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Potential application of pelagic *Sargassum* spp. in animal feeding

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Abstract
The abundance of pelagic *Sargassum* has increased in the Atlantic Ocean since 2011. Massive beaching of these algae causes environmental, socioeconomic, and human health problems in several countries in the Greater Caribbean and western Africa. *Sargassum* cleanup is expensive. Its valorization could reduce costs and impacts. The periodicity in landings, its high biomass, and the many bioactive compounds and minerals contained in these algae represent an opportunity for its use in animal feeding. A review of the existing literature regarding the chemical characteristics of *Sargassum* and the concentration of compounds to determine its potential use for animals used for human consumption is presented. The main findings are that these pelagic species have high amounts of fiber, salts, complex carbohydrates, and potentially toxic elements that limit their use in high quantities in animal nutrition. However, *Sargassum* also has minerals, trace elements, amino acids, fatty acids, and bioactive compounds that could benefit animal health if added as an ingredient at a concentration below 5%. Information gaps and recommendations for future research are presented.

Keywords Marine algae · Biomass · Chemical composition · Nutrition · Valorization · Perspectives

Introduction

Historically the distribution of pelagic *Sargassum* species (*Sargassum natans* (Linnaeus) Gaillon and *S. fluitans* (Borgesen) Borgesen) was centered in the Sargasso Sea (Franks et al. 2016). Periodical minor landings of these algae were common in the Caribbean and the Gulf of Mexico during certain months of the year. However, since 2011, massive beach cast events have become the "new norm" in several Caribbean and Western African countries, as well as Florida, Brazil, and Costa Rica (Gower et al. 2013; Smetacek and Zingone 2013; Gavio et al. 2015; Rodríguez-Martínez et al. 2016; Cabrera et al. 2021). In 2018, satellite observations confirmed the formation of a Great Atlantic *Sargassum* Belt extending from West Africa to the Gulf of Mexico with an estimated biomass of almost 20 million tonnes in the peak month of 2018 (Wang et al. 2019). *Sargassum* beach cast biomass can be considerable. In Brazil, for example, 614 t landed in one day per kilometer in 2015 (Sissini et al. 2017). On the northern Mexican Caribbean coast, 524 t were removed monthly per kilometer in 2018 (Rodríguez-Martínez et al. 2022). The increment in the abundance of these algae in the Atlantic has been related to climate change and ocean eutrophication (Lapointe et al. 2014; Wang et al. 2019).

Massive *Sargassum* landings produce ecologic, economic, and social impacts. The decay of thousands of tons of stranded *Sargassum* masses generates leachates and particulate organic matter that result in *Sargassum*-brown-tides in nearshore waters that lead to the mortality of seagrasses and fauna (van Tussenbroek et al. 2017; Rodríguez-Martínez et al. 2019). Bacterial activity results in the generation of gases (e.g., hydrogen sulfide and methane) that can be harmful to human health (Resiere et al. 2021), and cleanup activities are costly and result in beach erosion (Chávez et al. 2020). The annual

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Sargassum cleanup expenses in the Caribbean have been estimated at US$210 million (Davis et al. 2021). These factors combined affect the tourist industry and thus the economy of many countries (Milledge and Harvey 2016).

Sargassum valorization for food, biofuels, construction materials, or pharmaceutical products could alleviate the costs associated with its removal and management. Several studies have shown that *Sargassum* contains bioactive compounds and chemical elements that could serve for animal feeding (Milledge and Harvey 2016; Morais et al. 2020). However, it is critical to investigate its nutritional composition and potentially harmful components for animals and consumers.

The present review analyzes the opportunities and limitations of using *Sargassum* to feed farmed animals (livestock and some aquatic species) for human consumption based on the existing literature regarding its chemical composition. We also highlight research gaps and suggest future research directions. The insights offered in this review might help stakeholders responsible for *Sargassum* management and industries.

Materials and methods

We reviewed the existing literature on the chemical composition of pelagic *Sargassum* using Scopus, ISI Web of Knowledge, Google Scholar, and PubMed. The search engines used the following keywords: pelagic *Sargassum*, composition, utilization, animal feeding, rumen, fermentation, and toxicity. Thirty-two scientific manuscripts were obtained about research conducted in 15 countries and the Atlantic open ocean (Fig. S1).

