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TOPICAL REVIEW

Holopelagic sargassum beachings in the Western Atlantic Ocean: a scoping review ranging from causes to management

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Abstract

Over the past decade, recurrent sargassum beaching events have become a significant ecological and socio-economic concern across the tropical Western Atlantic Ocean, particularly affecting the Caribbean and the Gulf of Mexico. This scoping review aims to map the existing evidence related to these beachings, with the goal of synthesizing current knowledge, identifying key themes and highlighting research gaps. Through a comprehensive analysis of peer-reviewed and grey literature, the review reveals a rapidly expanding but uneven body of research, with concentrations in the detection of holopelagic sargassum, localized impacts assessment and valorization studies. Conversely, this study reveals gaps and further research opportunities in better understanding the factors causing offshore sargassum proliferation, the need for larger scale monitoring and characterizing beached sargassum composition, its variability and stabilization for industrial uses, as well as the need for more precise and complete forecasting systems used in synergy with detection methods.

1. Introduction

Sargassum is a genus of mainly brown benthic seaweeds including two holopelagic species, remaining in a floating state throughout their life cycle: *Sargassum fluitans* (Børgesen) Børgesen 1914, and *Sargassum natans* (Linneaeus) Gaillon 1828 [1]. These have historically thrived in the waters of the Sargasso Sea, in the North Atlantic Ocean, and has been documented in this area since the first records in the 15th century [2]. In recent years, however, researchers have observed an unprecedented shift in the distribution and biomass of holopelagic sargassum [3]. Since 2011, satellite imagery and field observations have documented the emergence of a massive and recurring transoceanic accumulation now known as the Great Atlantic Sargassum Belt (GASB), which extends over 8000 km from the west coast of Africa to the Caribbean Sea and the Gulf of Mexico (GoM) [4].

Ecologically, holopelagic sargassum provide refuge, nursery grounds, and feeding zones for numerous marine species in a pelagic context [5, 6]. However, when it gets to the coast, beaching events trigger a range of environmental, public health, and socio-economic impacts that can persist over time. Environmentally, large quantities of decomposing sargassum in coastal zones can smother coral reefs and seagrass beds [7], deplete dissolved oxygen in the water column, and disrupt marine food webs [8]. These ecological disturbances are compounded when stranded biomass accumulates on beaches, where anaerobic decomposition releases gases such as hydrogen sulphide, a toxic gas associated with respiratory issues and unpleasant odours that pose risks to human health and quality of life [8]. Economically, beaching events have had profound implications for industries such as tourism and small-scale fisheries. Coastal tourism—an economic lifeline for many Caribbean and Latin American countries—has been particularly affected, as algae-laden beaches deter visitors and reduce the revenues of tourism businesses [9]. Governments and local communities face mounting costs for monitoring, cleaning, and managing sargassum influxes, often diverting resources from other critical environmental and social needs.

On the other hand, sargassum has also been seen as a potential resource, with those so-called 'golden tides' being seen by some as a 'golden opportunity' to valorize this resource [10]. With high concentrations of nutrients, organic matter, and bioactive compounds, the macroalga has drawn attention for its potential in various biotechnological applications. These include the production of fertilizers, biofuels, animal feed, pharmaceuticals, food supplements, and even cosmetics [11]. Its high nutrient content can be harnessed in agricultural and industrial applications [12], providing an eco-friendly alternative to synthetic materials. However, despite growing interest, significant barriers to large-scale valorization remain. These include logistical challenges in collection and processing, seasonal and year-to-year variability in available biomass amounts, and concerns over contamination with heavy metals and pathogens, which limit the use of sargassum in food or feed applications [11], and prevents biomass from being composted.

Despite growing attention, the body of literature on sargassum beachings remains fragmented, with a variety of studies spanning multiple disciplines. A comprehensive synthesis of existing research evidence on the topic is crucial to guide future research and policy efforts, in a context where those events have become a yearly occurrence and a 'new reality' to which countries have to adapt.

Scoping reviews aim at mapping the key concepts, types of evidence, and research gaps on a particular topic, without assessing the quality of the studies included. As such, this paper aims to map the scope of current knowledge surrounding sargassum beachings in the tropical Western Atlantic area, and to specifically address three secondary problematics:

1. How are sargassum proliferation and beaching risk detected and forecasted at different spatial and temporal scales?
2. What environmental, economic, social and health impacts of sargassum beachings have been studied?
3. Which actions have been implemented for sargassum beachings?

This paper first presents the methods used to gather the information in the most comprehensive and specific way, then presents a mapping of the current knowledge and provides answers to these three sub-questions. Finally, we discuss the identified gaps for future research and investigate how this study will support decision making policies.

2. Methods

2.1. Type of review and protocol

This scoping review follows the guidelines of the Collaboration for Environmental Evidence for conducting systematic maps [13], and conforms to the reporting standard «Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews» (PRISMA-ScR, checklist available in Additional File 1). The *a priori* protocol of the scoping review was registered in PROCEED, an open access registry of protocols for prospective evidence syntheses in the environmental sector [14]. Slight deviations to the protocol emerged throughout the synthesis process and are acknowledged thoroughly in Additional file 2.

2.2. Searching for articles

The search strategy was developed using a test list of 46 articles (covering the 1999–2024 period). These helped identifying keywords and constructing the search string that maximized comprehensiveness and specificity. The retained search equation was (Web of Science format): TS (Topic Search) = (sargassum OR (Sargasso AND (beaching$ OR influx OR influxes OR accumulation$ OR stranding$ OR event$ OR inundation$ OR arrival$ OR landing$ OR bloom$ OR pollution$ OR mass OR masses OR massive OR invasion$ OR invasive$ OR mat$ OR tide$ OR aggregation$ OR circulation$ OR monitoring OR detection$))) [14].

The main search was conducted on 27 September 2024 on Web of Science Core Collection (WOS CC, Clarivate Analytics) with the above search string. It was completed with searches on the same date on four additional bibliographic databases, the search string being adapted to the specificity of each database: ScienceDirect (Elsevier), SciELO (Clarivate Analytics), ProQuest Dissertations & Theses (Clarivate Analytics), and CAIRN info. An additional search was also performed on the same date using the Google Scholar search engine and Harzing's Publish of Perish software to search and export the results, with search strings adapted to the specificity of the engine. Finally, additional searches were conducted on 18 organizational websites between 27 September 2024 and 15 October 2024. Details on the search including search strings,

Table 1. Eligibility criteria used for article screening.

	Include	Exclude
Concept	- Articles mentioning sargassum beachings - Articles mentioning the use or potential use of collected sargassum without explicit reference to the beachings - Articles dealing with the causes of sargassum proliferation or with the detection or forecasting of the distribution of sargassum offshore - Studies dealing with the characterization, composition or chemicals contained in *Sargassum fluitans* or *Sargassum natans* for use or potential use regardless of the context	- Articles on the taxonomy or biodiversity of sargassum not beached (i.e. in the open ocean) - Articles on sargassum species other than the holopelagic *Sargassum fluitans* and *Sargassum natans* - Studies conducted in the Sargasso Sea but not on sargassum
Context	- On the West Coast of the Atlantic Ocean (for sargassum beachings) - On the Atlantic Ocean (including the Sargasso Sea) for studies about sargassum offshore distribution	- On the East coast of the Atlantic ocean (Africa) or any other coasts for sargassum beachings - On any other ocean than the Atlantic for studies about sargassum offshore distribution
Language	- Articles in French, English, Spanish or Portuguese	- Articles in all other languages
Articles type	- Journal articles, book chapters, reports, conference proceedings, PhD, MSc or BSc theses, policy documents (action plans, directives, guidelines, …)	- Presentations, editorial material, magazine articles, newspaper articles, conference or meeting abstracts, posters, brochures, policy briefs, podcasts, videos
Content type	- Primary research contents (e.g. *in situ, ex situ*, experimental, observational, modelling, interviews, legal studies)	- Secondary research contents (reviews, meta-analyses), discussion or opinion papers

dates and results for all sources are provided in Additional file 2.

The overall search successfully retrieved the 46 articles from the test list. The final search string in WOS CC retrieved all the 40 indexed articles from the test list, and the remaining 6 articles were retrieved through the searches in Science Direct (1 article) and Google Scholar (5 articles).

2.3. Screening of articles

The screening of articles was performed in two stages according to the criteria presented in table 1.

First, articles were screened for eligibility based on their title and abstract by a reviewer (DYO) after checking for screening consistency with a second reviewer (HJ) on a sample of 300 titles/abstracts that were screened independently by both reviewers. Reviewers' overall agreement on this sample was 94%, Randolph's Kappa coefficient of consistency between reviewers' decisions was 0.89, and reviewers discussed and solved all disagreements. Titles and abstracts were manually screened using the Rayyan software [15] and articles without abstracts but with an eligible title, as well as articles with unclear eligibility status were included for the next screening stage. Second, included articles were screened based on their full texts in a Microsoft Excel spreadsheet. The full text screening was shared between two reviewers (DYO and HJ) and screening consistency was checked beforehand on a sample of 50 articles. Reviewers overall agreement on this sample was 80%, the Randolph's Kappa coefficient of consistency between reviewers' decisions was 0.6, reviewers discussed and solved all disagreements and the eligibility criteria were slightly revised. During all the screening process, reviewers never had to screen their own articles.

2.4. Data coding and extraction strategy

Data coding and extraction was shared between the two reviewers (HJ and DYO) and the consistency of their coding decisions was checked beforehand on a sample of 20 articles (15 selected randomly and 5 identified as potentially difficult to code during the screening stage) and all disagreements discussed and solved. The following information was extracted or coded, when applicable, in a spreadsheet available in Additional File 4:

- Bibliographic information (unique identifier, author, publication year, title, journal, DOI, source, language and type of document);
- General description of the article (main research theme, years studied, months or seasons studied, location, type of study);
- Information related to sargassum beaching events (country, impacts, characterization, detection, forecasting, management, valorization, policies);

- Information related to sargassum distribution offshore (causes of proliferation, detection, forecasting).

