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MULTISECTORAL COLLABORATION IN THE FACE OF ATYPICAL SARGASSUM INFLUXES ON THE MEXICAN CARIBBEAN: A COMPREHENSIVE REVIEW OF LOCAL PROJECTS AND STUDIES

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Article Info

Keywords: Sargassum, atypical influxes, Mexican Caribbean, ecosystem, economy, monitoring, modeling, early warning system, containment, harvest, disposal, regulation, potential uses, interinstitutional, transdisciplinary.

Abstract

This article presents a state-of-the-art review of research on atypical pelagic Sargassum influxes in the Mexican Caribbean. The study employs a heuristic-hermeneutic approach to collect and analyze information from a variety of sources, including published studies, government reports, and news articles. The article highlights the origin and ecological significance of Sargassum and its impact on the environment and economy. The study also discusses monitoring, modeling, and early warning systems, containment, harvest and disposal, regulations, and potential uses. The research underscores the need for interdisciplinary and transdisciplinary research and interinstitutional coordinated actions to address the impacts of Sargassum influxes. The article provides insight into initiatives and projects implemented in Mexico to manage the influxes' impacts, emphasizing the nation's diverse and valuable efforts. The study concludes by suggesting a shift in perspective from seeing Sargassum as a "national problem" to a "national resource" to further understand and leverage the ecological and economic benefits of this macroalgae.

Introduction:

Atypical pelagic Sargassum influxes have become a significant environmental and economic concern in the Mexican Caribbean. These influxes have impacted the coastal ecosystems and economies of the region, leading to concerns regarding the origin, understanding, and management of Sargassum. This study presents a state-of-the-art review of research on atypical Sargassum influxes in the Mexican Caribbean. Using a heuristic-hermeneutic approach, the article identifies and analyzes information from different sources to provide insight into the origin and ecological significance of Sargassum and its impacts on the environment and economy. The study further discusses monitoring, modeling, and early warning systems, containment, harvest and disposal, regulations, and potential uses of Sargassum. The authors highlight the need for interdisciplinary and transdisciplinary research and interinstitutional coordinated actions to better understand and address the impacts

of Sargassum influxes. The article provides an overview of the initiatives and projects conducted in Mexico to manage the influxes' impacts, emphasizing the nation's diverse and valuable efforts. The study suggests that a shift in perspective from seeing Sargassum as a "national problem" to a "national resource" could lead to a better appreciation of this macroalgae and its ecological and economic benefits. Overall, the article serves as a stepping-stone towards a more integrated multisectoral effort in understanding and addressing atypical Sargassum influxes in the Mexican Caribbean.

2. Methods

2.1. State of the Art

A state of the art considers the most up-to-date or current research in a certain area or field of study. It is a modality of a review and documentary research that presents an analytical study of knowledge [17]. Through a state of the art, it is possible to understand the current trends and the main knowledge gaps in a specific subject. To describe the present state of the art we followed the two-phase method proposed by Londoño-Palacio et al. [18]. The heuristic phase consists of the searching for and compilation of information, while the hermeneutical phase consists of explaining, interpreting and analyzing the accumulated information [18]. The stages within each of these two phases are summarized in Figure 1.

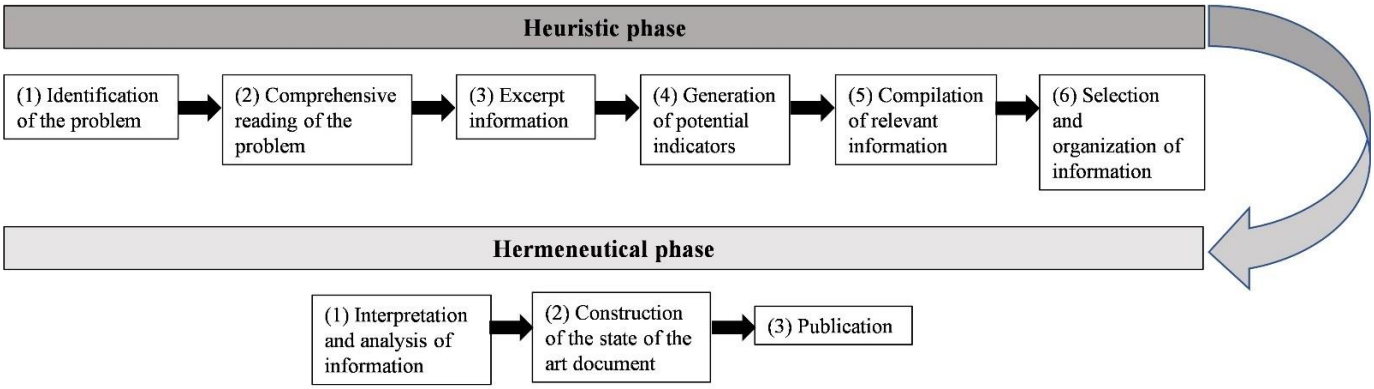

Figure 1. Phases and stages for the construction of a state of the art. Adapted and modified from Londoño-Palacio et al. [18].

2.2. Characteristics of the Heuristic Phase

For brevity purposes, we start describing our methods from stage 5 of Figure 1. During the information compilation stage, we considered several three-word combinations of the following keywords: "*Sargassum*," "sargazo," "arribazón," "atypical influxes," "Caribe Mexicano," "natans," "fluitans" and "Mexican Caribbean," and we searched the results from various sources and types of information (Table 1). For stage 6, we only selected documents that met at least two of the following criteria: (a) studies, projects or initiatives carried out in Mexico between 2010 and the first trimester of 2021, (b) direct references to *Sargassum* atypical influxes to the Mexican Caribbean coasts, (c) mention of the species *S. natans* and/or *S. fluitans* that arrive to Mexico and (d) projects or initiatives conducted in other countries where Mexican researchers participated either as principal investigators, or as co-investigators. The rationale for limiting the search process to these criteria was to obtain a focused review of management and research actions related to these macroalgae in Mexico.

Table 1. Identified documents by origin source as part of the heuristic stage of the state of the art. From this number of documents, 185 met the established criteria.

Information Source	**Identified Documents (n=)**

Consorcio de Investigación del Golfo de México (CIGOM)	2
Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV) Repository	2
Instituto Mexicano de Tecnología del Agua (IMTA) Repository	6
Centro de Investigación Científica de Yucatán (CICY) Virtual library	6
Centro Mexicano de Innovación en Energía Océano (CEMIE-Océano); Instituto Mexicano de la Propiedad Industrial (IMPI)	8
Universidad Nacional Autónoma de México (UNAM) Repository	9
Colegio de La Frontera Sur (ECOSUR) Repository	10
Databases of projects funded by the Consejo Nacional de Ciencia y Tecnología (CONACYT)	11
Non-structured online interviews	15
Consorcio Nacional de Recursos de Información Científica y Tecnológica (CONRICyT)	23
Instituto Politécnico Nacional (IPN) Repository	44
Web of Science	49
CONACYT Repository	55
Google search and Google scholar	435

During this stage, experts were also identified and cataloged within the academic, private, civil, foreign and government sectors. Experts with at least two projects, initiatives or studies on *Sargassum* as principal investigators (or project leader) were included in this database. Additionally, previously existing directories in CONACYT and other federal government agencies (e.g., Instituto Nacional de Ecología y Cambio Climático (INECC)) were also compiled.

2.3. Characteristics of the Hermeneutic Phase

During stage 1 of the hermeneutic phase, two databases were generated, one for projects, studies and initiatives, and the other for experts. The first database (Supplementary File S1) provides an in-depth overview of the diversity of actions that have been conducted in Mexico to address the pelagic *Sargassum* in the country since 2010. The fields' description of this database can be consulted in Supplementary File S1.1. The second database (Supplementary File S2) provides a list of stakeholders (researchers, businesspeople, Non-Governmental Organizations (NGOs) founders, private consultants, government officials, etc.) who are experts in different areas related to the *Sargassum* phenomenon. Fields' description can be consulted in Supplementary File S2.1.

