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Challenges and Opportunities in Relation to *Sargassum* Events Along the Caribbean Sea

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Mass blooms and stranding of pelagic *Sargassum* spp. in the Atlantic, termed *Sargassum* events are becoming more frequent in response to several factors: nutrient enrichment, increased temperature, changes in climatological patterns, but some causes remain unknown. The magnitude of *Sargassum* events in the Caribbean Sea since 2011 make us aware of the necessity to tackle these events, and macroalgal blooms generally, not only locally but on a regional scale. At least three pelagic species of *Sargassum* have been dominant in the blooms that have occurred along Caribbean coastlines in great quantities. Due to the regional scale of these events and its complexity, its management should be based on basic and applied information generated by different collaborative actors (national and international) through interdisciplinary and transdisciplinary work. To address this, we propose different phases (exploratory, valorization, and management) and the approach for their study should include detection, collection, stabilization and experimentation. This information will help identify the potential applications and/or ecological services to develop for the exploitation and mitigation strategies in the region. Relevant challenges and opportunities are discussed, remarking on the necessity to evaluate the spatiotemporal variation in the abundance and chemical composition of floating and stranded biomass. The above-mentioned will provide management strategies and economic opportunities as possible solutions to their extensive impact in the Caribbean.

Keywords: Caribbean, Golden tides, environmental concerns, *Sargassum*, valorization, management strategies

BEYOND THE SARGASSO SEA

The Sargasso Sea, always shrouded in mystery and an object of interest during antiquity, continues today to arouse interest in various fields of knowledge. Commonly known as the subtropical gyre of the North Atlantic, the Sargasso Sea is a region where an immense body of water is bounded by a vast system of circular currents flowing from east to west (North Equatorial Current) and west to east (Gulf Stream). Winds and oceanographic conditions combine to give these waters a very particular identity; from a physical point of view, they are waters of temperature >17°C and particular biogeochemical properties (Bates and Johnson, 2020), and from a biological point of view they are the habitat of several species of the pelagic algae in the genus *Sargassum*, which supports and incredible amount of marine life (Coston-Clements et al., 1991; Huffard et al., 2014).

The name of the Sargasso Sea was supposedly given by Christopher Columbus or by one of the Portuguese sailors who accompanied him. The term "sargaço," probably derives, according to the Dictionary of the Spanish Language, from "argaço" (via "algaço," used in ancient documents to designate algae) and from the Latin Salix (willow trees known colloquially as "sarga" morphologically similar to sargaso). The term could be also related the Portuguese "sal" or "salgado," meaning salted (Cabral, 2005). Currently, "sargasso" is the colloquial name given to pelagic marine macroalgae found within the Atlantic region.

Since 2011 climatological and environmental conditions promote the transport of floating biomass out of the Sargasso Sea, proliferating in tropical Atlantic between West Africa and South America (Putman et al., 2018; Johns et al., 2020). Tons of these seaweeds have been deposited on beaches, generating beach-cast events that severely impact the Atlantic and Caribbean coasts (**Table 1**). Although some of these macroalgal arrivals are part of a natural seasonal phenomenon due to biological (life cycles, reproduction and senescence, growth, elongation or biomass increase) and climatological factors (storms, currents, tidal waves, and/or winds) (Orr et al., 2005; Barreiro et al., 2011); additional factors such as increases in seawater nutrients and/or sea surface temperature, changes in ocean currents and wind patterns, hurricanes and maritime traffic have been reported as the causes of the excessive proliferation of *Sargassum* biomass and its transport to the coasts (Lapointe et al., 2014; Sanchez-Rubio et al., 2018; Wang et al., 2019; Johns et al., 2020; Trinanes et al., 2021). Scientific communities have raised a series of questions about the origin, prevalence and impacts of this phenomenon many of which remain unknown. In the present work we review some of the impacts reported for the Atlantic and Caribbean coasts and the strategies that should be followed to develop an adequate management of this phenomenon, while identifying some of the challenges and opportunities for the Caribbean region.

Different terminology has been applied for describing the unprecedent quantities of holopelagic *Sargassum* impacting the coasts, including "*Sargassum* blooms" (Lapointe, 2019; Wang et al., 2019), "Massive Golden Tides" (Smetacek and Zingone, 2013), "*Sargassum* Brown Tides" (van Tussenbroek et al., 2017), "*Sargassum* events" (Fidai et al., 2020) and "*Sargassum* influx" (Franks et al., 2012); or colloquially "massive arrivals" and "*Sargassum* massive accumulations". However, there is no consensus about the term to define the phenomenon observed. More recently, "*Sargassum* event" has been defined by Fidai et al. (2020) as a "continuous bloom of any *Sargassum* in open oceans or, an aggregation of landed *Sargassum* with the potential to disrupt local social, economic or ecosystem functioning, or to impact human health; an event can affect one country or several contiguous countries." In the present manuscript, we use "*Sargassum* event" as an appropriate term for the observed phenomenon in the Caribbean region, which includes a large quantity of stranded biomass that generates ecological and socioeconomic impacts in the coastal areas.