Using the abovementioned information, we created a database with the following information: authors, sampling dates, *Sargassum* species and morphotypes analyzed, sampling sites, zones, and seasons, drying and grinding methods, and if samples were washed before the chemical analyses. The pelagic *Sargassum* influx to Atlantic countries has three morphotypes: *S. fluitans* III, *S. natans* I, and *S. natants* VIII (Parr 1939). Some studies analyzed the morphotypes separately while others did not. None of the studies reported removing the epibionts (e.g., serpulids, bryozoans, and calcareous algae) or the motile fauna (e.g., crustacea, mollusks, and polychaeta) before the chemical analysis. The database containing the values (e.g., mean, median, or interval) reported for the chemical analyses of organic and inorganic elements is available as supplementary material (Table S1). The ranges for each compound or element are presented in Tables 1, 2, 3, 4, and 5; extreme values were removed and colored in red in the general database, and those whose units were transformed from the source are marked in blue. Every value is reported on dry matter basis unless otherwise is mentioned.

Results/ discussion

Moisture and energy

Fresh pelagic *Sargassum* has a high moisture content (82–95%; Milledge et al. 2020), making it difficult to transport, store, and use. When the algae are dried and transformed (ground) into meal the moisture reduces to 5–17% (Table 1), which is close to that desired in animal diets (~ 12%; EU 2015). The drying process reduces the volume and the risk of contamination by bacteria and fungi, prevents crude seaweed extracts from gelification, and allows storage for several years (Ling et al. 2015; Badmus et al. 2019). The drying method (e.g., oven-dried, lyophilized, or sun-dried) does not appear to affect the content of protein and lipids; however, it could modify the content of some minerals, ascorbic acid, fatty acids, and amino acids. The sun-drying method, for example, led to higher quantities of phenolic compounds and mannitol and lower ones of fucoxanthin and monosaccharides than freeze-drying (Machado et al. 2022).

Sargassum meal has low gross energy content (2.2–3.3 kcal g^{-1}; Table 1) in comparison to other energetic ingredients employed in animal feeding, such as cereal grains (3.8–4.4 kcal g^{-1}), fats (9.2–9.4 kcal g^{-1}), and oils (9.3–9.5 kcal g^{-1}) (Santiago Rostango et al. 2017). It cannot be included in animal diets in large volumes, such as with some cereal grains (55–70%; Cuca-García et al. 2009), due to the high amount of fiber, salt, and potentially toxic minerals.

Protein and amino acids

Crude protein content in *Sargassum* meal fluctuated from 2.2 to 15.4% (Table 1), with most of the values being similar to those of other brown algae or forage grasses (8.5–13.6%; Yuan 2008; Corino et al. 2019) and cereal grains (4.5–14%), like sorghum, corn, oat, wheat, barley, and rice (8–15%). According to Gojon-Báez et al. (1998) 95% of *Sargassum* spp. protein may be degraded. However, the protein content is low compared to that found in distillers' dried grains (27%), canola (32–38%), soybean meal (44%), meat meal (45–55%), and fish meal (64%) (Cuca-García et al. 2009; Santiago Rostango et al. 2017; De Blas et al. 2019). The relatively low protein content in *Sargassum* limits its use as the primary source of protein in the diet of monogastric animals, ruminants, and aquaculture, as these animal species have higher requirements (e.g., fish and shrimp 35–40%, broilers 17–23%, and laying hens 16–20%; Cruz-Suárez et al. 2008; NRC 2011; Nates 2016; Aviagen 2019; Hy-Line

Table 1 Proximate analysis and other components of pelagic *Sargassum* meal (dry matter basis)

Component	Unit	Content	References
Proximate analysis			
Moisture	%	5.0—17.0	1, 6, 7, 10, 9, 11, 16
Crude protein	%	2.2—15.4	2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 14
Ether extract	%	0.01—4.6	4, 5, 7, 9, 11, 14
Crude fiber	%	7.2—17.0	2, 7, 10
Ash	%	8.7—55.7	1, 2, 4, 5, 7, 8, 9, 10, 11, 13, 16
Carbohydrates	%	5.4—77.6	4, 5, 8, 9, 11, 14
Nitrogen free extract	%	57.7—74.2	2, 7, 10
Gross energy	kcal g^{-1}	2.2—3.3	2, 4, 8
Vitamins			
Ascorbic acid	mg (100 g)$^{-1}$	3.2	2
Thiamin	mg (100 g)$^{-1}$	0.02	2
Riboflavin	mg (100 g)$^{-1}$	0.3	2
Niacin	mg (100 g)$^{-1}$	1.5	2
Pigments			2
Carotenes	mg (100 g)$^{-1}$	0.01	2
Chlorophyll *a*	mg g^{-1}	0.13—0.27	11
Chlorophyll *c*	mg g^{-1}	0.04—0.07	11
Total carotenoids	mg g^{-1}	0.08—0.13	11
Fucoxanthin	µg g^{-1}	58—504	16
Phenolic compounds			
Total phenolic compounds	mg (100 g)$^{-1}$	80	7
Total phenolic content	mg GA g^{-1}	1.5—2.3	9
	mEq PG g^{-1}	1.0—29.5	1, 4, 16
Phenols	µg mL^{-1}	6.1—9.2	11
Tannins	mg (100 g)$^{-1}$	122.5	7
Flavonoids	mg (100 g)$^{-1}$	775	7
Terpenoids	mg (100 g)$^{-1}$	66.5	7
Phlorotannins	mEq PG g^{-1}	0.34—3.6	1, 16
Antinutrient factors			
Saponins	mg (100 g)$^{-1}$	525.0	7
Alkaloids	mg (100 g)$^{-1}$	77.5	7
Cardiac glycosides	mg (100 g)$^{-1}$	16.5	7

