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Sargassum beachings challenges in the Western Atlantic

A scoping review

Research papers

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***Sargassum* beachings challenges in the Western Atlantic**

A scoping review

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Résumé

Au cours de la dernière décennie, les échouements récurrents de sargasses holopélagiques (qui restent pélagiques tout au long de leur cycle de vie) sont devenus une préoccupation écologique et socio-économique majeure dans l'Atlantique tropical, affectant particulièrement la Caraïbe et le Golfe du Mexique. Cette revue cartographie les données existantes sur ces échouements, synthétise les connaissances actuelles, identifie les thématiques clées et met en lumière les lacunes de la recherche.

A travers une analyse de la littérature scientifique, académique et grise, cette revue révèle un corpus de recherches en expansion rapide avec pour thèmes principaux la détection des Sargasses en mer, l'évaluation des impacts de leurs échouements et la valorisation de cette ressource. En revanche, elle met en évidence des lacunes et des opportunités de recherche supplémentaires, notamment pour mieux comprendre les facteurs responsables de la prolifération des Sargasses en mer, la nécessité d'un suivi à plus grande échelle, la caractérisation de la composition des Sargasses échouées, leur variabilité et leur stabilisation pour des usages industriels, ainsi que le besoin de systèmes de prévision plus précis et complets, utilisés en synergie avec les méthodes de détection.

Mots-clés

Sargasses, échouements, Caraïbes, Golfe du Mexique, Atlantique Ouest, revue systématique

Classification JEL

D8, D9, J61.

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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 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 Sargassum, which stays pelagic throughout all ifts life cycle, 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.

Keywords
Sargassum, Caribbean area, Gulf of Mexico, Western Atlantic Ocean, evidence map

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Introduction

Sargassum is a genus of mainly brown benthic seaweeds including two holopelagic species, *Sargassum* fluitans (Børgesen) Børgesen 1914, and *Sargassum* natans (Linneaeus) Gaillon 1828, which have historically thrived in the waters of the Sargasso Sea, in the North Atlantic Ocean and have been documented in this area since the first records in the 15th century (1). In recent years, however, researchers have observed an unprecedented shift in the distribution and biomass of *Sargassum* (4). 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 8,000 kilometers from the west coast of Africa to the Caribbean Sea and the Gulf of Mexico (5). This expansion of its habitat distribution has led to a significant rise in the frequency and intensity of holopelagic *Sargassum* beaching events in countries of the tropical Western Atlantic region (5).

Ecologically, holopelagic *Sargassum* provide refuge, nursery grounds, and feeding zones for a wide range of marine species in a pelagic context (2,3), but when they arrive at the coast, beaching events trigger a suite of environmental, public health, and socio-economic impacts that are all immediate and long-lasting over time. Environmentally, large quantities of decomposing *Sargassum* in coastal zones can smother coral reefs and seagrass beds, deplete dissolved oxygen in the water column, and disrupt marine food webs (6). These ecological disturbances are compounded when stranded biomass accumulates on beaches, where anaerobic decomposition releases gases such as hydrogen sulfide, a toxic gas associated with respiratory issues and unpleasant odors that pose risks to human health and quality of life (6). 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. 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 (7). 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 (8). Its high nutrient content can be harnessed in agricultural and industrial applications (8), 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 biomass availability, and concerns over contamination with heavy metals and pathogens, which limit the use of *Sargassum* in food or animal feed applications (8), 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 these 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 breadth of current knowledge surrounding *Sargassum* beachings in the tropical Western Atlantic area, and to specifically address the following three research questions:

(i) How are *Sargassum* proliferation and beaching risk detected and forecasted at different spatial and temporal scales?
(ii) What environmental, economic, social and health impacts of *Sargassum* beachings have been studied?
(iii) Which actions have been taken to deal with *Sargassum* beachings?

1. Methods

1.1 – Type of review and protocol

This scoping review follows the guidelines of the Collaboration for Environmental Evidence for conducting systematic maps (9), and conforms to the reporting standard "Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews" (PRISMA-ScR). 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 (10). Slight deviations to the protocol emerged throughout the synthesis process and were acknowledged separately.

1.2 – Searching for articles

The search strategy was developed using a test list of 46 articles (covering the 1999-2024 period). These helped identify keywords and constructing the search string that maximized comprehensiveness and specificity. The retained search string 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$))) (10).

The main search was conducted on September 27th, 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 or 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 organisational websites between September 27th 2024 and October 15th 2024.

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

1.3 – Screening of articles

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

Table 1. Eligibility criteria used for article screening (10)

	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 Coasts of the Atlantic Ocean (for *Sargassum* beachings) • On the Atlantic Ocean (including the Sargasso Sea) for studies about *Sargassum* offshore distribution	
Language	• Articles in French, English, Spanish or Portugese	
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

First, articles were screened for eligibility based on their title and abstract by a first reviewer (called DYO) after checking for screening consistency with a second reviewer (called 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 (11) 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%, 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.

1.4 – Data coding and extraction strategy

Data coding and extraction were 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 were discussed and resolved. The following information was extracted or coded, when applicable, in a spreadsheet:

- 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' countries of affiliation was selected and assigned to the "most_common_country" column.

1.5 – Analysis and evidence mapping

The information extracted from all included articles was analyzed and synthesized narratively. First, a general depiction of the research landscape was conducted by analyzing the publication dates of all articles by research theme and the geographical distribution of authors and study areas. The analysis of author collaboration patterns was carried out manually by using VOSviewer to visualize authors' co-authorship networks. Then, issues associated with *Sargassum* beachings were analyzed 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.