SARGASSUM SPECIES IN THE CARIBBEAN EVENTS

The genus *Sargassum* C. Agardh has the highest morphological complexity in the class Phaeophyceae, with species distributed in almost all ocean basins (Phillips and Fredericq, 2000). The great variability of morphological characteristics between individuals of the same species or even in the same individual in response to climatic and environmental conditions (Kilar et al., 1992) complicates the delineation and identification of *Sargassum* species in the Atlantic (Parr, 1939; Mattio and Payri, 2011; Schell et al., 2015). Therefore, studies in recent years have included molecular and biochemical characters (Amaral-Zettler et al., 2017; González-Nieto et al., 2020; Rosado-Espinosa et al., 2020; Hernández-Bolio et al., 2021). Nevertheless, molecular markers (ITS, psaA, RuBisCO spacer, rbcl, COI, cox3, 23S-tRNA val spacer and partial mt23S) are not conclusive and the taxonomy of the group needs further analysis (Stiger et al., 2003; Mattio and Payri, 2011; Amaral-Zettler et al., 2017; González-Nieto et al., 2020). Recent studies in the Caribbean and Gulf of México have confirmed the presence of the holopelagic species *Sargassum natans* (morphotypes I and VIII) and *S. fluitans* (morphotype III) in the recent *Sargassum* events (García-Sánchez et al., 2020) (**Figure 1**). Ongoing research in our laboratory to characterize the stranded biomass in the Mexican Caribbean has allowed to identify the presence of the 3 holopelagic taxa mentioned above, representing 99.5% of the fresh biomass. Moreover, six *Sargassum* benthic species (*S. acinarium, S. buxifolium, S. platycarpum, S. polyceratium* var. *ovatum, S. pteuropleuron*, and *S. ramifolium*) and three seagrass species (*Thalassia testudinum, Syringodium filiforme*, and *Halodule wrightii*) have been also identified as a minor component of the events, but can reach up to 22% of the fresh biomass depending on the season. These efforts have expanded to include the development of digital tools to identify and characterize the pelagic and benthic species of *Sargassum* of the Mexican Caribbean (Vázquez-Delfín et al., 2020).

ENVIRONMENTAL AND SOCIOECONOMIC CONCERNS

Sargassum events have resulted in excessive seaweed-stranding biomass causing considerable damage to the environment, human health and local economy of the Caribbean, the Gulf of Mexico and West Africa (**Table 2**). In the Caribbean Sea, from the coasts of Trinidad and Tobago, Guadeloupe and Martinique, Dominican Republic, Cuba, Colombia and the Mexican Caribbean coasts, between 2011 and 2020, *Sargassum* events have been recorded and have increased in volume and damage over time (**Table 1**). Current reports estimate that around 20 million metric tons of floating *Sargassum* biomass can accumulate off the coast of northeastern South America and potentially distributed throughout the Caribbean (Wang et al., 2019).

Sargassum events have adverse impacts on the coastal ecosystems and human communities (**Table 2**). The contamination of beaches, due to the *in situ* decomposition

TABLE 1 | *Sargassum* events reported for the Caribbean region. Location, scope of the study and term used to describe the phenomenon.

Year	Location	Type of study and scope	Reported as	References
2011–2012	Eastern Caribbean states; U.S. and British Virgin Islands	Documentary report, no evaluations performed	*Sargassum* influx	Franks et al. (2012)
	Trinidad to Dominican Republic in Caribbean and other localities (African coast)	Review, no evaluations performed	Golden tides	Smetacek and Zingone (2013)
	Caribbean and other locations (North Atlantic and west coast of Africa)	Remote sensing: evaluation of spatiotemporal changes in distribution and coverage of floating biomass (MERIS and MODIS)	*Sargassum* event	Gower et al. (2013)
	East coast of Cienfuegos, Cuba	*In situ* evaluation of beached biomass: identification of species (SF)	Drift of *Sargassum*	Moreira and Alfonso (2013)
2014–2015	San Andrés island, Southwestern Caribbean	Documentary report (SF, SN), no evaluations performed	Massive quantities of *Sargassum*	Gavio et al. (2015)
	Eastern Caribbean; Western Tropical Atlantic and South Sargasso Sea	*In situ* evaluation of floating biomass: identification of species (SF, SN1, SN8), quantification of relative abundance and distribution	*Sargassum* inundation event	Schell et al. (2015)
	Quintana Roo coast, Mexico	Documentary report, data about volume of beached biomass and species (SF, SN) obtained from Governmental Institutions	Macroalgal bloom	Rodríguez-Martínez et al. (2016)
	Northeastern region of the Yucatan peninsula, Mexico	Remote sensing evaluation: quantification of floating biomass coverage (L8-OLI images)	*Sargassum* lines	Cuevas et al. (2018)
2016–2020	Mexican Caribbean	Remote sensing and deep learning evaluation: development of an automated monitoring system (MODIS)	Massive arrivals, algal bloom arrivals	Arellano-Verdejo et al. (2018)
	Tropical Atlantic	Remote sensing evaluation: quantification of floating biomass and its spatiotemporal changes (MODIS)	Great Atlantic *Sargassum* belt	Wang et al. (2019)
	Mexican Caribbean	*In situ* evaluation of beached biomass: identification of species (SF, SN1, SN8) and quantification of relative abundance	Massive influxes	García-Sánchez et al. (2020)
	Mexican Caribbean	Evaluation of geotagged photographs: monitoring of beached biomass	Atypical arrival	Arellano-Verdejo and Lazcano-Hernández (2021)
	Caribbean islands, Mexican Caribbean and other localities (Gulf of Mexico)	Remote sensing: development of a forecasting tool	*Sargassum* inundation	Trinanes et al. (2021)

MERIS, Medium Resolution Imaging Spectrometer; MODIS, Moderate Resolution Imaging Spectroradiometer; L8-OLI, Landsat 8 Operational Land Imager; SF, S. fluitans III; SN, S. natans; SN1, S. natans I; SN8, S. natans VIII.