References: [1]Davis et al. 2021: [2]Díaz-Piferrer 1979; [3]De Vrije 2016; [4]Milledge et al. 2020; [5]Mohammed et al. 2020; [6]Desrochers et al. 2020; [7]Oyesiku and Egunyomi 2014; [8]Robledo et al. 2021; [9]Saldarriaga-Hernandez et al. 2021; [10]Solarin et al. 2014; [11]Vázquez-Delfín et al. 2021; [12]Viana Ramos et al. 2000; [13]Wang et al. 2009; [14]Webber et al. 2019; [15]Van Ginneken et al. 2011; [16] Machado et al. 2022. GA: Gallic acid. PG: phloroglucinol

2020). The protein content in *Sargassum* could be increased through a biorefinery process, as has been done with *Ulva ohnoi* to produce salts, sulfated polysaccharides, and protein-enriched biomass (Magnusson et al. 2019). Nevertheless, this approach needs to be investigated in *Sargassum*.

Despite the low protein level, its quality is good since it contains all essential amino acids for birds, pigs, fish, and shrimp (Table 2). However, the bioavailability of amino acids from pelagic *Sargassum* needs to be evaluated because some compounds (e.g., alkaloids, tannins, and dietetic fiber) could shape their digestion and absorption in the gastrointestinal tract (Cherry et al. 2019).

Also, it must be considered that brown algae have a substantial non-protein nitrogen fraction, varying from 12–29% (Bikker et al. 2020). In ruminants, this may not represent a limitation since microorganisms in the rumen efficiently use non-protein nitrogen to increase the production of bacterial protein (Bikker et al. 2020), which may constitute 70 to 100% of the nitrogen available in the lower part of the digestive tract in animals that consume fibrous diets with low protein content (Shimada 2018).

Table 2 Amino acids content (g (100 g)$^{-1}$ dry matter basis) in pelagic *Sargassum* meal

Amino acid	Content	Amino acid	Content
Alanine	0.10 – 0.34	Lysine	0.10 – 0.28
Arginine	0.10 – 0.19	Methionine	0.04 – 0.14
Aspartic acid	0.16 – 0.48	Phenylalanine	0.10 – 0.19
Cystine	0.09 – 0.11	Proline	0.08 – 0.18
Glutamic acid	0.24 – 0.85	Serine	0.08 – 0.22
Glycine	0.08 – 0.32	Threonine	0.10 – 0.21
Histidine	0.04 – 0.07	Tyrosine	0.00 – 0.08
Isoleucine	0.09 – 0.18	Tryptophan	0.04 – 0.05
Leucine	0.13 – 0.28	Valine	0.09 – 0.35

References: Viana Ramos et al. 2000; Milledge et al. 2020

Lipids (ether extract, fatty acids, vitamins, and pigments)

The ether extract content in pelagic *Sargassum* is low (0.01–4.6%; Table 1), like in other *Sargassum* species (0.5–3.0%; Yuan 2008; Corino et al. 2019). This fraction includes all fat-soluble compounds, like vitamins, pigments, and fatty acids. *Sargassum* is considered a good source of vitamins when fresh (Yuan 2008), yet, when converted into meal, it contains low levels of thiamin (0.02 mg (100 g)$^{-1}$), niacin (1.5 mg (100 g)$^{-1}$), and riboflavin (0.3 mg (100 g)$^{-1}$) (Table 1), due to the drying process (Yuan 2008).

Carotenoid concentration in *Sargassum* ranged from 0.08 to 0.13 mg g^{-1} (Table 1) and consisted of β-carotene, fucoxanthin, violaxanthin, diatoxanthin, and chlorophyll *c* (Milledge and Harvey 2016; Corino et al. 2019). β-carotene is a vitamin A precursor with antioxidant properties for several mammals and aquatic species (NRC 2011; Çalişlar 2019; Mary et al. 2021). Fucoxanthin was reported in concentrations ranging from 58 to 504 µg g^{-1} (Machado et al. 2022) and is of particular interest due to its antioxidant, anticarcinogenic, anti-inflammatory, and antiobesogenic properties; it also reduces the plasmatic concentration of glucose and insulin, steatosis, and insulin resistance (Cherry et al. 2019; Ojulari et al. 2020; Peñalver et al. 2020).