3. Results

3.1. Findings on the Mexican Government Strategy to Address the Phenomenon

Based on the generated databases and interviews with subject-experts, we distinguished three historical stages of actions to address the phenomenon in Mexico from the federal, state and local governments:

(1) Awareness of the problem: The massive influxes of *Sargassum* began to represent a social problem in Quintana Roo until 2015, when there was media coverage about these influxes for the first time; however, they were presented as a transitory event. This stage was characterized by an awareness that *Sargassum* is not a temporary situation with a limited impact, but will be a recurring wide-spread problem. The solutions implemented during this period were characterized by beach cleaning interventions by local and hotel authorities, with minimal intervention from the state and federal government, as well as very limited funding to generate new scientific knowledge.

(2) First actions: The massive influxes of 2015 and 2018 reframed the situation and its definition as a comprehensive, permanent and multinational challenge. The federal government invested 62 million Mexican pesos (~3 million USD) from the Fondo Nacional de Emergencias (FONDEN) and an additional budget of 240 million Mexican pesos (~12 million USD) for the Secretaría de Medio Ambiente Estatal de Quintana Roo (SEMA) for the removal of *Sargassum* from touristic beaches [19]. In 2018, CONACYT addressed the phenomenon from a scientific and technological development perspective. The same year, the congress of the state of Quintana Roo approved the "environmental sanitation tax" which is applied to tourists for hotel occupancy in Cancun. This tax seeks to guarantee beach cleaning and beach conservation financial resources for the municipality [20].

(3) The SEMAR decree: The Secretaría de Marina (SEMAR) has been coordinating *Sargassum* containment and management efforts by government decree since 2019 [21]. In support of this decree, CONACYT defined a scientific, technological and innovation agenda for the attention, adaptation and mitigation of the massive influxes of *Sargassum* on the Mexican coasts in 2019 [22]. This Agenda was published as a collaborative effort between various federal and local government institutions, as well as specialists and experts in different disciplines and areas of knowledge (https://conacyt.mx/sargazo/images/Agenda/ 2020/Agenda_Conacyt_Sargazo-2020_.pdf, accessed on 18 April 2022) [22]. This Agenda defines nine strategic and multidisciplinary lines to address the *Sargassum* phenomenon in a comprehensive manner at different timescales: (1) origin and ecological importance, (2) monitoring, modeling and early warning, (3) socioeconomic and environmental impacts, (4) containment, harvest and disposal, (5) potential uses, (6) restoration of affected ecosystems, (7) regulations, (8) communication and education and (9) international cooperation.

3.2. Findings on Knowledge Generation

A total of 185 projects, initiatives or studies concerning the pelagic *Sargassum* in Mexico were generated between 2010 and 2021. We identified nine additional projects with a starting date or results expected after 2021 (Supplementary File S1). Most were review articles (30%) (Figure 2). A considerable number of projects (137) did not reach the peer-review publication stage. The project "Sistema de Información y Análisis Marino Costero (SIMAR)" of the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) was the only identified project with databases for free download or public access.

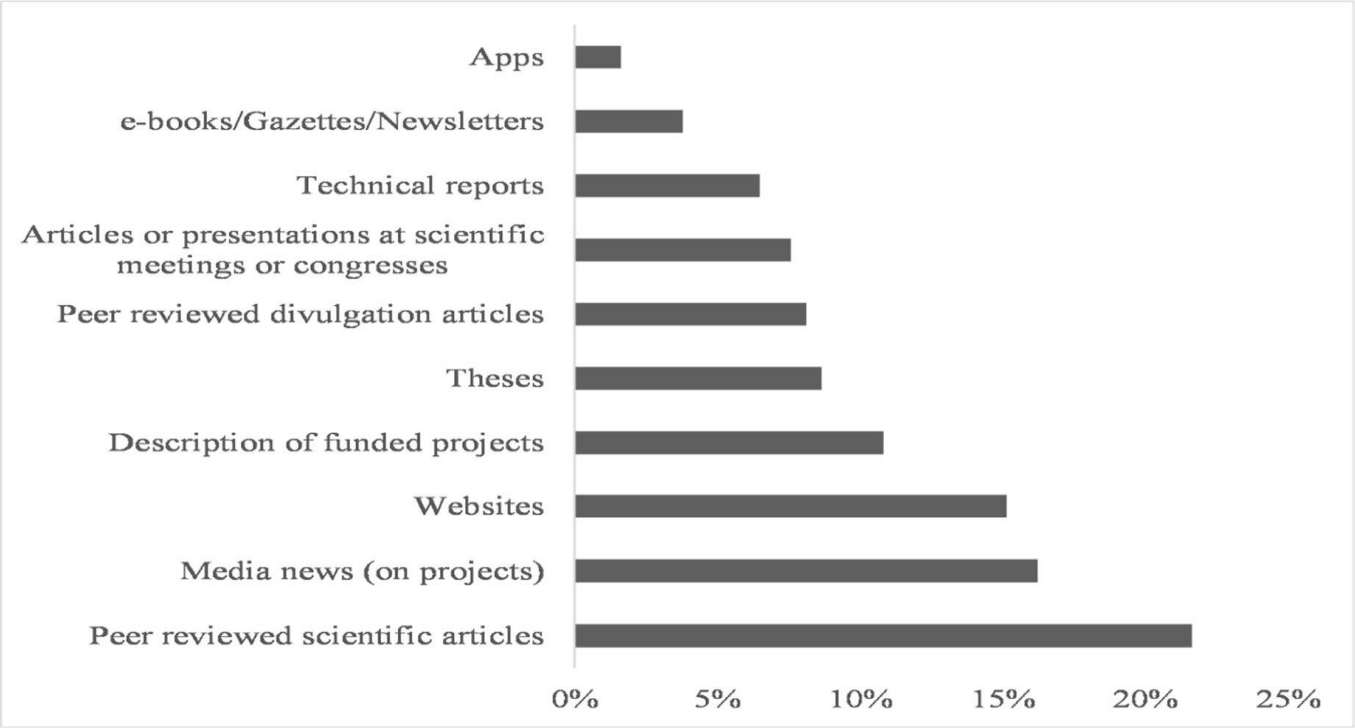

Figure 2. Percentage of projects or initiatives by type of document consulted.

Of all the projects, 68% were developed by the academic sector (Figure 3). Almost 30% of the projects were developed by four academic institutions: CICY, CINVESTAV, ECOSUR and UNAM (Figure 4).

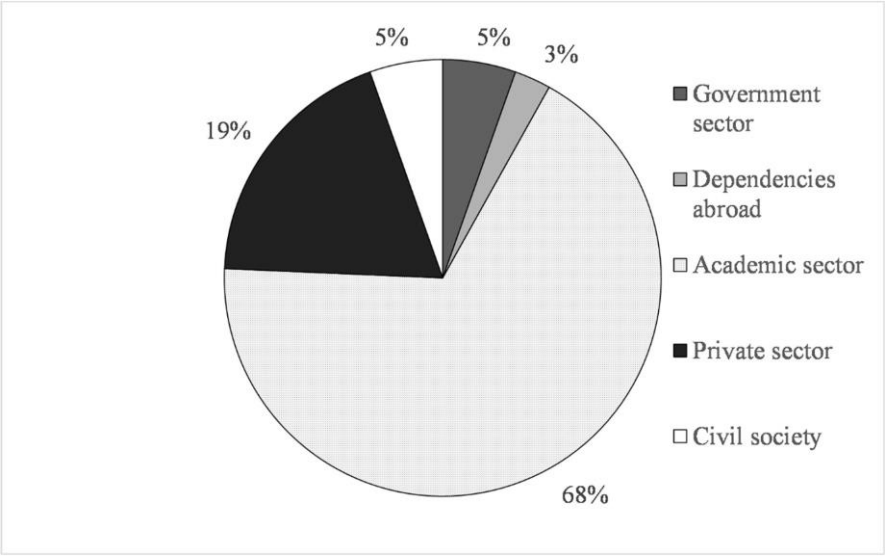

Figure 3. Percentage of projects or initiatives conducted by different sectors.