of excessive algal material, and groundwater, due to leachates from onshore algal disposal sites, impacts the environment and the economic activities developed in coastal areas (Franks et al., 2012; Chávez et al., 2020). It should be noted that the degradation of species of *Sargassum* depends on the dissolution and degradation of alginate, the main structural component of its cell walls, while other reactive compounds in the algae also affect degradation (Forro, 1987; Conover et al., 2016; Thomas et al., 2017). In most cases, the degradation of the algae after an event can cause adverse effects on the health of the surrounding ecosystems. In near-shore environments, and even in deeper areas, the rate of organic matter degradation is determined by

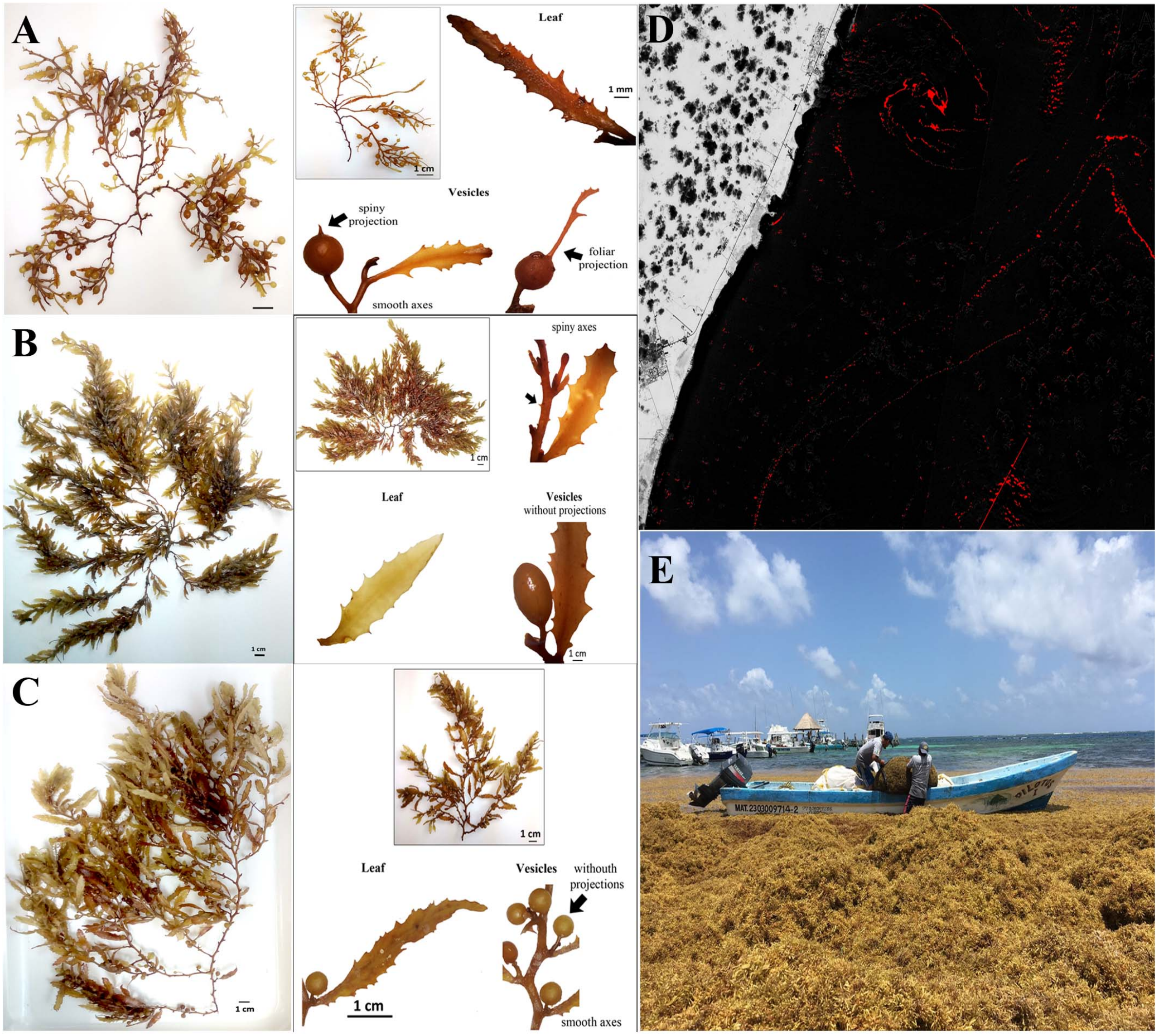

FIGURE 1 | Pelagic taxa involved in the *Sargassum* events at the Caribbean. **(A)**: *Sargassum natans* I; **(B)**: *S. fluitans* III; **(C)**: *S. natans* VIII (Parr, 1939). Scale: 1 cm. Leaf shape, axes and shape of vesicles are shown. For detailed morphological descriptions see Vázquez-Delfín et al., 2020. **(D)**: Sentinel-2 satellite image for the north coast of the Mexican Caribbean coast showing *Sargassum* floating biomass (red); **(E)**: Management of *Sargassum* stranded biomass in the Mexican Caribbean coast.

factors such as microbial accessibility, temperature, and pH. As a product of the biological degradation of brown algae, gases (H_2S, NH_3, CO_2, CH_4), organic matter, and a high biological oxygen demand (BOD) area is formed, giving rise to anaerobic zones (Song et al., 2020). In addition, different dissolved compounds, such as mannitol, volatile fatty acids, alcohols and polyphenols, can be released from their tissues. Bacteria involved in these processes generally use the products to maintain their own metabolism (Thomas et al., 2017), while some other nutrients or ions released may cause eutrophication (van Tussenbroek et al., 2017). Nevertheless, there is a lack of knowledge regarding the factors that trigger *Sargassum* proliferation and degradation, which constrains predictions of their impact on the environment.