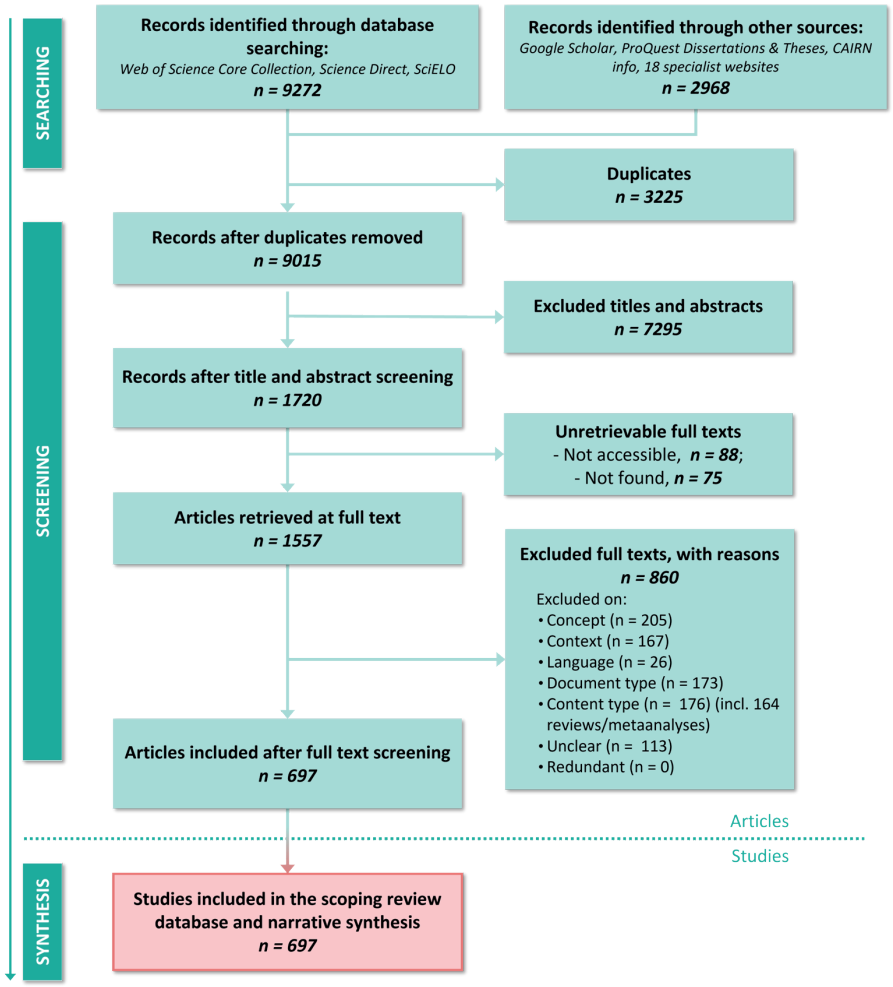
For the articles in the valorization category, which represents a large part of our corpus, a Multiple Correspondence Analysis (MCA) was performed to reduce the complexity of the information. This statistical analysis aims at reducing the complexity of a dataset by grouping variables according to a few axes, 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 co-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 relationships between those four variables.

2. Results

2.1 – Description of the review process

The initial search yielded 12,240 results, which resulted in 9,015 articles after removing duplicates (Figure 1). A total of 1,721 articles were retained after title and abstract screening, and after searching for full texts and full text screening, 697 articles met our inclusion criteria and were selected for the scoping review database.

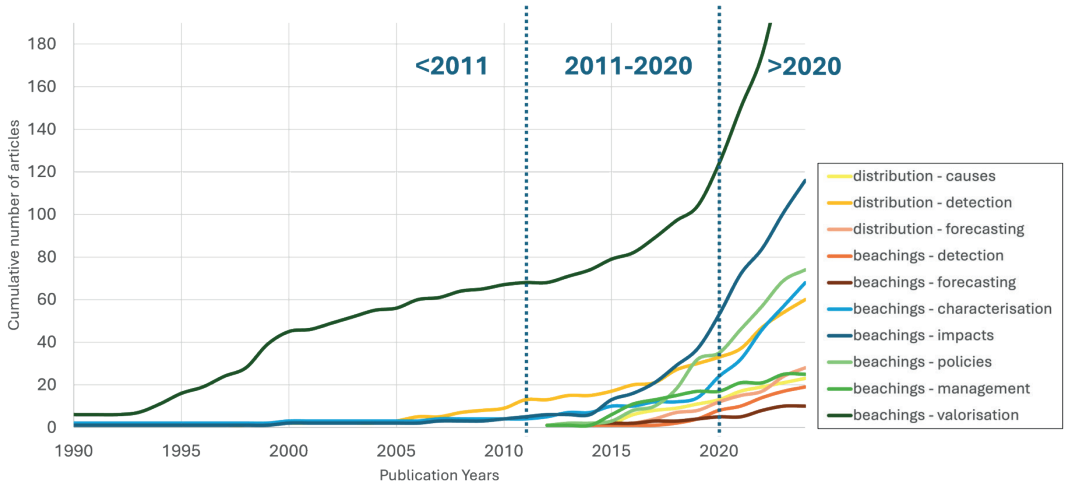
Figure 1. ROSES flow diagram (12) for article selection



2.2 – Description of the evidence

An analysis of the publication dates of the selected articles reveals that the majority (85%) of studies have been published after 2011. 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 especially by exploiting the algae's biosorption potential or investigating its capacity to remove pollutants from contaminated water (13). In 2005, Gower *et al*. published the first record of satellite detection of pelagic algae in the Gulf of Mexico (14), 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 started 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).

Figure 2. Cumulative number of articles covering each sub-theme through time (shades of orange: themes related to the first sub-question, shades of blue: themes related to the second sub-question, shades of green: themes related to the third sub-question)