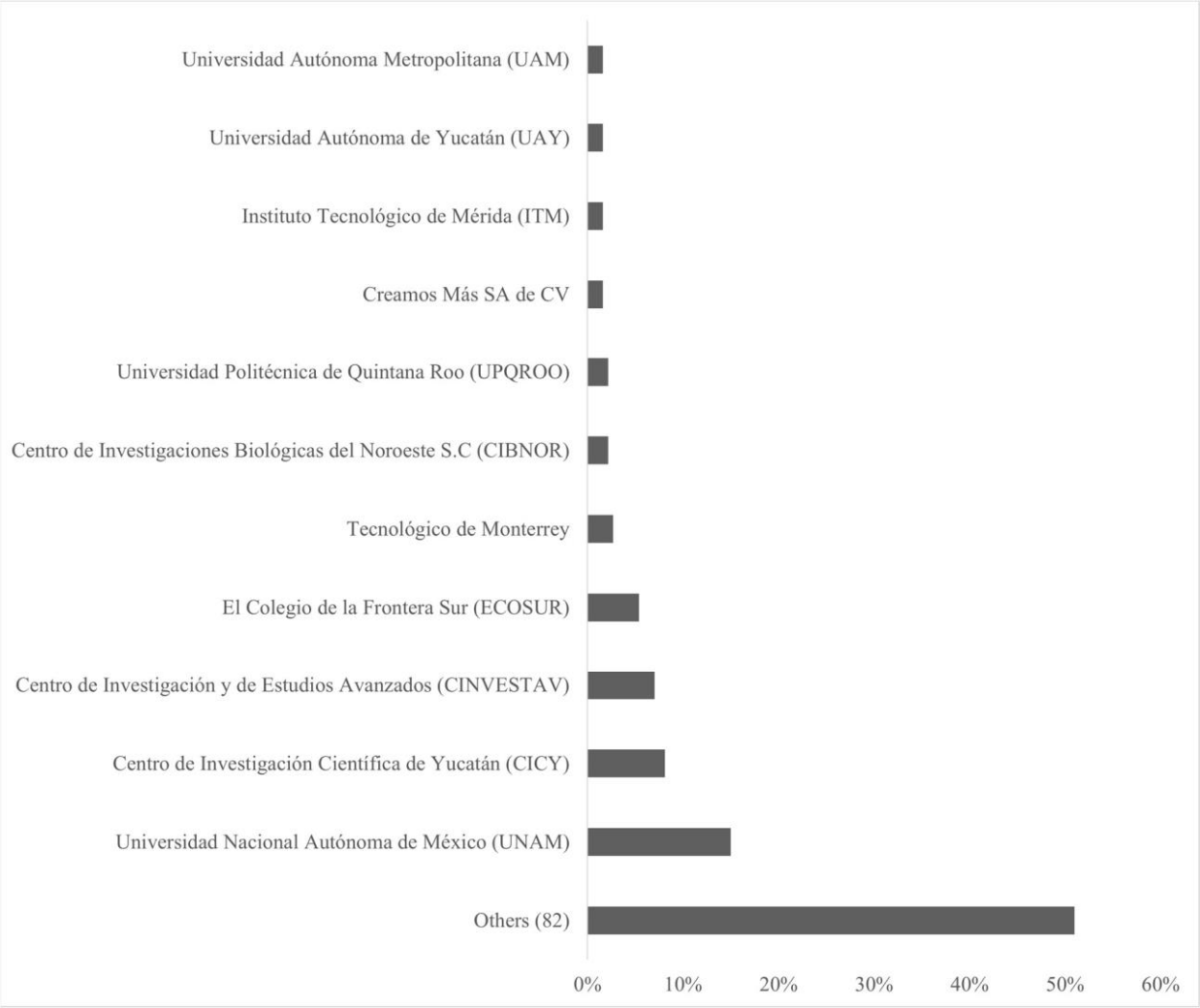

Figure 4. Percentage of projects or initiatives conducted by different institutions.

Most projects (41%) were found under the strategic line of potential uses. We identified a total of eight Mexican granted patents, four within this line and four within the containment, harvest and disposal strategic line (Supplementary File S1). The second most common strategic line was that of socioeconomic and environmental impacts, with 18% of the total projects (Figure 5). The less developed strategic lines, with longer temporal scales to achieve outputs, were those concerning the development of regulations and restoration efforts of affected ecosystems. These accounted for only 1% of the identified projects (Figure 5).

Next, we describe the content of each of these strategic lines and provide an overview focusing on what has been accomplished in Mexico and what the current consolidation needs are.

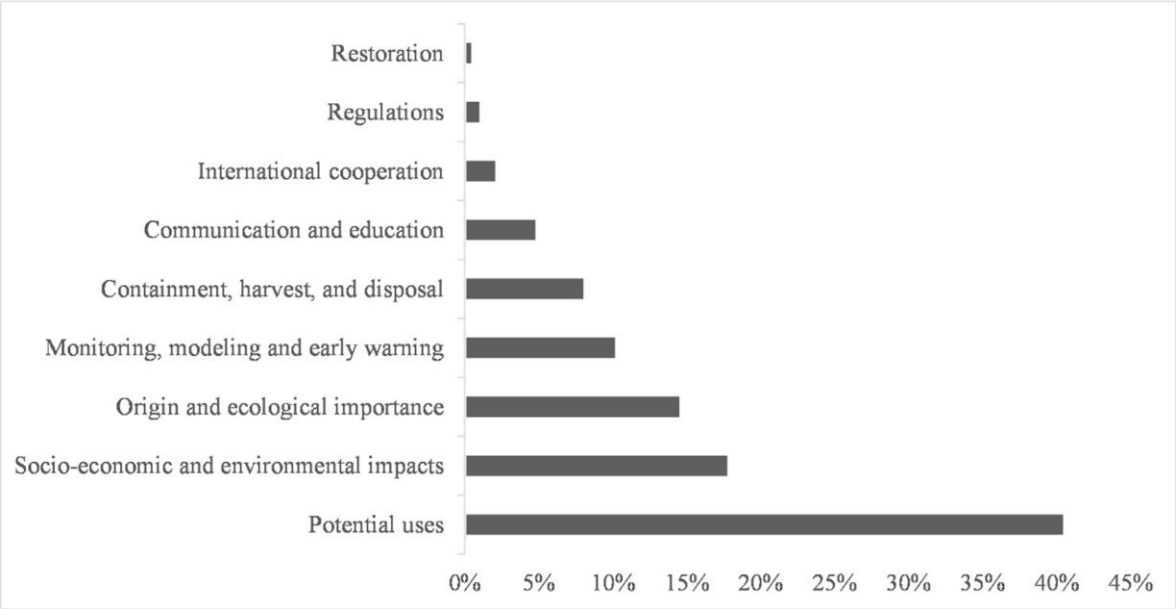

Figure 5. Percentage of projects assigned to each of the nine strategic lines.

3.2.1. Origin and Ecological Importance

The origin and causes of massive growth of *Sargassum* in the last decade are still being studied worldwide [11]. Blooms in the open ocean have been associated with changes in wind circulation and ocean currents [23]. Other hypotheses, such as the input of iron- and phosphorous-rich sand dust of the Sahara Desert [24] and the input of nutrients from river discharges [11], are still being tested. The identification and characterization of *Sargassum* species is also a critical component to understanding the bloom formations [25,26].

This strategic line also entails the importance of *Sargassum* in macro- and microecological processes. For example, *Sargassum* is one of the main carbon sinks in the ocean, forming a trophic link between pelagic and benthic habitats [27–29]. *Sargassum* also forms important biological associations with many marine organisms [2–4].

Studies in this line were initiated in Mexico in 2010 (Supplementary File S1). Many

(37%) of the identified projects regarding the origin of *Sargassum* atypical influxes are review articles (Supplementary File S1). Most of the studies (52%) are related to the ecological and environmental importance of *Sargassum* at the coastal scale and the identification and characterization of different morphotypes. Based on the compiled information, summarized by subarea, we described the existing knowledge and what is needed to consolidate this strategic line (Table 2). These studies, projects and initiatives are further described in Supplementary File S3.

