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Review

Sargassum: Turning Coastal Challenge into a Valuable Resource

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Abstract

The massive influx of pelagic *Sargassum* in the Caribbean poses a serious environmental, social, and economic problem, as the stranded biomass is often treated as waste and deposited in landfills. This literature review synthesizes recent research highlighting its potential for valorization in various industries, turning this challenge into an opportunity. *Sargassum* has low levels of protein and lipids. Still, it is particularly rich in carbohydrates, such as alginates, fucoidans, mannitol, and cellulose, as well as secondary metabolites, including phenolic compounds, flavonoids, pigments, and phytosterols with antioxidant and bioactive properties. These biochemical characteristics allow for its application in renewable energy (bioethanol, biogas, biodiesel, and combustion), agriculture (fertilizers and biostimulants), construction (composite materials, cement additives, and insulation), bioremediation (adsorption of heavy metals and dyes), and in the health sector (antioxidants, anti-inflammatories, and pharmacological uses). A major limitation is its high bioaccumulation capacity for heavy metals, particularly arsenic, which increases environmental and health risks and limits its direct use in food and feed. Therefore, innovative pretreatment and bioprocessing are essential to mitigate these risks. The most promising approach for its utilization is a biorefinery model, which allows for the sequential extraction of multiple high-value compounds and energy products to maximize benefits, reduce costs, and sustainably transform *Sargassum* from a coastal pest into a valuable industrial resource.

Keywords: *Sargassum*; biorefinery; fucoidans; alginates; biostimulants; biofuels; arsenic

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1. Introduction

The recurrent stranding of pelagic *Sargassum* in the Atlantic and Caribbean regions has escalated into a significant global concern [1]. Since 2011, the volume of biomass accumulating along the Mexican Caribbean has overwhelmed local management capacities, leading to its disposal in landfills in the absence of specific legal frameworks [2]. These unchecked accumulations have triggered a multidimensional crisis in the region [2]. The environmental impact is critical, characterized by coastal eutrophication and massive seagrass mortality driven by light attenuation from the extensive brown macroalgae mats [3]. Furthermore, there is a significant risk of aquifer contamination through the leaching of arsenic and other heavy metals accumulated in the biomass [4,5]. Economically, the degradation of scenic beauty imposes severe strains on the tourism industry [2]. At the same time, public health is increasingly compromised by the release of hydrogen sulfide (H_2S) and ammonia (NH3) during decomposition, which has been linked to acute toxicity cases [6]. Despite these challenges, this excess biomass represents an untapped opportunity. In recent years, the focus has shifted from disposal to valorization, exploring sustainable applications such as bioenergy generation and bioremediation, as well as the development of agricultural and pharmaceutical products [7].

Effective management of these *Sargassum* influxes requires a multi-phase strategy [8]. The initial 'exploratory phase' is critical, establishing the scientific baseline for the causes, spatiotemporal dynamics, biology, and chemical composition of the influxes. This knowledge lays the foundation for the subsequent 'valorization phase.' Successfully transitioning to this stage involves a comprehensive protocol: detection via remote sensing, in situ assessment of floating and beached biomass, biomass stabilization, and rigorous chemical analysis. Furthermore, experimentation is essential to understand the factors controlling the species' growth, physiology, and degradation processes [8].

A crucial prerequisite for achieving biomass valorization is understanding the specific species composition of these events. Despite the inherent variability of these natural phenomena, recent studies in the Mexican Caribbean confirm that pelagic *Sargassum* species (*Sargassum fluitans*, *Sargassum natans* var. *natans*, and *Sargassum natans* var. *wingei*) [9] constitute the vast majority of the influx, accounting for 78.1–99.6% of the fresh biomass [10]. However, the remaining fraction is significant; benthic *Sargassum* species (e.g., *S. acinarium*, *S. buxifolium*) and seagrasses (*Thalassia testudinum*, *Syringodium filiforme*, *Halodule wrightii*) have been identified in varying proportions. Depending on the season, these associated species can comprise up to 22% of the total biomass [10–12], a factor that must be strictly considered during characterization.

The unique biology of these holopelagic morphotypes (varieties of *S. fluitans* and *S. natans*), characterized by their strictly free-floating life cycle and rapid vegetative propagation [13], facilitates the continuous formation of massive biomass aggregations. These mats, driven by ocean currents, eventually strand along affected coastlines [1]. Industrially, *S. fluitans* and *S. natans* are valued primarily as sources of alginates and fucoidans, which are used for their gelling and therapeutic properties [7]. Additionally, their high content of phlorotannins (antioxidants) and cellulose positions them as ideal feedstocks for applications ranging from high-value cosmetics to bioenergy production [14,15]. However, to effectively transform this abundant resource into a sustainable industry, a biorefinery approach is increasingly recognized as the optimal strategy for maximizing value recovery.

Accordingly, this literature review synthesizes available knowledge on the chemical composition of pelagic *Sargassum*, including spatiotemporal and interspecific variations. Furthermore, it emphasizes potential high-value applications and evaluates how they can be integrated into a cascading biorefinery model to fully valorize the biomass [16,17].

2. Chemical Characterization and Variability

After thirteen years of *Sargassum* events along the Caribbean region, a significant amount of scientific information on the chemical composition of the three holopelagic taxa of *Sargassum* is now available, including proximal and elemental composition, as well as more complex components such as structural and/or reserve polysaccharides, pigments, and secondary metabolites [10,14,15,18].

To characterize the sampling efforts and biomass properties in the Caribbean, an integrative literature review was conducted using databases such as Scopus, Web of Science, and Google Scholar. The search strategy employed descriptors including '*Sargassum*', 'biomass characterization', and 'chemical composition' covering the period from 2011 to 2025. Through this systematic organization, we found a diverse range of research. Most of these works have been carried out in the Mexican Caribbean (from Tulum to Cancun), with a greater number in the Puerto Morelos area (Figure 1). We found studies that describe sampling at a single site, as well as other works with multiple sampling points, which show similarities or differences in the biochemical components of the biomass across different points along the coast. Another critical difference was the site where the biomass was collected (stranded versus floating).

