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Nori species (Rhodophyta, Bangiales): a brief review of nutritional and economic potential in Brazil[1]

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ABSTRACT - The species *Porphyra*, *Pyropia*, and *Neopyropia* are widely cultivated and consumed worldwide due their valuable nutraceutical properties. These red algae are rich in essential macronutrients, including carbohydrates, lipids, proteins, and minerals. They also contain bioproducts beneficial to human health, such as pigments (phycobiliproteins), phenolic compounds, polyunsaturated fatty acids (PUFAs), and polysaccharides, which exhibit antioxidant, anti-inflammatory, neuroprotective, and anti-obesity activities. These algae are particularly important as edible seaweeds, being most notably used in the production of Nori. This review examines recent research on the nutritional value of Nori species, based on 17 selected articles. The data were organized according to protein, carbohydrate, lipid, and ash content. Additionally, we explore the bioactive compounds found in these species, such as pigments, fatty acids, and phenolic compounds. Our discussion also emphasizes the economic potential of Nori in Brazil. Despite the country's rich biodiversity, Brazil remains a major importer of algae for human consumption. However, there is significant potential for expanding its presence in the aquaculture sector, creating opportunities for the cultivation of Nori species. These growing prospects could pave the way for the sustainable exploitation of this resource in both national and global markets.

Key words: Nori. *Rhodophyta*. Nutraceutical potential. Food bioproducts.

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INTRODUCTION

Seaweed, or marine macroalgae, has traditionally been consumed as a food source in various civilizations, particularly in Asia, in countries such as China, Korea, and Japan, where it continues to be a significant part of the daily diet (Mchugh, 2003). As an important category within novel foods, seaweed is increasingly included in diets due to its numerous health benefits (Ainsa *et al.*, 2022). Seaweed is notable for its exceptionally rich nutritional profile, which includes fiber, polyunsaturated fatty acids, vitamins, minerals, and substantial protein content. Additionally, the bioactive compounds found in seaweed such as polysaccharides, proteins, polyphenols, carotenoids, and omega-3 fatty acids make it a valuable resource for the functional food industry (Ainsa *et al*., 2022; Cherry *et al*., 2019).

Rhodophyta (red seaweeds) are composed of 80% to 90% water. When dried, they contain approximately 50% carbohydrates, 7% to 38% minerals, and 1% to 3% lipophilic compounds, as well as along smaller quantities of phenolic and vitamin compounds (García-Casal *et al*., 2007). The protein content varies significantly, ranging from 10% to 47%, and includes high levels of essential amino acids vital for human nutrition. Additionally, red algae are rich sources of both soluble vitamins (B1, B2, B3, B5, B12, and C) and insoluble vitamins (A, E, D, and K). They also provide essential minerals such as calcium (Ca), potassium (K), sodium (Na), iodine (I), iron (Fe), zinc (Zn), and others, along with essential amino acids (Trindade *et al*., 2016). In particular, the genera *Porphyra/Pyropia/Neopyropia*, belonging to the order Bangiales, are remarkable for their complex taxonomy. This complexity is due to factors such as the high number of species with widespread distribution, simple morphology with limited characters for species discrimination, phenotypic plasticity, and the presence of cryptic species (Milstein; Oliveira, 2005). These red algae are especially significant for their use as edible seaweeds, most notably in the production of Nori, a popular food in Asian cuisine. Dried Nori species contains numerous nutritional and biofunctional components and has been utilized both as food and for pharmacological purposes (Cao *et al.*, 2016; Zhongzhong; Jianguang; Huashi, 2009). Nori is widely consumed across Asia, often featured in soups, salads, sushi wraps, and snacks (Duarte; Bruhn; Krause-Jensen, 2022). Beyond direct consumption, Nori can be processed into food additives or supplements (Duarte; Bruhn; Krause-Jensen, 2022; FAO, 2018).

Additionally, during the current Oceans Decade (2021-2030), the significance of these algae transcends sustainability. They intertwine with the Sustainable Development Goals (SDGs) established by the United Nations, including SDG 2 (Zero Hunger), SDG 12 (Responsible Production and Consumption), SDG 13 (Climate Action), and SDG 14 (Life Below Water) (Cai *et al*., 2021; Spillias, Bruhn, Krause-Jensen, 2022; Spillias *et al*., 2022).

This article reviews the current landscape of the nutritional aspects of Nori algae (*Porphyra*, *Pyropia*, *Neopyropia*). The main goal is to provide a comprehensive review of the nutraceutical potential of various species within these genera. Our analysis reveals the potential of species that could be explored in Brazil, highlighting their economic value and viability for commercial exploitation as a fishery resource.

MATERIAL AND METHODS

The literature search was conducted using the Web of Science database, covering the period from 2016 to early 2024. The search focused on the descriptors “Porphyra and nutritional value,” “Pyropia and nutritional value,” and “Neopyropia and nutritional value,” refined using the operator “AND” with the terms enclosed in quotation marks. Only English-language studies addressing the nutraceutical potential of Nori algae were included.

A total of 17 articles were screened and evaluated based on their titles and abstracts, following a rigorous selection process that prioritized studies with quantitative data. The selected studies were thoroughly analyzed and systematically organized to create a comprehensive overview of the *Porphyra, Pyropia, and Neopyropia* genera (Rhodophyta, Bangiales). This methodology aimed to synthesize current knowledge, highlight key findings, and identify areas needing further research on the nutraceutical potential of Nori algae, providing valuable support for professionals in natural product chemistry and related fields.

RESULTS AND DISCUSSION

The bibliographic search, using the keywords “*Porphyra* and nutritional value,” “*Pyropia* and nutritional value,” and “*Neopyropia* and nutritional value,” resulted in the selection of 17 articles for this study. Duplicate articles and those not aligned with the study’s scope and objectives were excluded.