Among saturated fatty acids (Table 3), palmitic acid (C16:0) dominates (24–55%), while among the unsaturated fatty acids the presence of eicosapentaenoic (C20:5 EPA: 0.05–5%) and docosahexaenoic (C22:6 DHA: < 0.05–13%) acids is of particular interest since they are usually low in land vegetable sources and very important for human and animal health (Gammone et al. 2019). Thus, the lipid

Table 3 Fatty acids content in pelagic *Sargassum* meal (dry matter basis). %TFA: percentage of total fatty acid content

Fatty acid	%TFA	ug g^{-1} meal	Reference
Saturated			
C16:0 Hexadecenoic acid	23.61—55.14	3,006	1, 2
C17:0 Heptadecanoic acid	0.13—1.83		1
C18:0 Octadecanoic acid	0.85—7.60	369	1, 2
C20:0 Eicosanoic acid	- 0.94		1
C22:0 Docosanoic acid	0.63—1.28		1
C24:0 Tetracosaenoic acid	0.05—0.44		1
Monounsaturated			
C14:1 cis-9 Tetradecenoic acid	0.05—0.43		1
C15:1 5-pentadecenoic acid	0.05—0.39		1
C16:1 9- hexadecenoic acid	3.54—8.28	325	1, 2
C17:1 7- heptadecanoic acid	0.05—0.63		1
C18:1 7- octadecanoic acid	10.71—16.83	1,095	1, 2
C20:1 11-eicosanoic acid	0.05—2.47		1
C22:1 11-docosaenoic acid	< 0.05—2.11		1
Polyunsaturated			
C18:2 9-octadecanoic acid	3.00—7.90	230	1, 2
C18:3 6-octadecanoic acid	1.00—5.90	121	1, 2
C18:4 all-cis-6,9,12,15 -octadecatetraenoic acid	0.07—1.34		1
C20:4 all-cis-5,8,11,14- eicosatetraenoic acid	3.01—12.95	581	1, 2
C20:5 Eicosapentaenoic acid	0.05—5.00	329	1, 2
C22:4 all-cis-7,10,13,16-docosatetraenoic acid	< 0.05—1.17		1
C22:5 7,10,13,16,19- docosapentaenoic acid	0.05—0.36		1
C22:6 4,7,10,13,16,19- docosahexaenoic acid	< 0.05—13.00	970	1, 2

References: [1]Van Ginneken et al. 2011; [2]Milledge et al. 2020

Table 4 Fiber and polysaccharides content in pelagic *Sargassum* meal (dry matter basis)

Fiber fractions	Content	References
Dietary fiber		
Total dietary fiber (TDF) %	31.2—37.4	5
Carbohydrates		
Fucoidan %	4.4—20.0	6, 7, 8, 9, 10, 11
Alginic acid %	6.8—23.6	1, 6
Alginates %	5.1—34.6	2, 4, 7, 8, 9, 10, 11, 12
Alginate uronic acids %	19.8—24.4	7, 10
Fucoidan uronic acids %	5.5—11.9	7, 10
Alginate sulfates %	5.4—7.0	7
Fucoidan sulfates %	0.8—17.0	7, 10
Mannitol %	10.25	6
Laminarin %	12.6	6
Total sugars %	11.3	3
Glucose %	4.5	3
Fucose %	4.2	3
Galactose %	1.2	3
Xylose %	0.1	3
Arabinose %	0.2	3
Mannose %	0.2	3
Rhamnose %	0.1	3

References: [1]Aponte de Otaola et al. 1983; [2]Davis et al. 2021; [3]de Vrije 2016 (in Desrochers et al. 2020); [4]Díaz-Piferrer 1979; [5]Milledege et al. 2020; [6]Ocean Harvest 2016 (in Desrochers et al. 2020); [7]Ortega-Flores et al. 2022;, [8]Robledo et al. 2021; [9]Rosado-Espinosa et al. 2020; [10]Vázquez-Delfín et al. 2021; [11]Webber et al. 2019; [12] Machado et al. 2022

fraction of *Sargassum* could be a good supply of fatty acids for farmed animals.