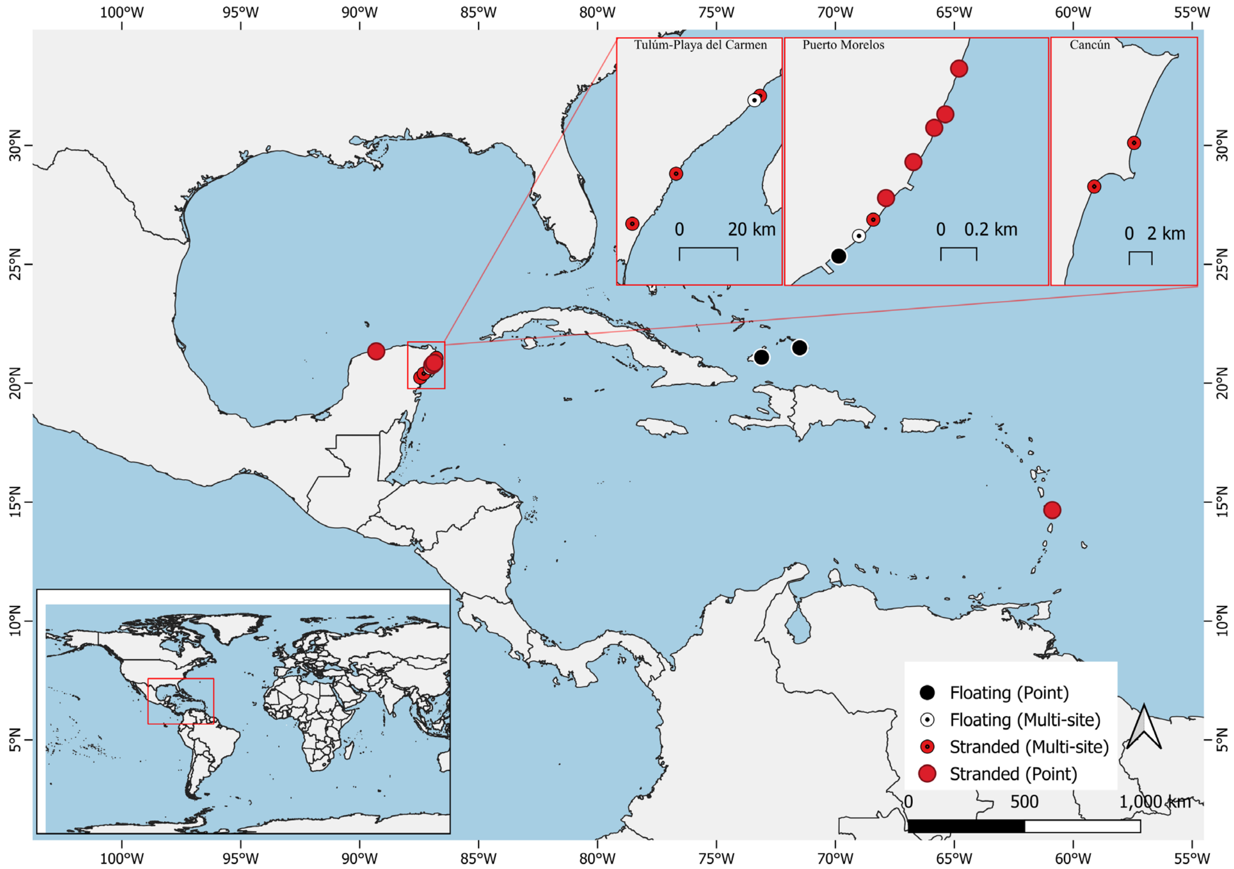

Figure 1. *Sargassum* event maps in the Caribbean region. The geographic distribution of pelagic *Sargassum* sampling sites in the Greater Caribbean region is identified in this review. The main map illustrates the regional dispersion of studies. Insets detail the sampling hotspots along the Mexican Caribbean coast: Tulum-Playa del Carmen, Puerto Morelos, and Cancún. The legend distinguishes between collection types: floating biomass (black circles) and stranded biomass (red circles), further differentiating between single-point studies (solid circle) and multi-site studies (ringed circle). The bottom-left inset indicates the global location of the study area. Map created using QGIS software (version 3.40.12, Bratislava, Slovakia) based on data from [11,12,14,15,18–30].

Far from being redundant, this heterogeneity in sampling efforts provides complementary information on the *Sargassum* phenomenon. Single-site studies [14,15,18,22] typically offer high temporal resolution, essential for understanding seasonal variations and local baseline conditions. Conversely, multi-site studies [10,19,20] reveal spatial heterogeneity in the biochemical profile along the coast, identifying potential environmental factors that modify its composition.

Additionally, distinguishing between collection sites (stranded versus floating biomass) is crucial for developing effective valorization strategies. Floating samples represent the ideal 'pristine' chemical baseline for high-value applications. In contrast, data from stranded biomass reflect the reality of management challenges, including weathering, sand inclusion, and early-stage decomposition.

The chemical composition of these holopelagic taxa shows variation according to the species (interspecific variation), the type of sample (stranded vs. floating biomass; fresh, degraded, or dried biomass), the season of the year, and the region of collection (Table 1). Holopelagic algae of the genus *Sargassum* spend their entire lives as floating organisms, traveling long distances across the Atlantic Ocean. They can incorporate nutrients or contaminants during their journey [2]. Consequently, their chemical composition can vary with environmental conditions encountered during oceanic transport (e.g., salinity, temperature, pH, nutrients, and light).

Table 1. Biochemical composition of holopelagic *Sargassum* species.

Compounds	*S. fluitans*	*S. natans* var. *natans*	*S. natans* var. *wingei*	Mixed Biomass
Proximate composition (% DW)				
Moisture	86.3 [19]	87.4 [19]	86.5 [19]	82.0 [19]; 13.0 [21]; 12 [22]
Ash	23.8 [18]; 3.4 [19]	23.5 [18]; 35.7 [19]	23.3 [18]; 34.3 [19]	46.9 [19]; 18.7 [24]; 19.3 [22]
C: N ratio	25.8 [18]	28.2 [18]; 9.2 [23]	28.9 [18]	28.2 [10]
Proteins	10.4 [18]	12.4 [18]	11.2 [18]	9.2 [10]; 5.9 [24]; 8.3 [22]
Lipids	1.0 [18]; 4.6 [19]	0.6 [18]; 4.5 [19]	0.7 [18]; 3.6 [19]	3.9 [19]; 3.0 [10]; 1.3 [24]; 6.0 [22]
Carbohydrates	27.4 [19]	19.0 [19]	21.8 [19]	11. 7 [19]; 32.4 [22]; 15.5 [10]; 13.7 [24]
Fibers	31.1 [19]	37.0 [19]	37.4 [19]	33. 3 [19]; 22.0 [22]
Structural and reserve polysaccharides (% DW)				
Alginate	34.6 [23]; 19.6 [18]; 9.4 [20]; 18.8 [25]; 24.6 [26]	15.7 [18]; 11.1 [20]; 19.9 [25]	23.5 [18]; 12.2 [20]	31.6 [10]
Fucoidan	4.4 [23]; 9.1 [18]	6.3 [18]	8.2 [18]	8.6 [10]; 7.2 [22]
Cellulose	12.9 [18]; 34.4 [27]	11.5 [18]; 45.4 [27]	18.8 [18]	--
Lignin	17.8 [18]; 25.40 [27]	25.0 [18]; 29.5 [27]	19.2 [18]	--
Mannitol	49.9 [18]	58.4 [18]	60.1 [18]	--
Pigments (mg g^{-1} DW)				
Chlorophyll *c*	0.06 [28]	0.08 [28]	0.009 [28]	0.06 [10]
Chlorophyll *a*	0.7 [10]	0.9 [10]	0.5 [28]	0.2 [10]
Carotenoids	--	--	--	0.1 [10]
Fucoxanthin	0.2 [28]	0.3 [28]	0.1 [28]	--
Metabolites (% DW)				
Polyphenols	1.4 [14]	1.3 [14]	1.1 [14]	--
Flavonoids	19.8 [27]; 0.4 [20]	0.6 [20]	0.9 [20]	0.3 [20]

Identifying economically valuable components is a prerequisite for finding applications for holopelagic *Sargassum* species. While species-specific data are ideal, some studies are only available for mixed samples. Notably, several studies have shown that, for most components, comparable or higher yields are obtained with mixed biomass without species separation [3]. This finding is critical for industrial scalability, as separating species is labor-intensive and cost-prohibitive. However, the feasibility of using mixed biomass depends on the compound of interest or the desired application, as some components can vary significantly across holopelagic *Sargassum* taxa [3,4].

Table 1 summarizes the proximate and biochemical composition reported for the three holopelagic *Sargassum* morphotypes and mixed biomass. As observed, the data reveal significant heterogeneity across all parameters, mainly attributable to differences in sample origin (fresh vs. stranded) and pre-treatment protocols rather than solely to interspecific variation. This is particularly evident in the ash content, which fluctuates drastically from 3.4% to 46.9%, reflecting the degree of washing and the presence of sand or sea salts in stranded samples. Regarding the carbohydrate fraction, the table highlights the potential of these species as biorefinery feedstocks, characterized by remarkably high levels of mannitol (up to 60.1% in *S. natans* var. *wingei*) and alginates. Conversely, while lignin values are reported as high as 29.5%, these figures are likely overestimated due to the analytical interferences discussed in the text. Finally, the profile includes bioactive metabolites and pigments, such as fucoxanthin and polyphenols, which, although present in lower concentrations, exhibit crucial seasonal variability essential for high-value applications.

2.1. Proximal Composition

As shown in Table 1, there is significant variation in the main components, which is directly related to the environmental and methodological factors mentioned previously. For example, moisture content (a critical parameter for calculating the energy balance in drying processes) is generally high, with reported values exceeding 80% in most studies involving fresh biomass [19]. However, other works report significantly lower humidity values (~12%) [21,22]. This discrepancy is not biological but rather reflects the state of the biomass at the time of collection (e.g., stranded biomass that has undergone natural dehydration outside the intertidal splash zone). Therefore, homogenizing sampling protocols is essential, as the yields of subsequent components are strictly dependent on calculations based on dry weight (DW).

Regarding proteins and lipids, pelagic *Sargassum* generally has lower levels than other macroalgae. Protein levels typically range from 10.4% to 12.4%, though these values can fluctuate with nitrogen availability in the water column during the bloom [29]. Lipid content is similarly low (0.6–4.56%), with variations often attributed to the specific species (*S. fluitans* vs. *S. natans*) and the extraction solvent used in the analysis.

2.2. Structural and Storage Polysaccharides

The biomass is characterized by a high total carbohydrate content (11.68–32.4%), which represents its primary potential for biofuel production [30]. Sulfated polysaccharides are the dominant fraction, including alginates (9.36–34.6%) and fucoidans (4.4–9.1%). It is important to note that the wide range in alginate yield reported in the literature often reflects differences in extraction methodologies (e.g., acid vs. enzymatic extraction) rather than biological variation alone. Cellulose (11.5–18.8%) constitutes the main rigid structural component, while mannitol (up to 56% in specific seasons) acts as the primary storage polysaccharide [31].

A significant controversy exists regarding the lignin content in holopelagic *Sargassum*. While phylogenetically macroalgae lack true lignin, recent studies using the Klason method have reported concentrations exceeding 17.8%, reaching up to 29.5% in *S. natans* var. *natans* [16,18]. However, these high values are likely an overestimation due to interference from protein-tannin complexes or "pseudo-lignin" that precipitate during acid hydrolysis, highlighting the need for more specific analytical techniques for marine biomass [15].