This review examined 25 species of Nori algae (Porphyra/Pyropia/Neopyropia spp.), with *Porphyra* being the most studied genus (55%), followed by *Pyropia* (25%) and *Neopyropia* (15%). The most researched species were *Porphyra dioica* (15%), *P. tenera* (10%), *P. umbilicalis* (10%), *Pyropia columbina* (10%), and

Neopyropia yezoensis (15%) (Figure 1A). It is important to highlight that species within these genera are under continuous taxonomic evaluation and reconsideration due to their cosmopolitan distribution and biological plasticity (Yang *et al*., 2020).

The biomass in these studies primarily originated from natural banks (76.47%), with additional sources including offshore cultivation (17.65%) and multitrophic cultivation (IMTA) (11.76%). The macroalgae were sourced from various countries across Europe, Asia, and South America, with Portugal (23.53%) and China (17.65%) being the most significant contributors and hosting the majority of studies (Figure 1B).

Nutraceutical potential

The red seaweed of *Porphyra, Pyropia* and *Neopyropia* were analyzed for its nutritional value, including fatty acid profile, protein, carbohydrate, lipid and ash content (Kavale *et al*., 2018). Table 1 presents the nutritional composition of the different Nori seaweed from the reviewed articles.

The nutritional analysis of *Porphyra, Pyropia,* and *Neopyropia* species revealed varied ash and carbohydrate content. Specifically, *Porphyra sp.* showed an ash content of 22.31 ± 0.38% DW (Arakaki *et al*., 2023; Paiva *et al*., 2014), *Porphyra dioica* 19.2 ± 0.01% DW (Ferreira *et al*., 2022), *Porphyra umbilicalis* 16.38 ± 0.93% DW (Freitas *et al*., 2022), *Neopyropia haitanensis* 12.25 ± 0.21 - 16.53 ± 0.66 (Liang *et al*., 2022) and *N. yezoensis* 12.2 ± 0.1 ± 0.15 - 15.38 ± 0.21 (Liang *et al*., 2022; Murayama *et al*., 2020). All analysed species exhibited lower ash content compared to the average reported for tropical seaweeds (41–45%, average 43%) (Ferreira *et al*., 2022; Neto *et al*., 2018; Tibbetts; Milley; Lall, 2016). The variations in ash content may be attributed to the collection season and location, with environmental conditions playing a crucial role. This highlights the potential for studying controlled cultivation conditions, such as multitrophic systems, to enhance mineral content. Notably, ash content referred to as fixed mineral residue represents inorganic minerals, contributing significantly to the nutritional value of mineral-rich foods (Redden *et al*., 2017).

Figure 1 - Nori species were studied between 2014 and 2024 for their nutraceutical potential. A. Representative images of the most studied species (*Porphyra dioica*, *P. tenera*, *P. umbilicalis*, *Pyropia columbina* and *Neopyropia yezoensis*) identified in the review. B. Registration of places of origin of macroalgae in studies on the nutritional potential of Nori algae from 2014 onwards

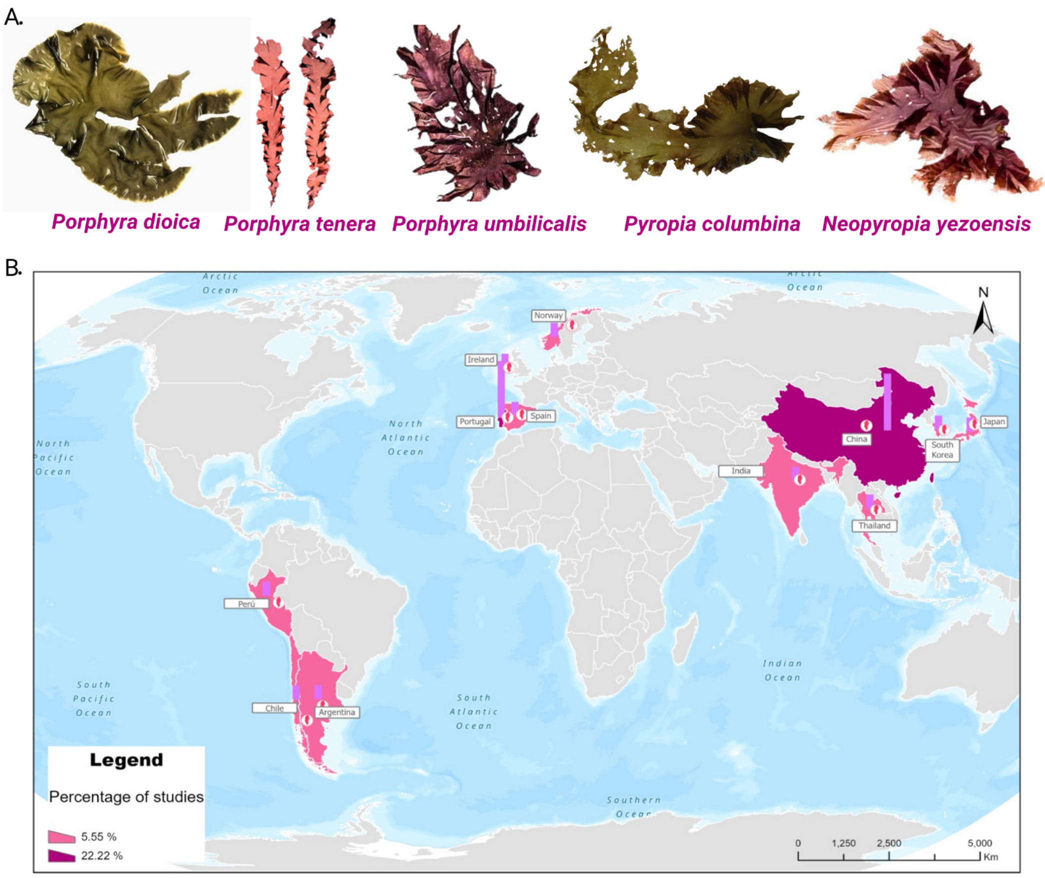


Table 1 - Nutritional composition of the different Nori seaweed (*Porphyra, Pyropia* and *Neopyropia*)