Pelagic *Sargassum* also contains metabolites, like tannins (123 mg (100 g)$^{-1}$), flavonoids (775 mg (100 g)$^{-1}$) and phlorotannins (0.3–0.9 mEq PG g^{-1}), and secondary metabolites, like terpenoids (67 mg (100 g)$^{-1}$) and carotenoids 0.08–0.13 mg g^{-1}) (Table 1). Seaweeds produce these compounds to protect them from external conditions, stress, and herbivory (Chojnacka et al. 2012). A moderate content of tannins may be beneficial in animal diets because they exert antimicrobial, antioxidant, antiviral, and anti-inflammatory activities (Shipeng et al. 2015; Tamama 2020). A high tannin content, however, can significantly reduce the digestibility of proteins and amino acids (up to 23%) in poultry and pigs. The tannin content in some cereals used for animal feedings, such as sorghum (50–7200 mg (100 g)$^{-1}$ DW) and barley (550–1230 mg (100 g)$^{-1}$ DW) (Gilani et al. 2005), can be higher than that in pelagic *Sargassum* (Table 1).

Among the antinutrient factors, saponins content in *Sargassum* is 525 mg (100 g)$^{-1}$ (Table 1), which is lower than in red and green seaweeds (13,000–17,000 mg kg^{-1} DW; Feroz 2018). Saponins have antioxidant, antibacterial, antifungal, and nematocidal activity (Feroz 2018). Alkaloids are also present at a concentration of 77.5 mg (100 g)$^{-1}$ (Table 1). Alkaloid presence in marine algae is rarer than in terrestrial plants (Güven et al. 2010). For example, Carrillo et al. (1992) did not detect alkaloids in *S. sinicola*; however, ephedrine, cuscohygrine, pyrvinium, and doxapram were reported in *S. tenerrimum* (Chitari et al. 2018). Pelagic *Sargassum* has sterols as structural components of its cell membrane at a concentration of 16.5 mg (100 g)$^{-1}$ (Table 1). Some of the *Sargassum*'s sterols are cardiac glycosides which could help to treat cardiac failure and atrial arrhythmias (Khalid et al. 2018).

Carbohydrates, nutrients, and organic elements

Carbohydrates (5–78%) and nitrogen-free extract (58–74%) contents in pelagic *Sargassum* showed high variability among studies (Table 1). The content of crude fiber (7–17%; Table 1) is below the quantity considered fibrous, such as that of alfalfa hay (25%), oat straw (41%), and weeds, grasses, and stubble (23–35%) (Shimada 1983). The amount of total dietary fiber (TDF: 31–37%) in pelagic *Sargassum* (Table 4) is lower than that reported for benthic *Sargassum* species (TDF: 63%; Yuan 2008.

The amount of soluble dietary fiber (SDF), composed of alginates (9–35%), fucoidan (4–20%), alginic acid (7–24%), alginate uronic acids (20–24%), fucoidan uronic acids (6–12%), alginate sulfates (5–7%), and fucoidan sulfates (1–17%), is higher than that in oat hulls (2%), alfalfa meal (8%), and cellulose (2%) but below that of pectin (65%) and inulin (> 90%) (Desbruslais et al. 2021). The SDF can improve the satiety of animals and produce short-chain fatty acids, but at high levels could increase the intestinal viscosity, promoting the presence of *Escherichia coli* while decreasing nutrient absorption, and thereby having an impact on growth performance and intestinal health (Jimenez-Escrig and Goñi 1999; Holdt and Kraan 2011; Bikker et al. 2020; Chuang et al. 2021). Therefore, *Sargassum* inclusion in animal diets should not be above 10% for monogastric and 30% for ruminants. Additions below 5% could even have potential benefits for both groups, as has been shown for other brown seaweeds (Holdt and Kraan 2011; Makkar et al. 2016; Corino et al. 2019; Bikker et al. 2020; Coudert et al. 2020; Desbruslais et al. 2021; Li et al. 2021). Further studies are needed to elucidate the best amount of *Sargassum* in the diet of different animal species to minimize undesirable side effects while obtaining maximums benefits.