Table 2. Knowledge advances from projects, studies and initiatives regarding the strategic line of origin and ecological importance.

Subarea	What It Is Known	Needs
Origin of the phenomenon	The transport of *Sargassum* from the ocean to coastal areas is not well understood and several variables are [30]. The nutrient input from rivers is not likely the main explanatory variable of atypical influxes [31]	Scientific evidence to support different hypothesis associated with massive growth; open-access databases of variables to support models
Sargassum morphotypes in Mexico differ		

Changes in biological and genetic structure of floating biomass (morphotypes)	from those reported in the Sargasso Sea [32] Morphology shows phenotypic variations according to habitat and season [25,26]	Systematized identification of species
Carbon sink and sediment supply to the deep sea and coasts	*Sargassum* fixate CO_2 and it is a vital carbon sink and calcium carbonate producer for the coasts [33,34]	Calcite production mechanisms in *Sargassum* and its epiphyte communities; *Sargassum* carbon flux measurements to deep ecosystems
Biological associations	Biological associations between *Sargassum* and various taxa vary in diversity and abundance according to the size of the *Sargassum* raft and its distance from the beach [3,4,35,36]	Characterization of biological associations in open ocean, nearshore waters, and on the beach

3.2.2. Monitoring, Modeling and Early Warning

The use of remote sensors has helped to detect *Sargassum* rafts in the open ocean [37]. However, *Sargassum* tracking and quantification still present technical challenges. For example, satellite information is limited by cloudiness, which means that information on the presence and route of *Sargassum* may be lost for several days. Another limitation is the spatial and temporal resolution provided by satellites. High spatial resolution satellites (e.g., Sentinel-2, Landsat-8, Planet) do not collect data over large areas and their temporal resolution can be low compared to satellites of lower spatial resolution. Low spatial resolution satellites (e.g., MODIS, Sentinel-3) limit the detection of small and isolated *Sargassum* rafts and are not suitable for detection in coastal areas [38].

Numerical models that can predict when and where *Sargassum* rafts that are detected in the open ocean may arrive are needed. Current models have not been highly effective in predicting influxes, since *Sargassum* is not just a floating particle but a living organism that interacts with and responds to a changing and complex environment [39]. In the coastline, nested models at fine resolutions are still required [40].

An effective *Sargassum* early warning system must be based on robust remote and in situ monitoring that feed highly predictive numerical models to determine the probability of beach strandings. This would allow for a system akin to hurricane forecasting [41], with a major impact on containment, harvesting and other management strategies [37,42].

Mexican efforts in *Sargassum* detection and the development of a monitoring and an early warning system began in 2014 (Supplementary File S1). The federal government and academic sectors are currently working to solve the technical limitations of both remote sensing and numerical models (Supplementary File S3). There are also important civil society initiatives to produce "*Sargassum* traffic lights", a widespread tool to inform tourists about the amount of the macroalgae in touristic beaches (Supplementary File S3). What we know and have accomplished in Mexico in the main subareas of this strategic line, as well as the main requirements in order to consolidate it, are summarized in Table 3. Some of these studies, projects and initiatives are further described in Supplementary File S3.

Table 3. Scientific and technological advances in the strategic line of monitoring, modeling and early warning.

Subarea	What It Has Been Done	Needs

Remote sensing and ocean coastal monitoring	Algorithms for the detection of *Sargassum* rafts from satellite images at different spatial and temporal resolutions [43–45]	Continuous (i.e., hourly) and high-resolution (i.e., meters) detection of *Sargassum* rafts in and coastal areas
	Interactive platforms to visualize *Sargassum* at open ocean (Supplementary File S3)	
Numerical models for drift prediction	Nested numerical models for the coastal zone [46,47]	Resolving bathymetric, hydrographic and atmospheric conditions at appropriate resolution
	Numerical models that include the biophysiological characteristics of *Sargassum* [39,48]	Numerical models with high predictive capacity that can simulate the behavior of *Sargassum*; knowledge about *Sargassum* physiology, biological parameters, etc.
	High-frequency radar coastal infrastructure to determine coastal scale wind and sea current patterns [49]	Expansion of coverage and maintenance of this infrastructure
Early Warning	Warning bulletins and *Sargassum* traffic lights (Supplementary File S3)	Development of a robust early warning system to predict beach strandings
Monitoring in situ	Online platform to collect and synthetize information on *Sargassum* volumes that arrive to the coast (Supplementary File S3)	Continuous and systematic records of the occurrence of the phenomenon at fine temporal (i.e., daily) and spatial (i.e., meters) scales
	Sargassum population dynamics [50]	
	Citizen Science for in situ monitoring [51,52]	Improvements in statal telecommunication infrastructure (i.e., widespread free internet access) and massive informative campaigns

3.2.3. Socioeconomic and Environmental Impacts

Atypical influxes of *Sargassum* have ecological, economic and social impacts that need to be described and quantified. These impacts have multisectoral effects at the local, state and national levels [53]. Economic and social activities such as tourism and fishing are affected [54].

Decomposing *Sargassum* in coastal waters or on beaches release toxic gasses such as methane and hydrogen sulfide [55] that have detrimental effects on human health [56]. In the reef lagoon, decomposing *Sargassum* produces high loads of organic material leading to eutrophication, where the water contains low levels of oxygen, high concentrations of nutrients, hydrogen sulfide and tannins [57]. Eutrophication of the water and leachates containing arsenic and other heavy metals has an effect on population structure and mortality of marine organisms [12,58]. The *Sargassum* that is transported and discarded inland contaminates the aquifer and cenotes (sinkholes) with leachates [59].

These impacts have been studied in Mexico since 2010 (Supplementary File S1). Most (61%) of these studies have been focused on ecological effects (e.g., mortality of marine organisms, detrimental effects on coral reefs and seagrasses). Effects on human health, commercial fisheries and beach erosion have been poorly documented.

Table 4. Knowledge advances in the strategic line of socioeconomic and environmental impacts.

Subarea	What It Is Known	Needs
Tourism	Not all indicators reflect a clear trend in relation to atypical influxes [53]	Continuous and systematic monitoring of tourism indicators that allows to distinguish *Sargassum*-related fluctuations from other variables (e.g., inefficient tourism promotion, local insecurity)
Commercial fisheries	During atypical influxes, fishermen reduce or alter their activity [60]	Documenting social impacts; a socio-economical perspective of the phenomenon
Human health and air pollution	Toxic gas emissions from decomposing *Sargassum* and the potential growth of pathogenic bacteria [61]	Documenting of health impacts; a public health perspective of the phenomenon
	Coastal eutrophication leads to mortality of marine organisms [12,57]	
Leachates, eutrophication and contamination of aquifers and cenotes	The region's aquifer, including the cenotes, are contaminated because of leachates [59]; indirect contamination of cenotes also occurs due to a shift in tourism activities from the sea to coastal areas [14]	
	Oxidative damage in turtles [62]; fewer turtle hatchlings [63]	
	Loss of the seagrasses and the seafloor [12]	
	Total or partial mortality of coral reefs [64–66]	
Erosion of beaches	Heavy machinery used to collect *Sargassum* affects the coastal dynamics by removing and compacting the sand [67]	Documenting containment and harvest technologies' impacts

.2.4. Containment, Harvest and Disposal

Efforts to contain *Sargassum* at sea before it can reach the beaches are conducted through the installation of barriers. These barriers stop and aggregate *Sargassum* to be collected by "*Sargassum* trawlers" or be redirected away from the coast [68]. Incipient *Sargassum* harvest at sea is conducted by vessels, trawlers or small coastal boats [21]. Some vessels have pre-processing systems such as milling to reduce *Sargassum* volume [69].

Once the *Sargassum* strands on the beach, it is collected with wheelbarrows and rakes by hotel staff, municipal brigades or local people [67]. In months of atypical influxes, mechanical machinery is used [69]. *Sargassum* collected at sea and on land is transported to collection points and then transported to treatment stations or final disposal sites with towing vehicles. The facilities of *Sargassum* treatment stations must be adequate to prevent leachates from reaching the aquifers [69].