Specie	Content % Dry weight (DW)						
	Ash	Carbohydrate	Lipids	Proteine	Country	Source	Reference
P. dioica	19.2 ± 0.01	12.9 ± 0.20	1.92 ± 0.15	23.9 ± 0.23	Portugal	IMTA (commercial font)	FERREIRA *et al*. (2022)
P. dioica	NR	NR	NR	NR	Portugal	IMTA (commercial font)	COSTA *et al*. (2018)
P. dioica	NR	57.48 ± 1.76	NR	4.79 ± 0.08	Ireland	Natural bank	STACK *et al*. (2017)
Porphyra sp.	NR	NR	NR	39.7	Norway	Natural bank	GAILLARD *et al*. (2018)
Porphyra sp.	NR	NR	NR	NR	South Korea	Natural bank	YANG *et al*. (2020)
Porphyra sp.	22.31 ± 0.38	17.59 ± 0.27	8.88 ± 0.05	9.71–24.82	Portugal	Natural bank	PAIVA *et al*. (2014)
Porphyra sp.	8.49 ± 0.08	58.74 ± 0.73	0.73 ± 0.05	27.40 ± 0.69	Peru	Natural bank	ARAKAKI *et al*. (2023)
P. tenera	NR	NR	NR	2.9	Spain	Natural bank (commercial font)	AINSA *et al*. (2022)
P. tenera	NR	NR	0.36 ± 0.11	28.61 ± 1.38	Thailand	Commercial font	BRASPAIBOON *et al*. (2022)
P. umbilicalis	16.38 ± 0.93	31.89	0.75	18.27 ± 0.19	Portugal	Natural bank	FREITAS *et al*. (2022)
P. columbina	10.0 ± 3.3	ND	ND	8.33 ± 1.6	Argentina	Natural bank	MONZÓN *et al*. (2022)
P. columbina	NR	NR	NR	NR	Chile	Natural bank	ASTORGA-ESPAÑA *et al*. (2017)
Pyropia haitanensis	NR	NR	NR	36.6 (Red-brown strain) and 39.8 (green strain)	China	Natural Bank	XU *et al*. (2020)
Pyropia sp.	9.07 ± 0.10	62.70 ± 0.58	0.87 ± 0.11	28.91 ± 1.15	Peru	Natural bank	ARAKAKI *et al*. (2023)
P. vietnamensis	7.4 ± 0.8	60.36 ± 0.94	2.7±0.1	20.5 ± 0.35	India	Natural Bank	KAVALE *et al*. (2018)
N. haitanensis	16.53 ± 0.66	22.40 ± 0.65	0.66 ± 0.02	30.50 ± 0.20	China	Offshore cultivation	LIANG *et al*. (2022)
N. yezoensis	15.38 ± 0.21	28.47 ± 1.03	0.74 ± 0.03	41.38 ± 0.04	China	Offshore cultivation	LIANG *et al*. (2022)
N. yezoensis	12.2 ± 0.1 (High quality) and 2.5 ± 2.0 (Low quality)	NR	NR	54.0 ± 2.2 (High quality) and, 24.8 ± 5.2 (Low quality)	Japan	Natural bank (commercial font)	MURAYAMA *et al*. (2020)
N. yezoensis	NR	NR	NR	17.5 - 47.5	China	Offshore cultivation	HUANG *et al*. (2023)

The gathered information refers to the highest values reported when the study cited the same parameter for the same species, albeit at different times or at different collection locations

The highest carbohydrate content was observed in *Pyropia sp.* 62.70 ± 0.58% DW (Arakaki *et al*., 2023), P. *vietnamensis* 60.36 ± 0.94% DW (Kavale *et al*., 2018) and *Porphyra sp.* 58.74 ± 0.73% DW (Arakaki *et al*., 2023; Paiva *et al*., 2014). Arakaki *et al.* (2023), noted that red macroalgae from the Bangiales (59.85%) and Gigartinales (58.73%) orders had higher median carbohydrate content compared to other orders (50.23% to 53.87%), confirming their exceptional carbohydrate levels. This high carbohydrate content in red algae is linked to the production of polysaccharides such as agar and carrageenans, which are widely utilized in food products as thickeners, gelling agents, and emulsion stabilizers, as well as for their biological activities (Tiwari; Troy, 2015).

Regarding fiber content, the species *Porphyra tenera* presented a content of 4.52 ± 0.28g.100g^{-1} (Braspaiboon *et al*., 2022). The effect of incorporating *P. tenera* into pasta increased the soluble fiber content by 0.92% compared to the control, improving the nutritional profile (Ainsa *et al*., 2022). Previous studies have shown a fiber content of 6.8% DW for this same species (Burtin, 2003; Zaragozano; Asín, 2019). Adding *Pyropia columbina* seaweed powder at 6.0% concentration in gluten-free pasta formulation increased total dietary fiber by 50% and ash content by 150%, while maintaining the quality characteristics required for consumer acceptance (Monzón *et al*., 2022). The fiber content ranged from 1.3 ± 0.4 to 18.9 ± 0.3% when a powder blend of three algae including the *P. columbina* species were used as ingredients in food such as bread, hamburgers, fettuccine, huiro fritters, huiro breadsticks, and luche-parsley pesto (Astorga-España *et al*., 2017). Red algae, in particular, are known for their high concentration of dietary fiber and polyphenols, which contribute to their moderate digestibility.