Any missing information was coded as such. After completing all the coding, authors' affiliation countries were retrieved from metadata of publications with DOIs using OpenAlex API. Then, the most common country out of all authors' origin countries was selected and assigned to the 'most_common_country' column.

2.5. Analysis and evidence mapping

The information extracted from all included articles was analysed and synthesized narratively. First, a general depiction of the research landscape was done by analysing the publication dates of all articles by research theme and the geographical distribution of authors and study areas. Then, issues associated with sargassum beachings were analysed through the frequency distribution of articles in the coded variables (histograms) and through cross-tabulations of these variables (heatmaps), and knowledge gaps and clusters were identified.

For the articles in the valorization category, which represents a large part of our corpus, a multiple correspondence analysis (MCA) was performed to reduce the complexity of the information. This statistical analysis method aims at reducing the complexity of a dataset by grouping variables according to a few axes (here, two), in a way that minimizes variability in the individuals (here, the articles). The MCA was done on a simplified subset of our database, only containing valorization articles (255 rows), and four variables (4 columns): 'author country' (most common author's affiliation country amongst all article's authors, retrieved with the above-described method), 'studied country' (country where the studied beaching happened), 'year publication' (year in which the article was published) and 'valorization theme' (main valorization sub-theme that was investigated in the article, namely: bioremediation, energy, biomaterial, medical, food, animal feed, and biofertilizer). The MCA allowed us to identify clusters within the research theme of valorization and dependencies between those four variables.

3. Results

3.1. Description of the review process

The initial search yielded 12 240 results (Additional file 3), which resulted in 9015 articles after removing duplicates (figure 1). A total of 1721 articles were included after title and abstract screening, and after searching for full texts and full text screening 697 articles met our inclusion criteria and were included in the scoping review database (Additional file 4). The list of articles excluded at full text screening is provided in Additional file 3 with reasons for exclusion or for unclear eligibility.

3.2. Description of the evidence

A majority of articles has been published after 2011 (85%). When categorizing the body of literature by thematic focus and publication period, three phases emerge, presented in figure 2. Prior to 2011, research was conducted on sargassum in the Sargasso Sea and studies primarily focused on the valorization of this resource by exploiting the algae's biosorption potential or investigating its capacity to remove pollutants from contaminated water [17]. In 2005, Gower and King published the first record of satellite detection of pelagic algae in the GoM [18], initiating the use of remote sensing to track the distribution of the seaweed offshore. Then, starting 2011, we notice increased focus on the characterization of beached sargassum and the ecological and socio-economic impacts of its landfall. Around 2017, policy and management strategies start to gain more attention as well. Finally, after 2020, we notice a large diversification in the research topics. This most recent period accounts for the majority of publications, and features a dramatic increase in studies on valorization techniques, with the total number of articles (included in this review) rising to over 200 publications (total).

The geographical distribution of sargassum-related studies reveals a clear concentration of research efforts along the Mexican coasts, with 26% of all articles studying sargassum beached on Mexican shores or detected in Mexican waters (especially the states of Quintana Roo and Yucatán). The United States of America follows with 14%, while the French overseas departments of Martinique (11%) and Guadeloupe (6%) also represent significant areas of study. All other countries in the region account for fewer than 4% of the publications, indicating a more evenly dispersed but less intensive research presence elsewhere. This distribution was compared with the national affiliations of contributing authors which shows a similar pattern with 28% of authors being affiliated with Mexican institutions, followed by 14% U.S. institutions, 14% French and 5% of British.

The landscape of sargassum research is notably diverse: amongst all 2118 authors present in our corpus, most of them only occasionally contributed to sargassum-related research with only one published article (83%), 342 (16%) had more than two publications, and only 48 (2%) published 5 articles or more, highlighting the dispersed and intermittent nature of contributions.

Although most documents of the corpus are journal articles, the thematic distribution across document types (figure 3) reveals that the management and policies themes (red squares on figure 3) are more frequently addressed in the grey literature

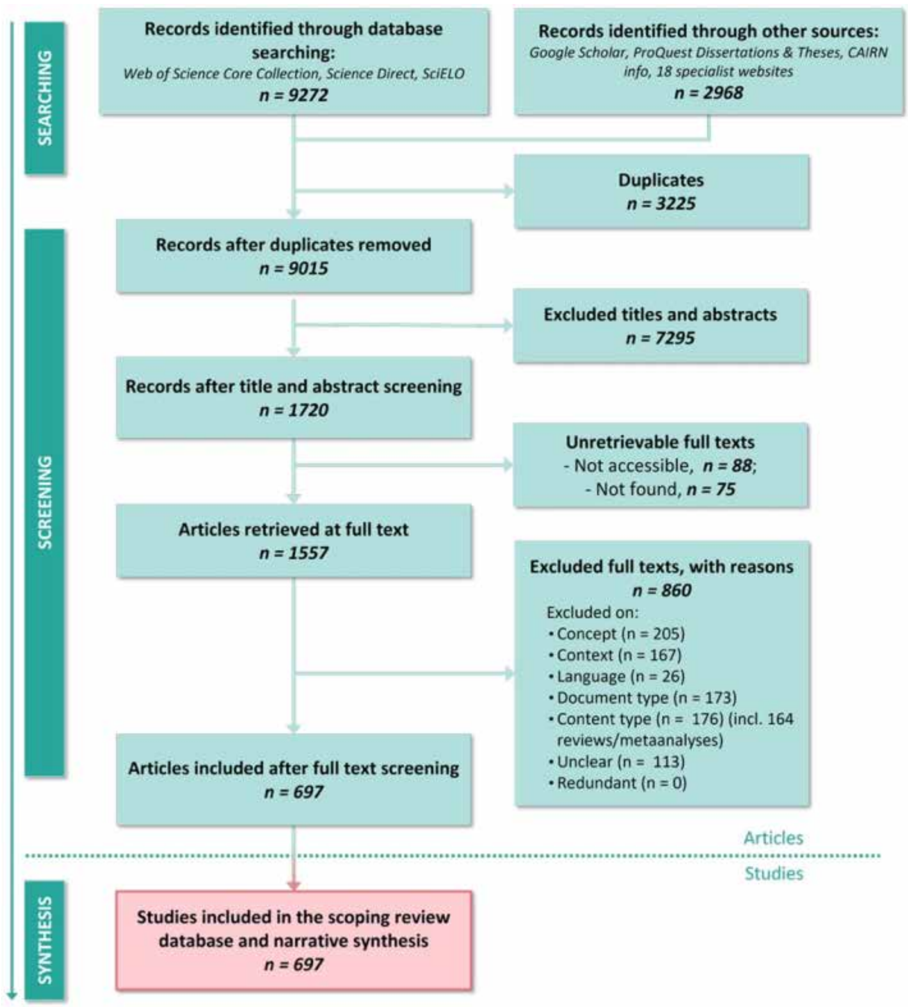

Figure 1. ROSES flow diagram for article selection. The diagram details the number of records retrieved, screened, and excluded at each stage of the process. Reproduced from [16]. CC BY 4.0.

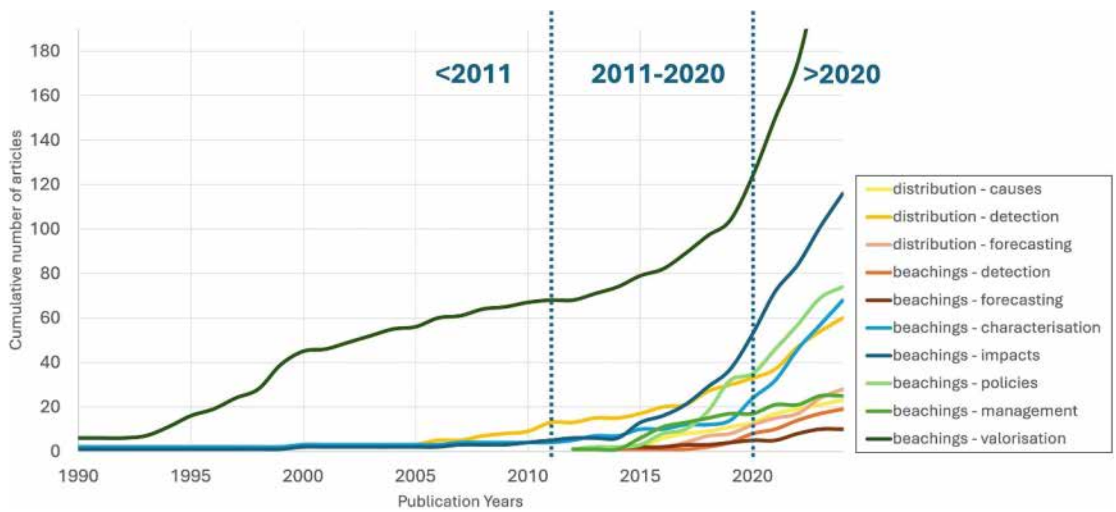

Figure 2. Cumulative number of articles covering each sub-theme through time.

(e.g. institutional or technical reports), whereas other themes like forecasting the offshore distribution of sargassum or characterizing the composition of the beached biomass are purely scientific and addressed mainly in scientific publications (journal articles, preprints…) (figure 3).