Most management efforts to date in Mexico are focused on *Sargassum* containment in coastal waters and harvest at beaches [22]. These strategies have been conducted since 2015 (Supplementary File S1). The containment and harvest actions are centralized by the state government through the different municipalities and by the federal government through SEMAR. Furthermore, most of the technological developments and innovations (i.e., barriers, trawlers, pre-processing equipment, beach clean-up equipment, etc.) are conducted by the private sector (Supplementary File S3). The document "Lineamientos Técnicos y de Gestión para la Atención de la Contingencia Ocasionada por Sargazo en el Caribe Mexicano y el Golfo de México"(https://www.gob.mx/cms/uploads/attachment/ file/636709/SEMARNAT-INECC-SARGAZO-2021.pdf accessed on 18 April 2022) [69] describes the characteristics that these developments must meet. What we know

and have done in Mexico in the main subareas of this strategic line, and the main things needed to consolidate it, are summarized in Table 5. Some of these studies, projects and initiatives are further described in Supplementary File S3.

65

Table 5. Knowledge advances in the strategic line of containment, harvest and disposal.

Subarea	What It Has Been Done	Needs
Containment and deflection at sea	Development and installation of barriers (Supplementary File S3)	Inventory of current technological developments, their effectiveness and their ecological effects (i.e., fauna disruption, substrate removal by anchorage systems, sand erosion and compaction, etc.)
Harvesting at sea	Development and use of trawlers (Supplementary File S3)	Increasing the number and processing capacity of trawlers; development of on-board pre-processing techniques (e.g., milling, washing, pressing, etc.
	Manual harvest (Supplementary File S3)	Adequate material and maintenance; working conditions' regulations
Collecting at beach	Mechanical machinery that prevents beach erosion and sand compaction (Supplementary File S3)	Technological developments and innovation; monitoring and development of indicators to assess erosion, compaction and other ecosystem perturbations
	Pre-processing techniques (e.g., sand removal, drying, etc.) (Supplementary File S3)	
Sargassum primary treatment stations; *Sargassum* disposal sites with Temporary transfer and final		
Incipient integrated management plans (Supplementary File S3)	adequate infrastructure characteristics to prevent leachates pollution; disposal stations regulations compliance	

.2.5. Potential Uses

Several uses for pelagic *Sargassum* have been explored in the last decade [70]. These are based on the biological, physical and chemical characteristics of the macroalgae [71].

Agriculture Industry and Livestock Goods

Composting has been explored for the conservation and enhancement of soil as one of the most economical and practical methods for the exploitation of fresh and dry *Sargassum* [72]. *Sargassum* has also been explored as a growth substrate for plants and as an additive to substrates due to its antifungal, antimicrobial and antiviral properties [73]. The use of *Sargassum* as a biofertilizer has become visible worldwide [70]. Biostimulants and biofertilizers are compounds that stimulate plant growth by providing nutrients, improving soil quality and creating a natural microbial environment [74].

Chemistry, Pharmaceutics and Nutritional Supplements

Macroalgae are an important source of alginates, fucoidans and fucoxanthins [70]. The compounds are used in the food industry as emulsifiers and gelling agents [75]; as food or dietary supplements with antioxidant, anticoagulant, antithrombotic, anti-inflammatory, antiviral, antilipidemic, antidiabetic and anticancer properties [76], and in the cosmetics industry as they contain important levels of nutrients and minerals [77,78].

Ecomaterials

Ecomaterials are economically viable products with a minimal ecological footprint that use existing local raw materials combined with existing technologies [79]. *Sargassum* has been used as a material (i.e., in concrete and bricks) for construction, for textile fiber production (i.e., in footwear), for bioplastics production and for paper manufacturing [70].

Livestock Feed

The suitability of *Sargassum* use in animal feed supplement is highly questioned due to potential toxic effects of heavy metals [70,80].

Bioenergetics

Sargassum that arrives on beaches or that becomes a residue from other industrial processes has a promising potential use as an energy source (i.e., bioethanol, biogas and biodiesel). It does not require fresh biomass like other processes (e.g., biofertilizers production) [71]. Limitations for this use are the high concentrations of recalcitrant components in *Sargassum*, such as sulfates, sodium chloride and heavy metals, which can act as inhibitors of anaerobic digestion, a process necessary for bioenergy production [81]; additionally, the amount of lignin found in *Sargassum* cell walls acts as a barrier to the microorganisms needed in the biofuel conversion process [82]. Other isolated efforts to produce bioenergy from *Sargassum* used direct pyrolysis of waste biomass. However, the high content of *Sargassum* ash leads to a low gross calorific value, resulting in a lower energy yield than that given by land-based plant biomass [83] and a large atmospheric impact with the release of several pollutants [84].

Advanced Materials

Sargassum can be used to obtain biocarbon and nanocarbon for the generation of electrocatalysts and specialized goods for high-tech industries. It has also shown great potential for the green synthesis of metal nanoparticles with multiple applications [85–87].

Bioremediation and Purification Mechanisms

The use of *Sargassum* in the production of activated carbon for biofilters that remove pollutants (dyes, ions, heavy metals, nitrogen, phosphorus, phenols, chlorine, etc.) from air, land, gas and water [88] has been explored.

The potential uses of *Sargassum* have been explored in Mexico since 2014 (Supplementary File S1). Most of these initiatives (76%) are focused on the development of biostimulants and biofertilizers, extraction of fucoidans and alginates, development of materials for bioconstruction and the generation of energy. Within this strategic line, we also determined a Technology Readiness Level (TRL) for applicable projects through interviews with

subject matter experts. There are nine levels of TRLs, ranging from the basic principles of creating a new technology (TRL = 1) to the successful testing in a real-world environment and subsequent commercial availability (TRL = 9) [89–91]. (Figure 6). The TRLs of the projects were averaged to determine the TRL of each major product as presented in Figure 6. In Mexico, the industries with the most immediate potential, based on the highest TRL, are the biostimulants and biofertilizers, fucoidan and alginates, textile materials, bioconstruction materials and paper production. What we know and have done in Mexico in the main subareas of this strategic line, and the main needs to consolidate it, are summarized in Table 6. Some of these studies, projects and initiatives are further described in Supplementary File S3.