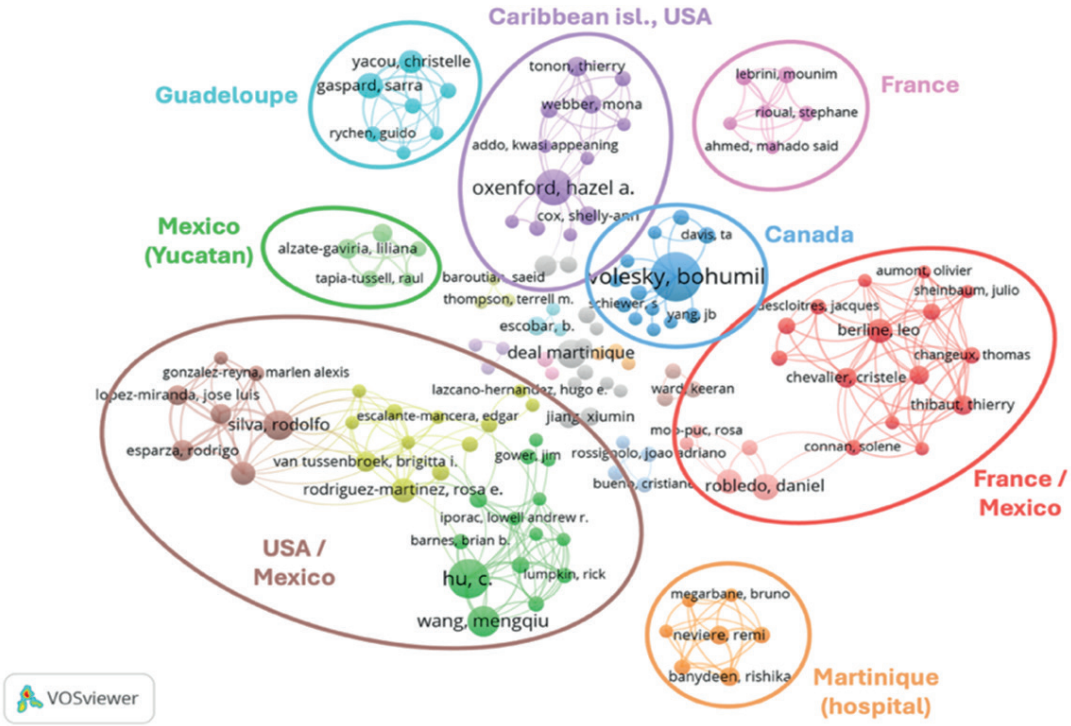


An examination of the articles' study areas reveals a clear concentration of research efforts along the Mexican coasts, with 26% of all articles studying *Sargassum* beached on Mexican shores or detected in Mexican waters (especially the states of Quintana Roo and Yucatan). The United States of America 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 affiliated with Mexican institutions, followed by 14% with U.S. institutions, 14% French, and 5% British.

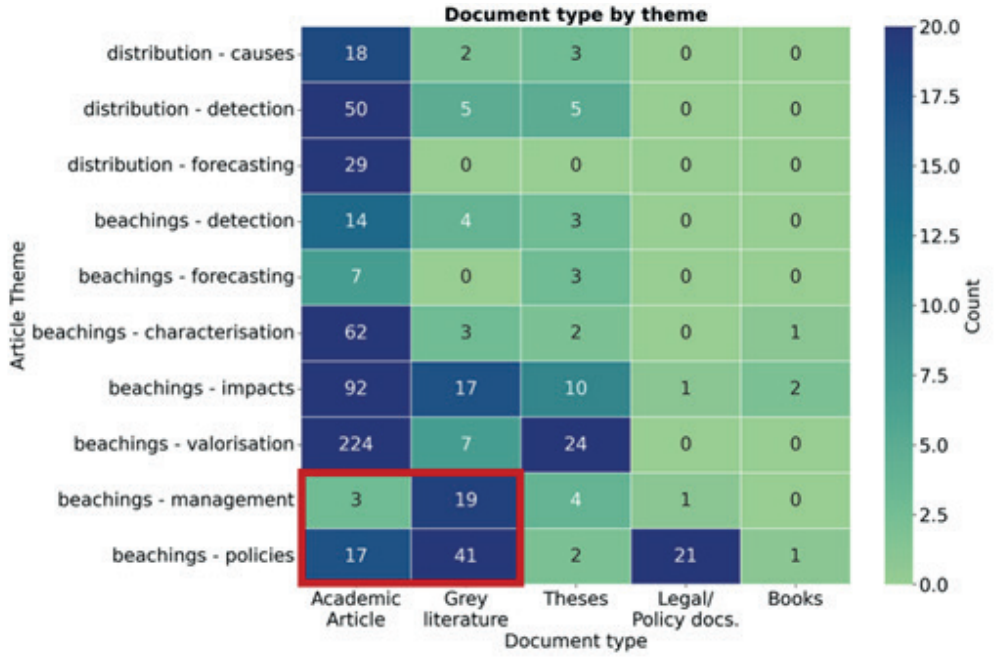
The landscape of *Sargassum* research is notably diverse, with contributions from a wide array of researchers. Amongst all 2,118 authors present in our corpus, most of them only occasionally contributed to *Sargassum*-related research with only one published article (83%), 342 (16%) had more than two publications, and only 48 (2%) published 5 articles or more, highlighting the dispersed and intermittent nature of contributions. To explore collaboration patterns, a co-authorship network was constructed using VOSviewer, focusing on the subset of authors with more than two publications. The resulting visualization (Figure 3) illustrates the international collaborative landscape of *Sargassum* research, highlighting the increasing integration of European and American actors by collaborating with different Caribbean authors but also the fragmented nature of the research landscape with certain groups still working in silos.

Figure 3. Co-authorship network of authors having more than two articles in our corpus created with VOSviewer. In this figure, few authors' names have been included to describe the authorship group, but the choice has been made randomly.



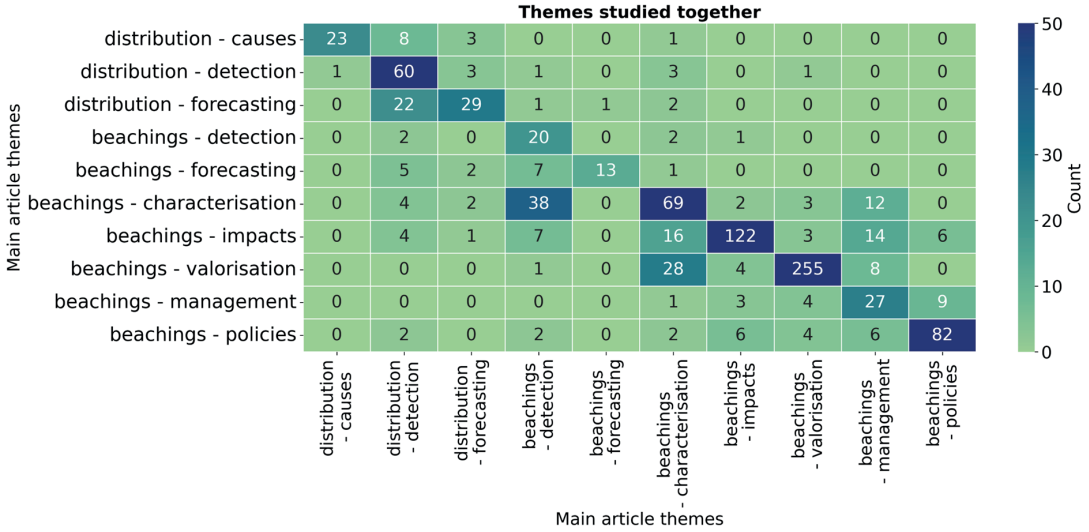
Although most documents of the corpus are journal articles, the distribution of document themes analyzed in relation to document type shows that certain themes, namely management and policies, corresponding to the red square on Figure 4, are addressed more in the grey literature (e.g. institutional or 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 4).