Regarding structural polysaccharides, seasonal influence extends beyond total yield to the specific chemical composition of their functional groups. Ortega-Flores et al. [26] reported significant temporal variations in the content of uronic acids (from alginates) and sulfate groups (from fucoidans) in *S. fluitans* collected in the Mexican Caribbean. Crucially, this study established that the seasonality of these components is a key driver of the biomass's biosorption capacity. The researchers demonstrated that seasonal fluctuations in these functional groups (particularly during the rainy season) are statistically correlated with the accumulation of toxic trace elements, such as arsenic (As). This finding underscores that the chemical quality of alginates and fucoidans is not static and directly impacts the safety profile of the biomass for potential valorization.

2.3. Secondary Metabolites

The secondary metabolites in pelagic *Sargassum* (crucial for high-value pharmaceutical applications) have been less extensively quantified than polysaccharides. The primary compounds include phenols (0.11–2.55%) and flavonoids (0.34–19.8%), which the algae produce primarily as a defense mechanism against UV radiation and oxidative stress while floating [32].

In a comprehensive phytochemical screening, Lambert et al. [27] characterized a hydroethanolic extract of *S. fluitans* collected in the south-east coastline of Martinique, reporting a diverse profile including coumarins (5.85%), anthocyanins (7.39%), quinones (5.88%), saponins (22.1%), tannins (7.99%), and triterpenes (18.28%). The high concentration of these bioactive compounds underscores *Sargassum*'s potential not only for energy but also as a source of antioxidant and antimicrobial agents, provided that extraction protocols are optimized to preserve their stability.

Recent research on pelagic *Sargassum* arriving at the Mexican Caribbean coast has highlighted the critical role of seasonality in the concentration of secondary metabolites. A study evaluating *S. fluitans*, *S. natans* var. *natans*, and *S. natans* var. *wingei* during the 2018–2019 influx found that antioxidant capacity and total phenolic content (TPC) were not stable throughout the year. Instead, significant peaks were observed in August and during the spring months (March–April), coinciding with periods of elevated seawater temperatures and maximum solar irradiance [14]. Consequently, for applications requiring high antioxidant potential, harvesting strategies should prioritize biomass collected during the summer months to ensure optimal yields of these bioactive compounds.

3. Elemental Composition and Safety Concerns

Elemental composition is a critical bottleneck for *Sargassum* valorization. Due to their holopelagic lifecycle and the high content of sulfated polysaccharides in their cell walls (which act as ion-exchange sites), these species efficiently bioaccumulate heavy metals such as Arsenic (As), Lead (Pb), Molybdenum (Mo), and Zinc (Zn) from the water column [26]. This raises significant environmental and health concerns regarding their utilization [4,12,18].

3.1. Heavy Metal Bioaccumulation and Seasonality

Research in the Mexican Caribbean has highlighted the magnitude of this issue. For instance, Rodríguez-Martínez et al. [4] reported that 86% of stranded biomass samples collected between August 2018 and June 2019 from eight localities along ∼370 km long coastline of the Mexican Caribbean Sea exceeded the maximum permissible arsenic concentration for animal feed under European regulations (40 mg kg^{-1}), and 100% exceeded the limits for agricultural soils in Mexico (22 mg kg^{-1}) [33]. Notably, the authors suggest these metals are likely of oceanic origin rather than local coastal pollution, given the absence of heavy industry in the region.

Crucially, this metal accumulation is not static; it exhibits significant seasonal variability driven by environmental factors. Ortega-Flores et al. [34] observed that while total arsenic concentrations tend to peak during the rainy season (potentially linked to nutrient inputs and metabolic activity), the metal's speciation changes. In a comprehensive analysis, they found that the highly toxic inorganic arsenic (iAs) content peaked during the warm-dry season (mean 41.0 mg kg^{-1} DW) and winter (33.8 mg kg^{-1} DW), being lowest in the rainy season (31.3 mg kg^{-1} DW) [35]. This distinction is vital because, regardless of the season, the iAs values consistently exceed the strict regulatory limit (3 mg kg^{-1}) established by China and the EU for food applications [34]. This seasonal decoupling between Total As and Inorganic As poses a complex challenge for risk management.

Table 2 summarizes the trace element and heavy metal profiles reported for the three morphotypes of pelagic *Sargassum* and mixed biomass. The data reveal a substantial variability in elemental concentrations, driven by interspecific differences and the high bioaccumulation capacity of these macroalgae. Among the micronutrients, Iron (Fe) exhibits the broadest range of concentrations, particularly in *S. fluitans* (9.8–832.97 mg kg^{-1}), followed by Aluminum (Al) and Phosphorus (P). However, the critical focus for valorization lies in the accumulation of toxic metals. As shown in the table, Arsenic (As) consistently presents alarming levels across all taxa, with total concentrations reaching up to 255 mg kg^{-1} in mixed biomass and 210 mg kg^{-1} in *S. natans* var. *wingei*. Furthermore, the levels of Uranium (U), Lead (Pb), and Cadmium (Cd) reported in certain studies underscore the need for rigorous chemical characterization before processing. Notably, the inorganic arsenic (iAs) fraction (the most toxic form) remains consistently high (47.7–71.5 mg kg^{-1}) across all species, far exceeding international safety limits for food and feed applications.

Table 2. Heavy metal content reported in *Sargassum* stranded events in the Mexican Caribbean.

Element/Parameter	*S. fluitans*	*S. natans*	*S. natans* var. *wingei*	Mixed Biomass
Trace and heavy metals (mg kg^{-1} DW)				
Iron (Fe)	832.97 [20]; 9.8 [26]	634.79 [20]	237.07 [20]	54.6 [10]
Manganese (Mn)	22.92 [20]; 112.0 [26]	39.62 [20]; 139.0 [18]	13.03 [20]; 135.0 [18]	--
Barium (Ba)	23.21 [20]	22.17 [20]	19.21 [20]	--
Zinc (Zn)	7.20 [20]	14.71 [20]	6.35 [20]	7.2 [10]
Copper (Cu)	4.47 [20]; 5.7 [26]	4.29 [20]	2.78 [20]	1.09 [10]
Nickel (Ni)	3.52 [20]	4.21 [20]	3.87 [20]	--
Vanadium (V)	4.21 [20]	2.37 [20]	2.28 [20]	--
Chromium (Cr)	9.18 [20]	3.18 [20]	1.50 [20]	--
Cobalt (Co)	0.89 [20]	0.91 [20]	0.47 [20]	--
Uranium (U)	0.83 [20]; 48.0 [18]	0.80 [20]; 47.0 [18]	0.79 [20]; 45.0 [18]	--
Cadmium (Cd)	2.0 [26]	--	--	0.8 [10]
Lead (Pb)	17.3 [26]	--	--	0.29 [10]
Aluminum (Al)	392 [18]	500 [18]	327 [18]	--
Thorium (Th)	17.0 [18]	23.0 [18]	20.0 [18]	--
Rubidium (Rb)	102.0 [18]	143.0 [18]	120.0 [18]	--
Phosphorus (P)	401.0 [18]	394.0 [18]	350.0 [18]	--
Arsenic (As)	58.32 [4]; 175 [26]; 172 [18]	64.91 [4]; 93.2 [26]; 172 [18]	60.30 [4]; 210 [26]; 145 [18]	255 [26]; 65.7 [10]
Inorganic Arsenic	71.5 [29]	47.7 [29]	64.7 [29]	62.9 [29]

3.2. Challenges in Remediation and Pretreatment

Developing cost-effective methods to remove these heavy metals is a prerequisite for industrial scaling. While freshwater washing effectively removes salts and sand, it is generally insufficient for extracting metals chemically bound to cell wall polysaccharides. Consequently, efficient pretreatment often requires acid washing (protonation) or specific ion-exchange processes [35,36].

A recent study by Cisneros-Ramos et al. [37] illustrates this limitation. By applying a sequential treatment of hot, fresh water and citric acid, they successfully reduced total arsenic levels from 62.2 to 7.2 mg kg^{-1}, bringing the biomass into compliance with animal feed regulations (<40 mg kg^{-1}). However, even with this aggressive treatment, the levels of inorganic arsenic did not fall below the threshold for human consumption (3 mg kg^{-1}). This finding underscores that while current remediation techniques can unlock agricultural applications, the safe use of *Sargassum* in the food or pharmaceutical industries requires more advanced, species-specific, and likely more expensive decontamination technologies.

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4. Potential Applications and Constraints: Is Sargassum Biomass a Real Opportunity for Coastal Communities? Are There Associated Risks?