One of the most commonly requested chemical analyses in food composition is the determination of protein content. Protein is a fundamental nutrient that is essential for life due to its crucial function in the body (Braspaiboon *et al*., 2022). Higher protein levels were recorded or the species *N. yezoensis* (54.0 ± 2.2% DW) (Murayama *et al*., 2020), *N. haitanensis* (30.50 ± 0.20% DW) (Liang *et al*., 2022), *Porphyra dioica* (23.9 ± 0.23% DW) (Ferreira *et al*., 2022) and *Porphyra tenera* (28.61 ± 1.38% DW) (Braspaiboon *et al*., 2022). Murayama *et al*. (2020) investigated the appropriate fermentation conditions to enhance the active flavor components of Nori when mixed with Nori koji. They demonstrated a clear increase in protein content (free amino acid content) of Nori and a modification in the taste score by aging the culture with Nori koji. The data of the studied species fall within the protein content range of some previously recorded values ranges for algae (33% to 47%) (Braspaiboon *et al*., 2022), which is higher than the average vegetable protein.

The literature indicates that red algae possess significant amounts of protein that can be fulfill essential amino acid (EAA) and non-essential amino acids (NEAA), thus enabling their use in food to diversify the protein source in the human diet (Arakaki *et al*., 2023). The highest levels of total amino acids (TAA) were recorded for the species *P. tenera* 1000 mg. g^{-1}. In the composition of EAA, the following stand out; Isoleucine (89.80 mg. g^{-1}), leucine (127.47 mg. g^{-1}) and lysine (141.11 mg. g^{-1}). For NEAA, the highest recorded contents of amino acids were tyrosine (97.60 mg. g^{-1}), glutamic acid (78.92 mg. g^{-1}), aspartic acid (54.48 mg. g^{-1}) and alanine (73.14 mg. g^{-1}) **(**Braspaiboon *et al*., 2022).

The *Porphyra* spp. showed a TAA content of 466.5 mg. g^{-1} of TAA. The highest average concentrations of amino acids were recorded for arginine (14.2 ± 1.0 mg. g^{-1}) and leucine (18.9 ± 1.3 mg. g^{-1}) (Arakaki *et al*., 2023). The species *Pyropia spp.* presented a TAA content of 454.6 mg. g^{-1}. Among the EAA, leucine (20.9 mg. g^{-1}), valine (18.9 mg. g^{-1}), threonine (17.0 mg. g^{-1}) stands out. For NEAA, alanine (37.5 mg. g^{-1}), glutamic acid (35.7 mg. g^{-1}) and aspartic acid (31.3 mg. g^{-1}) were prominent (Arakaki *et al*., 2023). The are similar to those reported for Nori species, including *Porphyra acanthophora*, *Porphyra columbina*, *Porphyra dioica*, *Porphyra purpurea*, and *Pyropia umbilicalis* (Arakaki *et al*., 2023; Dawczynski; Schubert; Jahreis, 2007; Lourenço *et al*., 2002; Nisizawa *et al*., 1987).

The seaweeds in this study are rich in glutamic and aspartic acids. These acidic amino acids, responsible for the typical umami taste of the seaweeds, together reach up to 23% of total amino acids in red algae. Both tissue nitrogen and the amino acid composition of seaweeds can be influenced by the nitrogen content of the environment, resulting in high individual variations (Biancarosa *et al.*, 2017). Therefore, studying and improving natural and cultivation conditions to obtain a balanced amino acid profile is important, as a balanced profile of EAA defines (in part) the quality of a protein.

Lipids, a class of organic biomolecules, play a fundamental role in human physiology by serving as a concentrated source of energy, providing structural components for cell membranes, and acting as precursors to important biochemical mediators (Santos *et al.*, 2023). Balanced intake of lipids, in appropriate quantities and in combination with other essential nutrients such as vitamins, carbohydrates, proteins, and minerals, is crucial to ensure optimal body function.

The lipid profile of seaweed varies significantly among different species, requiring specific evaluation to understand their potential for industrial application, whether as food ingredients or dietary supplements. Factors such as geolocation and exposure to different abiotic (e.g., temperature, salinity, pH, wave exposure, light, nutrient availability) and biotic factors (e.g., herbivory) can result in different biochemical profiles within the same species. Changes in fatty acid profiles, in particular, are of notable interest from a human nutritional perspective (Shin *et al.*, 2013). Seaweed lipids are regarded as a source of valuable compounds for both food and pharmaceutical products, and have been extensively studied worldwide (Costa *et al.*, 2018). In the species monitored in this study, lipid content ranged from 0.2 – 0.75% DW.

Table 2 - Amino acids content of Nori species (*Porphyra*, *Pyropya*, and *Neophyropia*)

Genus	Specie	EAA (mg. g^{-1})	NEAA (mg. g^{-1})	TAA (mg. g^{-1})	Reference
Por	Porphyra sp.	51.0	33.1	84.1	GAILLARD *et al*. (2018)
	Porphyra spp.	466.5	NR	466.5	ARAKAKI *et al*. (2023)
	P. tenera	588.73	411.27	1000	BRASPAIBOON *et al*. (2022)
Pyr	Pyropia spp.	454.6	NR	454.6	ARAKAKI *et al*. (2023)
	P. haitanensis	75.78 ± 5.14 (Red-brown strain) and - 78.35 ± 5.43 (green strain)	152.39 ± 11.44 (Red-brown strain) and, 243.32 ± 11.33 (green strain)	228.17 ± 16.58 (Red-brown strain) and, 321.67 ± 16.76 (green strain)	XU *et al*. (2020)
Neo	N. yezoensis	142.7	272.57	01.0 ± 0.1	LIANG *et al*. (2022)
	N. yezoensis	NR	NR	49.43 ±1.23 (Hight quality) and, 17.58 ±1.52 (Low quality)	MURAYAMA *et al*. (2020)
	N. haitanensis	79.3	203.2	282.5 ± 0.6	LIANG *et al*. (2022)

