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Integrative Literature Analysis of Holopelagic *Sargassum* (Sargasso) in the Western Atlantic (2011–2022): Status, Trends, and Gaps

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Abstract: Since 2011, the Caribbean and Gulf of Mexico coasts have been receiving massive influxes of holopelagic sargasso algae composed of *Sargassum natans* and *Sargassum fluitans*. This phenomenon has been causing several negative local impacts, such as ecological disturbances and socioeconomic and health concerns of communities in impacted areas. This work aimed to assess the status of scientific knowledge related to pelagic sargasso, including trends, emphases, and gaps. A literature review was conducted on publications and reports from 2011 to 2022, of which 251 articles were collected based on an inclusion–exclusion criteria. Aspects of each article were quantified, including location, description of sargasso, the type of study, and research theme. A region-wide research emphasis on ecology, remote sensing, and valorization was observed. Areas first affected by the inundations composed a higher percentage of sargasso studies than other locations, and the distribution of studies varied among subregions. Topics requiring further investigation include sargasso's growth and mortality rates and drivers, taxonomic and physiologic differences among morphotypes, and real-time forecasting resolution at local scales both on and offshore. This research emphasized efforts from the scientific community on research and mitigation initiatives.

Keywords: algal blooms; brown seaweed; sargasso-brown tide; pelagic sargasso; literature review

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1. Introduction

In 2009, the first reports on the voluminous deposition of holopelagic species of the genus *Sargassum* (hereafter referred to as pelagic sargasso) were made in West Africa. In 2011, a vast amount of sargasso was reported on the Caribbean and Gulf of Mexico coasts and ever since it has continued its deposit year after year [1,2].

The inundations of pelagic sargasso were shown to inhibit coastal access to beaches, exacerbated by the decomposition of algae that release hydrogen sulfide gas [3,4], which threatened tourism and fishing economies for local communities. The sargasso inundations and decomposition also induce anoxic conditions in the water column by decreasing oxygen availability and heightening ammonium levels, increasing seagrass losses and faunal mortality [5,6].

Pelagic species of the genus *Sargassum* were first described by Gaillon (1828) and Børgesen (1914) and were noted as *S. natans* (Linnaeus) Gaillon and *S. fluitans* (Børgesen) Børgesen, respectively. In 1923, Winge documented distinct morphotypes within each of the two species, *S. natans* I, II, VIII, and IX and *S. fluitans* III and X [7–10]. Parr, in 1939, refined the taxonomy distinctions made by Winge (1923) [10] and compared the distribution of

morphotypes across the Western Atlantic, which served as a baseline for later expeditions. Of these expeditions, those after 2011 [9,11] demonstrated major differences in composition and abundance of sargasso morphotypes compared to pre-2011 expeditions [7,12,13].

Traditionally, the primary source of pelagic sargasso was the Sargasso Sea [14]. This is a region contained within the North Atlantic Gyre, where sargasso provides a habitat for species endemic within the floating mats that were referred to as a "floating golden rainforest" [13]. On the coast, depositions of sargasso in small amounts on land can help prevent coastal erosion and deposit nutrients for dune vegetation [3,15]. However, the post-2011 influxes of sargasso originated in a newly developed "Great Atlantic Sargassum Belt" (GASB) further south in the North Equatorial Recirculation Region (NERR) between Brazil and West Africa [16,17]. The hypothesized contributing factors to these influxes and their origin are multifaceted and complex, including a negative event in the North Atlantic Oscillation, changes in surface currents [18], and nutrient input from multiple sources [19–21].

Given the complexity of the sargasso problem, there is a need to study this phenomenon in various aspects and disciplines. Therefore, through a survey of the literature published between 2011 and 2022, this review aims to identify the status of scientific knowledge about the pelagic sargasso phenomenon in the Western Atlantic, the trends of study pursued by the scientific community, and the knowledge gaps that need to be addressed.