When the massive influx of holopelagic *Sargassum* became an environmental problem in the Caribbean, scientific information on the biochemical composition of these species was scarce. The development of uses and applications for stranded biomass relied on existing knowledge of similar species or raw materials, and various artisanal applications emerged, including the production of building blocks, notebook paper, and organic agricultural products.

Figure 2 illustrates this diversified landscape of potential uses derived from our bibliometric analysis. The diagram classifies valorization pathways across various industrial sectors, ranging from high-volume applications, such as bioenergy and agriculture, to high-value niche products in the pharmaceutical and food industries. In the following subsections, we critically analyze these emerging applications, evaluating the opportunities they present in light of the previously identified biochemical limitations and safety issues.

It is important to note that while chemical characterization of Caribbean *Sargassum* is well documented, research on its industrial applications is still emerging. Therefore, this section reviews available local data alongside studies on *Sargassum* species from other regions (e.g., Europe, Asia) to illustrate the full range of potential applications for this biomass.

4.1. Bioenergy and Biofuels

The massive increase in industrialization and high population growth has led to problems such as the depletion of fossil fuel reserves, price fluctuations, negative environmental impacts, and climate change. The high dependence on fossil fuel reserves is evident in the fact that most energy is produced from them, with only 10% coming from renewable sources. Therefore, in response to the decline of fossil fuels and their associated pollution, a transition from the current fossil-fuel-based economy to a carbon-neutral economy based on renewable raw materials, such as biofuels, is expected [38].

Currently, three generations of biofuels have emerged based on different feedstocks. First-generation biofuels are derived from edible materials, mainly from seeds, grains, or simple sugars. Second-generation materials are derived from non-edible materials such as agricultural and forest residues and crops grown for biofuel. Unfortunately, debates arise over food versus fuel, land use, and freshwater resources for the first and second generations. In the third generation, the substrates are micro and macroalgae. In this context, holopelagic species of the *Sargassum* genus have been identified as a possible source of third-generation biofuel [7,10,22].

However, the main limitation to valorizing seaweed that can be used for this purpose is that extracting a single molecule or compound is often not profitable unless that molecule has an exceptionally high market value [39]. An integrated process in which bioethanol or biogas produced from the fermentation of *Sargassum* is simultaneously co-produced with other value-added compounds, such as alginates, proteins, or fucoidans, could make the process more attractive and profitable [39]. Orozco-González et al. [39] have proposed an experimental diagram in which, from the landed biomass of *Sargassum* and after several pretreatments, followed by enzymatic hydrolysis, biodiesel (from the extraction and transesterification of lipids), bioethanol (from the fermentation of sugars), or biogas (from the anaerobic digestion of the biomass) can be produced.

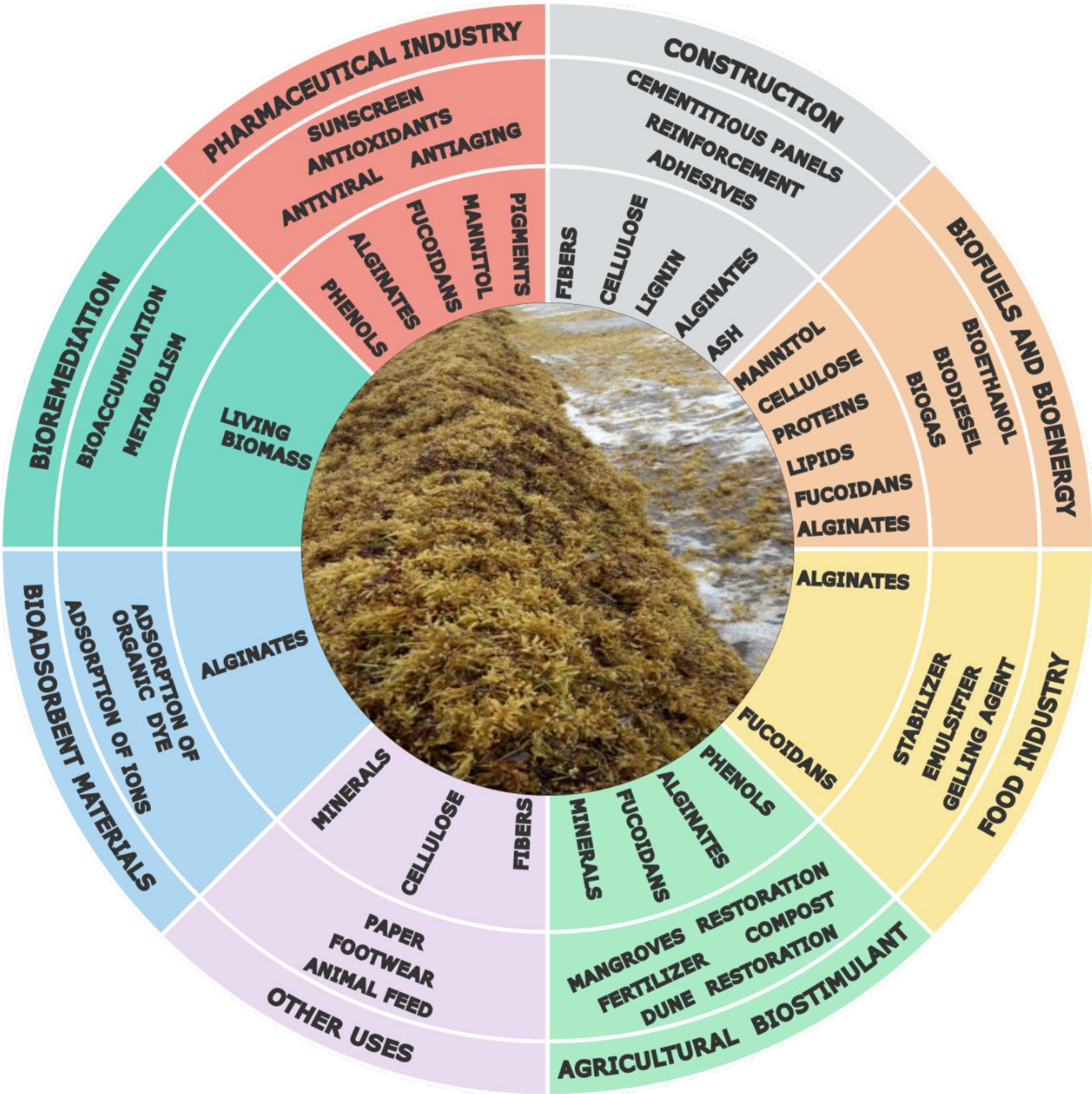

Figure 2. Biochemical components and uses of the biomass of holopelagic *Sargassum*. Overview of the potential valorization routes for pelagic *Sargassum* biomass. The inner ring identifies the primary biochemical fractions and functional components (e.g., alginates, fucoidans, cellulose, and phenols). The outer ring maps these components to their respective industrial sectors, illustrating a multi-product biorefinery approach that spans from high-volume/low-value applications (e.g., construction, energy) to low-volume/high-value products (e.g., pharmaceuticals, cosmetics).

4.1.1. Bioenergy

Direct combustion has been the primary method of obtaining bioenergy from dried biomass. Evaluating the combustion properties of seaweed can help determine its suitability for various bioenergy applications. There are significant differences between the combustion of seaweed and traditional biomass due to the physical and chemical characteristics imposed by their respective environments. Thus, although the combustion of macroalgae could be economically viable, the technical feasibility remains debatable due to their high ash and moisture content, which reduces energy efficiency. As mentioned before, the moisture content of biomass reported for *Sargassum* species is high; therefore, a drying stage is essential as a preliminary step for energy conversion [40].

The use of *Sargassum natans* biomass for direct combustion was revised by Wang et al. [41]. The authors concluded that its ignition temperature is low, and the biomass easily bursts into flame. The fusion temperature is also low because of the ash's many alkali metal elements. In this regard, because seaweeds can naturally absorb metal ions, the presence of alkali metals such as sodium (Na) and potassium (K), as well as halogens, can cause corrosion and saturation in boilers and conductive lines, leading to significant toxic emissions [42]. Seaweeds, including the holopelagic *Sargassum* taxa, can naturally absorb metal ions. The emission of heavy metals results from the thermal conversion of fuels to generate energy and heat. For this reason, it seems necessary to determine whether materials used as fuels may pose a risk of contaminating the atmosphere [43]. Thus, moisture and salts technically limit the direct combustion of *Sargassum* for energy purposes [44]. Sun drying would be a viable alternative to reduce the initial moisture content of biomass. However, large areas are required, as only about 100 g of dry matter can be dried per square meter of surface [42]. On the other hand, some authors have proposed that adding a previous washing step to the biomass has favorable effects on the bioenergetic characteristics of *S. fluitans*, increasing its calorific value by 36.80% [45]. The washing mechanism removes sand, salts, and residues, thereby increasing the content of C, H, O, and N, while reducing heavy metal concentrations to levels below international standards.