EAA: Essential Amino Acids (His: Histidine; Ile: Isoleucine; Leu: Leucine; Lys: Lysine; Met: Methionine; Phe: Phenylalanine; Thr: Threonine; Val: Valine). NEAA: Non-Essential Amino Acids (Ala: Alanine; Asp: Aspartic Acid; Cys: Cysteine; Glu: Glutamic Acid; Gly: Glycine; Pro: Proline; Ser: Serine; Tyr: Tyrosine). TAA: Total Amino Acids. The gathered information refers to the highest values reported when the study cited the same parameter for the same species, albeit at different times or at different collection locations

These species have been consistently characterized by high protein and low-fat content, as evidenced in previous studies (Liang *et al*., 2022; Nhui-Gen *et al*., 2020). However, *Porphyra* sp. Showed a notably high lipid content of 8.88 ± 0.05% DW (Paiva *et al.*, 2014). For this species, lipids content is higher in the winter and spring, and lower in summer with variation also influenced by geographical location and environmental conditions such as temperature, salinity, and nutrient content in the growth medium (Tiwari *et al.*, 2015). The lipidomic profile of two phases of the life cycle of the Atlantic species.

Porphyra dioica (early stage concorcelis produced in an indoor nursery, and young slides produced outdoors using an IMTA aquaculture framework) allowed to identify the presence of glycerolipids such as monogalactosyl diacyl-glycerol and digalactosyl diacylglycerol, and the acidic sulfolipids sulfoquinovosyl diacylglycerol and the sulfoquinovosyl monoacylglycerol (Costa *et al*., 2018). These compounds offer significant insights into the potential bioactive properties of lipid extracts derived from *P. dioica*, thereby enhancing the valorization of these seaweeds.

Fatty acids (FAs) are linked to potential health benefits and have various biotechnological applications, in addition to serving as food and feed ingredients. They have been widely bioprospected worldwide (Costa *et al*., 2018; Leal *et al*., 2013). The FAs are commonly found in Nori species and play important roles in the biology of living organisms (Santos *et al.*, 2023). Some studies have suggested that fatty acids from *Porphyra*, *Pyropya*, and *Neopyropya* species may have promising applications in both human and animal nutrition, as well as in industrial food production. Among the fatty acids identified in these species, notable ones include lauric acid, myristic acid, palmitic acid, linoleic acid, eicosapentaenoic acid and arachidonic acid, among others (Table 3).

The total content of saturated fatty acids (SFAs) was highest in *Pyropia vietnamensis* 60.92% (Kavale *et al.*, 2018), *Pyropia sp.* 54.32% (Arakaki *et al.*, 2023) e *Porphyra sp.* with 44.94% (Arakaki *et al.*, 2023). Despite the high SFAs content, ω6/ω3 ratio was found for *P. vietnamensis* was found to be within the recommended limit (i.e. <10) by the World Health Organization (WHO) (KAVALE *et al.*, 2018). In terms of, monounsaturated fatty acids (MUFAs - with one double bond), the highest levels were recorded in the *P. vietnamensis* (35.36%) (Kavale *et al.*, 2018), followed by 27.53% (Paiva *et al.*, 2014) and *Porphyra* sp. 26.50% (Arakaki *et al.*, 2023). At last, the content of polyunsaturated fatty acids (PUFAs - with two or up to six double bonds) was registered in high percentages for *Porphyra* sp. 59.83% (Paiva *et al.*, 2014), *Porphyra dioica* 57.86% (Costa *et al.*, 2018) and *Porphyra sp.* 48.30% (Arakaki *et al.*, 2023).

It is important to highlight that among these compounds, PUFAs are of particular interest to the scientific community as they are essential due to their inability to be synthesized by the human body (Misurcová *et al*., 2011; Rocha *et al*., 2021). Linoleic acid (ω6) was found in higher concentrations in *Neopyropya yezoensis* (19.56 ± 0.21 g/100 g), *Neopyropya haitanensis* (9.07 ± 0.19 g/100 g) (Liang *et al*., 2022), and *Pyropia vietnamensis* (5.33 ± 0.92 g/100 g) (Kavale *et al*., 2018). The compound α-linolenic acid fatty ω3 was present in concentrations below 1.0 g/100 g, however *Pyropia vietnamensis* showed 4.88 ± 0.71 g/100 g (Kavale *et al*., 2018).

In addition, *Pyropia vietnamensis* exhibited 14.56 ± 1.27% eicosadienoic acid (ω6) (Kavale *et al*., 2018). Arakaki *et al*. (2023) reported high levels of the PUFAs arachidonic acid (ω6) and eicosapentaenoic acid (EPA) in *Pyropia sp.* (29.46 ± 0.56 g/100 g and 46.46 ± 1.16 g/100 g, respectively) and *Porphyra sp.* (25.13 ± 0.20 g/100 g and 32.95 ± 0.28 g/100 g, respectively). Their study noted that arachidonic acid was found in high concentrations in both brown and red algae groups, including *Porphyra sp.* and *Pyropia sp.*, while EPA was primarily found in the red algae group. Dawczynski, Schubert and Jahreis (2007) determined the fatty acid (FA) distributions of several seaweed species, including *Porphyra* sp. which recorded a ratio of 20.9% DW. From this table it could be concluded that the fatty acid composition varies significantly between different species of Nori. However, *Porphyra, Pyropia* and *Neopyropia* have good levels of FA such as EPA, which may suggest its potential as a commercial supply of PUFAs, assuming that biomass can be harnessed as a valuable nutritional resource.