Figure 4. Heatmap of document type by document theme



Furthermore, we evaluated how the different research themes intersected in our corpus' articles. While previous analyses considered only the main theme of each article, we here incorporate secondary themes to capture a more nuanced understanding of how topics are studied in conjunction. The following heatmap represents, for each main theme, the number of articles dealing with additional "secondary" themes. In the following sections, variables (themes) are analyzed using all information points, not only articles for which the "main theme" is the considered variable. Most themes are studied individually (see the high numbers on the diagonal on Figure 5) but certain themes are recurrent. For instance, we see on Figure 5 that the number of information points related to characterization is much higher than the number of articles focused 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. 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



2.3 – How are *Sargassum* proliferation and beaching risk detected and forecasted at different spatial and temporal scales?

Among the studies included in this review, 23 articles specifically investigate the underlying causes of these offshore blooms. To detect these blooms when they occur in the open ocean, researchers have developed a wide range of detection techniques to monitor the offshore distribution of *Sargassum*. This is extensively covered 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 important, yet relatively under-represented in the literature, 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 themselves. Only 13 studies have investigated this topic.

2.3.1 – Causes for proliferation

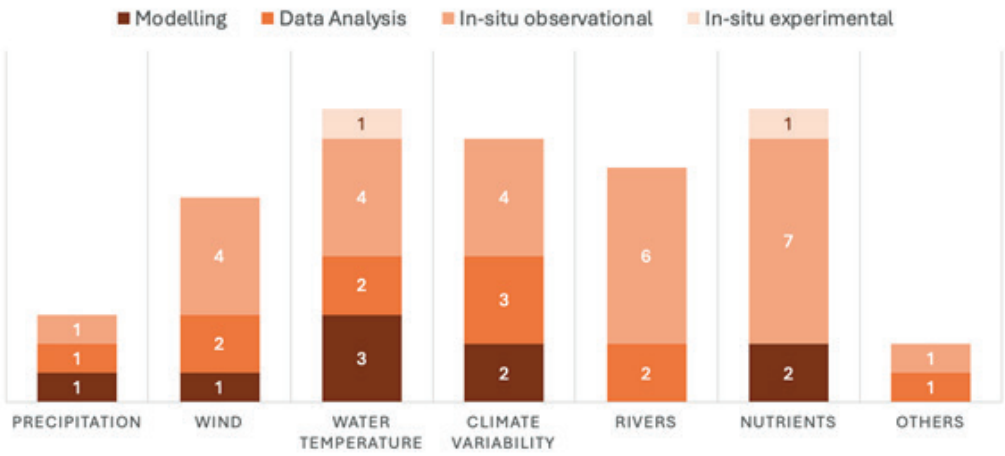
The causes of *Sargassum* proliferation are generally investigated through correlative analyses that examine the temporal coincidence of bloom events with various environmental factors (measured in-situ or modelled). Consequently, most studies explore a wide range of potential causes. However, the primary categories of 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), and 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 to the variability of these indices over the past decade. For instance, anomalously high precipitation has been correlated with bloom events in three studies, suggesting a potential link between rainfall patterns and nutrient enrichment (15).

The Extreme Negative Phase of the North Atlantic Oscillation (NAO) of the 2009-2010 winter is studied as a potential cause of *Sargassum* transport from the Sargasso Sea to the NERR in four articles. In a 2020 article, Johns *et al.* (16) 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 6.

Beyond climate drivers, nutrient availability is another key factor that can influence *Sargassum* proliferation, as it is common for many macroalgae species (17). 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. The co-occurrence of blooms with the plumes of 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 (18). However, other studies report conflicting findings that challenge the significance of riverine inputs (19). 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 (20) as well as nutrient recycling via fish excretion (21).

Figure 6. 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 measures including satellite images, In-situ experimental: study involves some kind of experiment done on site)



2.3.2 – 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 (22).

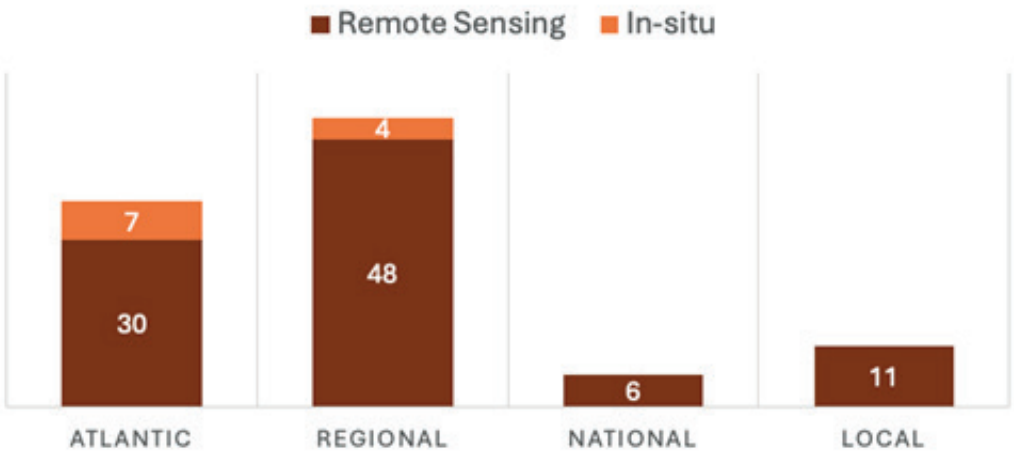
Gower *et al.* (2005) provide the first record of a satellite detection of floating *Sargassum*, in the Gulf of Mexico (GoM) (14). Using data from the Medium Resolution Imaging Spectrometer (MERIS) onboard the European Space Agency's Envisat-1 satellite, the authors applied the Maximum Chlorophyll Index (MCI)—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, used in almost 90% of articles utilizing detection techniques (Figure 7).