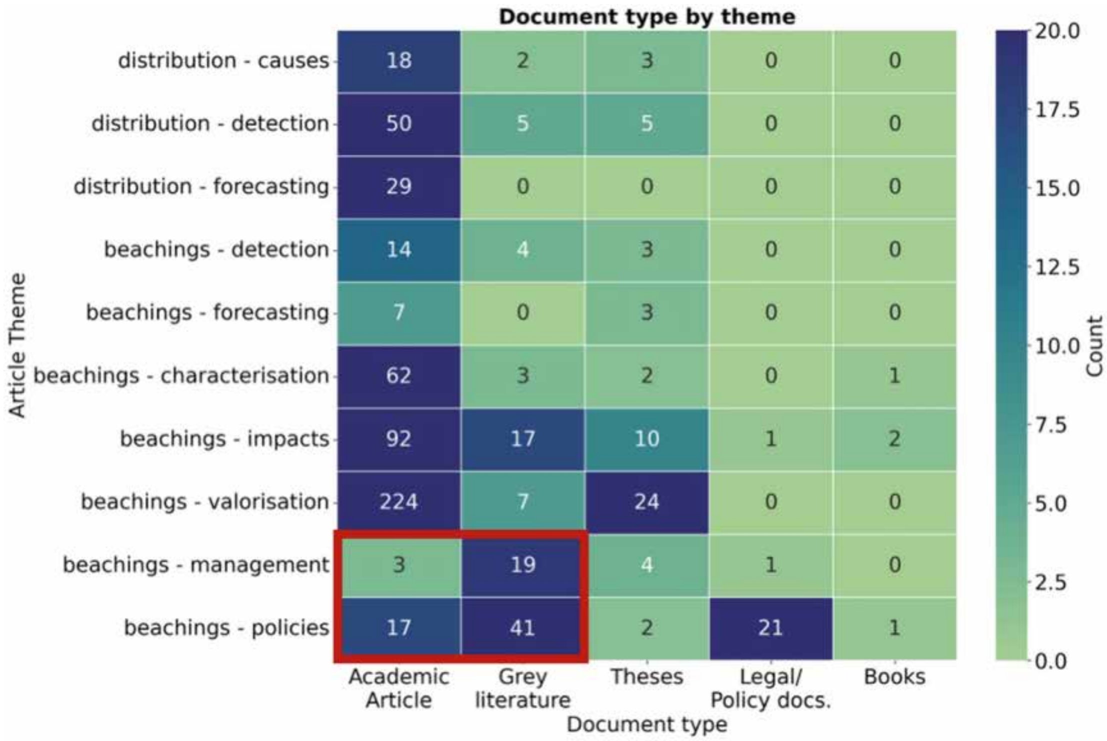

Figure 3. Heatmap of document type by document theme. Red square highlights the two themes that are addressed mainly in the grey literature.

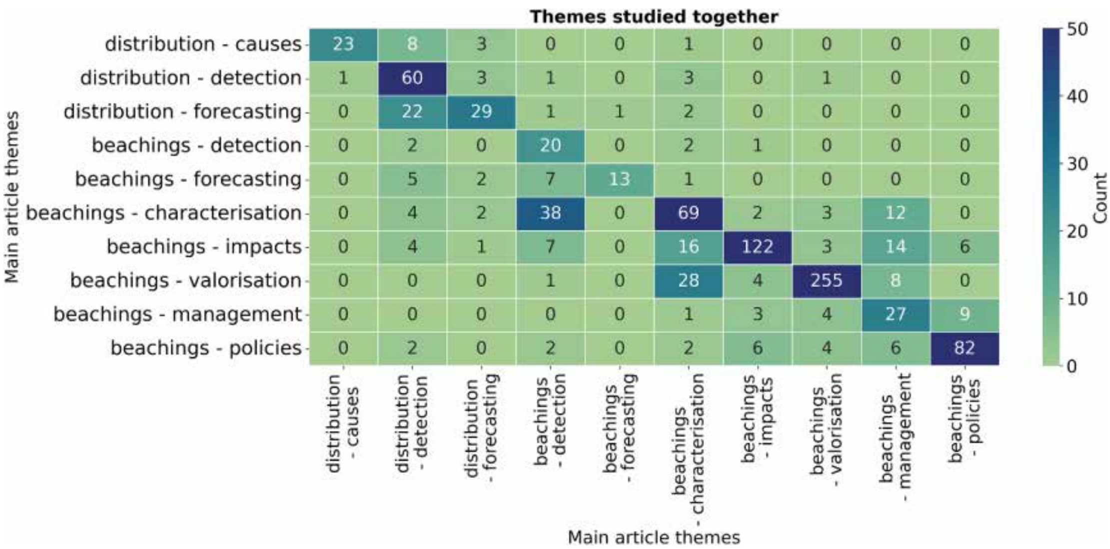

Figure 4. Heatmap of themes studied conjointly: y-axis is the main theme of the articles, x-axis is the number of information points we have for each theme.

While previous analyses considered only the main research theme of each article, in the following sections we consider secondary themes as well to capture a more nuanced understanding of how topics are studied in conjunction. For instance, figure 4 shows that the number of information points related to characterization is much higher than the number of articles focusing primarily on this topic, since biomass characterization is frequently included in articles classified under valorization. Similarly, most articles dealing with the forecasting of the distribution of sargassum offshore include detection techniques and beaching characterization studies often include a prior detection of the studied beaching.

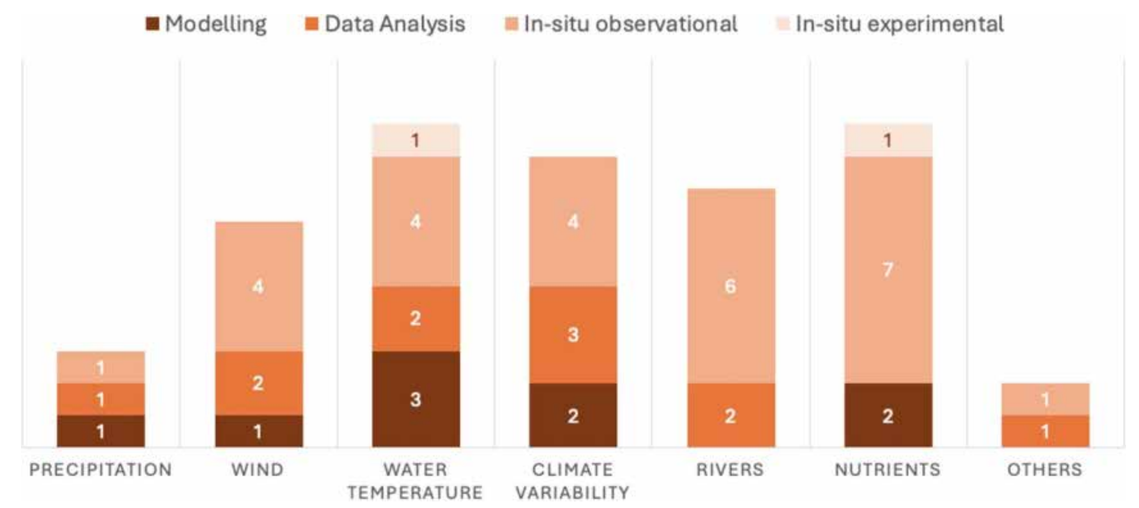

Figure 5. Number of documents by investigated cause and study type (modelling: study involves numerical climate/ocean models, data analysis: study analyses all types of data and their relation to sargassum blooms, in situ observational: study involves in situ measurements including satellite images, in situ experimental: study involves some kind of experiment done on site).

3.3. How are sargassum proliferation and beaching risk detected and forecasted at different spatial and temporal scales?

Among the 697 articles included in this review, only 23 articles specifically investigate the underlying causes of these offshore blooms. To detect them in the open ocean, researchers have developed a wide range of detection techniques to monitor the offshore distribution of sargassum. This is a well-represented topic in the literature, addressed in 107 articles, of which 60 focus explicitly on detection methods (see figure 5). Once detected, the next step involves forecasting the evolution of sargassum distribution across the ocean surface. This question is addressed in 40 articles. The detection of sargassum beachings is an important but somewhat under-represented area, appearing in 77 studies, though only 20 consider it their primary focus. The least explored area in this thematic sequence is the forecasting of beaching events, with only 13 studies addressing this topic.

3.3.1. Causes for proliferation

The causes of sargassum proliferation are generally investigated through correlative analyses that examine the temporal coincidence of bloom events with various environmental factors (measured *in situ* or modelled). Consequently, most studies explore a wide range of potential causes, but the most investigated drivers can be broadly grouped into climate-related variables and nutrient dynamics, including sources and transport dynamics.

Generally, climate patterns such as the Atlantic Multi-decadal Oscillation (AMO), North Atlantic Oscillation (NAO), Atlantic Meridional Mode (AMM) or the El Niño Southern Oscillation (ENSO) influence wind patterns, sea surface temperature and nutrient distribution. Some studies attribute recent bloom intensification in the Western tropical Atlantic Ocean to the variability of these indices over the past decade. For instance, abnormally high precipitation has been correlated with bloom events in three studies, suggesting a potential link between rainfall patterns and nutrient enrichment [19].

The Extreme Negative Phase of the NAO of the 2009–2010 winter is studied in four articles as a potential cause of sargassum transport from the Sargasso Sea to the NERR (the North Equatorial Recirculation Region, a narrow strip of currents situated between northern Brazil and western Africa bounded by the South Equatorial current to the south and the North Equatorial Counter Current to the North). In a 2020 article, Johns *et al* [20] describe the associated unusual westerly winds as '*triggering a biosphere "tipping point" that caused important ocean-scale ecosystem changes in the tropical Atlantic, with significant recurrent social and economic consequences*'. Finally, most studies ($n = 10$) propose that sargassum blooms could be linked with higher seawater temperatures. The effects of these climate-related variables are typically assessed using numerical modelling and *in situ* observations, as illustrated in figure 5.