Bioproducts with nutraceutical value

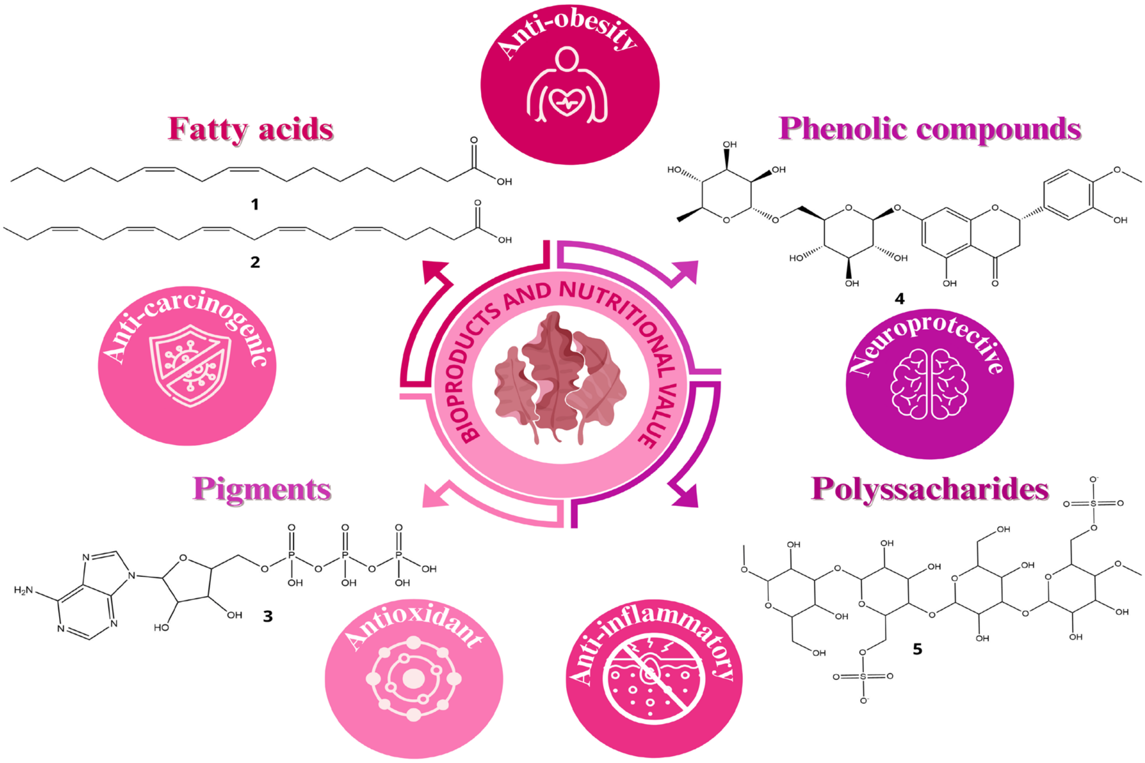
The chemical profile of Nori species reveals a significant nutraceutical potential warranting in-depth technical analysis. It is crucial to highlight the distinct chemical properties and characteristics of each bioproduct to justify exploration from both natural and cultivated sources, not only globally but also within the specific context of Brazil. A detailed approach to studying the nutraceutical properties, grounded in the actual chemical composition of these species, has the potential to drive commerce and impact within the food industry. This foodstuff presents ample potential for widespread exploration in the food industry. Concretely, *Porphyra*, *Pyropia* and *Neopyropia* species contain various biologically active compounds such as polysaccharides, pigments (phycobiliproteins), FA, and phenolic compounds that help add nutritional value to these species (Figure 2). These bioactive compounds show anti-inflammatory, antioxidant, and antitumor activities, among others (Bito; Watanabe, 2017).

Table 3 - Fatty acids profiles of Nori species (*Porphyra*, *Pyropya*, and *Neopyropya*)

Fatty Acid	Notation	Concentration						
Lauric Acid	C12:0	NR	NR	T	NR	6.54 ± 0.51	NR	NR
Tridecanoic Acid	C13:0	NR	NR	3.27 ± 0.26	NR	2.54 ± 0.67	NR	NR
Myristic Acid	C14:0	28.84 ± 0.83	0.71 ± 0.08	1.56 ± 0.12	3.24 ± 0.01	5.36 ± 0.47	1.88 ± 0.01	0.94 ± 0.01
Tetradecanoic Acid	C14:1	NR	NR	0.74 ± 0.06	NR	5.81 ± 3.66	NR	NR
Pentadecanoic Acid	C15:0	35.24 ± 0.13	NR	NR	NR	5.57 ± 0.88	NR	NR
Pentadecenoic Acid	C15:1	NR	NR	NR	NR	1.58 ± 0.18	NR	NR
Palmitic Acid	C16:0	784.7 ± 21.1	35.96 ± 0.05	47.41 ± 3.5	37.27 ± 0.80	23.40 ± 1.54	212.70 ± 4.84	180.62 ± 0.13
Hexadecanoic Acid (ω7)	C16:1	210.3 ± 5.06	0.97 ± 0.09	2.75 ± 0.22	18.82 ± 0.36	6.22 ± 1.40	1.45 ± 0.0	0.80 ± 0.0
Stearic Acid	C18:0	52.26 ± 8.0	1.29 ± 0.03	2.08 ± 0.16	3.72 ± 2.71	5.75 ± 2.33	8.30 ± 0.02	4.02 ± 0.05
Oleic Acid (ω9)	C18:1	366.1 ± 50.0	2.29 ± 0.05	8.65 ± 0.67	3.54 ± 0.09	13.65 ± 0.98	20.77 ± 0.24	9.90 ± 0.02
Linoleic Acid (ω6)	C18:2	171.6 ± 18.6	2.93 ± 0.10	T	3.56 ± 0.42	5.33 ± 0.92	19.56 ± 0.21	9.07 ± 0.19
α-Linolenic Acid (ω3)	C18:3	16.62 ± 0.05	0.30 ± 0.17	5.37 ± 0.43	0.47 ± 0.06	4.88 ± 0.71	0.38 ± 0	0.44 ± 0.01
Eicosadienoic Acid (ω6)	C20:2	30.56 ± 2.70	NR	T	NR	14.56 ± 1.27	4.34 ± 0.03	4.91 ± 0.07
Arachidonic Acid (ω6)	C20:4	751.0 ± 87.3	25.13 ± 0.20	1.34 ± 0.11	29.46 ± 0.56	11.93 ± 1.97	8.28 ± 0.06	4.29 ± 0.01
Eicosapentaenoic Acid (EPA)	C20:5	579.5 ± 96.4	32.95 ± 0.28	T	46.46 ± 1.16	NR	256.44 ± 2.48a	412.32 ± 1.61
Docosanoic Acid	C23:0	NR	NR	ND	NR	8.08 ± 0.45	NR	NR
Σ SFAs (%)	33.59	25.20	44.94	54.32 ± 2.53	60.92 ± 7.6	39.33	41.64	
Σ MUFAs (%)	10.83	26.50	27.53	17.31 ± 0.92	35.36 ± 6.76	NR	NR	
Σ PUFAs (%)	57.86	48.30	59.83	24.96 ± 1.33	46.28 ± 3.47	60.57	58.36	