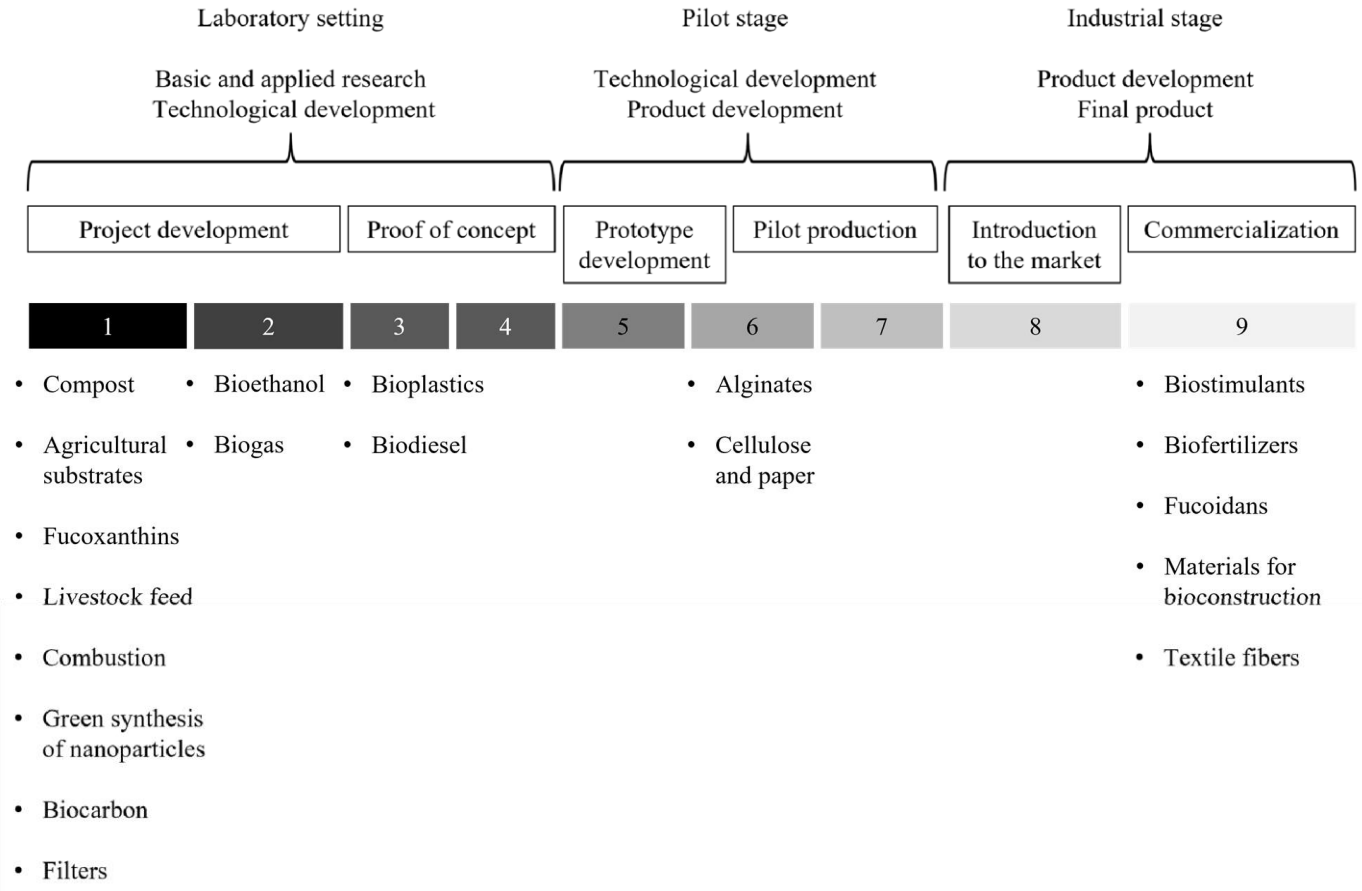

Figure 6. TRL Scale (Adapted from [89]) and an averaged TRL value for each major product or development in MexicoDevelopment of compost (Supplementary File S3)

Extraction of alginates and fucoidans and commercialization of nutritional supplements

Chemistry, pharmaceutics and (Supplementary File S3); fucoidan explored as treatment against herpes virus type I [94] and nutritional supplements COVID-19 [95]

Development and commercialization of bioconstruction materials (concrete, bricks and plates) (Supplementary File S3; [96,97])

Development and commercialization of *Sargassum* cellulose fiber footwear (Supplementary File S3)

Ecomaterials Development of biopolymers with similar

characteristics to those of conventional plastics (Supplementary File S3; [98])

	Sargassum cellulose extraction and the development and commercialization of sustainable products (notebooks, agendas, folders, cup holders, menu holders and business cards, etc.) (Supplementary File S3)
Livestock feed	*Sargassum* as food for laying hens (Supplementary File S3)

Bioethanol production using a high-pressure technology pretreatment [99,100].

Change adverse perception of stranded *Sargassum*; intra and interannual characterization studies and bromatological analysis; determine suitability and

safety of products and by-products; harvesting and processing (i.e., drying, pressing, desalination,

milling) logistics; disposal procedures that facilitate technically, ecologically and economically viable

conservation and storage for a permanent supply; *Sargassum* biomass pre-treatment with fungi and other microorganisms to increase energy efficiency

iomethane production (Supplementary File S3; [81])

Bioenergetics

Biodiesel prototype product (Supplementary File S3)

	Energy generation through hydrothermal carbonization (Supplementary File S3)
Advanced Materials	*Sargassum* aqueous extracts for electrocatalysts and the synthesis of platinum, gold and silver nanoparticles that can be used in the construction of electrochemical glucose sensing platforms, in the catalytic activity for blue methylene degradation and as antibacterials for *Staphylococcus aureus* and *Pseudomonas aeruginosa*) [85–87,101–103]
Bioremediation andEffectiveness of a *Sargassum*-based bioremediation system for the removal of metal ions and toxic	
purification mechanismsdyes in water [104]	

.2.6. Regulations and Other Strategic Lines

The strategic line referring to the legal framework and regulations for all activities associated with *Sargassum* management is crucial to establishing consolidated industries around the use of the macroalgae and reducing socioecological risks associated with macroalgae decomposition at shallow coastal waters and on the beaches. However, this strategic line has very limited information and coordinated technical efforts for its consolidation.

The development of communication and education strategies on the *Sargassum* phenomenon is necessary in order to move from a problem perspective to a resource perspective and to promote a culture of care for the oceans. The *Sargassum* phenomenon affects several nations in the Western tropical Atlantic and the Caribbean region. Thus, it is necessary not only to have a comprehensive national strategy to address this phenomenon, but also a multilateral strategy that brings together the solution-oriented knowledge and experiences of different countries and sectors [22].

Finally, as described above, the extent of the direct and indirect environmental impacts of atypical *Sargassum* influxes is not known at this time. Thus, restoration efforts in affected areas are incipient or nonexistent. Moreover, there is no adequate coastal regionalization that would allow differentiated, zoned *Sargassum* management plans (e.g., marine protected areas, uninhabited areas, fishing areas) [22].

In Mexico, these strategic lines have been addressed, with limited tangible results, since 2019 (Supplementary File S1). In terms of regulations and legal instruments, most of the initiatives are ongoing efforts by different governmental entities (Supplementary File S3). Further actions are needed in all population sectors to consolidate these lines. What we know and have done in Mexico in terms of the main subareas of these strategic lines and the main requirement of consolidating them are summarized in Table 7. Some of these studies, projects and initiatives are further described in Supplementary File S3.

Table 7. Advances in the strategic lines of regulation, international cooperation, communication and education and restoration.

Subarea	What It Has Been Done	Needs
Regulations and legal framework	The Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) National Guidelines (Supplementary File S3)	Compulsory compliance of these guidelines; regulatory frameworks such as a NOM (Norma Oficial Mexicana or Mexican Official Standard)
Communication and education strategies	Articles, specialized magazines, websites of different federal government agencies, and mobile applications (Supplementary File S3)	Local, state and regional informative campaigns
International cooperation	Mexico joined SargCoop [105]	Multilateral strategies that bring together the knowledge and experiences of different nations
Restoration of affected habitats	Efforts to restore and rehabilitate ecosystems affected by atypical *Sargassum* influxes have not been documented in Mexico	Understanding of environmental impacts of influxes; indicators to measure and monitor the ecological and environmental impacts over time; an adequate coastal regionalization that would allow a differentiated *Sargassum* management in different zones

Regarding the geographic representativeness, 72% of the projects, studies or initiatives provided analyses at the state or regional level (Caribbean), and only 28% indicated sitespecific analyses. For the latter, most of the sampling sites are in the northern region of the state of Quintana Roo, between Playa del Carmen and Cancun (Figure 7). In terms of timing, 87% of the projects or studies have been developed since 2018, with a peak in 2019, one year after the most impactful influx of *Sargassum* ever registered.