4.1.2. Bioethanol Production

Bioethanol production from terrestrial feedstocks (mainly crops) has brought robust debates on food security, land use, and freshwater [46,47]. These discussions on the use of critically limited resources, coupled with the low yields from lignocellulosic biomass (wood, agricultural, and forestry residues) and the high cost of separating lignin from fibers to access beneficial sugars, have made macroalgae a potential source of raw materials in this industry [48].

Marine macrophytes have lower cellulose concentrations than terrestrial plants. However, they have high growth rates, high carbohydrate content and diversity, and low or no lignin content [49]. It is proposed that *Sargassum* biomass from landfall can serve as a viable feedstock for bioethanol production due to its abundance, underutilization, and low cost [18]. Bioethanol production involves the conversion of polysaccharides into simple sugars, a process that primarily comprises pretreatment, hydrolysis (acidic or enzymatic), and fermentation. The ability to achieve conversion rates of over 80%, combined with low energy consumption and high yields, under an environmentally friendly approach, makes the enzymatic process more attractive for bioethanol production [18]. Moreover, positive results, including cost reductions achieved through eco-friendly procedures combining enzymatic hydrolysis with fermentation, have been reported for *Sargassum* species [50].

Borines et al. [30] reported an ethanol conversion rate of 89% for the enzyme hydrolysate, which is significantly higher than the theoretical yield of 51% based on glucose as the substrate. This may indicate that the remaining non-glucan components were hydrolyzed and fermented. *S. fluitans*, *S. natans* var. *natans*, and *S. natans* var. *wingei* contain readily fermentable glucose in the form of mannitol (56%) and cellulose (18.8%) in addition to specific carbohydrates such as alginates (31%) and fucoidans (8.2%) that may be present in the hydrolysate [18]. Mannitol values for these *Sargassum* species are reported to be between 49.9 and 60.1%, while the levels of cellulose (11.5–18.8%), alginates (15.7–34.6%), and fucoidans (6.3–11.4%) are also reported (Table 1). Mannitol, a sugar alcohol derived from D-mannose, is the first accumulation product of photosynthesis in brown algae [20]. Since the calorific value of mannitol is higher than that of glucose (3025 kJ mol^{-1} versus 2805 kJ mol^{-1}), its carbon distribution and different redox states have been revealed to make mannitol more favorable than glucose for ethanol production [40].

Another essential factor to consider when proposing biomass as a bioethanol source is the C:N ratio. De Bertoldi et al. [51] suggest that the C:N ratio should be 20–30 to optimize the development of a biological degradation process, as simple carbon compounds, such as soluble sugars and organic acids, must be degraded as the first step in producing bioethanol. The average C:N ratio of *Sargassum* reported for oceanic waters is 47 in contrast to 27 which corresponds to most of the studies of Caribbean events [18], including *Sargassum* where the C:N ratio moves in the optimal range proposed by De Bertoldi [51] (Table 1) except in the study by Rosado-Espinosa et al. [23] where the C:N ratio was 9.2. Biomass with an excess of degradable substrate represented by a C:N ratio > 30 slows the process likewise, a C:N ratio < 20 results in nitrogen losses that also slow down the process because it causes the release and accumulation of nitrogen in the form of ammonium ion, the high level of which increases the pH in the digester and is toxic to methanogenic bacteria [52].

The high water content (72–83%) and ash content (15.1–27.61%) in these species could be a disadvantage for bioethanol production. However, production could be sustained from a biorefinery perspective by simultaneously extracting other high-value commercial components, such as proteins, alginates, or fucoidans [18]. Additionally, it is suggested that high protein levels in the system enable fermentation without the need for additional nutrients [53].

Based on various studies on the valorization of holopelagic *Sargassum* as a source of bioethanol, this resource has been described as rich in polysaccharides composed of glucose, as well as high levels of mannitol and other fermentable carbohydrates, such as alginate and fucoidan. However, bioethanol production from macroalgae is still in the early stages, primarily conducted at the laboratory scale before scaling up. Therefore, technologies for large-scale production are underdeveloped, and the primary obstacle is the development of species-specific and appropriate methodologies for the complete hydrolysis of complex polysaccharides to obtain fermentable sugars [18,39]. To compensate for the high production cost, some authors claim that holopelagic *Sargassum* species could be a promising raw material for biorefineries, enabling the production of bioethanol and the isolation of high-added-value compounds [18,54,55].

4.1.3. Biogas Production

Biogas production is a long-established technology, and the conventional feedstocks used include crops, animal waste, sewage sludge, and some household refuse. Biogas consists of methane (also known as biomethane) and carbon dioxide, and biomethane serves as a valuable source of energy. Biogas can be upgraded to produce more biomethane, reducing greenhouse gas emissions. Therefore, it is essential to make it in closed systems [56]. Through anaerobic digestion, seaweed is a valuable feedstock for producing biogas due to its high carbohydrate content, which is favorable for enzyme activity, and its relatively low lignin content [52,57,58]. Moreover, anaerobic digestion is generally the preferred method for energy production from high-water-content biomass.

The biogas produced by anaerobic digestion can be used to convert various types of seaweed waste into renewable energy. To produce biogas from seaweed, the biomass must be hydrolyzed to yield biomethane. Strategies such as pretreatments (acid, enzymatic, mechanical, thermal, and hydrothermal processes), anaerobic co-digestion, and the use of additives, including volatile fatty acids, can be implemented to enhance biogas production from seaweeds.

Thompson et al. [59] report that holopelagic *Sargassum* from the Caribbean can optimize biogas production when used in conjunction with hydrothermal pretreatment and anaerobic co-digestion of food waste. Results revealed that hydrothermal pretreatment promoted the hydrolysis of organics, thereby increasing methane recovery by 212.57% compared with untreated samples.

Nevertheless, seaweed biomass contains several inhibitory compounds that hamper biomethanation. Two of them are referred to the high salinity of the biomass, which can inhibit the anaerobic digestion process and reduce production rates by up to 50% [60], as well as the presence of phenols accumulated in the cell walls of seaweeds that also hinders anaerobic digestion, mainly due to enzyme deactivation [61]. On the other hand, *Sargassum* species have a high salt content (Table 1), which negatively affects biogas production. High salt levels cause bacterial cells to dehydrate due to osmotic pressure, leading to slow growth and potentially severe inhibition or toxicity [62].

4.1.4. Biodiesel Production

Biodiesel is produced directly by chemically catalyzed transesterification of oils and lipids derived from vegetable, animal, or other commercially available plant fats. Regarding seaweeds, their limited lipid content has restricted their use as traditional candidates for biodiesel production [39]. However, Gordillo-Sierra et al. [24] proposed an experimental design that could utilize a mixed *Sargassum* sample containing *S. fluitans* and *S. natans* var. *natans* as a carbon source for oleaginous yeast in biodiesel production. First, the authors obtained alginate, and the extraction residues were pretreated by autohydrolysis and enzymatic degradation. In a novel approach, the resulting *Sargassum* sugar medium was fermented by the genetically modified *Yarrowia lipolytica* E26S1S2 to generate lipids. The latter transesterification demonstrated a novel biodiesel production with profiles similar to those of conventional plant-derived oils.

4.2. Agricultural Biostimulants and Fertilizers

In addition to biogas, anaerobic digestion of biomass produces a nutrient-dense solid–liquid digestate. Thompson et al. [63] suggest that digestate generated from *Sargassum* biomass decomposed in landfills could be applied to agriculture as fertilizer after treatment and removal of ammonia and heavy metals. The recovered solid fraction can be directly applied to agriculture. However, the high ammonia content of the liquid fraction must be removed by evaporation, reverse osmosis, or struvite precipitation [63]. Heavy metals accumulate in agricultural soils through repeated fertilization, leading to soil acidification and toxicity that stunts plant growth and reduces crop productivity. Furthermore, heavy metals pose a significant hazard to human health and ecosystems through direct ingestion and physical contact. These cations can be removed by incorporating remediation techniques such as soil washing, phytoremediation, and immobilization [64].

In coastal areas, the seaweed that reaches the coast by tides and wind washes up on beaches has been used for centuries as a natural fertilizer. In this regard, applying pelagic *Sargassum* to soils as a conditioning agent can enhance plant growth, health, and yield by modifying soil texture and improving moisture-holding capacity [18]. Williams & Feagin [65] reported using *S. fluitans* and *S. natans* var. *natans* from Galveston Island, Texas, as fertilizers for dune plants, and observed improved growth. This is related to its high content of mineral salts, water-soluble polysaccharides, and phenolic compounds that, together, improve the health, quality, productivity, and enzymatic activities of the soil in terrestrial crops [66]. This has made pelagic *Sargassum* an excellent candidate for use as a biostimulant and fertilizer, as the mixed biomass of *S. natans* and *S. fluitans* can increase crop growth rates and yield compared to traditional chemical fertilizers [67].