Beyond climate drivers, nutrient availability is another key factor influencing sargassum proliferation, as for many macroalgae species [21]. The emergence of a persistent sargassum belt in the Western Tropical Atlantic Ocean, often referred to as the 'New Sargasso Sea', is thought to be closely linked to increased nutrient concentrations in this region. As such, numerous studies aim to identify the sources and transport mechanisms of nutrient inputs that could contribute to bloom development, mainly through analysis of *in situ* data (whether actual measurements or satellite images) (figure 5). The co-occurrence of blooms with the plumes of

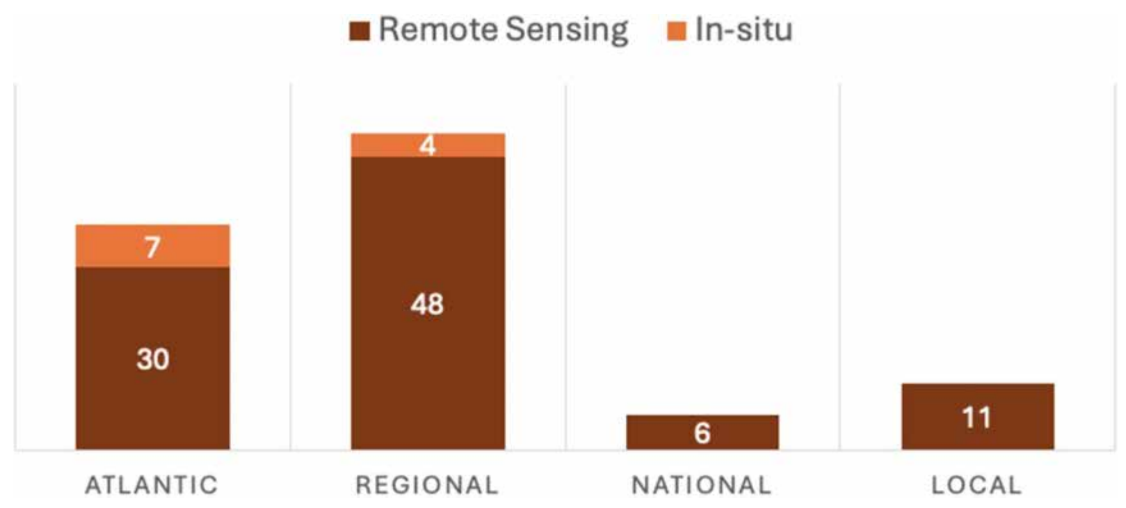

Figure 6. Number of articles by spatial scale of sargassum detections and used detection method.

major rivers such as the Amazon, Orinoco, and Congo has led to the hypothesis that riverine nutrient discharge—exacerbated by anthropogenic pressures such as intensified agriculture and urbanization—is a primary driver of sargassum growth, especially due to elevated nitrogen inputs [22]. However, other studies report conflicting findings that challenge the significance of riverine inputs [23]. In addition to fluvial sources, other nutrient pathways have been investigated, including atmospheric deposition of Saharan dust, which contributes iron and phosphorus to surface waters [24] as well as nutrient recycling via fish excretion [25].

3.3.2. Detection of the offshore distribution

The earliest recorded observations of holopelagic sargassum date back to the 15th century, during the initial trans-Atlantic voyages of European explorers. These *in situ* detections, documented by ship logs and navigational reports, represent the first evidence of floating sargassum in the North Atlantic Ocean. Throughout the early 20th century, oceanographic expeditions in the Sargasso Sea continued to report the presence of sargassum offshore [26].

Gower and King [18], in 2005, is the first record of a satellite detection of floating sargassum, in the GoM. Using data from the Medium Resolution Imaging Spectrometer (MERIS) onboard the European Space Agency's Envisat-1 satellite, the authors applied the maximum chlorophyll index—an algorithm originally designed to detect phytoplankton blooms—to identify the floating seaweed based on its characteristic red-edge reflectance. Since then, remote sensing has become the most popular detection method, being employed in almost 90% of articles that employ detection techniques (figure 6).

To improve the accuracy and consistency of satellite-derived sargassum estimates, several spectral indices have been developed. These indices are designed to exploit the distinct spectral signatures of pelagic sargassum and distinguish them from other floating materials. The floating algae index (FAI) has been among the most widely adopted, and more recently, the alternative FAI (AFAI) was introduced. AFAI incorporates additional masking algorithms to correct cloud cover and solar glint, improving detection reliability under challenging atmospheric conditions [27].

While satellite remote sensing remains the primary tool for offshore sargassum detection, other platforms have also been explored. A small number of studies ($n = 5$ in this review) have employed drone or UAV-mounted (UAV: Unmanned Aerial Vehicle) sensors to monitor sargassum in coastal and nearshore environments [28].

Figure 6 presents an overview of the spatial scales and detection methods employed across the reviewed literature. Detections of sargassum have largely focused on broad regional or basin-wide scales, with common study areas including the tropical Atlantic Ocean, the Caribbean Sea, the GoM, and the West Indies area.

3.3.3. Forecasting of the offshore distribution

Forecasting models complement detection tools by estimating the trajectories of detected sargassum mats (aggregation of floating algae) and predicting their arrival in coastal areas. To this end, Lagrangian particle-tracking models are the most widely employed method, used in 64% of the reviewed studies. In this context, 'Lagrangian' means that water motion and algal rafts are represented by virtually 'following' their path through time, like tracking the trajectory of a floating marker on the ocean surface. Within the Lagrangian framework, two primary modelling strategies can be

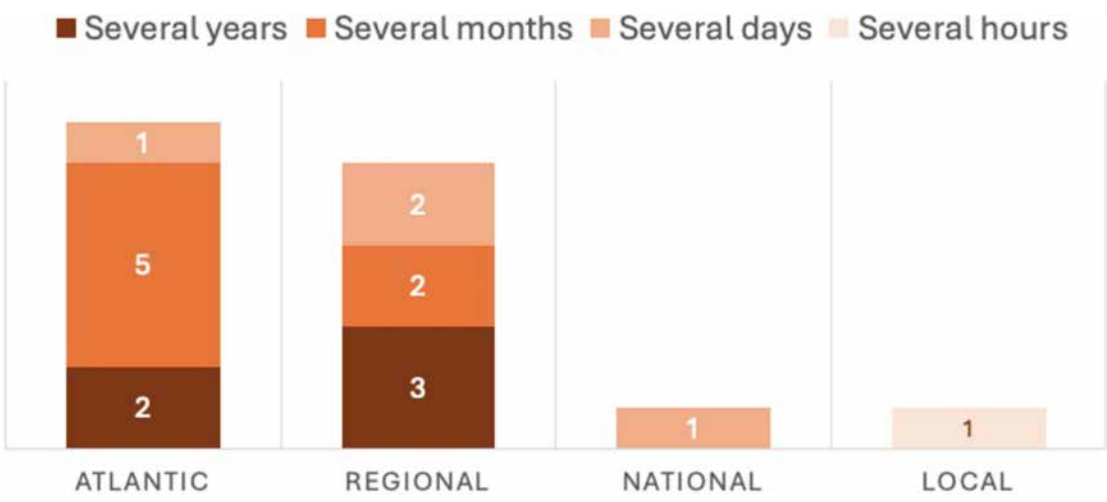

Figure 7. Number of articles by spatial scale of forecasting models and duration of the simulation (several years: model run for over 1 year, several months: model run for over 1 month and less than a year, several days: model run for over 1 d and less than 1 month, several hours: model run for less than 1 d).

distinguished. Forward-tracking algorithms simulate the drift of particles initialized from satellite-detected offshore mats to forecast their eventual beaching; this approach is implemented in 19 studies. Conversely, backtracking algorithms operate in reverse, tracing the origin of sargassum mats from known beaching sites; this method is used in 8 studies. The incorporation of biological processes- such as growth and mortality—is only featured in a minority (28%) of the reviewed models.

Alternative modelling approaches have also been developed. For instance, Jouanno *et al* [29] used an Eulerian approach, in which the properties of the water and algae are described at fixed-locations in space rather than by following individual particles. Their model integrates transport and biological factors by resolving currents and nutrient availability and models growth as a function of reserves of nutrients, dissolved organic matter, and the external medium. Beron-Vera *et al* [30] builds a model that considers sargassum as an elastic network evolving according to the Maxey–Riley equation, capturing its mechanical and transport dynamics. Finally, sargassum movement can also be modelled with a stochastic approach, with a few studies using Markov chains where the probability of the algae moving from one region to another is governed by a transition matrix derived from observed drifter trajectories [31, 32].

Forecasting articles' study areas show similar patterns as figure 6. Most forecasting efforts have been conducted at broad spatial scales—such as across the Atlantic Ocean or the Caribbean basin—with relatively few studies focusing on national or local coastal waters (two in our corpus, shown on figure 7). Simulations at these larger scales typically cover extended timeframes and aim to anticipate long-term inundation events (figure 7).

3.3.4. Detection of beaching events along the coasts

In addition to detecting and forecasting the offshore distribution of sargassum, several studies have specifically addressed methods used to assess the occurrence and dynamics of beaching events. While *in situ* beach surveys remain the most employed method, alternative techniques have been developed to provide automated, large-scale detection of sargassum accumulation along coastlines. Figure 4 shows that beaching detection methods are often described in articles whose main theme is characterization, valorization or impacts. Indeed, these methods usefully complement forecasting models by offering field validation and can guide decisions on the optimal timing for biomass collection, analysis, or valorization, and inform assessments of the ecological and socio-economic impacts of beaching events.

Most of the reviewed studies ($n = 77$) rely on *in situ* methods to detect beachings. Beach surveys to detect sargassum arrivals are used in 53 articles (figure 8), most of them focusing on beachings characterization. Other *in situ* techniques include fixed coastal cameras (14 studies), typically coupled with automated image-processing algorithms to distinguish sargassum from other shoreline features such as sand or rocks. A smaller subset of studies ($n = 8$) uses aerial imagery—captured via drones, UAVs, or helicopters—to map the spatial extent of sargassum coverage along the coastline. In addition, beachings can be indirectly detected through gas sensors, which measure emissions of hydrogen sulphide (H_2S) and ammonia (NH_4) produced during biomass decomposition. However, this method is infrequently used (2 studies), largely due to the limited deployment of such systems.

