassum* on the shores of san andres island, southwestern caribbean. *Acta Biológica Colomb.* **2015**, *20*, 239–241. [CrossRef]
44. Louime, C.; Fortune, J.; Gervais, G. *Sargassum* Invasion of Coastal Environments: A Growing Concern. *Am. J. Environ. Sci.* **2017**, *13*, 58–64. [CrossRef]
45. Lin, S.-M.; Huang, R.; Ogawa, H.; Liu, L.-C.; Wang, Y.-C.; Chiou, Y. Assessment of germling ability of the introduced marine brown alga, *Sargassum horneri*, in Northern Taiwan. *J. Appl. Phycol.* **2017**, *29*, 2641–2649. [CrossRef]
46. Fine, M.L. Faunal variation on pelagic *Sargassum*. *Mar. Biol.* **1970**, *7*, 112–122. [CrossRef]
47. Amador-Castro, F.; García-Cayuela, T.; Alper, H.S.; Rodriguez-Martinez, V.; Carrillo-Nieves, D. Valorization of pelagic *Sargassum* biomass into sustainable applications: Current trends and challenges. *J. Environ. Manag.* **2021**, *283*, 112013. [CrossRef]
48. Fidai, Y.A.; Dash, J.; Tompkins, E.L.; Tonon, T. A systematic review of floating and beach landing records of *Sargassum* beyond the Sargasso Sea. *Environ. Res. Commun.* **2020**, *2*, 122001. [CrossRef]
49. García-Sánchez, M.; Graham, C.; Vera, E.; Escalante-Mancera, E.; Álvarez-Filip, L.; van Tussenbroek, B.I. Temporal changes in the composition and biomass of beached pelagic *Sargassum* species in the Mexican Caribbean. *Aquat. Bot.* **2020**, *167*, 103275. [CrossRef]
50. Hojas-Gascon, L.; Eva, H. *Field Guide for Forest Mapping with High Resolution Satellite Data*; Monitoring Deforestation and Forest Degradation in the Context of the UN-REDD Programme. The Tanzania REDD+ Initiative; Joint Research Center, Publications Office of the European Union: Luxembourg, 2014.
51. Yin, Q.; Hu, Q.; Liu, H.; Zhang, F.; Wang, Y.; Lin, Z.; An, W.; Guo, Y. Detecting and Tracking Small and Dense Moving Objects in Satellite Videos: A Benchmark. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 5612518. [CrossRef]
52. Hsu, M.C.; Shyur, J.C.; Watanabe, H. Pseudo Ground Truth Segmentation Mask to Improve Video Prediction Quality. In Proceedings of the 2020 IEEE 9th Global Conference on Consumer Electronics (GCCE), Kobe, Japan, 13–16 October 2020; pp. 831–832.
53. Fleurence, J. Chapter 5—Seaweeds as Food. In *Seaweed in Health and Disease Prevention*; Fleurence, J., Levine, I., Eds.; Academic Press: San Diego, CA, USA, 2016; pp. 149–167.
54. Levine, I. Chapter 1—Algae: A Way of Life and Health. In *Seaweed in Health and Disease Prevention*; Fleurence, J., Levine, I., Eds.; Academic Press: San Diego, CA, USA, 2016; pp. 1–5.

55. Bocanegra, A.; Bastida, S.; Benedi, J.; Rodenas, S.; Sanchez-Muniz, F.J. Characteristics and Nutritional and Cardiovascular-Health Properties of Seaweeds. *J. Med. Food* **2009**, *12*, 236–258. [CrossRef] [PubMed]
56. Barbot, Y.N.; Al-Ghaili, H.; Benz, R. A Review on the Valorization of Macroalgal Wastes for Biomethane Production. *Mar. Drugs* **2016**, *14*, 120. [CrossRef] [PubMed]
57. Balina, K.; Romagnoli, F.; Blumberga, D. Seaweed biorefinery concept for sustainable use of marine resources. *Energy Procedia* **2017**, *128*, 504–511. [CrossRef]
58. Baghel, R.S.; Suthar, P.; Gajaria, T.K.; Bhattacharya, S.; Anil, A.; Reddy, C.R.K. Seaweed biorefinery: A sustainable process for valorising the biomass of brown seaweed. *J. Clean. Prod.* **2020**, *263*, 121359. [CrossRef]
59. Domínguez, H. 1—Algae as a source of biologically active ingredients for the formulation of functional foods and nutraceuticals. In *Functional Ingredients from Algae for Foods and Nutraceuticals*; Domínguez, H., Ed.; Woodhead Publishing: Sawston, UK, 2013; pp. 1–19.
60. Amanjyoti; Nehra, M.; Khan, M. Algae as a Nutritional and Functional Food Source. *Madridge J. Food Technol.* **2022**, *7*, 189–199. [CrossRef]
61. Konda, N.V.S.N.M.; Singh, S.; Simmons, B.A.; Klein-Marcuschamer, D. An Investigation on the Economic Feasibility of Macroalgae as a Potential Feedstock for Biorefineries. *BioEnergy Res.* **2015**, *8*, 1046–1056. [CrossRef]
62. Widera, B. Possible Application of Seaweed as Building Material in the Modern Seaweed House on Laesø. In Proceedings of the 30th International Plea Conference, Ahmedabad, India, 16–18 December 2014.
63. Park, K.Y.; Jo, Y.H.; Ghassemi Nejad, J.; Lee, J.C.; Lee, H.G. Evaluation of nutritional value of *Ulva* sp. and *Sargassum horneri* as potential eco-friendly ruminants feed. *Algal Res.* **2022**, *65*, 102706. [CrossRef]
64. Alzate-Gaviria, L.; Domínguez-Maldonado, J.; Chablé-Villacís, R.; Olguin-Maciel, E.; Leal-Bautista, R.M.; Canché-Escamilla, G.; Caballero-Vázquez, A.; Hernández-Zepeda, C.; Barredo-Pool, F.A.; Tapia-Tussell, R. Presence of Polyphenols Complex Aromatic "Lignin" in *Sargassum* spp. from Mexican Caribbean. *J. Mar. Sci. Eng.* **2021**, *9*, 6. [CrossRef]
65. Chinnadurai, K.; Venkatesalu, V. Utilization of seaweed *Sargassum myriocystum* extracts as a stimulant of seedlings of *Vigna mungo* (L.) Hepper. *Span. J. Agric. Res.* **2012**, *10*, 466. [CrossRef]
66. Fernandes, D.R.P.; de Oliveira, V.P.; Yoneshigue Valentin, Y. Seaweed biotechnology in Brazil: Six decades of studies on natural products and their antibiotic and other biological activities. *J. Appl. Phycol.* **2014**, *26*, 1923–1937. [CrossRef]
67. Li, J.; Liu, Y.; Liu, Y.; Wang, Q.; Gao, X.; Gong, Q. Effects of temperature and salinity on the growth and biochemical composition of the brown alga *Sargassum fusiforme* (Fucales, Phaeophyceae). *J. Appl. Phycol.* **2019**, *31*, 3061–3068. [CrossRef]
68. Hwang, E.K.; Park, C.S.; Baek, J.M. Artificial seed production and cultivation of the edible brown alga, *Sargassum fulvellum* (Turner) C. In Agardh: Developing a new species for seaweed cultivation in Korea. In Proceedings of the Eighteenth International Seaweed Symposium, Bergen, Norway, 20–25 June 2004; pp. 25–31.