However, it is necessary to consider the high levels of heavy metals in the biomass that can be passed to crops and bioaccumulate. Abdool-Ghany et al. [68] found that in crops enriched with *Sargassum* compost, the cultivated radishes exhibited levels of arsenic and cadmium that did not meet the guidelines set by international standards. A possible solution to the problem of arsenic bioaccumulation in crops is vermicomposting, which involves the use of worms to decompose organic materials since it decreases the levels of high arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr) and zinc (Zn), which are absorbed by the worms making them less bioavailable [69].

The physicochemical conditions of compost are essential for crop viability [68]. Regarding pH, ideal compost values should be between 5.0 and 8.5, and all values should be above 8.91. For C: N ratios, levels recommended by relevant bodies should be <20; however, in both experiments, C: N ratios did not reach <20, although C and N content were within acceptable ranges. Several authors suggest that *Sargassum* compost could be used for non-food crop applications to support the growth of ornamental or coastal plants, such as mangroves, thereby enhancing dune restoration efforts [63,68].

In this regard, Trench et al. [70] suggest that composting has the most significant potential to improve mangrove soil, as both soil properties (texture and water-holding capacity) and nutrient content are enhanced. These authors show that, in the right proportions, *Sargassum* compost enhances the growth of mangrove seedlings. Furthermore, it is suggested that mangrove soils have a high capacity to sequester heavy metals, as mangrove species, especially *Rhizophora mangle*, have evolved strategies to minimize their uptake, thereby leaving these metals in the soil [71]. This could ensure the tremendous success of rehabilitation efforts in these areas and utilize algal biomass, benefiting impoverished coastal communities, which are ultimately the most affected by *Sargassum* spp. flooding and mangrove loss [70].

4.3. Construction Materials

Another proposed use of *Sargassum* biomass is in civil construction. Due to its polysaccharide-rich composition [22] and high fiber content [19], it could be a sound reinforcement for composite materials. In addition, byproducts of its processing, such as ashes obtained from burning for energy generation, may have potential use as mineral additions to cementitious compounds and to compounds with alkaline-activated binders, given the chemical composition of said ashes [72]. In this regard, there are few studies on holopelagic *Sargassum* species. However, Rossignolo et al. [72] suggest that several products can be produced depending on the components in the biomass: Cementitious and medium-density wood panels using fibers from algae (holocellulose and lignin) in different proportions with other elements such as cement, resins or sawdust; Polymeric composite of plant origin (wheat gluten or biodegradable polyethylene from sugar cane) reinforced with algae fibers; complementary material to Portland cement (mineral-rich ash, with a predominance of Ca, K, Na, S, Cl and Mg) that brings with it a reduction in capillary water absorption values, due to better particle packing; pavement reinforcement such as modified bituminous agents, reinforcing and self-healing fibers; raw earth bricks (adobe) that act as an adhesive (soil stabilizer) and as fibers (reinforcement); facades and roofs functioning as thermal and acoustic insulation.

The use of residual algal biomass to manufacture building materials and additives significantly enhances tensile strength and stiffness, even without chemical treatments of the plant fibers [72]. The alginate present in the holopelagic species of *Sargassum* presents adhesive properties due to the interaction between carboxylic groups and divalent ions [73], which can lead to an increase in the durability of alginate-added concrete with a reduction in water absorption and a significant increase in the compressive and tensile strength of the concrete for the optimal addition level of 20% [74]. Alginate can also contribute to soil stabilization in block production by increasing compressive strength by 70% [75]. Bilba et al. [76] studied the viability of *Sargassum* biomass ash as a pozzolanic (corrosion-reducing) material in mineral binders for civil construction, concluding that *Sargassum* ash was not a pozzolanic-type material. These ashes cannot be considered alkaline activators for geopolymers due to their low silica content; however, they can be used as a source of calcium carbonate.

4.4. Bioremediation Potential

Increased development and human activities, such as industrial, agricultural, and domestic practices, have introduced various polluting substances into marine ecosystems, including heavy metals, which are persistent in the environment and highly toxic at high concentrations. Different technologies have been developed to recover and degrade pollutants; however, they have limitations, including the production of toxic sludge, high costs, and low efficiency. On the other hand, bioremediation is one of the primary strategies for reducing the levels of these pollutants, representing a low-cost, simple, and safe alternative. Bioremediation has been developed through two fundamental pathways: (a) bioaccumulation or absorption of contaminants by living organisms (primarily microorganisms and plants) generating biomass through metabolism [77], (b) biosorption, referred to as the ability of a non-living organism to allow the passive removal of different substances through its capture/binding in aqueous solution [57,78].

Through the bioaccumulation pathway, macroalgae can integrate nutrients such as phosphorus (P) and nitrogen (N) and metals such as iron (Fe), cobalt (Co), zinc (Zn), copper (Cu), manganese (Mn), and nickel (Ni) into the organism through metabolism. This process occurs because cysteine-rich proteins can bind metals and macronutrients, which are subsequently immobilized in vacuoles and other vesicles by enzymes [79]. However, bioaccumulation capacity has been observed to depend on optimal conditions for macroalgae growth, such as pH, temperature, and light [79]. The use of macroalgae for contaminant bioaccumulation primarily focuses on nutrient and waste remediation from aquaculture farms through integrated multitrophic cultures. In these cultures, macroalgae utilize the excreta of fish or other animals, as well as food remains, for their growth, which are then used for various purposes [78]. Fish feed is supplemented with mineral additives containing metals as preservatives. In addition, they may contain zinc, copper, cadmium, iron, manganese, cobalt, nickel, lead, magnesium, selenium, and mercury [80]. Therefore, efficient bioremediation mechanisms would be essential to mitigate the damage caused by aquaculture, a rapidly developing economic activity. *Sargassum epiphyllum* and *Sargassum henslowianum* are highly efficient at absorbing inorganic nutrients and heavy metals from the water surrounding their aquaculture farms [80].

On the other hand, implementing macroalgae cultivation in coastal areas affected by eutrophication and harmful algal blooms could help reduce pollution [77]. In addition to acting as a bioremediation agent, macroalgae can inhibit phytoplankton growth and indirectly alleviate harmful algal blooms through nutritional competition, shading, and allelopathy [81]. Tian et al. [82] suggest that large-scale cultivation of *S. fusiforme* can reduce nutrient loading and eutrophication levels in the cultivation area, slightly increase dissolved oxygen levels, pH, phytoplankton abundance, and diversity index, and support the fixation and removal of C, N, and P from coastal seawater.

Few bioaccumulation studies have been conducted using holopelagic *Sargassum* species from the perspective of effluent bioremediation. However, high levels of heavy metals have been found in pelagic *Sargassum* species from the Mexican Caribbean [4,10,26,34], indicating that these algae have a high capacity to bioaccumulate metals in their biomass, likely due to their holopelagic lifestyle.

The primary mechanism of biosorption in brown macroalgae is ion exchange, which is given by the chemical bond and electrostatic attraction between various functional groups present in the polysaccharide alginate and fucoidan in their cell walls [83]. Mass transfer can be achieved through physical, chemical, and electrostatic interactions [84]. Cationic metals can bind to the surface of macroalgae by the presence of hydroxyl, carboxyl, amino, and sulfate groups that are part of polysaccharides (alginate and fucoidan) and proteins on the cell surface [85]. Light metals, such as sodium, potassium, and magnesium, are first bound to the cell surface. Then, as pH increases, light metal ions are released, and heavy metals occupy the binding sites [86].

In the literature, several methods for utilizing macroalgae biomass as a bioabsorbent have been reported, including the use of dry biomass and the extraction of specific compounds, such as alginates and fucoidans, with acidification pretreatments to enhance the adsorption capacity for heavy metals [87]. Pareja-Rodríguez et al. [88] report the adsorption capacity of Pb^{2+} in graphene oxide-like materials obtained from the pyrolysis of *S. fluitans*, *S. natans* var. *natans*, and *S. natans* var. *wingei* biomass. Jalali et al. [89] suggest that *Sargassum* biomass can undergo ten biosorption-desorption cycles while maintaining a lead adsorption capacity of 98%. Even when starting with residual biomass from alginate extraction, it is possible to maintain adsorption capacities of 100% and 99.4% for cadmium and zinc, respectively [90].

At the end of the adsorption process, biomass contaminated with toxic metals must be disposed of appropriately to avoid environmental damage. The primary forms of disposal currently used are direct disposal, composting, and incineration [91]. Each of these methods is used to determine the bioaccumulation and biosorption capacity of biomass and its components. These alternatives have associated risks, with incineration being the least harmful and most widely used. It reduces the total dry weight of contaminated biomass by more than 90% and enables recovery of metals [91]. Additionally, the ash can be used in road filling, agriculture, or as fuel [92].