Remote sensing techniques have also been applied to beaching detection, albeit in a limited number of

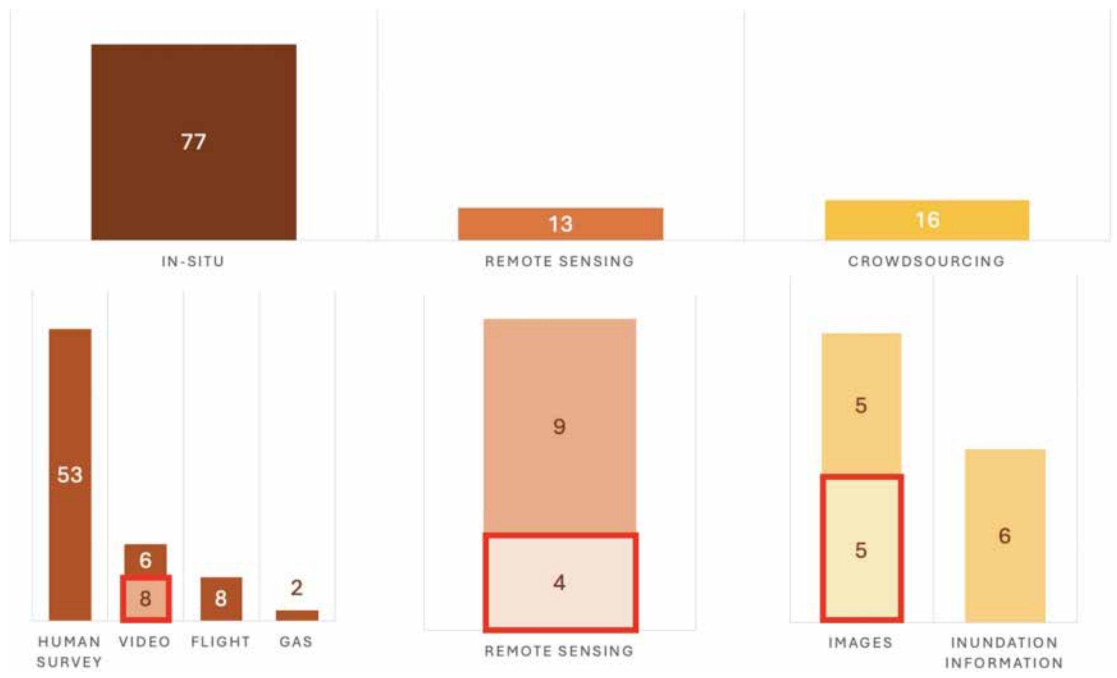

Figure 8. Number of articles by beaching detection method (in situ, remote sensing, crowdsourcing) and associated details, with or without use of AI to automate detections (red squares).

studies [13, figure 8]. This contrasts sharply with the widespread use of satellite data for detecting offshore sargassum distribution.

Finally, citizen science and crowdsourced data offer a promising avenue for detecting and documenting sargassum beaching events. Among the 16 listed in this corpus (figure 8), Bernard *et al* [33] first used such methods in 2019 by using a database of 154 observations referenced on the DEAL Guadeloupe's website as an input for its clustering model. Others like Arellano and Lazcano-Hernandez [34] with their Collective View app collect images, which are then filtered out by AI tools to remove false detections and automatically classify the potentially large number of crowdsourced images.

3.3.5. Forecasting of beaching events

Only a limited number of studies focus explicitly on forecasting sargassum beaching events. Most existing models derive coastal arrival predictions from offshore detections using Lagrangian trajectory simulations. However, few studies have sought to understand the specific drivers and conditions that lead to localized beaching events.

Closely related to broader distribution forecasting approaches, local distribution modelling aims to estimate the probability of sargassum landings along specific coastal segments. These models typically employ Lagrangian methods to simulate offshore drift but applied at finer spatial scales and in proximity to the coastline. For instance, Lara-Hernández *et al* [35] applied such a model to the Mexican Caribbean area, enabling the identification of areas with high beaching likelihood. A regional-scale operational tool, the Sargassum Inundation Reports (SIRs), was introduced in 2019 to estimate weekly coastal inundation risks across the Intra-Americas Sea at a spatial resolution of 10 km [36]. These reports use the FAI to quantify sargassum coverage in nearshore waters and derive beaching risk metrics. Validation efforts by Putman *et al* [37] and Trinanes *et al* [36] in 2023 have shown a strong correlation between the predicted risk levels and *in situ* observations, supporting the robustness of this modelling approach.

Certain studies investigate the climatic patterns that lead to local inundations. By relating currents, wind directions and coupling it with observed beachings, models like the SEAS model [38] can provide beach managers an estimated timeframe for when offshore-detected mats will make landfall on their beach. Bernard *et al* [33, 39] came up with an original approach, using clustering methods to identify the current patterns that lead to local inundations in the Lesser Antilles islands.

3.4. What environmental, economic, social and health impacts of sargassum beachings have been studied?

Sixty-eight studies focus primarily on sargassum characterization, while a total of 125 incorporate some form of characterization within broader thematic frameworks (see figure 4). Amongst those, most provide a general characterization of the stranded biomass (volume, level of decay, species composition). 47% of the studies estimate the chemical composition of the stranded algae and potentially the leachate resulting from its decomposition. Fewer articles characterize the biodiversity associated with beached sargassum and participating in the decomposition process (13%).

A total of 138 articles investigate the impacts caused by sargassum inundations, 122 of which focus on this issue (see figure 5). Most of them study environmental impacts (63%), and a sizeable minority documenting impacts on the economy (17%), social impacts (12%) and health impacts (11%) (percentages do not add up to 100% because some of the 138 articles document different types of impacts at once).

3.4.1. Characterization of sargassum beachings

Characterization studies frequently report spatial and temporal variability in biomass composition and volume. *Sargassum* species composition is reported in 48 articles as it varies temporally and geographically and is not always composed exclusively of *Sargassum* spp [40]. Some studies ($n = 5$) apply backtracking models to estimate the origin of the biomass and explore its relationship to observed variability [41–45]. Most of these general characteristics are reported as a complement to chemical, forecasting or impact studies, as seen on the topical heatmap in figure 4.

Amongst the 59 articles analysing the chemical composition of the sargassum, *m*ost ($n = 59$) evaluate the chemical composition of the beached biomass with the goal to valorize it. Specifically, heavy metal concentrations (esp. arsenic) are measured in 36 articles. For those valorization purposes, valuable compounds that are often characterized in beached sargassum include polysaccharides (alginate, fucoidans) which have a range of applications in the medical, food or cosmetics industries [1, 46], and phenolic compounds like phlorotannins that spark interest for their antioxidant properties [47]. Finally, chemical characteristics such as proximate composition (moisture, ash, protein, lipid contents) and nutrient ratios (especially C:N) also affect the potential viability for sargassum valorization [48] and are measured in half of the studies.

Fewer articles ($n = 17$) characterize the associated communities (ghost crabs, flies, birds… [49]). Although beached sargassum is largely considered a nuisance, it still serves as a habitat for different species. Here, we included only articles studying the communities associated with beached sargassum wracks, not offshore mats which provides ecosystem services to a whole range of other species. However, we also included articles documenting the biodiversity of stranded mats in nearshore waters as the decomposition process often starts as sargassum is approaching coastal waters.

3.4.2. Impacts of sargassum beachings

Most studied impacts are environmental, and amongst those, 42 studies detail effects on coastal fauna, with sea turtles being the most frequently studied group (59% of the 42). Documented impacts include alterations in nest incubation temperatures [50–52], nesting behaviour [53–58], and increased rates of false crawls [52, 55, 59–62]. Impacts on fish communities are less frequently documented (24% of fauna-related studies. Other affected taxa include crustaceans (16%), sea urchins (14%), worms (12%), and mollusks (9%). A substantial body of work (34 studies) addresses water quality degradation due to biomass decomposition. Of these, 62% report hypoxic conditions, while 24% focus on the emission of toxic gases, particularly hydrogen sulphide (H_2S) and ammonia (NH_4). Additionally, 15% highlight the role of sargassum as a vector for plastic pollution, as offshore mats tend to accumulate plastics which are subsequently deposited onshore [63]. Twenty-five studies assess changes to benthic ecosystems, particularly coral reefs and seagrass beds, which are equally represented. A smaller number of studies ($n = 14$) investigate the effects on mangroves and soil contamination, while 8 explore sargassum's influence on coastal geomorphology. The latter is subject to debate: while sargassum wracks may reduce shoreline erosion by buffering wave energy, mechanical removal efforts often result in sand displacement and may exacerbate erosion [64]. This paradox is recognized in several reports, with positive effects of unremoved wracks primarily documented on Galveston Island, Texas [65]. Conversely, a study in Mexico suggested that inaction may lead to erosion via the loss of protective benthic algae [66], indicating that the net effect of sargassum on erosion is context-dependent.

All other impacts are far less studied. They are often studied together, as economic activity has a direct impact on livelihoods and way of life and can change social structures and social cohesion. In the same way, health issues lead to social problems and unequally affect different social groups, together with also having an impact on local economies.

In terms of economic impacts, 12 studies report a change in tourism activities, mainly in well-known tourist areas (Riviera Maya, Costa Rica's Caribbean coast, Guadeloupe's coastal beach towns…). These studies include mainly interviews with the impacted actors. In the same way, a similar number of studies study the impact on fishing activities through fishermen interviews. Finally, a few articles ($n = 8$) document the economic impacts of material degradation near the coasts, with observational studies noticing increased corrosion and degradation of fishermen gear [67].