2. Methods

To carry out the integrative analysis of the literature on the pelagic species of the Phaeophyceae genus *Sargassum*, the publications available from 1 January 2011 to 31 December 2022 were used; publications from 2023 were not considered, although over 80 new publications related to sargasso were published by the time of this study was finalized. The Scielo, ScienceDirect, and Web of Science literature databases were utilized to capture a broad swath of literature for subsequent review. To filter publication searches, the following keywords were utilized to include all possible studies on pelagic sargasso: "*Sargassum*", "pelagic *Sargassum*", "*Sargassum* in the Caribbean", "*S. natans*", and "*S. fluitans*". The species names were used in their complete form in the database search. Following the first literature compilation, criteria of inclusion and exclusion were applied to the title and abstract of each article (Table 1). The same inclusion/exclusion criteria were then applied to the objectives, methods, and results of the filtered literature compilation. All duplicated publications were removed leading to the final sampling used in this study, as shown in Figure 1.

Table 1. Criteria of inclusion and exclusion of publications used for the literature survey.

Inclusion	Exclusion
• Articles on the west coast of the Atlantic Ocean • Studies focusing on and/or citing seaweed and/or pelagic seaweed landings in the Caribbean and/or the Gulf of Mexico • Scientific journal articles, empirical studies, book chapters with empirical studies • Articles from Jan/2011 to Dec/2022 • Articles that mention the chosen keywords in the Methods and/or Results section. • Publications that report on or collect stranded sargasso from landings.	• Studies not focused on the west coast of the Atlantic Ocean • Studies focused only on the Sargasso Sea or on benthic sargasso • Theoretical/bibliographical studies, encyclopedias, doctoral and master's theses, book chapters without empirical studies • Articles before 2011 or after 2022 • Articles that do not mention the chosen keywords in the Methods and/or Results section of the study. • Articles that only describe *Sargassum* in the Introduction, Discussion, and/or Conclusion section of the study. • Publications that only mention, in the research article's introduction, the phenomenon of landings in the Caribbean and/or the Gulf of Mexico.

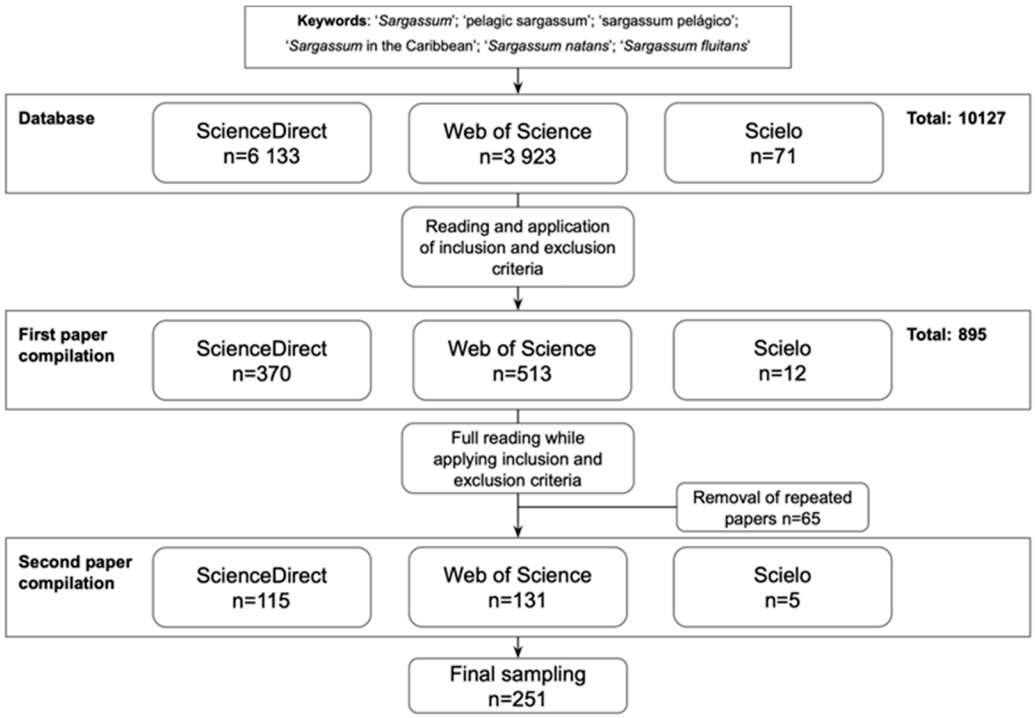

Figure 1. Flowchart depicting the literature filtration process for the systematic analysis of bibliographies. Each box contains the number of publications that fit the criteria and publication database source.