Beyond the negative effects of *Sargassum* events, it should be noted that floating and stranded biomass provides some important elements to coastal and marine ecosystems (**Table 2**) and some emergent opportunities have been identified for local communities (see section "Valorization and management of Sargassum biomass: opportunities"). *Sargassum* holopelagic species may also play a unique role in the North Atlantic subgyre as they are home to an iconic drifting pelagic ecosystem, including some endemic species (Lopez et al., 2008; Louime et al., 2017; Brooks et al., 2018). Large quantities of holopelagic *Sargassum* suggests that carbon sequestration can be a positive outlook of this phenomena, particularly counterbalancing habitat loss and sequestration capacity of seagrasses and mangroves, both highly impacted and degraded by anthropogenic activities (Duarte, 2017). The relevance of macroalgae communities to sequester and transfer carbon and consequently their potential use as mitigation strategy to climate change seems clear, albeit

TABLE 2 | Ecological and socioeconomic impacts of *Sargassum* events for the Atlantic coasts, with special attention to the Caribbean region/Western Atlantic.

Sector	Impact	Reference
Ecological impacts		
Coastal impacts	Beach erosion, changes in benthic community structure and function. Coastal dead zones due to biomass decomposition and beach fouling. Killing of mangrove and seagrass seedlings.	UNEP (2018)
	Eutrophication, reduction in light, oxygen (hypoxia or anoxia) and pH in the near-shore waters. Changes in the species composition of the benthic community and seagrass loss. Toxic leachate production.	van Tussenbroek et al. (2017)
	Risk of environmental contamination by heavy metals (As).	Rodríguez-Martínez et al. (2020)
	Changes in the food webs, with consequences on the balance of the trophic structure.	Chávez et al. (2020)
Fauna	Changes in the behavior of nesting sea turtles. Lower nesting success. Decomposing *Sargassum* biomass creates lethal temperatures for the developing embryos.	Maurer et al. (2015); Azanza and Pérez (2016); Chávez et al. (2020)
	Dead fish, turtles and other marine wildlife (crustaceans, echinoderms, mollusks and polychaetes).	UNEP (2018); Chávez et al. (2020)
Ecosystems and biodiversity	While floating, biomass provides habitat and refuge for diverse species.	Coston-Clements et al. (1991); Huffard et al. (2014); Chávez et al. (2020)
	Introduction of nutrients to the marine-terrestrial ecotone, representing a natural fertilizer that favors the growth of vegetation on some beaches and dunes.	Williams and Feagin (2010); Chávez et al. (2020)
	Carbon sequestration (CO_2 remover) and mitigation of climate change: floating Atlantic biomass represents a carbon stock up to 7.5 Pg C, comparable to key marine ecosystems.	Gouvêa et al. (2020); Paraguay-Delgado et al. (2020)
Socioeconomic impacts		
Fisheries	Fishing operations interrupted and reduced access to fishing. Increase in the mortality of fish and other marine life and reduced fish catches.	UNEP (2018)
Human Health	Production of hydrogen sulfide and anhydrous ammonia as a result of decomposition, which produce irritation to the upper airways, headache, nausea, confusion and extreme damage.	UNEP (2018); Chávez et al. (2020); Resiere et al. (2020)
Tourism	Decaying *Sargassum* biomass reduced tourism activity by 35%, due to bad smells and unattractive visual impact.	UNEP (2018); Chávez et al. (2020)

arguable (Duarte, 2017; Krause-Jensen et al., 2018; Smale et al., 2018). Macroalgal communities can take up to 1.5 Pg C yr^{-1} globally via net production from which 0.173 Pg C yr^{-1} (88%) is sequestered in deep ocean (Krause-Jensen and Duarte, 2016; Krause-Jensen et al., 2018). The *Sargassum* biomass in Atlantic, spread over 227×10^4 km^2, produces an estimated mean annual carbon stock of 7.5 PgC (Gouvêa et al., 2020) similar to seagrass or mangroves (5–8 Pg C) (Howard et al., 2017). If those numbers are correct, holopelagic *Sargassum* must be considered as an important pathway for CO_2 removal from the atmosphere. Moreover, its interconnectivity with deep ocean and coastal zones makes pelagic *Sargassum* a key element for Blue Carbon strategies, but the fate of this carbon should be further investigated. Alternatively, artificial burial in isolated areas or deposition in the deep ocean deserves attention since it will take carbon out of its cycle. Nevertheless, *Sargassum* biomass does not constitute a static resource and the estimates of sequestration potential should be taken with caution. Additionally, possible uses of the harvested seaweed biomass, either to be used as biofuel (López-Sosa et al., 2020), methanisation and/or for extracting valuable compounds could be an efficient solution for the management of the *Sargassum* biomass. The adequate management of this resource to counteract negative impacts of *Sargassum* events is desirable but requires further investigation.