Social impacts of sargassum inundations on coastal communities are poorly studied. Half (11/21) of the listed documents is dedicated to this specific topic only. The other half studies social impacts in

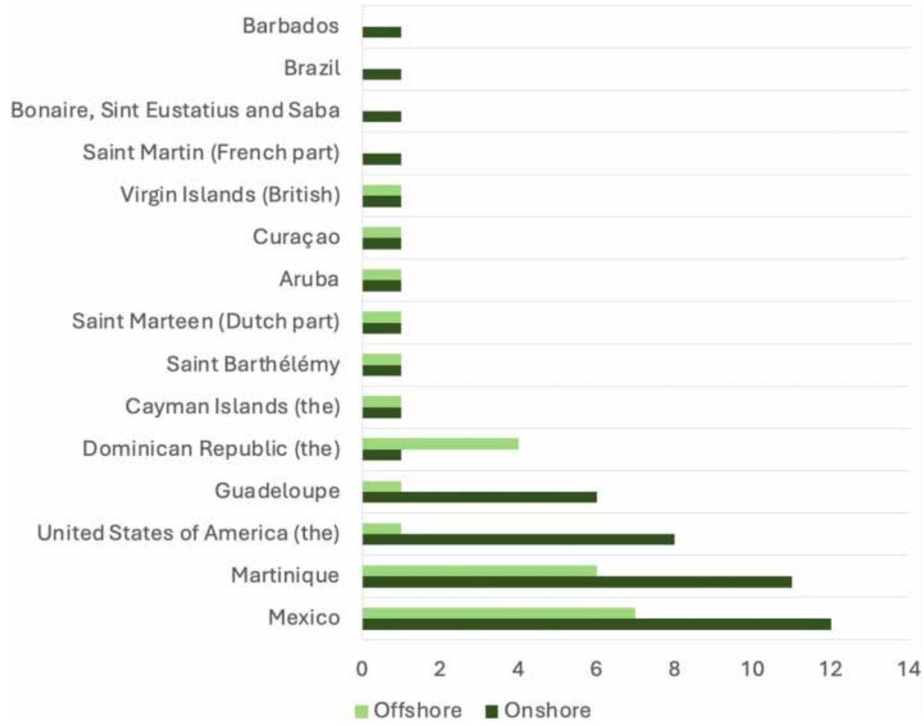

Figure 9. Distribution of offshore and onshore management actions implemented by country (in number of records).

conjunction with economic or health impacts. The main topic is public perception, often conducted through interviews (70% of studies). These interviews also show evidence of annoyances (foul odour, landscape degradation) that communities must adapt to in their daily lives.

Reported health problems are usually related to gas (H_2S, NH_4) inhalation and related symptoms (respiratory issues, neurological symptoms, ocular and skin irritations…) [68]. Few studies focus on sanitary impacts specifically (10/18): they all come from the University Hospital Martinique (by Resiere Dabor) or reports from DEAL Martinique.

3.5. Which actions have been taken to deal with sargassum beachings?

A total of 28 reviewed articles deals with beaching management. The valorization of sargassum biomass, which has gained significant attention in the past few years and is now the most represented topic in our corpus, with 255 documents. In addition, 82 documents are grouped into the « policy » category, with the goal of synthesizing all governance actions that have been taken by countries or institutions in the Western Atlantic area to tackle this problem.

Although most documents about valorization are journal articles, there is an over-representation of grey literature for policy and management articles. Indeed, as expected, management strategies and governance issues are addressed with reports or policy documents rather than academic studies (see figure 3).

3.5.1. Management of sargassum beachings

Evidence of implemented management actions shows a small majority of onshore techniques, both manual and motorized (e.g. using tractors and rakes) removal, reported in 38 documents mentioning the implementation of an onshore collection method. Removal at sea using boats or barriers is slightly less common, featured in 22 documents. Eleven papers report some beaches left untouched, without removal intervention, as in protected areas [69] or in locations where sargassum arrivals are sparse and can provide ecosystem services [70]. Most of the time, the removed sargassum are stored on site, either by making a pile a few meters from the beach or by burying the collected seaweed.

Mexico is the country where management actions are the most referenced and implemented, followed by French Caribbean islands and the United States (figure 9). Countries apply management measures both offshore and onshore. However, the small differences in articles' frequency distribution in figure 9 show onshore management techniques are most often applied by U.S., and offshore barriers by the Dominican Republic in order to protect its touristic coastline [71].

3.5.2. Valorization of sargassum biomass

Valorization emerges as the most common research theme in the present corpus: 255 documents (36% of all reviewed articles) address the potential for transforming sargassum biomass into value-added

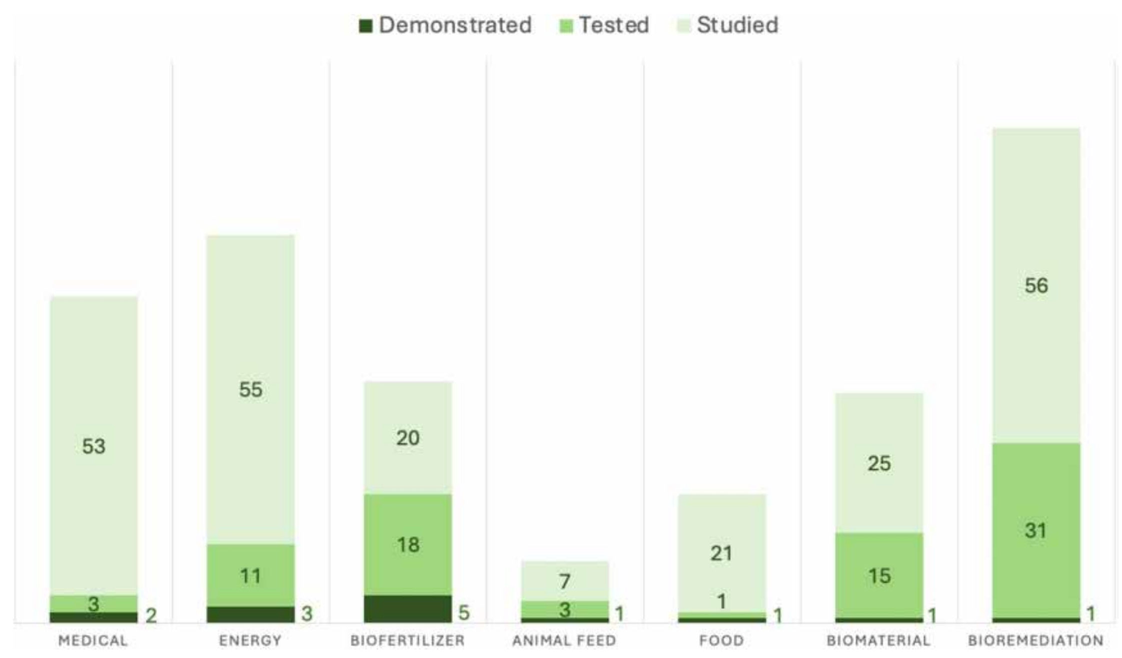

Figure 10. Article distribution by sargassum valorization theme and by level of development.

products. Based on content used to classify the relevant studies (figure 10):

- Medical-related products—58 articles explore the pharmacological and cosmetic potential of bioactive compounds found in sargassum, including those derived from alginates and other polysaccharides. These studies investigate antioxidant, anti-inflammatory, and antimicrobial properties with prospective applications in pharmaceutical and dermatological formulations.
- Energy production—69 studies evaluate the potential of sargassum as a feedstock for bioenergy, encompassing processes such as direct combustion, anaerobic digestion (methanization), and biofuel production.
- Agricultural applications (biofertilizers)—43 studies investigate the use of sargassum biomass as an agricultural input in 43 studies, either through solid digestate as compost or through liquid extracts as foliar or soil-applied biofertilizers.
- Animal feed—11 studies examine the incorporation of sargassum into animal diets (e.g. for shrimp, goats, poultry), assessing nutritional value, growth performance, and potential toxicity.
- Food Industry applications—23 articles focus on the use of sargassum-derived compounds for human consumption, investigating both its nutritional properties and potential functional ingredients in food products.
- Biomaterials—41 studies explore the use of sargassum in the development of construction and industrial materials. Applications include composites, bioplastics, and structural components, contributing to circular economy approaches.
- Bioremediation—The most frequently studied pathway (88 articles) concerns the use of sargassum for water decontamination, leveraging its biosorption capacity to remove heavy metals and other pollutants from aquatic systems.

To evaluate the technological readiness and feasibility of each valorization pathway, studies were further classified based on the reported level of development (three shades of green on figure 10):

- Studied—Conceptual or exploratory investigations, often theoretical or based on laboratory-scale experiments without direct implementation.
- Tested—Experimental demonstrations of the valorization pathway at pilot or small scale, with no evidence of commercial or routine application.
- Demonstrated—Documented evidence of reproducible outcomes and/or successful commercialization or integration into existing production systems.

A temporal analysis of publication dates reveals heterogeneous temporal dynamics across the different valorization pathways (figure 11). Bioremediation appears as the earliest explored valorization route, with initial studies emerging in the late 1990s. However, this research theme declined sharply (as seen with the stagnation of the blue line on figure 11), before regaining interest around 2020.

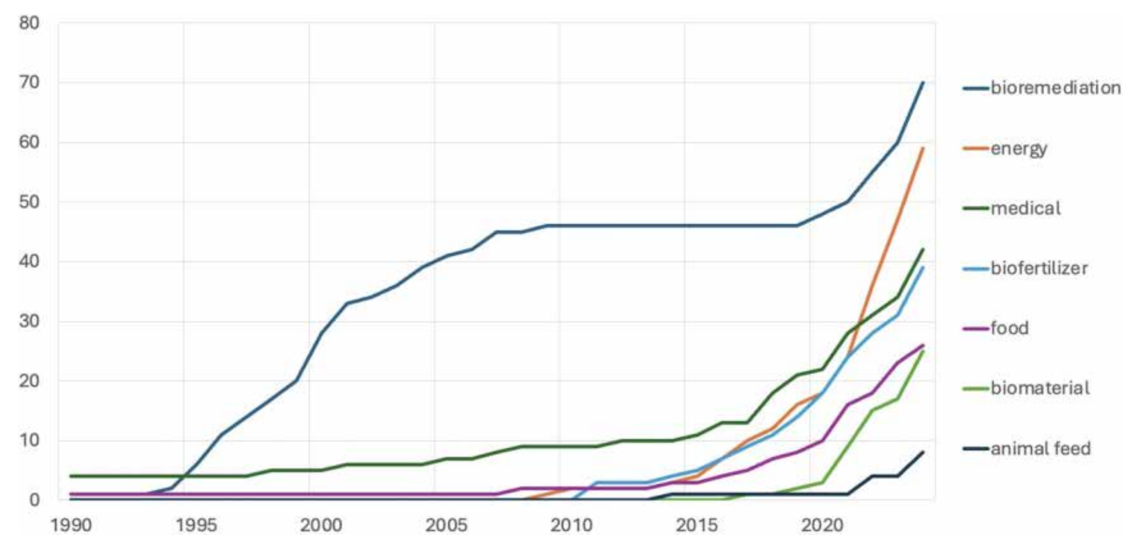

Figure 11. Cumulative number of articles by year for each valorization theme through the years.