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 Floating Algae Index (AFAI) was introduced. AFAI incorporates additional masking algorithms to correct for cloud cover and solar glint, improving detection reliability under challenging atmospheric conditions (23).

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 sensors to monitor *Sargassum* in coastal and nearshore environments (24).

Detections of *Sargassum* have largely focused on broad regional or basin-wide scales, with common study areas including the tropical Atlantic, the Caribbean Sea, the Gulf of Mexico, and the West Indies (Figure 7). Figure 7 presents an overview of the spatial scales and detection methods employed across the reviewed literature.

Figure 7. Number of articles by spatial scale of *Sargassum* detections and used detection method, and map of studied zones (approximative location)



2.3.3 – Forecasting of the offshore distribution

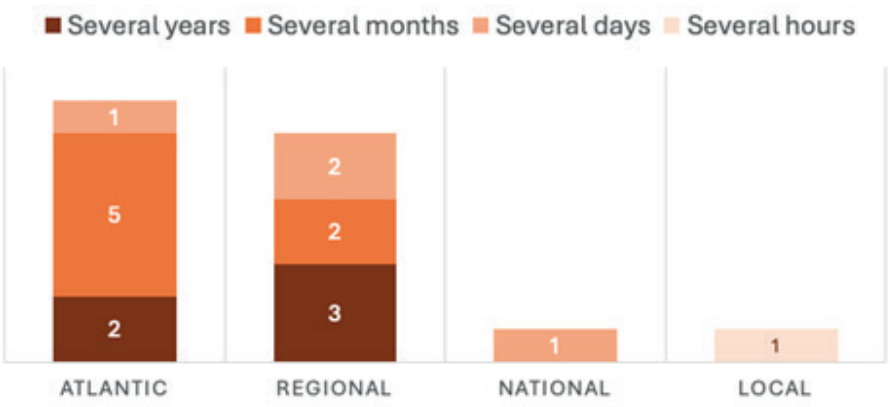
Forecasting models complement detection tools by estimating the trajectories of detected *Sargassum* mats (aggregations of floating algae) and predicting their arrival in coastal areas. To this end, Lagrangian particle-tracking models are the most widely employed methods, used in 64% of the reviewed studies. Within the Lagrangian framework, two primary modeling strategies can be 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 featured in only a minority (28%) of the reviewed models.

Alternative modelling approaches have also been developed. For instance, Jouanno *et al.* (2021) (25) use an Eulerian approach that 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.* (26) 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 evolving according to a transition matrix derived from drifter trajectories (27,28).

Most forecasting efforts have been conducted mostly at large spatial scales —such as the Atlantic Ocean or the Caribbean basin— with relatively few studies focusing on national or local coastal waters. Simulations at these larger scales typically cover extended timeframes and aim to anticipate long-term inundation events (Figure 8).

Figure 8. 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 day and less than 1 month, several hours: model run for less than 1 day)



2.3.4 – 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 monitor 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 5 shows that beaching detection methods are often described in articles that have characterization, valorization or impacts as their main theme. Indeed, these methods effectively complement forecasting models by offering field validation and can help guide decisions regarding 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 onsite methods for beaching detection. This is the case for most studies focusing on characterization of beachings which mainly use regular beach surveys, a method used in 53 articles, to detect *Sargassum* arrivals. 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) utilizes 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 sulfide (H_2S) and ammonia (NH_3) 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 studies (13). This contrasts sharply with the widespread use of satellite data for detecting offshore *Sargassum* distribution (see Figure 7).

Finally, citizen science and crowdsourced data offer a promising avenue for detecting and documenting *Sargassum* beaching events. Bernard (27) first used such methods in 2019 by using a database of 154 observations referenced on the website of the *Direction de l'Environnement, de l'Aménagement et du Logement de la Guadeloupe* (http://www.guadeloupe.developpement-durable.gouv.fr/actualitessargasses-r989.html) as an input for its clustering model. Others like Arellano (28) with his Collective View app collect images, which are then filtered by AI tools to remove false detections and automatically classify large volumes of crowdsourced images.

Figure 9. 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)

2.3.5 – 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, a limited number of 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 modeling 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*. (29) applied such a model to the Mexican Caribbean, 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 (30). These reports use the Floating Algae Index (FAI) to quantify *Sargassum* coverage in nearshore waters and derive beaching risk metrics. Validation efforts by Trinanes (30) and Putman (31) 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 current and wind direction data to observed beachings, models like the SEAS model (32) can provide beach managers an estimated timeframe for when offshore-detected mats will make landfall on their beach. Bernard (27,33) proposed an original approach, using clustering methods to identify the current patterns that lead to local inundations in the Lesser Antilles islands.

2.4 – 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 5). Among them, most characterize stranded biomass in terms of volume, level of decay, and species composition. Specifically, 47% of the studies estimate the chemical composition of the stranded algae and, in some cases, the leachates resulting from its decomposition. Fewer articles characterize the biodiversity associated with beached *Sargassum* and involved in the decomposition process (13%).

A total of 138 articles investigated the impacts caused by *Sargassum* inundations, 122 of which have this as their main objective (see Figure 5). Most of these study environmental

impacts (63%), and a sizeable minority document 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 report on multiple impact categories simultaneously).

2.4.1 – 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 by region and is not always composed exclusively of *Sargassum* spp. (34). Some studies (n = 5) apply backtracking models to estimate the origin of the biomass and explore its relationship to observed variability (35-39). Most of these general characteristics are reported as a complement to chemical, forecasting or impact studies.