STRATEGIES TO APPROACH THE STUDY OF THE PHENOMENON: FROM THE EXPLORATION TO MANAGEMENT

Sargassum events are complex phenomena that involves different participatory actors and decision makers, affects human health, the economy and ecological marine and coastal systems. It also has a large spatiotemporal variation that affects different countries at a regional scale, either simultaneously or at different time points. Therefore, to address this phenomenon, we should include different perspectives, interdisciplinary and transdisciplinary approaches and participative management, which are current topics in sustainability and international collaboration (Kasemir et al., 2003; Lang et al., 2012). Some of the priority issues identified are: gathering information to forecast the distribution and arrival of floating biomass, explore the causes and effects of the phenomenon, identify the challenges of their offshore collection and the implementation of stabilization strategies to avoid degradation of the feedstock. Finally, it is crucial to obtain information to valorize the biomass of pelagic *Sargassum*, and for the development of its exploitation and mitigation strategies to achieve effective management. To reach this ambitious objective we summarize the different phases and some of the factors that should be considered, focusing on the exploratory phase, which is a current ongoing phase in several Caribbean countries (**Figure 2**). Although in some countries different exploitation proposals (Rodríguez and Orellana, 2008; Carrillo et al., 2012; Velasco-González et al., 2013; Cuxim and Balam, 2015; Rodríguez-Martínez et al., 2016; Mohammed et al., 2019) and some mitigation strategies have been developed (SEMARNAT, 2015; CONACYT, 2020), they have been unsuccessful due to the lack of exploratory and basic information, and the lack of international cooperation that is required to address a phenomenon of this magnitude. It is worth mentioning that *Sargassum* events impacts the coastal human communities, thus, anthropological and socio-economic studies are required in the exploratory phase to develop normativity and regulations. In relation to the participatory actors (government, academic institutions, local communities, private enterprises), we remark on the necessity of their involvement in all the proposed phases in a collaborative way. It is noteworthy that the relevance of local communities to natural resource management has been demonstrated as both effective and relevant on sustainability and conservation topics (Shackleton et al., 2002; Fabricius, 2004; Fabricius and Collins, 2007). However, there is no published information on the role of local communities to address the *Sargassum* events in the region for the proposed phases, so its role is undefined and the opportunity for participation is missing.

The exploratory phase of *Sargassum* events has allowed the development of valuable information about the phenomenon. The detection and monitoring of floating biomass has been successful for over a decade (Franks et al., 2012; Gower et al., 2013; Congedo, 2016; Arellano-Verdejo et al., 2018; Cuevas et al., 2018; Wang et al., 2018; Arellano-Verdejo and Lazcano-Hernández, 2021). Thus, low, moderate and high spatial resolution satellite images have been employed to implement algorithms for the monitoring of pelagic *Sargassum*. The most used remote sensing inputs for mapping *Sargassum* coverage are the optical images which use solar radiation (Landsat, Sentinel-2, MODIS, and SPOT). The Maximum Chlorophyll Index (MCI) (Gower et al., 2006), the MODIS Red Edge (MRE) (Gower et al., 2013), Normalized Difference Vegetation Index (NDVI) (Lasquites et al., 2019) and the Floating Algae Index (FAI) are some of the straightforward image-processing algorithms that are also commonly used. However, more complex algorithms need to be implemented such as Alternate Floating Algae Index (AFAI) (Wang and Hu, 2016), Random Forest algorithm (Cuevas et al., 2018) and Deep Learning and Recursive Neural Networks approaches (Arellano-Verdejo et al., 2018). Hence, low resolution data allows for covering more extensive areas in one image and daily monitoring of *Sargassum*, whereas high resolution data gives more specific details, but lacks the daily supply of images. The spatial configuration of pelagic *Sargassum* masses tends to generate elongated lines of few metres wide, termed windows, or its accumulation in small patches. If these configurations do not exceed the minimum detection size and density limit (20% of the area of the pixel), then the ability to detect *Sargassum* through satellite images is severely restricted (Hu et al., 2015). In this sense, low resolution sensors may underestimate the presence of floating algae. Therefore, the use of high-resolution data ($<$10 m resolution) is highly recommended to detect and map the distribution and cover of *Sargassum* on open sea surface. According to Hu et al. (2015), the area of *Sargassum* inside of a 10 m resolution pixel should be bigger than 20 m^2 in order to be accurately detected by any of the aforementioned algorithms.

Other actions needed in the exploratory phase are scarce or restricted to some countries and focus on specific aspects such as the determination of the chemical composition of pelagic *Sargassum* (Lapointe et al., 2014; Sissini et al., 2017; Lapointe, 2019; Chávez et al., 2020; García-Sánchez et al., 2020; Rodríguez-Martínez et al., 2020; Amador-Castro et al., 2021; Davis et al., 2021).