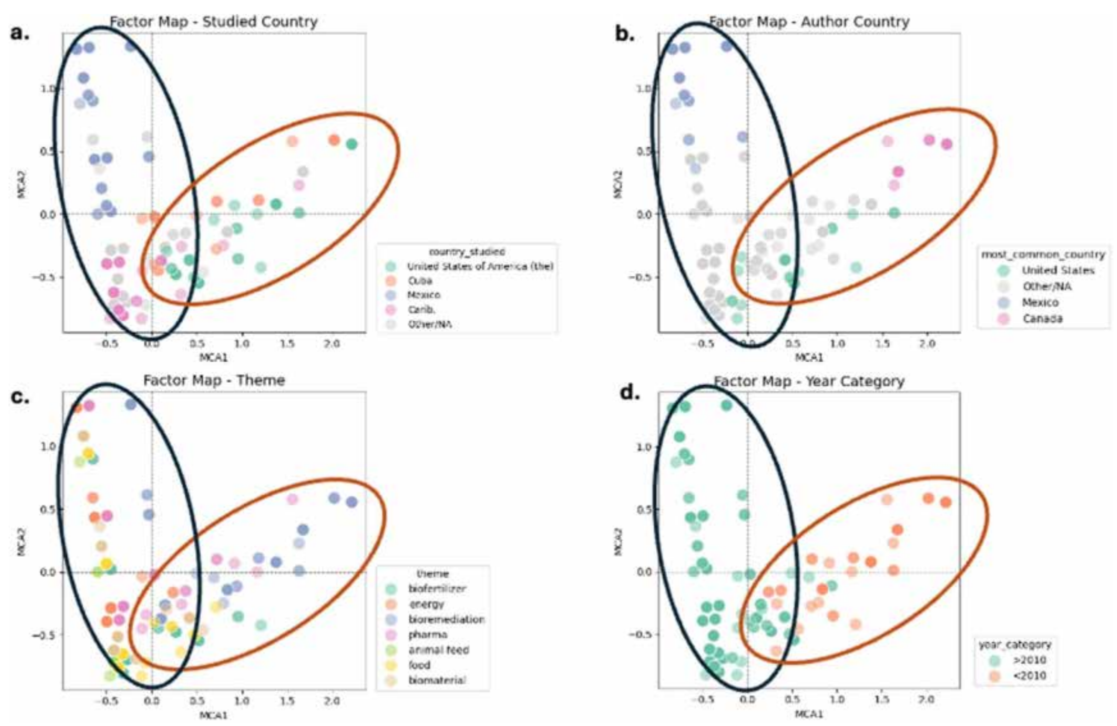

Figure 12. Factor maps of valorization articles in the MCA reduced plane & cluster delimitation (blue circle: Cluster 1, orange circle: Cluster 2). MCA1 axis mainly discriminates articles on their publication year and MCA2 discriminates articles based on geographical characteristics (origin of author and study area).

This early start, combined with recent resurgence, may account for the comparatively high number of documents dedicated to bioremediation in our corpus. Investigations into the medical potential of sargassum-derived compounds, particularly alginates, started prior to 2011 but remained limited. A sharp increase in research output after 2015 in this area is displayed on figure 11.

Investigations in other valorization pathways (energy production, biofertilizers, food applications, biomaterials, and animal feed) are more recent and followed the significant sargassum strandings in 2011. An acceleration in publication frequency across these themes occurs after the 2015–2020 period.

The factor maps of the MCA (figure 12)—realized on a subset of variables on valorization articles—reveal a geographical/temporal division in research dynamics. Temporal dimensions are discriminated by the MCA1 axis (x-axis of the factor maps) whereas, spatial dimensions, represented by both the country of origin of the valorized sargassum (Country Studied on figure 12(a)) and the first author's affiliation country (Author Country on figure 12(b)), are discriminated by the MCA2 axis (y-axis of the factor maps). Articles whose study area is in Mexico and the Caribbean area are mainly located on the left side of the MCA1 axis, overlapping with more recent themes. Studies focusing on Mexico have high MCA2 values and are highly correlated with Mexican authors (figure 12(b)). Conversely, articles in the second cluster (orange) study sargassum of U.S. or Cuban origin and from unspecified countries but written by American and Canadian authors (figure 12(b)). This suggests that early valorization research, particularly bioremediation, was largely led by American and Canadian institutions in the Sargasso Sea. More recent diversification in both thematic focus and regional contribution is reflected in the wider distribution of author and study countries in the post-2010 cluster (blue one on figure 12).

Overall, valorization research can be divided into two groups:

- Late 1990s—Early 2000s studies on bioremediation of sargassum from its original source area: the Sargasso Sea, mainly conducted by North American authors (orange cluster on figure 12).
- More recent studies led by Mexican institutions on a broader set of topics and carried out on beached sargassum in the Caribbean (blue cluster on figure 12).

3.5.3. Policy actions

A total of 82 documents were classified under the 'policy' category in this scoping review. This category includes all documents that referenced governance actions taken by countries in the region, encompassing investments in scientific research programs, legislative and regulatory measures, and stakeholder-targeted guidelines and recommendations. Despite this relatively high number of documents, several critical analyses point to persistent shortcomings in policy responses, highlighting a lack of timely government action [72], insufficient cross-sectoral collaboration [73, 74], and a broader absence of coordinated international governance mechanisms [72].

According to the corpus, approximately 76% of the identified policy content pertains to governance at the local or national level. These documents frequently outline management strategies drafted at varying scales—ranging from municipal-level action plans to island-wide or regional strategies. Prominent contributors include governmental agencies such as DEAL in Martinique and Mexico's SEMARNAT. However, these strategies are notably heterogeneous: for example, while certain jurisdictions, such as Texas, regulate sargassum removal from beaches (Texas Administrative Code, Chapter 15.4), others have implemented mandatory removal programs and actively fund cleanup operations (e.g., Martinique's PULSAR initiative and Mexico's seasonal beach cleaning efforts).

The remaining 24% of documents pertain to international-level governance, though nearly half of these consist of non-binding guidelines rather than enforceable policies or legal instruments. These include regional coordination initiatives like the Caribbean Regional Fisheries Mechanism's draft management plan [75], UNEP's recommendations for policymakers [76], and frameworks proposed under the UN Decade of Ocean Science for co-developing ocean policies [77].

This fragmented legal and regulatory environment results in a patchwork of responses. For instance, while France and its overseas territories have invested substantially in both mitigation and valorization efforts—launching multiple national action plans and implementing real-time air quality monitoring through ARS and Madininair—many other countries lack the necessary infrastructure to respond efficiently. Notably, the bulk of policy efforts in the region prioritize the development of management strategies over structural legal reform. Some focus on operational aspects—such as guidelines for manual versus motorized removal, barrier specifications, or site-sensitive protocols for turtle nesting areas—while others propose participatory and knowledge-sharing approaches, including stakeholder mapping, Group Model Building workshops [78], and the integration of local ecological knowledge into policy formulation [74, 79].

Ultimately, the review of these 82 documents highlights both the dynamism and the fragmentation of sargassum-related policies. While multiple governance levels are actively engaged, particularly at the national and subnational scales, the lack of binding international coordination, the uneven legal status of the algae, and limited enforcement mechanisms highlight the pressing need for a coherent, cross-border legal and policy framework capable of supporting long-term adaptive management strategies.

An international coordination should be promoted through the sharing of information and best practices between countries in the region, through the funding of international scientific consortia, and through any international initiatives. Furthermore, bridges must be built between policymakers and scientists, as public policies must also be able to take ownership of the results of research on sargassum. In that perspective, a policy brief accompanying this work has been published (Julia *et al* in press [80]), and is aimed at a wide audience, including policymakers.

4. Discussion

The analysis of the 697 included articles revealed a rise in attention towards sargassum-related themes

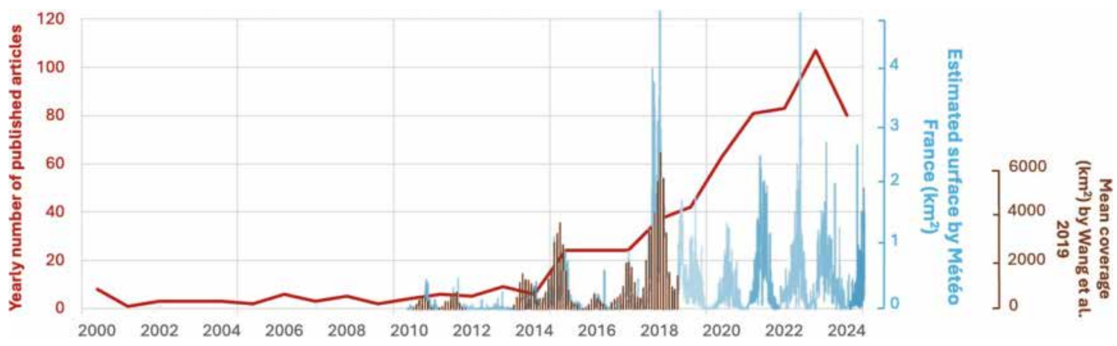

Figure 13. Total number of published articles superimposed with mean sargassum coverage (km^2) estimated by Wang et al. 2019 and Surface estimated by Météo France (km^2) (https://meteofrance.mq/fr/sargasses/bilan-de-la-saison-2024-des-echouements-de-sargasses-en-martiniquehttps://meteofrance.mq/fr/sargasses/bilan-de-la-saison-2024-des-echouements-de-sargasses-en-martinique).

during the last few years, particularly in areas such as sargassum detection (focused on its pelagic phase), localized impact studies, and valorization efforts. However, several key aspects remain underexplored. These include a deeper understanding of the drivers behind offshore sargassum proliferation, the development of large-scale and coordinated monitoring efforts, comprehensive characterization of beached biomass—including its variability and stabilization for industrial applications—and the integration of more accurate and complete forecasting systems with detection technologies.