The concentration of organic elements in pelagic *Sargassum* meal is 27–33% carbon, 3–5% hydrogen, 21–32% oxygen, 0.05–1.7% nitrogen, and 0–1.4% sulfur (Table 5). Organic element concentration can vary between morphotypes, collection sites, processing methods, and types of

Table 5 Nutrients and inorganic matter in pelagic *Sargassum* meal (dry matter basis). LOD: limit of detection. Conc.: Concentration; Ref.: References

Compound	Conc	Ref	Element	Conc	Ref
Nutrients			Macroelements (ppm)		
N %	0.05—1.7	1, 2. 3, 4, 5, 6, 7	Al	<LOD—4,187	4, 11, 12, 13, 22
C %	26.8—33.0	1, 2, 4, 7	Ag	0.01—119	3, 12
H %	3.1—4.8	1,4	B	102,243 -116,294	12
O %	20.6—31.8	4	Ba	19.2—23.2	11
S %	0—1.4	1, 4	Be	0.006—0.05	12
C:N ratio	17.0—35.0	2	Ca	29.0—136,146	4, 6, 9, 11, 12, 13, 21
Phosphate (ppm)	0.8—51.0	8, 9, 10	Cl	23.0—53,101	8, 13
Ammonia (ppm)	354—741	8	K	0.7—69,359	4, 8–13, 20
Nitrates (ppm)	180 – 2,377	8,9	Mg	30.0—18,241	4, 5, 9, 11–13, 20
			Na	3,802—78,094	5, 9, 11, 12
Salts			P	2.3 – 1,460	1, 3–6, 13, 20
NaCl (% DM)	15.2—23.1	4	S	9,462—24,773	13
NaCl (% ash)	19.0—71.6	4			
$CaCO_3$ (% ash)	11.7—42.1	4	Microelements (ppm)		
$CaCO_3$ (% DM)	6.3—10.8	11	Co	0.2–1	1, 11, 12
$CaSO_4$ (% ash)	3.4—7.7	4	Cr	0.3–56	1, 4, 11, 12, 13, 1, 22
KCl (% ash)	0.3—23.9	4	Cu	0.2- 264	1, 2, 4, 5, 8, 9, 11, 12, 17, 22
MgO (% ash)	4.9—8.3	4	Fe	12–5,910	1, 2, 4, 5, 6, 8, 9, 11, 17, 20, 22
$K_3Na\,(SO_4)_2$ (% ash)	0.3—8.3	4	I	0.4–85	18, 20
Na_2SO_4 (% ash)	0.2—3.2	4	Mn	<3–139	4, 11, 13, 22
			Mo	0.6–3	12
Potentially toxic trace elements (ppm)			Ni	3.5–39.8	11, 12, 19,
As_{Total}	0.0001—225	1, 2, 4, 8, 11–17, 22	Rb	30–143	13
$As_{Organic}$	17.0	18	Se	<0.01	13
$As_{Inorganic}$	0.2—28.0	18, 21	Si	447–2,877	13
Cd	0.1—119	1, 2, 4, 8, 11, 12, 14, 17–19, 22	Sr	1,605–2,564	13
Pb	0.2—335	1, 2, 4, 8, 11, 12, 14, 17–19	Th	3–23	13
Hg	<0.005—2	4, 8, 12, 14, 18, 22	U	0.8–48	11,13
			V	2.3–31.9	11,22
			Zn	0.05–100	4, 8, 12, 14, 18

References: [1]Saldarriaga-Hernandez et al. 2021; [2]Vázquez-Delfín et al. 2021; [3]Collado-Vides, 2020; [4]Milledge et al. 2020; [5]Wilson-Harward 2015 (in Desrochers et al 2020), [6]Díaz-Piferrer 1979;[7]Robledo et al. 2021; [8]Dzama and de Graft 2016, [9]Webber et al. 2019, [10]Solarin et al. 2014; [11]Davis et al. 2021; [12]Fernandez et al., 2017; [13]Rodríguez-Martínez et al. 2020; [14]Tirolien 2019 (in Desrochers et al. 2020); [15]Johnson and Braman 1975; [16]Mohammed et al. 2020; [17]Amado-Filho et al. 2008; [18]Ocean Harvest 2016 (in Desrochers et al. 2020); [19]Tejada-Tejada et al. 2021; [20]Oyesiku and Egunyomi 2014; [21]Devault et al. 2022; [22]Dassié et al. 2021

analysis (Table S1). The C: N relation fluctuates between 17 and 35%.

Inorganic elements (ash, salts, minerals, and trace elements)

The ash content (9- 47%) and the concentration of inorganic elements in pelagic *Sargassum* meal can be highly variable, depending on the morphotypes, sampling date and site, drying method, and sample processing technique (Table S1). Salts occupy a significant portion of the chemical fraction (Table 5). The high quantity of calcium carbonate (6–11% dry weight and 2.1% wet weight) results mainly from the presence of epibionts that have skeletons made by this compound (e.g., bryozoans, serpulids, and calcareous algae) and can cover up to 70% of the stem and blades (Salter et al.