With the final sampling determined, each article was then searched to identify whether the collection or observation of pelagic sargasso was using the common name "sargasso", or genus, species, or morphotype taxonomic descriptors. This was performed by assigning a value of 1 if a taxonomic descriptor was used (1 = descriptor used, 0 = descriptor not used). The broadest descriptors of sargasso include "*Sargassum*" and "pelagic *Sargassum*", followed by the species "*S. natans*", "*S. fluitans*", and morphotypes being the most specific ("*S. natans* I", "*S. natans* VIII", and "*S. fluitans* III"). In studies that used multiple descriptors, only the most specific term was considered, therefore giving 0 (zero) points to other broader descriptors under the same publication. The exceptions were for descriptors of the same taxonomic order, as in the case of the species name ("*S. natans*", "*S. fluitans*") and morphotypes ("*S. natans* I", "*S. natans* VIII", and "*S. fluitans* III"). In these cases, the terms of the same taxonomic order were all given the same score (1 point each), according to the following order from least to most specific: "*Sargassum*"; "pelagic *Sargassum*"; "*S. natans*" and "*S. fluitans*"; "*S. natans* I", "*S. natans* VIII", and "*S. fluitans* III".

For each publication, the following information was extracted:

- Publication year: The year the scientific paper was published;
- Reporting year: The year in which the species of pelagic sargasso was found. If the study does not present the year of collection/observation, the year of publication was considered;
- Study location: The specific location where the study was conducted. If the article does not present this information, the author's institution was considered;
- Subregion: The affected region was divided into subregions to categorize articles based on the location of the study, as shown in Figure 2. For this, seven regions were defined, adapted from Iporac et al. (2022) based on surface current patterns in the Gulf of Mexico and the Caribbean Sea [22,23]. The subregions include the Greater Caribbean (GC), Western Caribbean (WC), Gulf of Mexico (GoM), Floridian (FL), and the Bahamian (BH). Two additional regions were added for this study: Brazilian (BR)

and North Atlantic Ocean (NAO). The NAO subregion was used to include studies carried out in the high seas or in multiple locations and subregions;

- Oceanic Zone: Where the pelagic sargasso was found. Only two zones were defined: coastal or oceanic;
- Themes used to classify each type of study:
    1. Taxonomy: species molecular identification.
    2. Ecology: interaction with other species or impact on ecosystems.
    3. Biochemistry: nutrient, metals, and other chemicals' tissue content.
    4. Remote sensing: satellite imagery and mapping.
    5. Valorization: raw material used in product development.
    6. Health: impacts on human health.
    7. Geology: climate changes at the geological scale.
    8. Oceanography: oceanic current impacts on sargasso transportation.
    9. Management: biomass influx management.
- Each publication was allocated to only one theme, and the distribution was determined from the keywords and objectives of the research conducted. If a publication applied multiple themes, only the more predominant theme would be considered.
- Type of Science: Studies were categorized into "basic science" and "applied science". The allocation of each publication depended on the authors' purpose of the study as determined in the introduction or abstract sections. "Applied science" articles were designated as those with the intention of creating a product or service, while "basic science" articles were designated as those with the intention of contributing to knowledge;
- Keywords: Provided in the article.