Amongst the 59 articles analyzing the chemical composition of the *Sargassum*, most (n = 36) measure heavy metal concentrations (especially arsenic), and other chemical characterizations are usually carried out with a view to valorization. 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 (40-41), and phenolic compounds like flavonoids or phlorotannins that spark interest for their antioxidant properties (42). 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 (43) and are measured in half of the studies.

Fewer articles (n = 17) study *Sargassum* wracks from a biodiversity perspective and characterize the associated communities. Although beached *Sargassum* is largely considered a nuisance, it still serves as a habitat for different species. Here, we included only articles studying the community associated with beached *Sargassum* wracks (accumulated biomass on shorelines), not offshore mats which provides ecosystem services to a whole range of other species. But 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.

2.4.2 – Impacts of Sargassum beachings.

As previously mentioned, most studied impacts are environmental. Amongst those, 42 instances 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 (44-46), nesting behavior (47-52), and increased rates of false crawls (46)(48)(53-56). 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 sulfide (H_2S) and ammonia (NH_3). 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 (57). Twenty-five studies assess changes to benthic ecosystems, particularly coral reefs and seagrass beds, which are equally represented. A smaller number of studies (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 (58). This paradox is recognized in several reports, with positive effects of unremoved wracks primarily documented on Galveston Island, Texas (59). Conversely, a study in Mexico suggests that inaction may lead to erosion via the loss of protective benthic algae (60), indicating that the net effect of *Sargassum* on erosion is context-dependent.

Other impacts are significantly less documented. 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. Likewise, health issues lead to social problems and unequally affect different social groups and can also have 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 (61).

Social impacts of *Sargassum* inundations on coastal communities are poorly studied. Half (11/21) of the listed documents are dedicated to this specific topic only. The other half of the document's studies social impacts in 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 odor, landscape degradation) that communities must adapt to in their daily lives.

Reported health problems are usually related to gas (H_2S, NH_3) inhalation and related symptoms (respiratory issues, neurological symptoms, ocular and skin irritations...) (62). 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 reports.

2.5 – Which actions have been taken to deal with *Sargassum* beachings?

A total of twenty-eight reviewed articles deals with beaching management. The valorization of *Sargassum*, which has gained significant attention in the past few years and is 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 to tackle this problem.

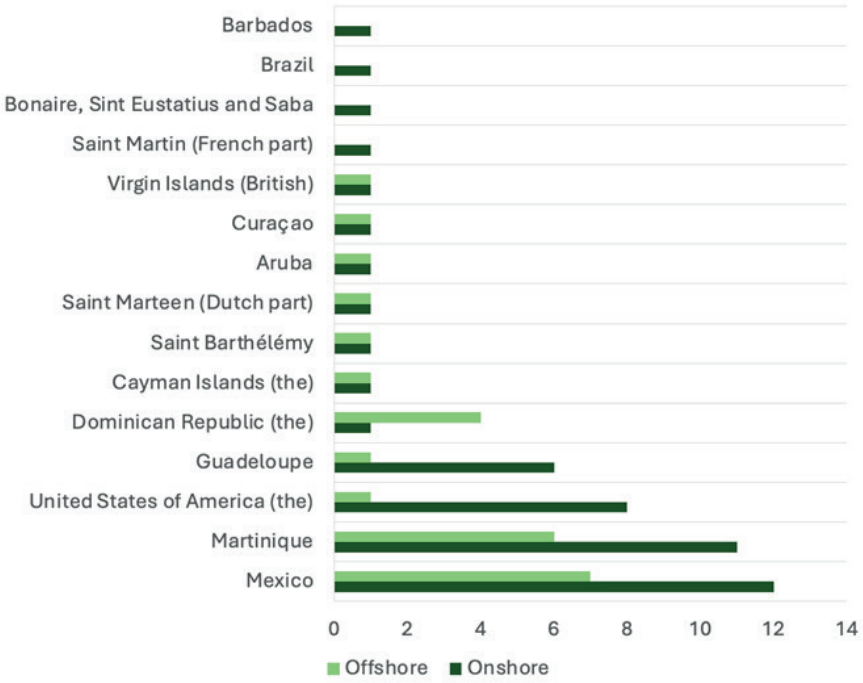
Although most documents about valorization are journal articles, there is an over-representation of grey literature for policy and management articles. Indeed, management strategies and governance issues are addressed with reports or policy documents rather than academic studies (see Figure 4).

2.5.1 – Management of Sargassum beachings.

Evidence of implemented management actions shows a small majority of onshore removal techniques, both manual and motorized (e.g. using tractors and rakes), 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, such as in protected areas (63) or in locations where *Sargassum* arrivals are sparse and can provide ecosystem services (64). Most of the time, the removed *Sargassum* is 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 10). Countries apply management measures both offshore and onshore. However, onshore management techniques are most often applied by U.S., and offshore barriers by the Dominican Republic in order to protect its tourist coastline (65).

Figure 10. Distribution of onshore and offshore management actions implemented by country (in number of records)



2.5.2 – 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 products. Based on content analysis, seven broad categories of valorization were identified, used to classify the relevant studies (Figure 11):

Medical-related products - A total of 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 - This category includes 69 studies evaluating the potential of *Sargassum* as a feedstock for bioenergy, encompassing processes such as direct combustion, anaerobic digestion (methanization), and biofuel production.

Agricultural applications (biofertilizers) - *Sargassum* biomass is investigated as an agricultural input in 43 studies, either through the use of solid digestate as compost or 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.