Another type of pollutant that has gained relevance today is synthetic azo dyes (azo group (-N=N-)) due to their persistence, toxicity, and carcinogenic effect [92]. In addition, they are the most widely used dyes (60–70%) in industrial applications. Around 15% of these are released directly into the environment during dyeing, potentially altering the ecosystem [93]. Pelagic *Sargassum* biomass can be a viable alternative for removing some dyes due to its low cost and availability. However, Nielsen et al. [94] suggest that biomass can be efficiently used to remove cationic dyes such as methylene blue because the functional groups present in the wall (amino, hydroxyl, carboxyl, and sulfate) can exert electrostatic attraction, ion exchange or complexation with this type of dyes, which does not occur with the anionic dyes brilliant blue and Congo red, which showed low or no affinity with the adsorbent. Other analyses with other cationic dyes, such as malachite green, have been treated with *Sargassum latifolium*, with a maximum removal rate obtained (69.8%) at pH 7 [95].

4.5. Food and Health-Related Biomolecules

Given the *Sargassum* species' nutrient and bioactive compound composition, there is a compelling case for further research into their potential as dietary supplements for human consumption and as animal feed. By analyzing their proximate and elemental composition, it can be observed that holopelagic *Sargassum* species have remarkably high levels of fiber (31.1–37.4%) [19] compared to commonly used cereals such as rice [96], making these a potential replacement source of essential carbohydrates for human consumption during the current food crisis. Additionally, most of the fibers present in the biomass are alginates, which can function as bioactive compounds and induce feelings of satiety. The protein content in these species is low (10.4–12.4) [18] compared to other macroalgae species included in diets, such as *Ulva ohnoi* (41%) [97]. The lipid content is also low

(0.6–6.02%) [18,22] when using mixed biomass separated by species. The mineral content of the holopelagic species of *Sargassum* is exceptionally high, so its consumption in large quantities can be harmful to health.

However, the potential of holopelagic *Sargassum* as a dietary supplement is tempered by the need for caution due to its high bioaccumulation capacity, as species spend their entire lives adrift and can accumulate heavy metals. Several studies have reported levels of heavy metals above the maximum permissible concentration in *Sargassum*, even for animal feed under European regulations [4,12].

On the other hand, marine macroalgae, with their remarkable resilience, constitute an essential source of bioactive compounds, among which antioxidant agents are particularly notable [98,99]. Algae produce these molecules as part of their mechanisms to counteract oxidative stress and combat the chemical imbalance caused by the environmental conditions in which they develop.

Their antioxidant capacity underlies most medicinal uses of macroalgae, as free radicals are involved in the development of various pathologies and bodily processes, including coronary heart disease, certain types of cancer, inflammatory and neurological disorders, and photoaging of the skin [100].

Antioxidants help protect cells against damage from reactive oxygen species (ROS) and oxidative stress. Among the main antioxidant compounds present in *Sargassum* are polyphenols, sulfated polysaccharides, pigments, tocopherols, and phytosterols [101]. For holopelagic *Sargassum* species, the content of total phenolic compounds varies between 0.3 and 5% [14,102–104]. These variations may be due to seasonality, among other factors [14], and it is also suggested that differences may occur between the different parts of the thallus or vegetative structures [105]. Fagundo-Mollineda et al. [14] found that higher levels of total phenolic compounds produced by *S. fluitans*, *S. natans* var. *natans*, and *S. natans* var. *wingei* occur in spring-summer (August and March-April).

Phenolic compounds are mainly related to antioxidant activity. Seasonality in the production of phenolic compounds could be a limitation when establishing an economic activity based on their extraction. However, in the study by Fagundo-Mollineda [14], the authors found that antioxidant activity was generally greater than 60% in practically all months for the three holopelagic species, using the ABTS technique. When working with a hydroethanolic extract, other antioxidant compounds, such as alginates, fucoidans, and mannitol, were found in the mixture. These compounds can act synergistically to maintain antioxidant activity during periods when phenol production is lower. Therefore, working with mixtures of compounds could potentially yield more favorable results.

Sulfated polysaccharides (alginates and fucoidans) present in the holopelagic *Sargassum* also show antioxidant activity due to their chemical structure rich in sulfate groups, which allows them to chelate pro-oxidant metals by binding them to their structure [106]. Although fucoidans from holopelagic *Sargassum* species have been little studied, studies of benthic species have shown that they exhibit anticoagulant, antitumor, antibacterial, antiangiogenic, and anti-inflammatory activities [107–111]. The biological activity of fucoidans from different species depends on factors such as seasonality, chemical structure, sugar composition, position, and degree of sulfation [106]. Chale-Dzul et al. [112] analyzed the hepatoprotective effect of a fucoidan extract from *Sargassum fluitans*, finding that it has an antifibrotic and anti-inflammatory effect on the liver. On the other hand, Fernando et al. [113] analyzed the cytoprotective properties of fucoidan from *Sargassum natans* against urban aerosol-induced damage to keratinocytes. They found that treatment with fucoidans exhibits high antioxidant activity, dose-dependently attenuating the increase in intracellular free radical levels in keratinocytes by increasing antioxidant defense enzymes and chelating the metal ions Pb^{2+}, Ba^{2+}, Sr^{2+}, Cu^{2+}, Fe^{2+}, and Ca^{2+}.

Alginate is primarily valued in medicine for its rheological properties, such as gelling capacity, viscosity enhancement, and dispersion stabilization, rather than for its biological activity. Furthermore, it is non-toxic, biocompatible, biodegradable, biostable, and a hydrophilic biopolymer, making it a good candidate for various advanced clinical and biomedical applications, such as wound dressings, tissue repair and regeneration, and the production of biomaterials (hydrogels, films, foams, nanofibers, gauze) [114]. It is considered a highly versatile material for the production of wound dressings, as it enables the polymer to absorb wound exudate and create a moist environment, thereby promoting healing and facilitating the delivery of bioactive substances [114]. In addition, Tønnesen & Karlsen [115] suggest the benefits of using alginates in the administration of drugs as a binder in tablets or a disintegrant in controlled-release drugs, accelerating or slowing down the release of the active compound depending on the amount used in the formulation. The applications and biological activity of alginate from different *Sargassum* species depend on several factors, including seasonality, the structural composition of their uronic acids, and the extraction methodologies used.

Pigments are another group of compounds with biomedical properties present in *Sargassum* species. Among the various pigments in algae, xanthophylls and carotenes are efficient singlet oxygen inhibitors, interacting at very high reaction rates [116]. One of the most widely used xanthophylls in dietary and cosmeceutical formulations today is fucoxanthin, due to its antioxidant and anti-inflammatory properties, which have been shown to decrease the risk of cancer, obesity, diabetes, and hypertension [117,118]. The levels of fucoxanthin present in holopelagic *Sargassum* species have been little studied and may be affected by sunlight duration and seawater temperature [119]. Kergosien et al. [28] performed an analysis of the levels of pigments present in the three morphotypes of *Sargassum* upon arrival, finding that fucoxanthin is the second primary pigment, followed by chlorophyll a, with values of 0.245, 0.383, and 0.483 μg mg $^{-1}$(dw) for *S. natans* var. *wingei*, *S. natans* var. *natans,* and *S. fluitans*.

Another family of compounds present in *Sargassum* biomass is phytosterols. They are fatty compounds present in the biological membranes of plant cells and exhibit antioxidant, antidiabetic, anticancer, and cholesterol-lowering properties [120]. *Sargassum* species are considered good sources of phytosterols, such as fucosterol, β-sitosterol, and saringosterol [119]. Smith et al. first reported the presence of fucosterol in the biomass of *S. fluitans*. However, they claim that they did not find saringosterol [121].

5. Biorefinery as a Challenge

Up to this point, we have compiled the main uses reported in the scientific literature and grouped them by category. We observed that among the most widely used biochemical components are sulfated polysaccharides (alginates and fucoidans), with primary applications in energy generation and biofuel production, and that they are emerging as novel materials in civil construction. Most analysts agree that a biorefinery would be the best approach to address the problem [7]. This approach enables the sequential extraction of most components, paving the way for a more sustainable future. Consequently, based on the chemical properties reviewed herein, previous models for brown algae [16,17], and the authors' experience with this specific feedstock, we propose the following sequential biorefinery scheme optimized for Caribbean *Sargassum* (Figure 3).