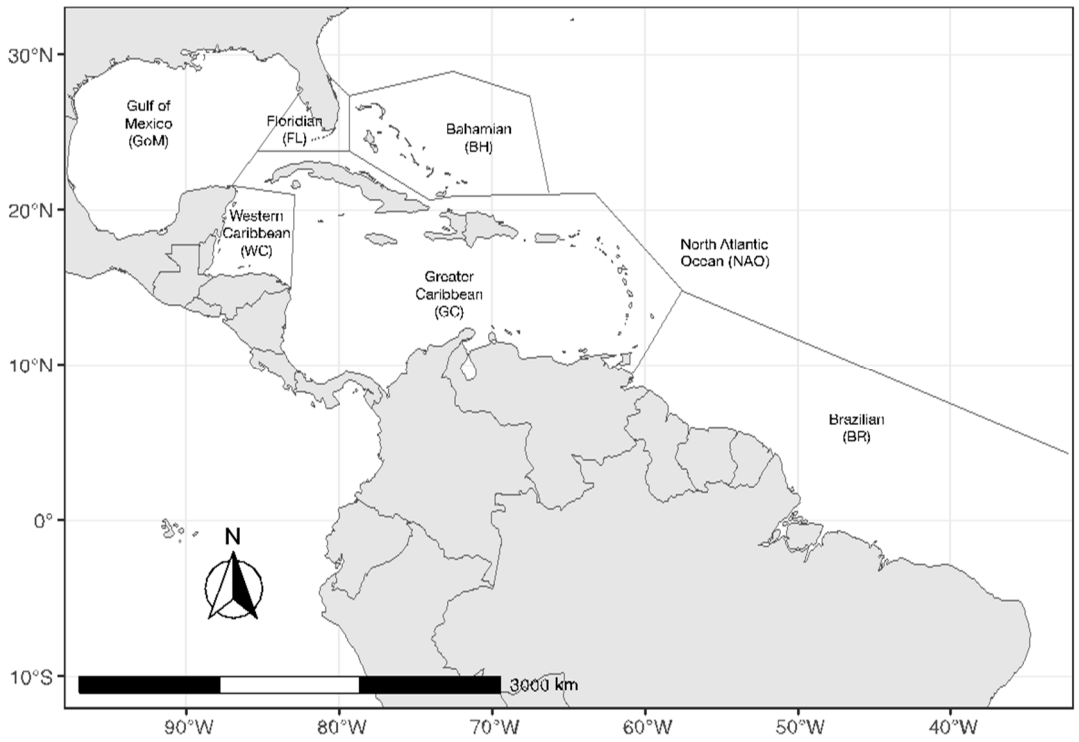

Figure 2. Map showing geographical scope and subregions for this literature survey.

3. Results

Initial publication searches returned a total of 10,127 publications. After the first criterion was applied, the number of relevant articles dropped to 895, while the second application of the criteria to objective, methods, and results further decreased that number to 316 publications. Following the removal of 65 duplicated studies, there were a total of

251 studies among the three databases between 2011 and 2022 used for further analyses (see Supplementary Materials File S1 for all publications used in this review).

There was an evident increase in new research related to pelagic sargasso published from 2011 to 2022 (Figure 3). Most of the years showed an increase in total new research, with the greatest increase in the number of publications found between 2020 and 2021.

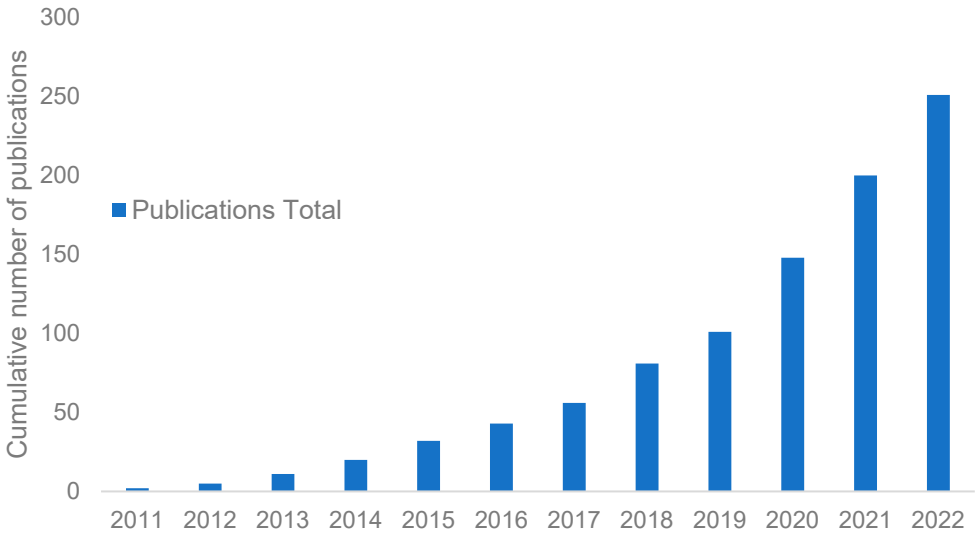

Figure 3. Total number of new publications describing pelagic Sargassum compared to the number of publications mentioning the morphotypes between 2011 and 2022.