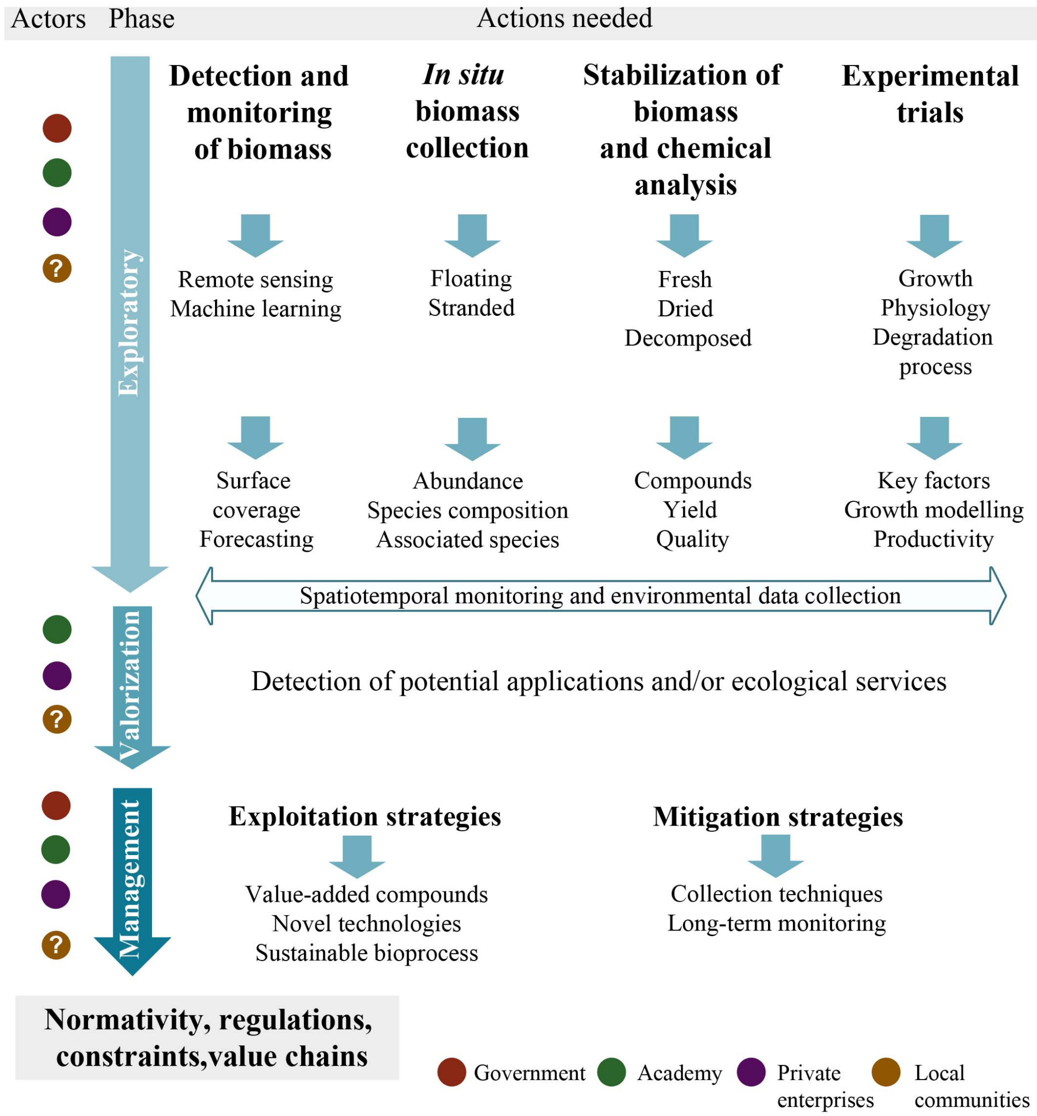

FIGURE 2 | Strategies to address the management of *Sargassum* events in the region. The actions needed, relevant factors and actors involved are included, from exploratory to management phase. ?: indicates that official information is not available to identify the specific role of local communities.

In the management phase, national and local authorities, civil society and private sector have made some efforts, which include implementation of forecasting systems, trials on different strategies of containment to avoid the arrival of floating biomass to the coasts, and removal actions of the stranded biomass either by hand or using machinery (Rodríguez-Martínez et al., 2016; Chávez et al., 2020). However, some of these efforts have been unsuccessful. For example, in 2018 a barrier system project was implemented in some areas of the Mexican Caribbean coast, but the amount of *Sargassum* biomass exceeded the capacity of the barriers and failed, causing severe accumulations not only on the beaches but on the seabed due to the sinking of the biomass accumulated in the barriers (personal observation EVD, DR). Some private initiatives have developed not only containment barriers, but diversion barriers to deflect the biomass to particular areas where it is removed (DESMI project, 2021). Nevertheless, the collection of pelagic *Sargassum* at sea should include the development of methods to avoid incidental capture of the macrofauna associated with pelagic masses, such as juvenile fishes and turtles (Maurer et al., 2015).

VALORIZATION AND MANAGEMENT OF *SARGASSUM* BIOMASS: OPPORTUNITIES

The valorization of algal biomasses, i.e., improving or attempting to improve the value, price or use of *Sargassum*, can be an opportunity to ameliorate the economic damage generated in the region (**Table 2**). This may be particularly effective if authorities