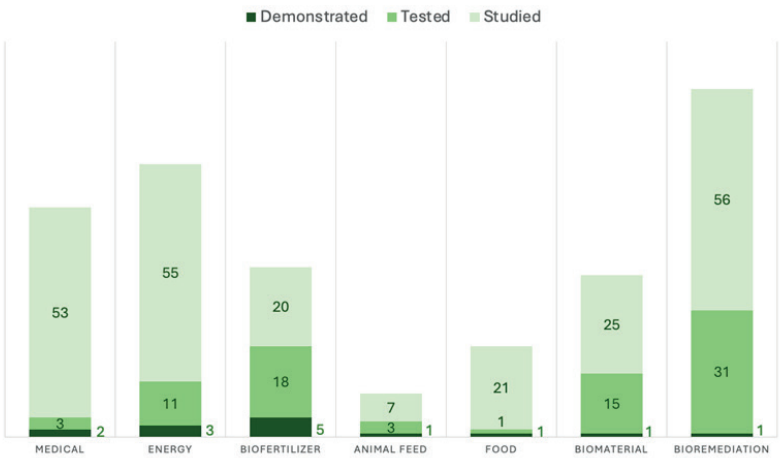
Biomaterials - The use of *Sargassum* in the development of construction and industrial materials is explored in 41 studies. Applications include composites, bioplastics, and structural components, contributing to circular economy approaches.

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 11):

- **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** - Reproducible outcomes and/or successful integration into commercial systems.

Figure 11. Article distribution by *Sargassum* valorization theme and by level of development

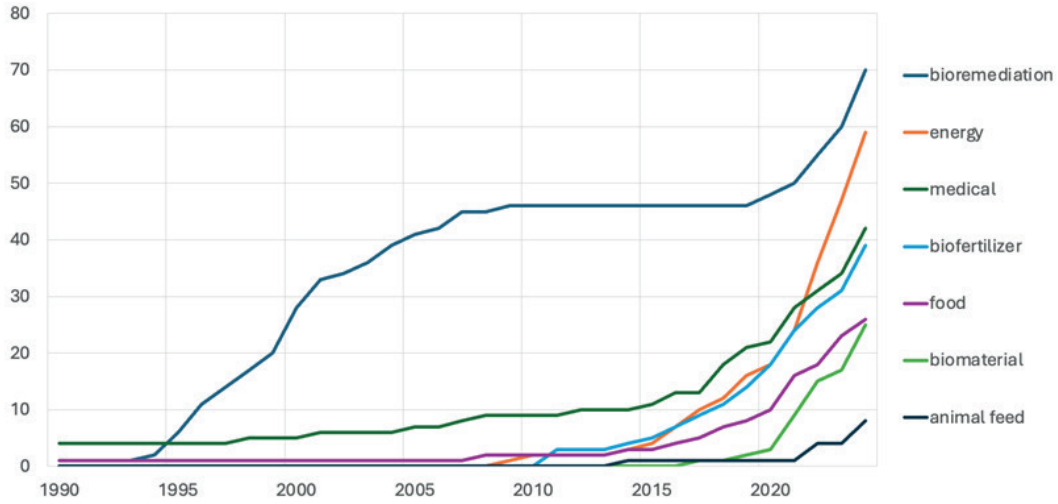


A temporal analysis of publication dates reveals heterogeneous temporal dynamics across the different valorization pathways (Figure 12). Bioremediation appears as the earliest explored valorization route, with initial studies emerging in the late 1990s. However, this research theme experienced a sharp decline, before regaining interest around 2020. 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. Research output in this area increased sharply after 2015, as shown in Figure 12.

Conversely, other valorization avenues –including energy production, biofertilizers, food applications, biomaterials, and animal feed– are more recent, and follow the occurrence of major *Sargassum* beaching events in 2011. An acceleration in publication frequency across these themes occurs after the 2015-2020 period.

Figure 12. Cumulative number of articles by year for each valorisation theme through the years

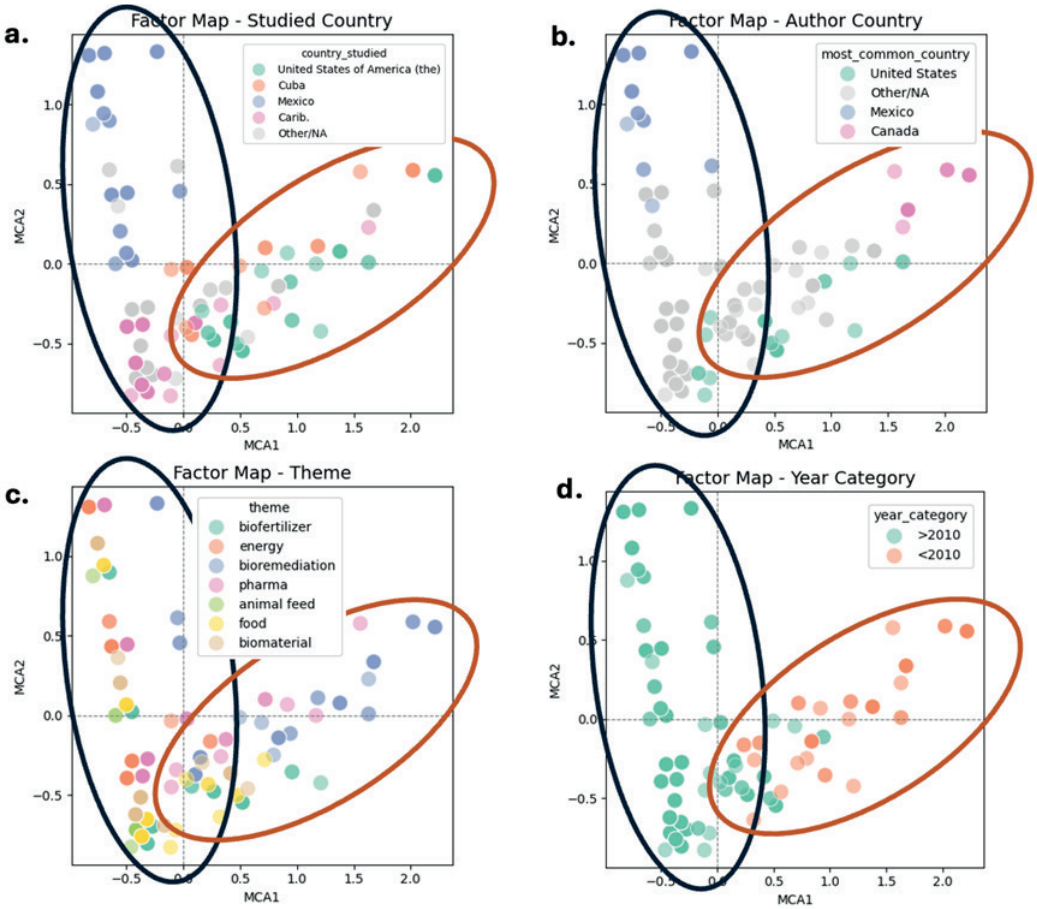


The factor maps of the MCA (Figure 13), emphasize our analysis and reveal a geographical/temporal division in research dynamics. The first axis (MCA1), separates articles on their publication year, with articles published before 2010 grouped on the right-hand side, and the recent articles clustering on the left side with negative coordinates (see Figure 13.c). This temporal trend closely corresponds to the distribution of valorization themes (Figure 13.d), confirming what was displayed on Figure 12. Of note, studies on bioremediation of *Sargassum* are associated with the pre-2010 cluster, suggesting that this application