The use of morphotype descriptors began to appear in 2019 and has seen an increase in publications each year since then. Between the morphotype descriptors, they had roughly an equal number of mentions, while the species names "*S. fluitans*" and "*S. natans*" were not as equally mentioned in frequency when compared to each other. The name of the genus, "*Sargassum*", was the most used descriptor, with 51% of studies containing the term (Figure 4)

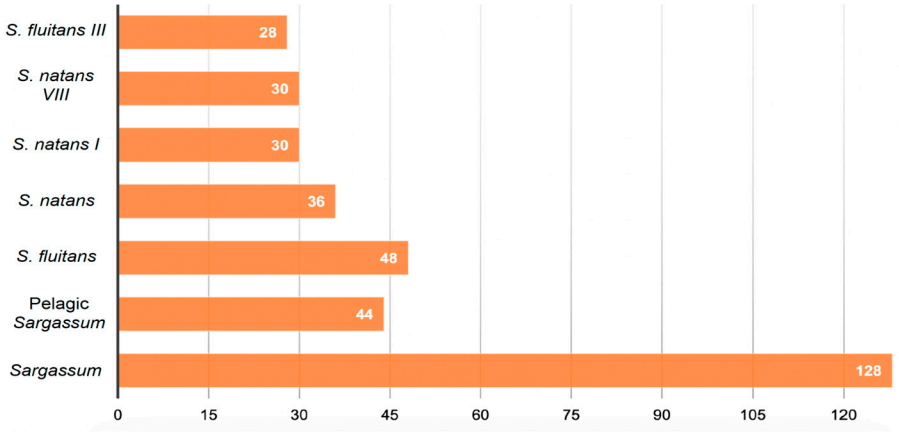

Figure 4. Number of sargasso descriptor words used in publications between 2011 and 2022.

A transitional trend away from offshore to coastal studies was also detected. In 2011, 100% of the studies were carried out offshore compared to 2020 when coastal studies dominated, making up 70% of the studies.

Three categories dominated most of the studies: ecology (n = 59), remote sensing (n = 56), and valorization (n = 51) (Figure 5). Altogether, these three research themes comprise 66.12% of all sargasso studies. Biochemistry was the fourth category with 37 publications; the last 15.96% were divided among management (n = 17), taxonomy (n = 14), oceanography (n = 8), health (n = 6), and geology (n = 1).

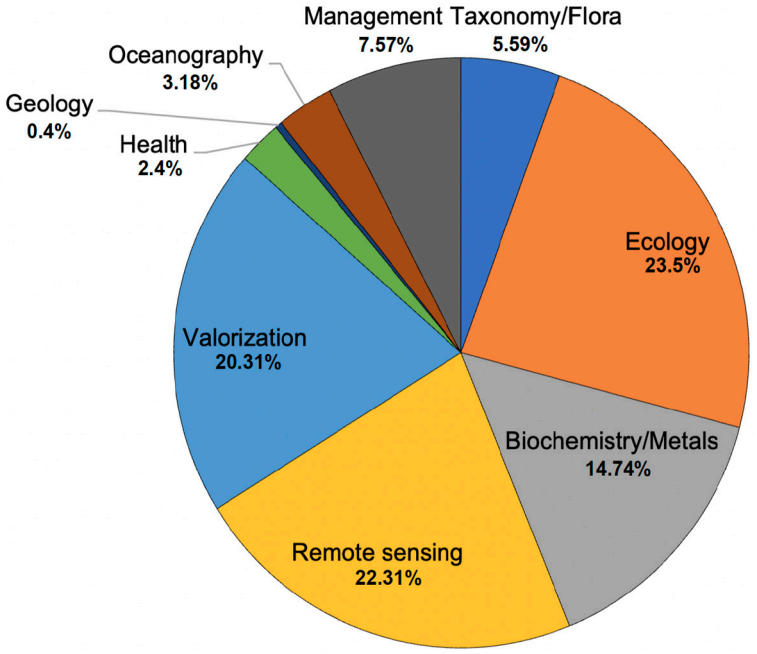

Figure 5. Distribution of publications by research theme.

Publications Per Subregion

The GC subregion composed the highest number of publications on sargasso (n = 69), followed by the NAO (n = 60) and the WC (n = 57) (Figure 6). All three subregions compose 74.1% of all studies on sargasso throughout the Western Atlantic. The BR (n = 5) and BH (n = 2) subregions had the least amount of sargasso studies.