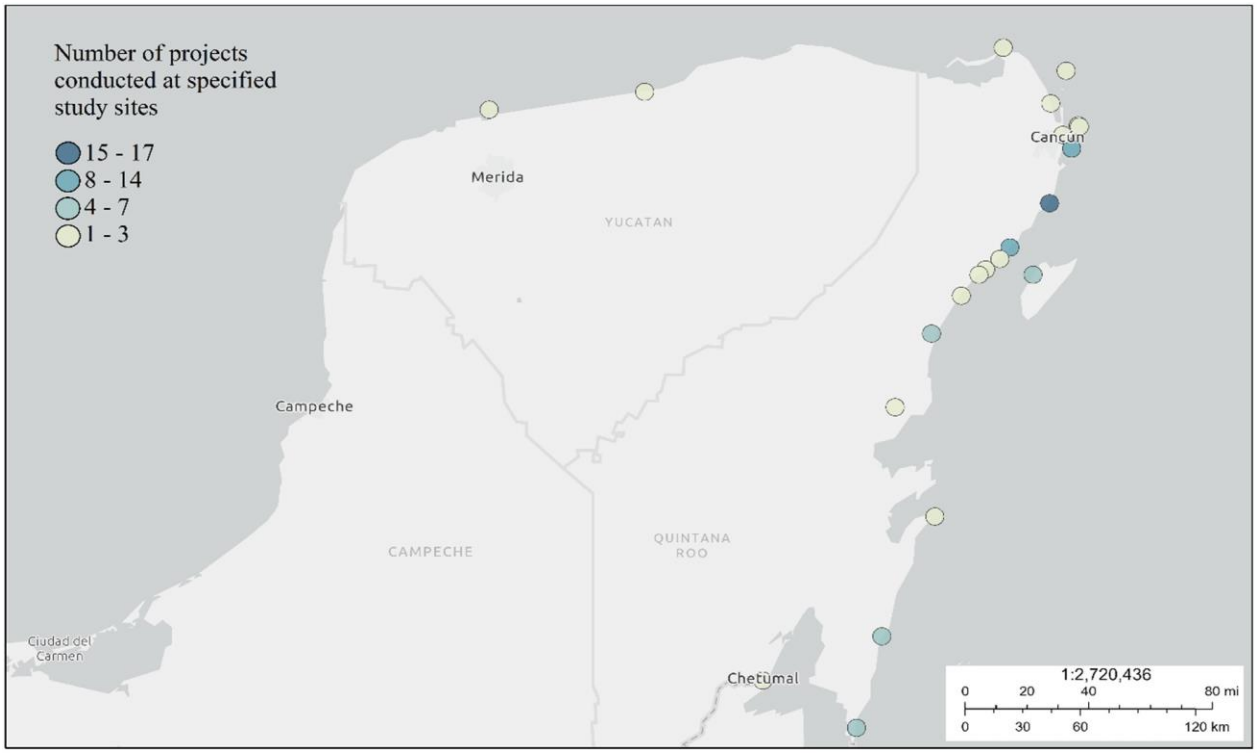

Figure 7. Number of projects conducted per study site.

3.3. Findings on Key Experts and Multisectoral and Interinstitutional Collaboration

We identified a total of 261 experts in the topic of pelagic *Sargassum* in Mexico (Supplementary File S2). Of these, 177 were assigned to a specific strategic line. The others were assigned to an additional classification called "comprehensive attention" due to their inherent multidisciplinary work; most of them were from the government sector. Most experts work within the strategic lines of potential uses, socioeconomic and environmental impacts and monitoring. Most of them work in the academic sector, followed by the private sector. The smallest number of experts was associated with the lines of regulations and restoration of affected ecosystems (Figure 8).

Sector/ Strategic line	Comprehensive attention	Potencial uses	Communication and education	Containment, harvest, and disposal	International cooperation	Socio-economic and environmental impacts	Monitoring, modeling and early warning	Regulations	Origin and ecological importance	Restoration
Government sector	60			1		1	2		1	
Dependencies abroad	1				2				1	
Academic sector	1	44	2	3	1	39	25	1	17	1
Private sector	10	15	1	9		3				
Civil society	10		3		1	2	2			1

Figure 8. Number of experts per strategic line and sector. Green represents highest numbers, while lower numbers are colored in red.

The four institutions with the highest number of experts are UNAM, SEMARNAT, CICY and CINVESTAV, with an average of fourteen experts per institution (Figure 9).

In terms of geographical representation, the largest number of experts were located in Quintana Roo (89), followed by Mexico City (85) and Yucatan (35), while the rest were dispersed in seventeen other states of Mexico.

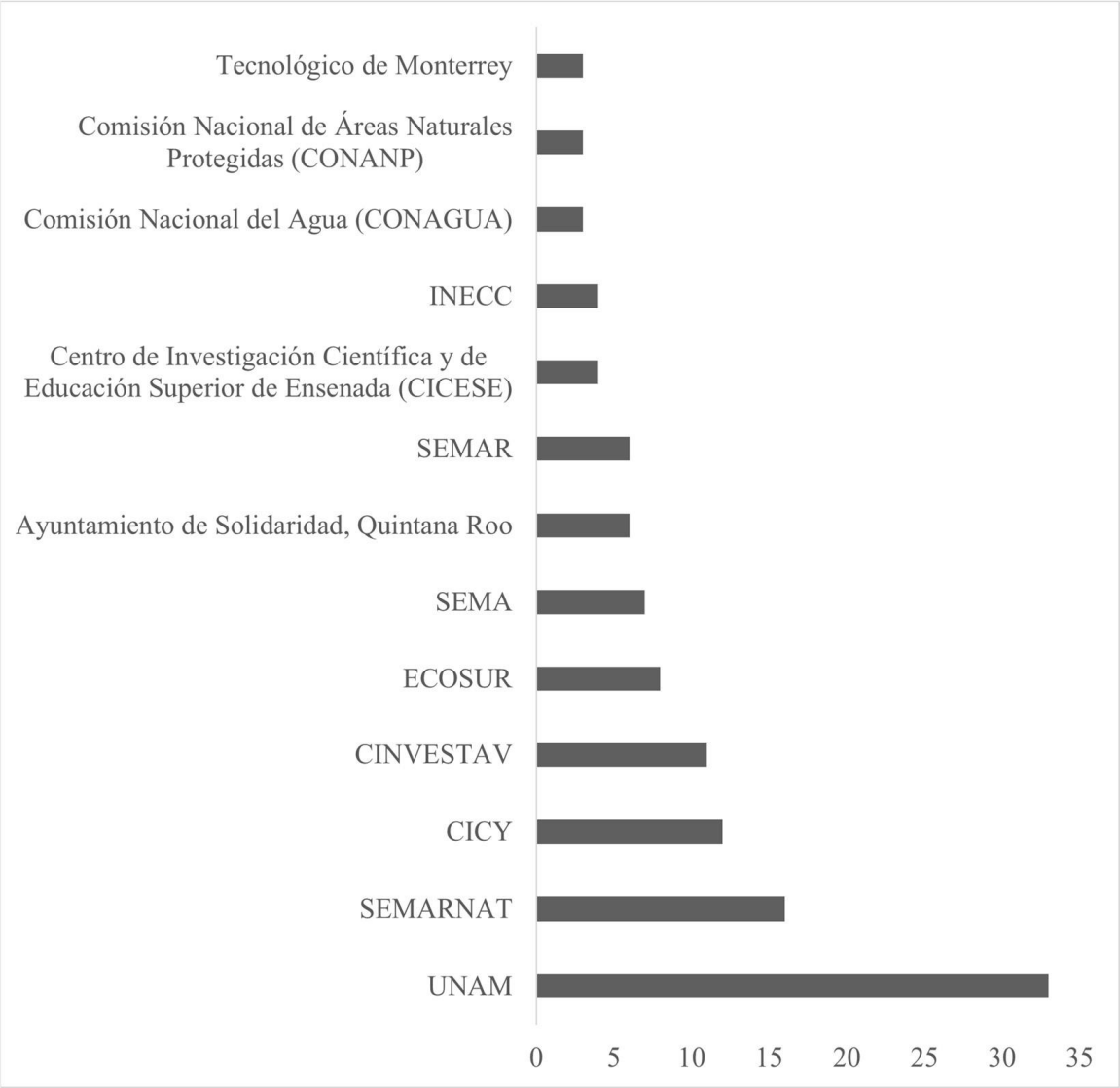

Figure 9. Number of experts per institution in Mexico.

At least one national or international collaboration was identified in 87 of the projects. The average number of collaborations was three within each project. From these, 76% were national academic, private, civil or governmental collaborations, while 24% were international academic and private collaborations (Supplementary File S1). The academic institutions with more established collaborations were UNAM and CINVESTAV, while the government agencies that collaborated the most were CONACYT, SEMAR and CONABIO (Supplementary File S1).