Temporal analysis of publication distribution (figure 2) shows a sharp increase in research activity after 2011, coinciding with the onset of large-scale sargassum blooms in the region. This trend aligns with the findings from previous studies [81, 82] and reflects growing academic and policy interest in understanding and addressing this emergent phenomenon. Furthermore, the three research 'periods' that were identified on figure 2 correspond to increasing frequency and volume of beaching events in the region. Notably, when the timeline of publication frequency is juxtaposed with satellite-derived sargassum coverage data from the GASB (figure 13), a correlation emerges between bloom intensification and increased scientific production. Following the major beaching events of 2011 and 2014, a discernible evolution in research priorities was observed (figure 2). Initial investigations focused primarily on the occurrence and composition of beached sargassum. As the phenomenon became more frequent and widespread, subsequent studies increasingly addressed the cascading impacts on coastal ecosystems and human communities. From approximately 2017 onwards, there was a notable pivot toward policy analysis and the development of management strategies, reflecting a growing recognition of the need for systematic mitigation and adaptation efforts. Recent years have seen a diversification in research themes, highlighting both the global spread of the problem and the multidisciplinary responses it has elicited. In particular, a growing number of studies focus now on valorization strategies, indicating that this environmental challenge can be seen as a potential resource. This trend suggests a broader transition in the research landscape, from reactive assessment to proactive innovation.

Analysis of the accessible content related to each of our sub-questions revealed scientific gaps which could be investigated in further works. First, the evidence gathered on the causes of sargassum proliferation offshore showed the multi-factorial nature of bloom dynamics. This complexity presents a challenge in determining which specific drivers have been the most comprehensively studied. Particularly, conflicting results concerning the contribution of riverine nutrient inputs underscore the necessity for continued research to better understand the complex interplay between factors causing blooms in the GASB.

Effective management of sargassum depends on accurate detection and forecasting systems, for both offshore drifting trajectories and coastal beaching dynamics, which serve as essential tools for decision-making and as research areas in their own right. Used operationally, they inform early warning systems, guide coastal response strategies, and support industrial valorization processes. Scientifically, they help understanding sargassum dynamics and refine predictive models. As shown on figure 5, the development of forecasting methods strongly depends on detection tools to initialize models and validate predictions, as both topics are often studied conjointly.

Regarding offshore detection methods, current systems predominantly rely on remote sensing, which has largely supplanted earlier *in situ* techniques. Indeed, the visual and point-based sampling limitations of these early methods proved inadequate for characterizing the spatial extent or seasonal variability of sargassum aggregations at basin scale. The absence of synoptic observation tools at the time complicated efforts to delineate the geographical boundaries of the Sargasso Sea itself [2]. However, both approaches should be pursued in parallel. Indeed, ground-truth observations remain essential for calibrating remote sensing algorithms and the development of advanced *in situ* methods—such as the deployment of autonomous oceanographic platforms or drifters tangled in sargassum mats—could enhance the validation and refinement of remote-sensing-based models.

Despite advances integrating biological processes (growth, mortality) into sargassum transport models, forecasting capabilities remain limited and imperfect. Most studies are done at large scales and few study dynamics at higher resolutions. A more integrated framework—combining satellite and *in situ* observations with numerical models and a better understanding of the biological properties driving sargassum growth—would provide a better base for sargassum forecasting.

Although remote sensing offers unparalleled coverage of offshore sargassum distributions, most studies continue to favour *in situ* methods for monitoring beach strandings. Nearshore observations, typically conducted via beach surveys or fixed cameras, are generally more cost-effective and yield reliable data, albeit over limited spatial extents. Innovations in *in situ* monitoring—such as the incorporation of artificial intelligence and crowdsourced observations—may provide valuable datasets for validating predictive models of sargassum landings. These enhanced observations strategies could play a pivotal role in bridging offshore detection with actionable coastal forecasts.

We also showed the interest for an extensive characterization of sargassum's chemical composition, with particular emphasis on its heavy metal content (see section 3.4.1). This focus stems from sargassum's biosorbent capacity which participates in the accumulation of these metals and makes it a bioindicator of marine pollution. However, this feature also induces a risk of contamination in coastal ecosystems [81] and a risk for the valorization of this biomass. The high variability in compounds, especially heavy metals, stays a concern. In the reviewed documents, measured total arsenic concentrations range 3.67–217.87 ppm dw, exceeding most global guidelines. Such disparities complicate efforts to standardize valorization processes and assess environmental risks. In the same way, some studies report highly variable amounts of extractable alginate in sargassum, posing challenges for its consistent utilization in industrial applications. This inconsistency may be attributed to the varying states of the biomass at the time of collection, ranging from freshly beached specimens to those that have undergone several days of decay. This lack of understanding of the causes of this variability in compounds and of the dynamics of heavy metal biosorption by sargassum hinder the development of effective management and valorization, increasing contamination risks if mismanaged.

Regarding the impacts of sargassum beachings, the most documented impacts are environmental. However, for a lot of them, these effects stem from management practices (e.g., mechanical beach cleaning, offshore barriers) rather than sargassum itself [83], with direct causality often inconclusive [84]. Impact studies could then benefit from continuous, long-term, large scale monitoring projects, aiming to assess impact at the ecosystem level, as well as carrying out transdisciplinary work to cross-study environmental impacts with socio-economic consequences of the beaching events.

The policy response has been numerous but fragmented. Despite these efforts, critical legal studies highlight the absence of a harmonized international legal framework. In operational terms, sargassum influxes across the tropical Atlantic share several characteristics with large-scale marine pollution events such as oil spills: both are transboundary, rapid in onset, and demand coordinated regional responses. Yet, while international frameworks such as the International Convention on Oil Pollution Preparedness, Response and Cooperation (OPRC, 1990) and regional mechanisms under the Cartagena Convention ensure immediate collaboration in the case of an oil incident, no equivalent structure currently exists for sargassum events. Developing a similar framework combining early-warning systems, shared monitoring protocols, and resource mobilization mechanisms could transform the management of sargassum beachings from reactive cleanup to proactive preparedness.

Policy responses and valorization stay hindered by the legal status of sargassum which remains ambiguous and highly context-dependent, differing, for instance, based on whether the algae is considered living or decomposed, or where it is located (in water, on beaches, or in storage). In 2022, David [85] describes sargassum as an 'unidentified legal object', underlining the jurisdictional uncertainty surrounding its classification and management. Addressing these inequalities requires the creation of a regional coordination platform that facilitates long-term monitoring, capacity building, and data-sharing among Caribbean and West African nations.

5. Outlook

This review maps a rich and growing body of literature on sargassum beachings. Despite advances in detection, impact assessment, and valorization, significant gaps remain in understanding bloom drivers, biomass stabilization and governance frameworks. Strengthening international collaboration and standardized monitoring will be crucial to address these challenges. While providing landscape of the research work on the topic, this work could be complemented by other studies aiming at answering more specific questions and overcoming the limitations of the scope of this review.

Our analysis of author affiliations reflects a strong research presence in Mexico, the United States, and France—countries that have significantly contributed to sargassum-related knowledge. However, this geographic concentration also underlines the need to support and better capture research efforts in underrepresented regions, particularly in smaller Caribbean and Central American states. Many of these countries may engage in relevant monitoring or management activities that are not widely documented or published within the global academic infrastructure. Further work could focus on improving data accessibility and encouraging the dissemination of local knowledge, especially in regions with limited connectivity to major indexing systems.

Similarly, while our analysis of grey literature provided valuable insight into management practices, much of the documentation originated from a limited number of countries. Expanding the scope to include locally produced and informal sources—possibly through fieldwork or regional collaborations—could shed light on unreported or context-specific strategies developed by small island nations.

Our review also deliberately focused on research dealing with beached sargassum, excluding studies on holopelagic sargassum and its open-ocean biodiversity. This opens an opportunity for future reviews to explore the ecological transitions between floating and stranded sargassum, particularly in terms of associated species and habitat changes. A systematic synthesis of this kind could enhance our understanding of the biodiversity continuum across marine and coastal ecosystems.

Additionally, the notion of 'policy' in this review was interpreted broadly, encompassing not only binding regulatory actions but also strategies, funding programs, and planning documents. This inclusive approach highlights the richness of institutional responses, but further investigation could differentiate between aspirational frameworks and fully implemented regulations, offering a clearer view of policy effectiveness across regions.

Finally, while this study was developed to support policy thinking in the Caribbean—especially the French West Indies—it is essential to recognize the growing relevance of sargassum events along the West African coast [74, 86]. Although outside the scope of this analysis, a subset ($n = 26$) of the retrieved literature focused on countries like Senegal, Ghana, Nigeria, and Côte d'Ivoire. Further work could explore these regions more systematically, allowing for a comparative perspective on management strategies, ecological impacts, and research priorities between the American and African sides of the Atlantic Ocean.

Like the spread of invasive species as Lionfish in the Caribbean region or the American blue crab *Callinectes Sapidus* in Mediterranean Sea, the proliferation of sargassum represents a sudden regime shift in ecosystem structure and functioning. Its emergence illustrates how subtle shifts in climate, ocean circulation, and nutrient dynamics can cascade into new, large-scale ecological realities. Understanding the sargassum crisis within this comparative framework highlights its value as a sentinel event—a case study in how coupled ocean–climate–human systems is being rapidly reconfigured under global change.

Addressing the emerging questions brought to light in this paper and broadening the geographical and thematic scope of future reviews could contribute to a more inclusive—context-sensitive, and operational understanding of sargassum dynamics worldwide. But beyond the specific case of sargassum, the insights gathered here may inform responses to other abrupt or large-scale ecosystem disruptions. By situating the sargassum experience within this wide set of environmental challenges, future research can help build more resilient frameworks for anticipating and managing the ecological transformations that lie ahead.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary data 1 available at https://doi.org/10.1088/1748-9326/ae4d60/data1.

Supplementary data 2 available at https://doi.org/10.1088/1748-9326/ae4d60/data2.

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