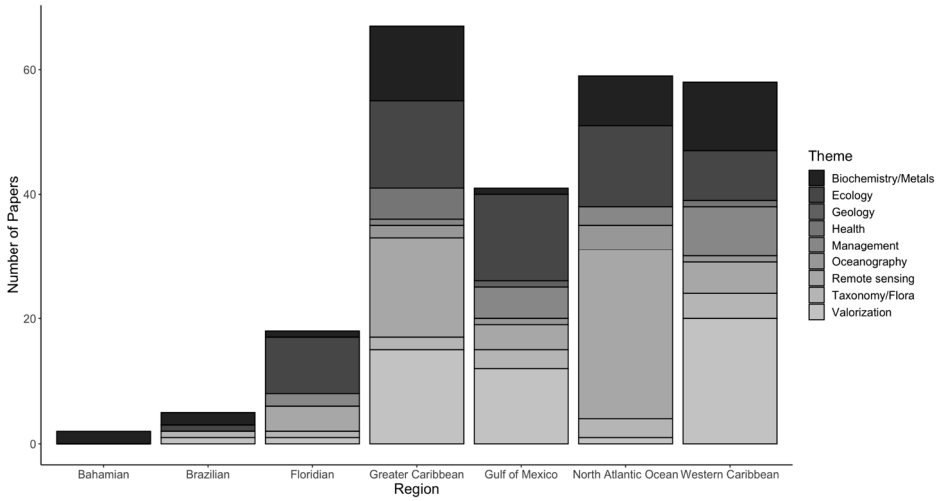

Figure 6. Distribution of research themes of publications by subregions.

In the NAO subregion, there were more remote sensing publications (n = 27) than in the rest of the studied subregions, representing 48% of total studies in the region for this theme. This subregion also had a high number of studies in ecology (n = 13). In both ecology (22%) and oceanography (n = 4 or 50%), the NAO had a high contribution to the total number of studies in each theme for the entire region compared to the other subregions. However, papers in other themes, while present, were less represented (Figure 6).

In the GC, remote sensing (n = 17), ecology (n = 15), and valorization (n = 15) showed the highest numbers of publications for the subregion. Themes such as biochemistry (n = 11) and health (n = 5) also presented the largest number of studies for each of these categories for the whole region (29% and 83%, respectively).

The research topics with the highest number of papers in the GoM were ecology (n = 13) and valorization (n = 12), comprising 32% and 30% of the studies, respectively. This subregion produced the only research article related to geology (n = 1).

The WC contained the most amount of valorization studies (n = 20), both throughout the West Caribbean (34%) and the entire region (40%). The WC also presented the highest number of taxonomy (28%), biochemistry (29%), and management (42%) studies between the subregions, although these studies were among the least notable to the West Atlantic.

From the few papers in the FL, the highly used theme was ecology (n = 9), as there were 50% of studies published for the category in this subregion. The other nine papers were distributed between remote sensing (n = 4), biochemistry (n = 2), taxonomy (n = 1), valorization (n = 1), and management (n = 1).

In the BR subregion, biochemistry had the highest number of papers (n = 2) between the themes. Only three other themes had papers completed in the BR; they were taxonomy (n = 1), ecology (n = 1), and valorization (n = 1).

Ecology was present in every subregion except in the BH. All of the studies produced in the BH were related to biochemistry (n = 3).

Basic science articles, comprising 76.9% of all publications, have demonstrated higher use of morphotype descriptors compared to applied science (23.1%). Within the papers mentioning the morphotypes, 90% of publications were categorized as "basic science" and the other 10% were classified as "applied science".

The total number of studies using morphotype descriptors was low, accounting only for 12% of all studies (Figure 7). Among the 30 publications that mentioned the three morphotypes, the biochemistry category utilized morphotype descriptors the most (n = 12); however, taxonomy proportionally utilized morphotype descriptors the most as a research field (50%). Among the other categories, very few publications were found, for example, oceanography, remote sensing, and ecology; each had only three articles that mentioned morphotypes. Two themes (geology and health) did not present any publication mentioning morphotypes. Out of 251, 221 scientific articles did not mention the morphotypes.