2020). The concentration of sodium chloride (NaCl) is also high (15 – 23% dry weight). Thus, incorporating *Sargassum* in quantities above 10% of animal diets could negatively affect animal metabolism. In chickens and hens, for example, high quantities of NaCl produce a laxative effect, favoring the development of microbial pathogens in wet beds and affecting the productive variables and animal performance (Rojkind 1977; Bikker et al. 2020). Poultry, pigs, and bovines can tolerate concentrations of NaCl of 17, 30, and 45 g kg^{-1} (dry weight), respectively (NRC 2005). Higher quantities can reduce the digestibility of other components of the algae by 65–80% (Milledge et al. 2020). In ruminants, the tolerance to mineral salts is higher, considering that clean and low-salinity water is provided (Underwood and Suttle 1999). However, in ovine and goats, the inclusion of 25 to 30% of a benthic *Sargassum* species in the diet resulted in higher water consumption and urine excretion (Marín et al. 2003, 2009; Casas-Váldez et al. 2006), which compromise kidney functioning and may result in kidney failure. In fish, NaCl is absorbed straight from the water; thus, its addition as a dietary supplement is usually ineffective. However, adding NaCl via food may provide a physiological benefit for some marine fish cultured in freshwater, resulting in enhanced growth (NRC 2011).

Like other brown algae, *Sargassum* can absorb macro and microelements from the water. Some minerals in pelagic *Sargassum* are adequate dietary supplements for animals, including calcium, iron, manganese, potassium, selenium, sodium, and zinc (Table 5). In the case of iodine, the concentration range (0.4–85 ppm) is low compared to that reported for benthic *Sargassum* species (216–5,940 ppm; Zubia et al. 2003; Corino et al. 2019). A study by Gojon-Báez et al. (1998) on bovine livestock showed that the mineral degradability of *Sargassum* spp. was 78%, making it an adequate alternative for supplying the minerals needed for their health and growth. In the case of pelagic *Sargassum,* specific mineral absorption by different animal species (terrestrial and aquatic) and their potential benefits or constraints need to be studied.

A significant limitation posed for pelagic *Sargassum* in animal feeding is its capacity to absorb potentially toxic trace elements due to alginates and fucoidans in their cell wall, which serve as binding sites for metal and semi-metal ions (Mohammed et al. 2022). Several studies found that pelagic *Sargassum* usually has low concentrations of Co, Cr, Mn, Ni, and Zn (Table 5). Cd, Pb, and Hg concentrations are usually low, but can rarely be high (Table S1), with maximum values of 119, 335, and 2 ppm (DW), respectively. In the case of Cd, the maximum limit allowed in the diet for bovines, ovines, and caprines is 1 ppm. For other terrestrial animal species (excluding pets), the limit is 0.5 ppm (EU 2002), and for fish is 10 ppm (NRC 2005). Regarding Pb, the maximum limit allowed in raw material that will be included in animal diets is 10 ppm, and when used as complete food (with a maximum humidity of 12%) is 5 ppm (NRC 2005; EU 2015). The concentration of Hg in pelagic *Sargassum* samples fluctuated from < 0.005–2 ppm; therefore, on occasions, it can surpass the limit allowed for ingredients in food of terrestrial animals (0.1 ppm) and fish (1 ppm) (EU 2015).

Arsenic deserves particular attention because, even though the concentration in *Sargassum* can be variable among sites and morphotypes (< 1 – 225 ppm), most studies reported values (Table S1) that exceed the limit allowed for the use of algae for nutritional uses in most countries. *Sargassum* seems to bioaccumulate arsenic due to its resemblance to phosphate, allowing arsenate to enter algal cells via a phosphate-transporting mechanism (Wang et al. 2013). According to the European Union, seaweed meal and feed materials generated from seaweed must not contain more than 40 ppm of total As, whereas complete animal feed containing seaweed may not have more than 10 ppm (EU 2015). The concentrations of total arsenic reported by several studies for pelagic *Sargassum* led the French Government to recommend not using it for food products (ANSES 2017). Nevertheless, it is crucial to consider that arsenic toxicity depends on several factors, as discussed below.

Arsenic occurs in organic and inorganic forms, with the latter considered highly toxic. Several authors have pointed out that the organic form predominates in seaweeds (Cabrita et al. 2016; Taylor et al. 2017; Circuncisão et al. 2018; Mongail et al. 2018). However, the few studies analyzing arsenic speciation in pelagic *Sargassum* report inorganic As concentrations ranging from 0.2–28 ppm (Johnson and Braman 1975; Desrochers et al. 2020; Devault et al. 2022). This finding restricts the direct use of pelagic *Sargassum* in animal feeding, as the maximum limit of inorganic As allowed in seaweeds intended for animal nutrition is < 2 ppm (EU 2015). However, different processing techniques can reduce the concentration of arsenic, including activated carbon, citric acid, hydrochloric acid, boiling water (pre-cook), or a combination of these treatments (Sugawa-Katayama et al. 2005; Kang et al. 2021). In *S. fusiforme*, for example, arsenic concentration was reduced from 75 to 1.6 ppm through a sequential process of hot water, citric acid, and fermentation (Wang et al. 2022). The processes mentioned above should be tested in pelagic *Sargassum* as this could enhance its acceptance by the animal-fed industry if the benefits exceed the cost.