was explored earlier than others. Other themes such as biofertilizer, energy, animal feed and pharmaceutical applications are mostly situated in the blue cluster, consistent with a later start for this research theme –probably stimulated by the first massive beaching events in 2011.

Spatial dimensions, represented by both the country of origin of the valorized *Sargassum* (Country Studied on Figure 13.a) and the first author's affiliation (Author Country on Figure 13.b), emphasize these temporal distinctions. Articles associated with Mexico, the Caribbean and Cuba are mainly located on the left side of the MCA1 axis, overlapping with more recent themes. These studies are highly correlated with Mexican authors (Figure 13.b). Conversely, articles in the second cluster include those of U.S. origin and from unspecified countries, but written by American and Canadian authors. 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.

Figure 13. Factor maps of valorization articles in the MCA reduced plane & cluster delimitation (blue circle: Cluster 1, orange circle: Cluster 2)



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.
- More recent studies led by Mexican institutions on a broader set of topics and carried out on beached *Sargassum* in the Caribbean.

2.5.3 – 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. These include a lack of timely government action (66), insufficient cross-sectoral collaboration (67, 68), and a broader absence of coordinated international governance mechanisms (66).

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 communal-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 vary considerably: for example, while certain jurisdictions, such as Texas, have prohibited *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 (69), UNEP's recommendations for policymakers (70), and frameworks proposed under the UN Decade of Ocean Science for co-developing ocean policies (71).

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 (72), and the integration of local ecological knowledge into policy formulation (73) (68).

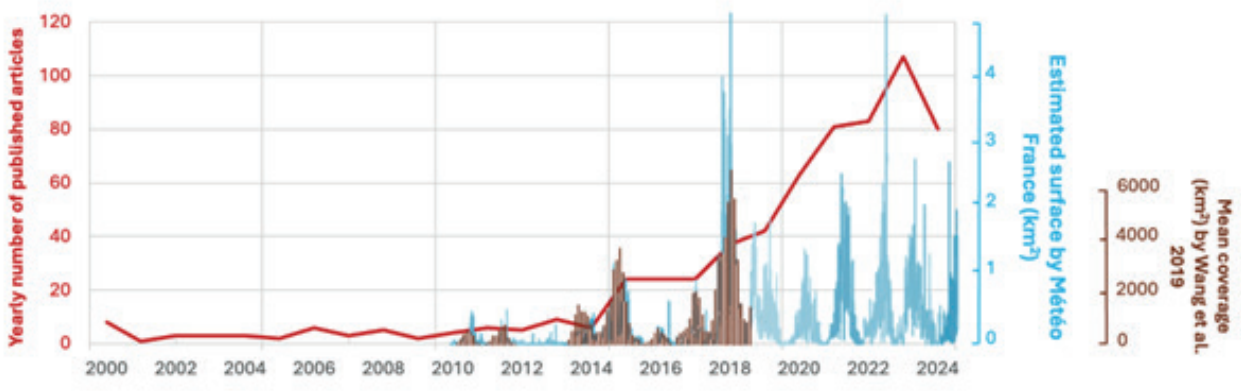
Ultimately, the review of these 82 documents highlights both the dynamism and the fragmentation of *Sargassum*-related policies. While multiple governance levels are actively engaged —particularly at the national and subnational scales— the lack of binding international coordination, the uneven legal 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.

3. Discussion

The analysis of the 697 included articles revealed a rise in attention towards *Sargassum*-related themes 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 previous studies (Fidai, 2020 (74) and Joniver, 2021 (75)) and reflects growing academic and policy interest in understanding and addressing this emergent phenomenon. Furthermore, the three research "periods" identified in 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 14), a clear 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*; however, 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 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.

Figure 14. Total number of published articles superimposed with mean *Sargassum* coverage (km²) estimated by Wang *et al.* 2019 and Surface estimated by Météo France (km²) (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)



Analysis of the accessible content for each sub-questions revealed scientific gaps which could feed more specific questionings that could be investigated in further works. First, 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. In particular, 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, both onshore and offshore, which serve both 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 (1). 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, in-situ methods remain preferred 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 (76) 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 our second question, it was showed in section 3.4.2 that most documented impacts were environmental. Some reported environmental impacts stem from management practices (e.g., mechanical beach cleaning, offshore *Sargassum* barriers) rather than *Sargassum* itself (77), with direct causality often inconclusive (78). 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. Indeed, most of the reviewed international policy documents were non-binding, and focused on management strategies. *Sargassum*'s legal status remains ambiguous and context-dependent, varying by its condition (living or decomposed) and location (water, beaches, storage). In 2022, David (79) describes *Sargassum* as an "unidentified legal object", underlining the jurisdictional uncertainty surrounding its classification and management.

4. Outlook

This review highlights the richness and growing complexity of *Sargassum* related research, especially in valorization, detection techniques and impact studies. We also point to possible avenues for further investigation, as discussed in the previous section, to better understand the causes of this phenomenon, as well as a larger-scale and more integrated monitoring and forecasting framework and a better understanding of the variability of its composition. 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 greatly 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 (80). 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.

By addressing these emerging questions and broadening the geographical and thematic scope of future reviews, the research community can contribute to a more inclusive, context-sensitive, and operational understanding of *Sargassum* dynamics worldwide.

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