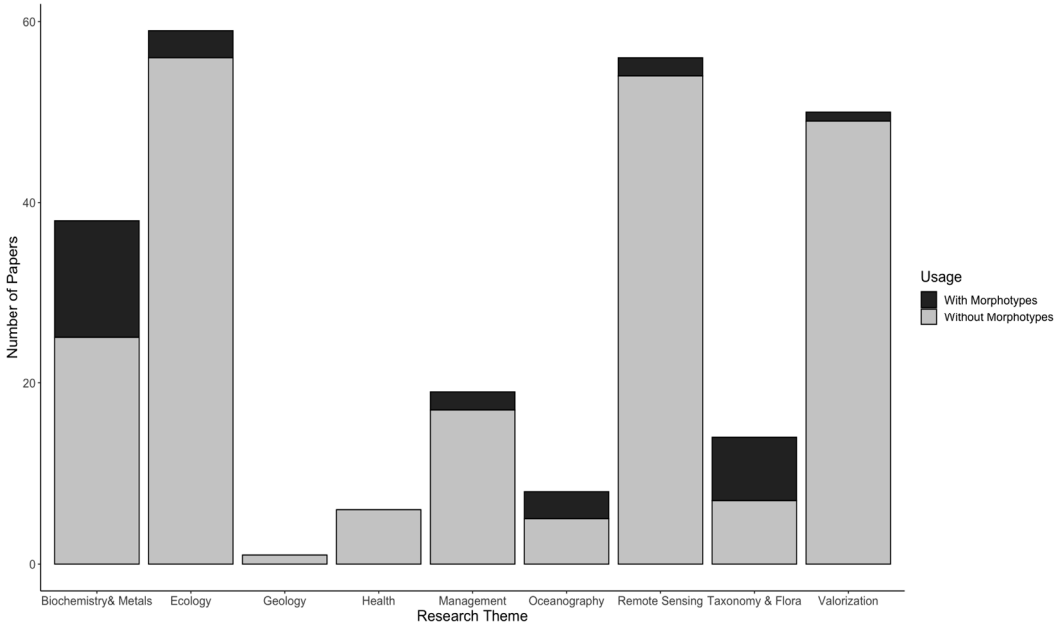

Figure 7. Frequency of references to morphotypes per research theme.

4. Discussion

There was an overall increasing trend in publications related to sargasso from 2011 to 2022, which can be explained by the increasing intensity and frequency of sargasso landing events that have occurred in recent years [3,24,25]. This result is consistent with Joniver et al. (2021), who observed a general increase in the number of peer-reviewed publications

related to macroalgal blooms from 1976 to 2018, indicating an increase in macroalgal bloom events [26]. As macroalgal blooms increase in frequency and intensity, there is an increasing drive from the scientific and broader community to study and understand the triggers and dynamics of those events, followed by initiatives for valorization and use [27].

In the earlier years, there was a prevalence of oceanic studies, with 100% of the studies carried out in the ocean, until 2018 when coastal research comprised 70% of the studies. This change may have occurred due to the overwhelming volume of sargasso present on shore; this shift can stem from an increasing demand to manage the biomass and mitigate the ecological and socioeconomic impacts caused by the influx of biomass [3]. Alternatively, there was a shift in perception of sargasso from a "problem" to a "resource" as was observed in the different economic sectors in the Mexican Caribbean [28].

The total number of studies using morphotype descriptors was low, consistent with the global analysis conducted by Fidai et al. (2020) [29]. Distinguishing the morphotypes can be a complex task without prior training [30], and the establishment of pelagic sargasso at the species or morphotype level is still being investigated following molecular evidence [8,9,31]. Restricting taxonomic identification to the genus or species level may be more appropriate for those more interested in biomass valorization or remote sensing. Studies that identify sargasso down to the morphotype level are focused on the biological or biochemical aspects of sargasso at the species level rather than as a broad region-wide phenomenon. There were previous studies that determined biochemical, genetic, and physiological differences between morphotypes [8,32], as well as demonstrated variability in local-scaled monitoring of sargasso [30,33,34].

In broader-scaled studies involving remote sensing and valorization, the high biomass and scope of study make the identification of sargasso either trivial or unfeasible [25,35–37]. However, the lack of morphotype identification in sargasso-related studies should not be overlooked given the possibility of minute differences in physiology and tissue content scaling up to oceanographic distribution and biomass valorization with varying sargasso composition.