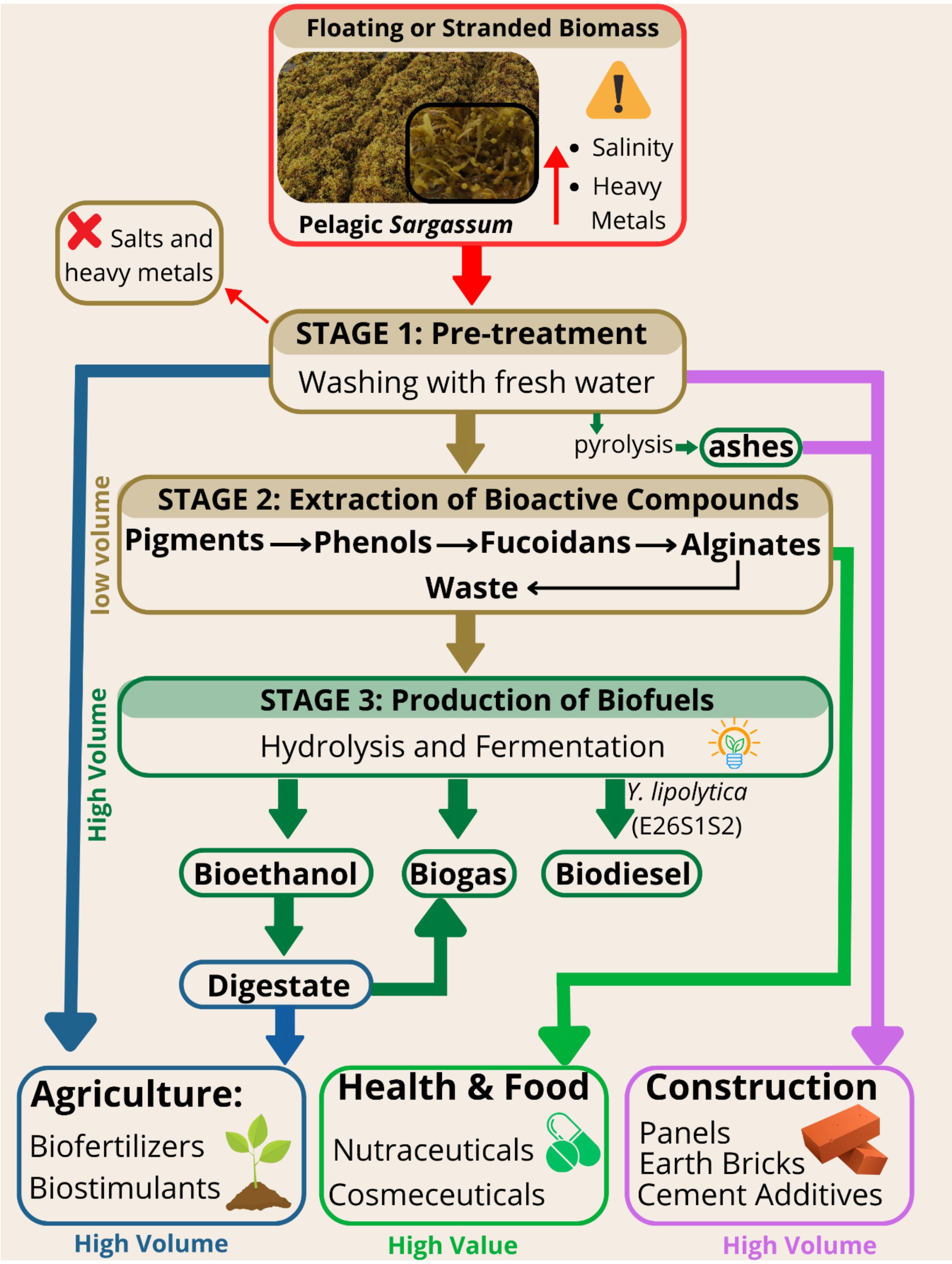

Figure 3. Circular Biorefinery Model for the Comprehensive Valorization of Pelagic *Sargassum*. Proposed cascade biorefinery scheme for the integral valorization of pelagic *Sargassum* biomass. The process is structured in three sequential stages to maximize resource recovery. Stage 1 involves pretreatment with fresh water to remove salinity and heavy metals. Stage 2 focuses on the extraction of low-volume, high-value bioactive compounds (pigments, phenols, fucoidans, and alginates). Stage 3 utilizes the residual biomass for the high-volume production of biofuels (bioethanol, biogas, and biodiesel) via hydrolysis and fermentation (using *Y. lipolytica*). Finally, the diagram illustrates the valorization of process residues (ashes and digestate) into construction materials and agricultural amendments, promoting a circular economy approach.

In Figure 3, we propose a conceptual diagram of a zero-waste biorefinery strategy using mixed *Sargassum* biomass. The process begins with pretreatment to address initial challenges (high humidity, salinity, and heavy metals). This is followed by sequential fractionation that prioritizes the extraction of high-value compounds (for the pharmaceutical and food industries), followed by the conversion of the residual biomass into biofuels and materials (for bioenergy and construction). Byproducts and residues from each stage (wash water, digestate, fibers, and ash) are reincorporated into the production cycle as biofertilizers or construction additives, or are treated through biosorption, closing the cycle under a circular economic approach.

5.1. Stage 1: Biomass and Pretreatment

The process begins with the collection of mixed *Sargassum* biomass, which is practical and economical as it avoids the costs associated with species separation. This biomass presents three initial challenges: high moisture content (over 80%), high salinity that can inhibit biological processes, and a strong capacity to bioaccumulate heavy metals such as arsenic.

Washing: An initial washing process is applied to reduce salt and heavy metal content, thereby improving the materials' properties for downstream uses such as biofuel production and construction. Furthermore, these pretreatments allow for working with contaminant-free biomass. The resulting contaminated biomass can be incinerated to reduce its volume by over 90% and allow for metal recovery.

5.2. Stage 2: Extraction of High-Value Compounds

For a profitable process, it is crucial first to extract high-value compounds, such as pigments, phenols, fucoidans, and alginates, which can be extracted sequentially due to their distinct chemical structures. These compounds have proven antioxidant, anti-inflammatory, and pharmacological properties, with applications in the pharmaceutical and nutraceutical industries. The solid residual biomass remaining after these extractions is rich in carbohydrates, such as cellulose and mannitol, and is ready for conversion into biofuels.

5.3. Stage 3: Production of Biofuels and Materials

The residual biomass is used to produce energy and construction materials, leveraging its high carbohydrate and fiber content. Through well-known processes such as hydrolysis and fermentation, polysaccharides can be broken down into simple sugars, which are then fermented to produce bioethanol (obtained from the fermentation of sugars such as glucose and mannitol), biogas (generated through the anaerobic digestion of biomass), and biodiesel (although the lipid content is low, the sugars in *Sargassum* can be used to feed oleaginous yeasts that produce the lipids needed for biodiesel).

Waste and Valorization: Digestate for Agriculture: The sludge or digestate resulting from anaerobic digestion is rich in nutrients and, after treatment to remove excess ammonia or metals, can be used as a biofertilizer or biostimulant. Its use is recommended for non-food crops or for the restoration of ecosystems such as dunes and mangroves. Construction Fibers: Residual fibers (cellulose, lignin) that do not ferment are excellent reinforcement for construction materials. They can be used to create panels, reinforced adobe bricks, or thermal and acoustic insulation.

Construction Ashes: If a portion of the biomass is burned directly to generate bioenergy, the resulting ash can be used as a mineral additive in cementitious compounds.

6. Conclusions

The recurrent massive influxes of pelagic *Sargassum* in the Caribbean represent a complex duality: they are a severe environmental stressor but simultaneously a promising

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reservoir of renewable biomass. This review confirms that the chemical profile of *S. fluitans* and *S. natans* is highly dynamic, driven by interspecific variability, seasonality, and the distinct oceanic conditions encountered during transport. While the biomass is characterized by a low lipid and protein content, its richness in sulfated polysaccharides (alginates and fucoidans), mannitol, and bioactive secondary metabolites (phenols, fucoxanthin) positions it as a competitive feedstock for diverse industries.

However, the safe valorization of this resource faces a critical bottleneck: the significant bioaccumulation of heavy metals, particularly arsenic. Our analysis highlights that while *Sargassum* holds immense potential for high-volume applications in bioenergy and construction, its use in food, feed, and agriculture is strictly constrained by international safety regulations. Consequently, simple processing methods such as freshwater washing are often insufficient for deep decontamination, necessitating advanced pretreatments or restricting certain products to non-food chains (e.g., construction materials or mangrove restoration).

Ultimately, the transition from an environmental liability to an asset requires a paradigm shift from single-product extraction to an integrated biorefinery model. As proposed in this review, a "zero-waste" cascade approach (prioritizing the extraction of high-value phytochemicals before converting the residual biomass into biofuels and construction materials) offers the most viable path to economic feasibility and sustainability. Future research must focus on optimizing these sequential extraction protocols, developing cost-effective heavy-metal remediation technologies, and establishing standardized monitoring programs to ensure the safety and quality of *Sargassum*-derived products.

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