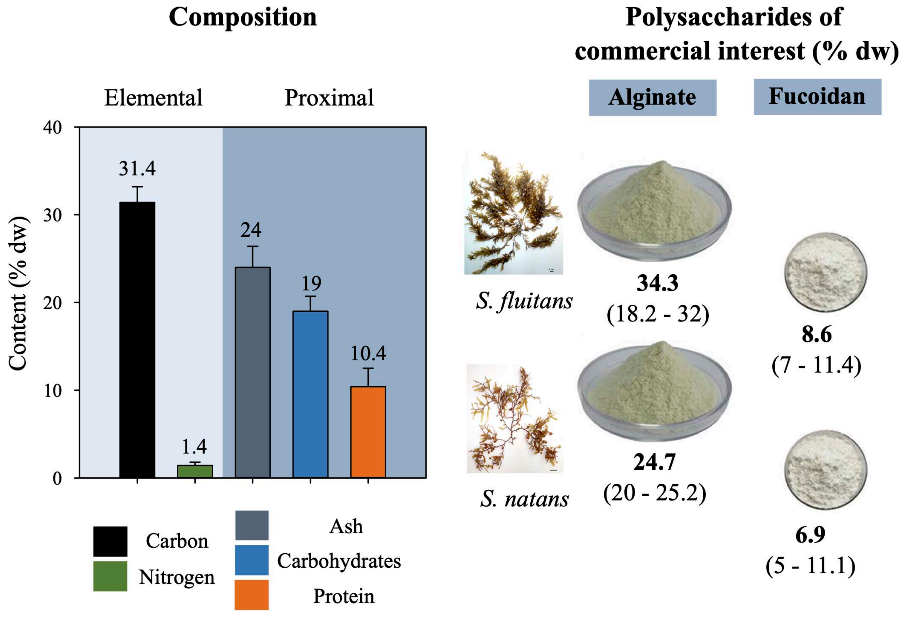

FIGURE 3 | Chemical composition of stranded biomass of *Sargassum* spp. from Mexican Caribbean. Elemental and proximal composition and commercial interest polysaccharides. Analysis from samples collected at Puerto Morelos, Quintana Roo, Mexico during 2018 *Sargassum* event. Values are reported with respect to the dry weight (dw).

are able to harvest biomass at a proper time and exhaustively avoiding its accumulation in order to prevent some of the damage caused after stranding. However, this task has proven to be difficult, especially during massive events, as mentioned above. Also, *Sargassum* spp. capacity to absorb heavy metals and its discontinuous and unreliable supply due to seasonal variations are the main constraints to harvest this alga for commercial exploitation, as has been shown for the invasive *S. muticum* in Europe (Lodeiro et al., 2004; Carro et al., 2015). Therefore, understanding the spatiotemporal changes in its abundance, biochemical composition and the impact of *Sargassum* proliferation, persistence and degradation is critical.

During the inundations of the Gulf of Mexico and the Caribbean in 2015, approximately 10,000 tons of fresh seaweed were stranded on beaches daily (Milledge and Harvey, 2016). Tourism in the Caribbean is worth $29.2 billion dollars, and it has been estimated that it will cost at least $120 million dollars to clean-up the *Sargassum* inundations in this region (Milledge and Harvey, 2016). Due to the economic cost of removing the stranded seaweed, there is an imperative need to define technical and ecological measures to forecast an event and reduce its proliferation and valorize its biomass. Large volumes of algae reaching the beaches have a great potential to be used for different purposes, as proposed in recent publications (Milledge et al., 2015; Milledge and Harvey, 2016; Amador-Castro et al., 2021; Davis et al., 2021). However, in order to propose its further use and harvesting strategies, it is essential to know basic aspects of the incoming resource. Several elementary questions need to be answered: Which are the species found and what is its relative abundance? What are the regional and local factors that promote proliferation and accumulation of biomass in the beaches? What is the chemical composition of the species, and how this composition varies spatiotemporally? These are fundamental areas of research to understand the potential use of the resource.

Interestingly, each year *Sargassum* events in the Caribbean have been characterized by the predominance of a particular taxon depending on the geographical location. For example, *S. natans* VIII was described as the predominant species in 2015 events (Amaral-Zettler et al., 2017), but recent studies have shown that predominant taxa could vary according to location and time (Schell et al., 2015; García-Sánchez et al., 2020). In other coastal areas such as the Mexican Caribbean the predominance of *S. fluitans* has been more evident throughout the years, although different proportions of the other holopelagic and benthic species of *Sargassum* are also present (Vázquez-Delfín et al., 2020). Differences in the occurrence and relative abundance of *Sargassum* species/taxa may translate into significant differences in the biochemical composition of the biomass, including toxic metals content such as Arsenic (Rodríguez-Martínez et al., 2020). Furthermore, the high ash and water content are important constraints in the use of *Sargassum* biomass as a biofuel source (Milledge et al., 2014). Nevertheless, previous studies on *Sargassum* species have shown that through a biorefinery approach other high value compounds such as antioxidants are viable to obtain (Namvar et al., 2013; Milledge et al., 2015).

Sargassum species have the potential to produce a wide range of high value biochemicals, nutraceuticals and pharmaceuticals (Davis et al., 2021). However, considerable research is still required in order to characterize and understand *Sargassum* events, including seasonal variation in biochemical composition, as well as processes with high added value and the development of commercial products. Biomolecules of interest may vary with physical-chemical parameters such as light intensity, nutrient availability, and temperature (Tanniou et al., 2013). Therefore, work should focus on the quantity and quality of potential compounds, for example those with antioxidant properties such as carbohydrates, lipids, carotenoids, phenols and proteins, which may vary spatiotemporally. Important insights on when and how to collect and preserve the algae or how heavy metals uptake and accumulation behaves in relation to species are research areas of interest. Holopelagic *Sargassum* is always moving and exposed to very contrasting environments, from marine to coastal areas, with significant differences in temperature, nutrient loading, exposure to heavy metals, etc., and thus changing and adjusting its metabolic performance. This, in turn affects the chemical composition of pelagic seaweeds. The main challenge of the affected countries is to manage and valorize *Sargassum* biomass under a sustainable and economically efficient approach. Nevertheless, we must first understand what are the main environmental factors that induce their proliferation, regulate physiology and growth, and how these affect yield and quality of commercial interest compounds (**Figure 2**).