a: Concentration in $g.100g^{-1}$. b: Concentration in $mg.kg^{-1}$. c: Concentration in % of methyl fatty acids esters. T: Compound identified in the trace. ND: Compound not detected. NR: Not Registered. Σ SFAs: Total saturated fatty acids. Σ MUFAs: Total monounsaturated fatty acids. Σ PUFAs: Total polyunsaturated fatty acids. The gathered information refers to the highest values reported when the study cited the same parameter for the same species, albeit at different times or at different collection locations

Figure 2 - Bioproducts class with nutritional value from Nori species and their biological properties. Fatty acids: eicosapentaenoic acid (1) and docosahexaenoic acid (2); Pigment: phycoerythrin (3); Phenolic compound: hesperidin (4); and Polysaccharide: Porphyran (5)



There is a growing need to diversify food sources to mitigate the overexploitation of terrestrial ecosystems, which has led to the exploration of marine resources, such as seaweed, as potential sources of fatty acids. Although seaweed generally contains a lower total lipid concentration compared to terrestrial sources, it is notable for its richness in essential unsaturated fatty acids, such as omega-3 and omega-6 fatty acids (Leandro *et al.*, 2020). On average, seaweed has a lipid productivity ranging from 0.61% to 4.15% of DW. However, some seaweed species may exceed these values, making them a potential source of unsaturated FA.

The Nori species are rich in PUFAs, of which 50% consists of EPA, along with omega-3 fatty acids, and docosahexaenoic acid (DHA), highly valued for their benefits to human health. Additionally, the content of omega-6 fatty acids, such as linoleic acid, plays an essential role in regulating the immune system and skin health. The FA content in Nori and its potential was discussed in the item "Nutraceutical potential" (Table 3).

Among functional ingredients identified from seaweed, *Pigments* such as chlorophylls, carotenoids and phycobiliproteins exhibit several beneficial biological activities like antioxidant, anti-carcinogenic, anti-inflammatory, anti-obesity, anti-angiogenic and neuroprotective (Cuellar-Bermudez *et al.*, 2015; Guedes; Amaro; Malcata, 2011). Chlorophylls are fat-soluble photosynthetic pigments produced by algae, higher plants and cyanobacteria (Ioannou; Roussis, 2009). Carotenoids are polyunsaturated hydrocarbons that increase the light-harvesting properties of algae and are considered accessory pigments (Lemoine; Schoefs, 2010). Similar to carotenoids, phytobiliproteins are intensely colored, water-soluble accessory pigments organized in supramolecular complexes produced by cyanobacteria and red algae (Rhodophyta) (Sekar; Chandramohan, 2007). Phycobiliproteins are used as food and have advantageous physical properties that make them suitable for applications in multiple industrial sectors (Guedes; Amaro; Malcata, 2011).

It is important to highlight that Nori species have a red color due to the presence of these pigments (Bito; Watanabe, 2017). *Porphyra umbilicalis* presented the higher concentrations of phycoerythrin, carotenoid and chlorophyll (1.88 µg. g^{-1} Fresh weight) (Freitas *et al.*, 2022). A study with the species *Pyropia haitanensis* demonstrated that high concentrations of nutrients significantly increased the average phycoerythrin (28–45 mg. g^{-1} DW) and phycocyanin (18–35 mg. g^{-1} DW) contents (Xu *et al.*, 2020). In summary, the study demonstrates that nutrient enrichment can enhance the market value of *P. haitanensis* via stimulating the synthesis of phycobiliproteins (Xu *et al.*, 2020).

The Porphyran (Polysaccharide) is a widely distributed sulfated anionic polymer in nature, exhibiting significant biological and pharmaceutical properties. Structurally, it consists of a linear chain of alternating β-D-galactosyl units with 3 linkages and units of 6-sulfate α-L-galactosyl with 4 linkages, or 3,6-anhydro-α-L-galactosyl units (Zhang *et al.*, 2004). Its composition contains 78.2% sugar, 49.5% galactose, 17.5% 3,6-anhydrogalactose, and 2.0% and 5.6% free and bound sulfur, respectively. While the ash and protein content are 9.1% and 0.9%, respectively (Bhatia *et al.*, 2008). More than 40% of the dry weight of *Porphyra* is composed of porphyran, a substance assessed for its potential nutritional and health benefits. Molecular weight, degree of sulfation, position of sulfate groups, type of sugar, and glycosidic branching are critical parameters influencing the activity of polysaccharides (Venkatraman; Mehta, 2019).