Ecology, remote sensing, and valorization, respectively, had the most studies carried out. This result is consistent with Fidai et al. (2020), where there was a strong research emphasis on remote sensing of sargasso in the Atlantic Ocean Region. Sargasso in ecological studies was framed as either with association of another species of biota [36–38] or framed to assess the impacts of sargasso-brown tides on local biotic communities [39–41]. These are impacts that could incur socioeconomic costs and loss to local communities that are dependent on their local coastal areas [42]. Remote sensing studies are used as the primary method for monitoring and forecasting sargasso inundations that can result in the formation of an alert system or summary report essential for stakeholder use [43]. A large amount of biomass was also utilized by private enterprises to harvest and develop products from the biomass, including possible secondary products such as proteins and nutrient content [3,44].

Emphases among research themes differed among all subregions, which could be explained by the variation in the intensity and frequency of inundations within the West Tropical Atlantic, where the GC and WC subregions usually experience higher intensity and frequency than other subregions [34]. However, this could also be a reflection of higher research capacity situated in some areas more than others that lack similar levels of highly qualified research groups.

It was even observed that the GC and WC were the only ones that presented health-related studies [45–50], which reflected how sargasso inundations were considered a public health issue in those subregions. Attitudes about sargasso as a public health issue vary, with Florida governmental officials perceiving it as a nuisance rather than a public health threat, as it is seen in the Lesser Antilles [50,51].

The high prevalence of studies related to pelagic sargasso in the last decade was demonstrated through this integrative analysis of the literature. After 2015, a noticeable increase in publications was observed from the Caribbean and Gulf of Mexico. Several research activities were triggered to determine the causes and effects of sargasso influxes,

as well as development to monitor and valorize sargasso biomass. While there was considerable attention to sargasso blooms in the Western Atlantic, major gaps and shortcomings remained unaddressed [29]. The research capacity to monitor, manage, and valorize sargasso is growing rapidly from increased collaborations between governments, academics, and the private sector [52].

It is very likely that sargasso-related research will increase as observed by an explosion of publications for 2023, although that period was not part of this study. It is also likely that applied science studies will become more prevalent than basic science studies, as the landings are still unpredictable and solutions for monitoring and valorizing large biomass accumulations are needed. Although there was a shift in focus of sargasso research from oceanic areas to coastal areas, it is important to maintain research capacity in both areas to maximize the regional monitoring efforts of sargasso. There are also other research gaps that need to be addressed, particularly in the field of geology and public health regarding sargasso inundation causes and effects. Even among well-established research themes, the role of key factors such as sources of nutrient input, surface water temperature, and carbon intake still remains unclear on how they may contribute to the development of the GASB. It is still needed to understand how physical factors such as temperature and luminosity control the excessive growth and death of macroalgae [20,34]. This knowledge can not only help to better understand the biochemistry of the species but can also contribute to the improvement of oceanographic models [53,54]. Recent efforts described the growth rate, lifespan, and decomposition of pelagic sargasso [55], indicating that the scientific community is already addressing these important questions.

Even in remote sensing, a research theme that had the highest amount of publications, there are still limitations that need to be overcome. Although satellite images can provide an overview of offshore quantities, it is still difficult to acquire high-resolution images, since fragments smaller than 2 m in a 1 km pixel are not easily detectable [35,36,56]. There are also reports that sargasso can sink and remain under the surface of the water [57], which may indicate that the amounts in the high seas can be underrepresented. The presence of clouds can also decrease pixel resolution, making it difficult to obtain images [58,59]. Limitations of remote sensing near the coast include the heterogeneity of the coastal pixel composition, the ease in shallow waters of suspension of total particles, and the shallowness of coastal waters. Pixels up to 30 km from the coast are not considered, which means that there is still no adequate forecast of the arrival of sargasso in high resolution [56,58–60].

On a larger scale, this phenomenon has affected other regions like Ghana and Nigeria in West Africa where studies of sargasso have been conducted [1,61], although these studies were not included in our analysis. Since sargasso influxes are becoming more established as a seasonal and intense phenomenon, the number of studies related to pelagic sargasso will likely increase in the foreseeable future.

From this literature review, impacted regions were producing more publications, even though areas that have marine research centers such as South Florida produced fewer publications and emphasized remote sensing, at least during the studied period. Programs that have state-of-the-art knowledge and infrastructure were well-positioned to provide invaluable service to the community such as the Sargassum Watch System from the University of South Florida [59]. As global ecological phenomena such as sargasso influxes and blooms remain uncertain, strong professional community networks and the ability to provide rapid responses from the scientific community will depend on the present status of scientific development and impacts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/phycology3040030/s1, File S1: List of Publications Used in Literature Analysis.

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