4. Discussion

Sargassum overgrowth and atypical influxes in the western tropical Atlantic and Caribbean coasts poses a challenge for the ecosystem (marine and terrestrial), the economy, the society, and the politics of affected countries [106]. Public and private initiatives in all sectors have evolved to understand, address and provide solutions to

this complex problem. These initiatives in Mexico are numerous and valuable, as described here. However, several issues preclude effective advancements in reaching an integral management of the macroalgae.

We found limited peer-reviewed research publications and open-access databases compared with the number of conducted projects. The latter is critical because it prevents repetition of research efforts over time [107]. Most projects that did not develop publications had an estimated duration of less than two years (Supplementary File S1). Funding duration may not be optimal and multiple-year projects should be prioritized, and especially so along strategic lines that require longer periods to obtain results with meaningful implications in decision-making processes (e.g., monitoring, restoration) [108].

Another important issue is that the research funding seems to respond to atypical influxes events, without continuity or long-term planning (Supplementary File S1). This makes it difficult to understand the cause of the phenomenon, generate adequate predictions or consolidate industries around the resource, especially since efforts continue to focus mainly on mitigation (containment and cleanup) [22] and not on generating a foundation for a robust monitoring and early warning system.

We also found a cluster of research and experts in a few institutions. We think it is important to push more institutions towards innovative excellence across all aspects of this complex topic, without compromising the expertise already achieved. National cooperation between different institutions should be a criterion for future call for proposals and funding [22]. Projects in co-design, co-development and co-delivery are needed, expanding and strengthening existing channels of multisectoral collaboration.

The geographical representation of initiatives and projects addressing the *Sargassum* phenomenon across the Mexican coasts is imbalanced. The attention of academic and other sectors has focused primarily on areas of touristic importance, neglecting rural areas, protected natural areas, fishing zones, etc., where atypical *Sargassum* influxes and their impacts have not been assessed and hence not understood nor quantified [22]. This imbalance needs to be addressed by prioritizing initiatives and research that involve local communities and study sites outside highly developed areas [109]. This will be more feasible when infrastructure in the field allows researchers to reach these sometimes isolated, difficult to reach locations [52].

There is a disparity of efforts between the different strategic lines, which hampers a comprehensive understanding and management of the phenomenon [22]. This disparity responds to the temporal and spatial scales required to generate the knowledge, and should be reduced by emphasizing efforts on those lines with more gaps. Development of capacities and experts within these lines are also required. Communication strategies, international cooperation and paths towards a legal regulatory framework establishing an adequate *Sargassum* management and use are all issues that should be promoted and improved by the governmental sector [80].

Within all strategic lines, there exist significant obstacles to advancing their consolidation. There are logistical and financial limitations, especially to conducting research in the open ocean [110]. For example, in the line of origin and ecological importance, the limited research on the origin of the phenomenon or the role of *Sargassum* rafts as an essential habitat may be related to limited financial resources to conduct research cruises. Another limitation is the inherent long project extension within some strategic lines. For example, in the line of monitoring, data availability, model validation, technology development, etc., require multi-year research funding to achieve a level where the resulting tools can have practical applications. Finally, there is a lack of a comprehensive regulatory framework in Mexico, hindering advancements towards the establishment of value chains (Ministry of Foreign Affairs [111]) and a *Sargassum*-based circular economy. The SEMARNAT guidelines are a first step to fixing regulation voids; however, these are not compulsory.

This state of the art addresses the advances and needs of each of the strategic lines and provides a road map for future research and actions. By having a clear picture of the existing knowledge, it is possible to coordinate more effectively the interinstitutional, multisectoral and multidisciplinary efforts. Based on the identified needs, we determined ten major challenges that need to be addressed at different temporal scales and with different complexity levels (i.e., where major needs and limitations are and where the resources to overcome those needs and limitations are higher) to achieve measurable impacts on the integrated *Sargassum* management, with national level implications (Figure 10).

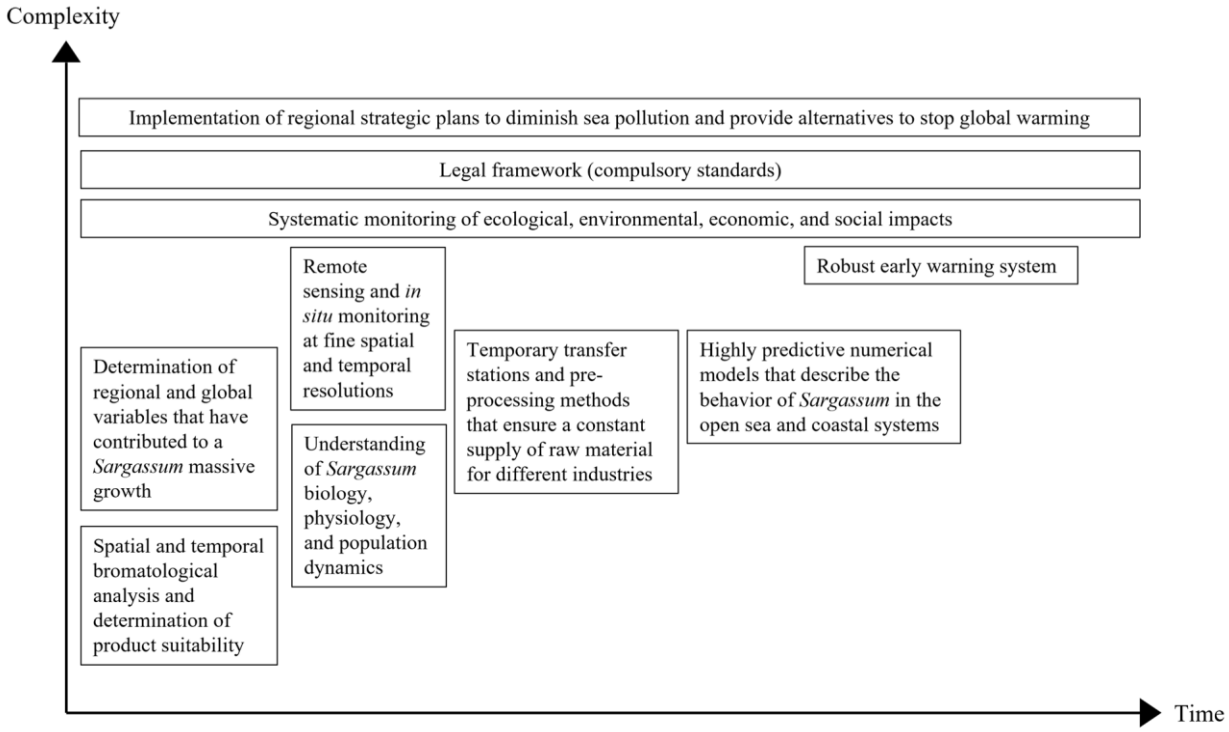

Figure 10. Identified challenges for an integrated *Sargassum* management.

To overcome these challenges, it is crucial to change the perspective that *Sargassum* is a waste and that it should be managed as such. Instead, we should embrace *Sargassum* as a national resource. *Sargassum* is not only a golden pelagic forest of great ecological and environmental value (e.g., CO_2 sequestration capacity) [2,28,29], but it also has an undeniable economic potential for society [80]. Atypical *Sargassum* influxes will continue to occur [12], so it is necessary to establish a mechanism that facilitate biomass harvest at sea with a robust early warning system that will allow timely actions. The negative impacts of *Sargassum* on coasts and beaches will be minimized once it is properly valued as is any other fishery resource. To achieve this status, it is necessary to diminish existing knowledge gaps by means of research and tangible coordinated actions.

The *Sargassum* topic is complex and extends beyond a single country's problem. One of the main goals of this research was to facilitate the transfer of knowledge of successful *Sargassum* actions conducted by different Mexican sectors and stakeholders. Some of these actions can be scaled up regionally and promote the development of joint regional solutions to understand the long-term multifactorial effects on ocean and human health of the massive *Sargassum* standings at a regional scale [112]. Without appropriate management, beached *Sargassum* will keep resulting in ecological, environmental and public health problems including the high costs of biodiversity and ecosystem resilience loss.

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