The basic chemical composition of stranded *Sargassum* biomass from the Mexican Caribbean is shown in **Figure 3**; however, these values may vary depending on several factors including species, seasonality and extraction methods (Rosado-Espinosa et al., 2020; Terme et al., 2020). Care must be taken to consider the level of degradation of *Sargassum* spp. while stranded in the beach, where microbial composition and decomposition rates vary with physical-chemical parameters. Moreover, high light intensities will also promote photodegradation of both floating and stranded *Sargassum* (Powers et al., 2019). The decay of macroalgal also depends on their biochemical composition and morphological complexity (Braeckman et al., 2019).

Amongst the brown seaweeds commonly used commercially, *Sargassum* spp. is the least exploited genus, despite its enormous quantities found all over the world and in recent events. Valuable hydrocolloids, such as alginate and fucoidan, are also found in *Sargassum*, as in other Phaeophycean algae. Alginates are cellular wall polysaccharides found in the matrix of brown seaweeds, composed of linear binary copolymers of (1 → 4)-linked β -D-mannuronic acid (M) and ∝ -L-guluronic acid (G) monomers, whereas fucoidans designate a group of fucose-containing sulfated polysaccharides, which are highly heterogeneous in structure, made up of fucose, galactose, mannose, xylose, glucose, uronic acids, sulfate substituents, and sometimes acetyl groups (Draget et al., 2005). A broad number of applications have been described for brown algae polysaccharides, most notably antioxidant, anticoagulant and antithrombotic, antiviral, anticancer, antidiabetic, immunomodulating, anti-inflammatory, antilipidemic and anti-fertilization effects (Ale et al., 2011). However, *Sargassum* species typically give low yields ($< 19\%$) of poor-quality alginate (Torres et al., 2007), but they may be potential sources of fucose-containing sulfated polysaccharides.

As part of an ongoing research program in the Mexican Caribbean, estimates of alginate or fucoidan content in stranded *Sargassum* biomass were determined (**Figure 3**). Mean content of alginates and fucoidans are higher in *S. fluitans* than *S. natans* I, and both cell wall polysaccharides account for ∼40% in dry weight (dw), with alginate content almost four-fold higher than fucoidan. Manuronic (M) and guluronic (G) blocks forming the alginate structure are also important to define the quality of alginates, a higher proportion of G blocks results in higher gel strength (Mohammed et al., 2019). These authors found optimum extraction conditions for *S. natans* with a yield between 17 and 28% after a two stage extraction processes resulting in an alginate with an M/G ratio of 0.45, indicating high guluronic acid content, aligned to high gelling capabilities (Mohammed et al., 2019).

On the other hand, fucoidans found in various *Sargassum* species are prominently sulfated galactofurans, which may differ considerably in chemical composition, molecular mass and structure, depending on the algal species studied, spatial and temporal variation, or on the type of tissue sampled (Duarte et al., 2001). Extraction and purification methods may greatly affect the structure and the composition of the isolated fucoidan and may significantly affect the results obtained when the fucoidan products are being evaluated for bioactivity (Hifney et al., 2016). These authors developed an efficient and effective extraction process for the sulfated polysaccharides from *Sargassum* sp. with a fucoidan yield and sulfate content of 19 and 47.6% (dw) respectively, preserving their structure and biological activity.

Currently, alginates and fucoidans are the only compounds of *Sargassum* spp. with a current developed value chain. However, further studies should be performed to find other potential uses and other extractable compounds. Thus, the variation in the relative abundance of species and its chemical composition during each *Sargassum* event will determine their valorization and management strategy.

CHALLENGES AND CONCLUDING REMARKS

The management of *Sargassum* events represent a challenge to the participatory actors, stakeholders and decision makers, which includes governments, research institutions, local communities, tourist industry and other private sectors. Some priority actions are needed:

a) Continuous monitoring of physicochemical parameters in strategic areas. Relevant seawater physicochemical parameters, i.e., dissolved oxygen (DO), pH, turbidity and nutrient concentrations. Measurement of toxic gases (H_2S and NH_3) when significant amounts of *Sargassum* remain stranded in the beach for more than 72 h is required (Resiere et al., 2020). This monitoring is fundamental for understanding how *Sargassum* events impact ecosystems/locations and to define management policies. Safe protocols for *Sargassum* collection and biomass removal will help prevent negative impacts during extreme events.
b) To address the *Sargassum* events in the Caribbean Sea under a sustainable development approach, we must combine

ecological, physiological, biotechnological and socioeconomic approaches. Interdisciplinary research must focus, not exclusively, but consistently in: (i) improving our knowledge on the physiology of *Sargassum* species and how they respond to environmental changes in order to estimate the triggering factors and abundance of their biomass. (ii) understanding how environmental conditions affect the quality and quantity of compounds of interest in *Sargassum* species and therefore determine the optimal collection opportunities, in order to develop a sustainable bioprocess to valorize *Sargassum* biomass.

c) Develop standardization protocols for *Sargassum* studies through international cooperation and transdisciplinary work, i.e., threshold values for heavy metal content, H_2S and NH_3 air concentrations (ANSES, 2017; Lähteenmäki-Uutela et al., 2021). International consensus on regulations for *Sargassum* detention, collection and treatment methods to avoid/reduce environmental damage are required. Caribbean Regional Fisheries Mechanisms (CRFM) has a model protocol for the management of extreme accumulations of *Sargassum* for member States (CRFM, 2016); whereas countries like France and Mexico have also prepared recommendations to manage and regulate *Sargassum* events (ANSES, 2017; CONACYT, 2020).

The above-mentioned actions will definitely aid in finding the right balance between the valorization of natural resources, technological development and responding to the need for coastal management in the affected areas. Interaction between the different actors is fundamental to the development of strategic management, processes and technologies.

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