Arsenic toxicity also depends on the demethylation processes during its passage through the gastrointestinal tract. Some authors suggest that the cooking process allows organic As to remain intact after the digestive process and to be absorbed by the hepatic portal system, thus avoiding the transformation of organic As into inorganic As (Chavez-Capilla et al. 2016). Choi et al. (2020) also found that in ruminants fed with *S. fusiforme* (with As concentration of 94.17 ± 4.96 ppm DM), the consumption did not necessarily cause toxicity. According to Beresford et al. (2001), the inorganic arsenic true absorption coefficient of ruminants is considerably lower than that of non-ruminant animals, which can have complete absorption. Anaerobic fermentation in the rumen may play an essential role in this respect. In some aquatic species, like tilapia, less organic arsenic is deposited in tissues when it enters through food than when absorbed from the water (Suhendrayatna et al. 2001). More research is necessary on the routes that arsenic takes within the bodies of different animal species when consumed.

Several studies suggest that the transfer of As from the food to edible tissues of animals reared for human consumption is low due to the process of detoxification and the rapid excretion of metabolites (Ghosh et al. 2012; Mongail et al. 2018; Upadhyay et al. 2019). Mongail et al. (2018) observed that when including the brown algae *Ascophyllum nodosum* (As_{Tot}: 31.1–56.3 ppm; As_{Inorg}: 0.1–1.4 ppm) in the diet of poultry (2.5%) and ruminants (100–120 g day^{-1} for bovine meat and 120–150 g day^{-1} for milk cows), the quantity of As deposited in chicken meat, beef meat, and cow milk was low, with values of 0.00015, 0.002, and 0.00035 ppm, respectively. These values are below the limit SENASICA (2020) established for different animal species and products (Table S2). Finally, when heavy metals and semi-metals that are bound to alginic acid or alginates enter the human body, they are chelated or rendered insoluble because the enzymes in the gastrointestinal tract cannot digest alginic acid or its salts (Ruperez and Toledano 2003; Holdt and Kraan 2011; Szekalska et al. 2016; Circuncisao et al. 2018).

Conclusion

The high biomass of pelagic *Sargassum* that periodically beaches in several Atlantic countries represents an opportunity to obtain valuable compounds for the livestock and aquaculture industries. These algae have high amounts of fiber, mineral salts, complex carbohydrates, and potentially toxic elements that limit their use in high quantities in animal nutrition. However, they also have many minerals, trace elements, amino acids, and bioactive compounds that can benefit animals, even in small quantities. *Sargassum* addition to the diet can ensure a good supply of calcium, sodium, potassium, phosphorus, and magnesium. Fucoxanthin is particularly interesting due to its antioxidant, anticarcinogenic, and anti-inflammatory properties. Tannins may also benefit animals if added in moderate quantities due to their antimicrobial, antioxidant, antiviral, and anti-inflammatory activities, and saponins due to their antibacterial, antifungal, and nematocidal properties. The bioactive compounds with antimicrobial activity could be a natural alternative in countries where prophylactic antibiotics for animal farms are banned. Some sterols in these algae could also treat cardiac failure and atrial arrhythmias.

The presence of the unsaturated fatty acids EPA and DHA are relevant due to their importance for animal health and their scarcity in land vegetable sources. However, until efficient arsenic removal methods are in place, adding *Sargassum* meal to diets is recommended below 5% of the inclusion. This amount will ensure that the content of potentially toxic elements in livestock feed is below the limits established by international organizations and would not represent a risk to animals or the final consumers' health. Research on the transference of potentially toxic elements to products and consumers is necessary before employing higher quantities of *Sargassum* meal in animal diets. Adequate methods to collect, process, and store these algae to preserve the quality of compounds and compensate for scarcity periods are essential due to the high spatial and temporal variability in beach cast volumes. Finally, it should be noted that the concentration of elements and proportion of compounds found in pelagic *Sargassum* can be variable among morphotypes, in space and time, and depending on the processing methods employed. Thus, after selecting the best processing methods for specific elements or compounds, *Sargassum* assemblages intended for animal nutrition should be tested periodically to ensure they meet safety standards.

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Data availability The dataset generated during the current study is available in supplementary Table 1.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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