Studies have shown that the percentage of porphyran in bleached Nori (*Pyropia yezoensis*/*Neopyropia yezoensi*) is significantly higher than in normal Nori. Additionally, the composition of porphyran in bleached Nori differs, and it has a much lower molecular weight. The antioxidant activity of porphyran from bleached Nori was higher than that of porphyran from normal Nori in a dose-dependent manner. These findings suggest that porphyran is a potent antioxidant among naturally occurring substances in macroalgae and could be a valuable addition to antioxidant diets (Isaka *et al.*, 2015).

It is also important to highlight that porphyran exhibits hypocholesterolemic and hypolipidemic effects, primarily by reducing the cholesterol absorption in the intestine, which leads to an increase in fecal cholesterol content and a hypoglycemic response. Additionally, it reduces total cholesterol, free cholesterol, triglycerides, and phospholipids in the liver. These beneficial effects make porphyran a promising compound for nutraceutical companies, which may market it as a health supplement (Tsuge *et al.*, 2007).

The *Phenolic compounds* are a class of metabolites characterized by a hydroxyl group linked to an aromatic hydrocarbon group directly (Gomes *et al.*, 2022). There is a wide range of structurally different phenolic compounds that can range from simple phenols to complex polyphenolic structures, such as flavonoids (Besednova *et al.*, 2020). The importance of phenolic compounds in diets lies in their antioxidant, anti-inflammatory, and neuroprotective properties (Gomes *et al.*, 2022). They are known to help combat oxidative stress, reduce inflammation in the body, and protect against chronic diseases such as cardiovascular diseases, cancer, and neurodegenerative diseases (Jaganath; Crozier, 2010). Additionally, phenolic compounds may play a role in metabolism regulation, including reducing LDL cholesterol (Lutz *et al.*, 2019) and improving insulin sensitivity, which is beneficial for the prevention and management of metabolic diseases such as type 2 diabetes (Lin *et al.*, 2016).

Nori species have been reported to contain health-promoting phenolic compounds which are beneficial for human health (Xu *et al*., 2022). Phenolic compounds such as catechol, rutin and hesperidin were identified in the crude extract of *Porphyra dentata* (Kazlowska *et al*., 2010). Other studies registered the total phenolic content for extracts ranging from 10.81– 32.14 mg gallic acid equivalent (GAE). g^{-1} extract of *Porphyra tenera* (Hwang; Do Thi, 2014). The study by Ferreira *et al.* (2022), showed a total of phenolic compounds 4.47 ± 0.37 g. GAE kg^{-1} for *Porphyra dioica*.

Economic potential in Brazil

In recent years, there has been a growing interest in using seaweed as a food source, with the seaweed market in the Western Hemisphere experiencing an annual growth rate of 7 to 10% (Sultana *et al.*, 2023). In 2020, 36 million tons (wet weight) of seaweed were produced globally through aquaculture, primarily marine-based. China leads production with 62,8% of the total output, followed by Indonesia with 13,7%, the Philippines at around 10,6% and Korea (North and South) with 8% (FAO, 2022). Global trade in seaweed products reached US$5.6 billion in 2019 FAO (2022), and is projected to grow to US$ 22.13 billion by 2024, based on an annual growth rate of 8.9% (Cotas *et al*., 2020; Sultana *et al*., 2023). Only five genera accounted for more than 95% of cultivated algae, including *Porphyra*/*Pyropia* spp. with approximately 8,6%, according to FAO (Cai *et al.*, 2021). *Porphyra* species generally have the highest values, around 1.727 euros per fresh ton (FAO, 2018).

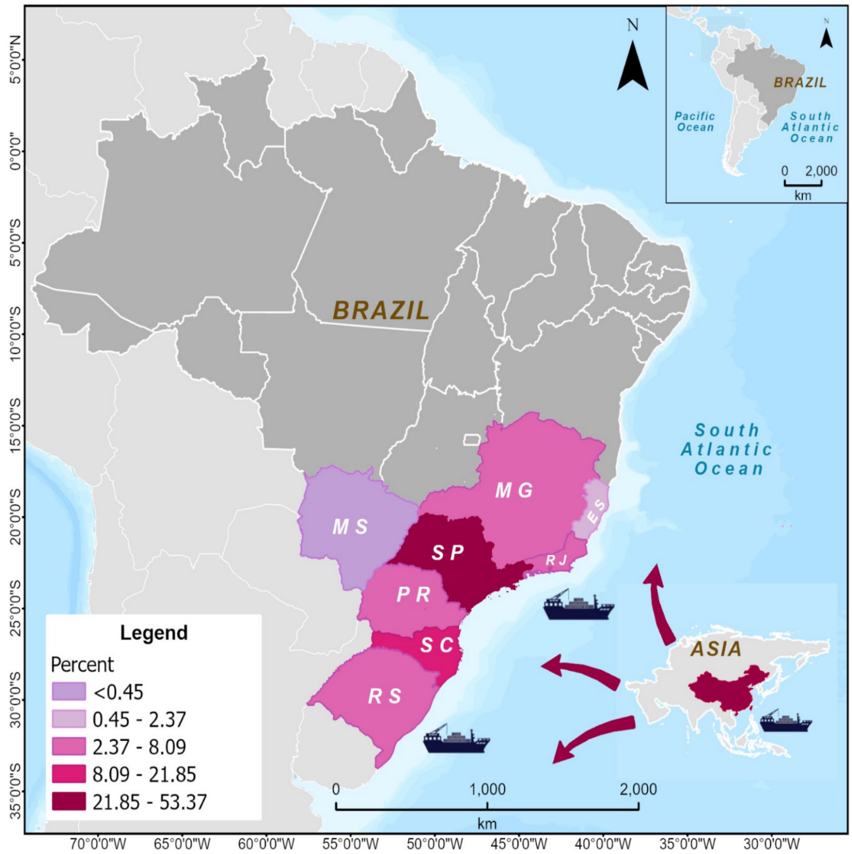
The global production of Nori is concentrated in China, followed by South Korea and Japan, and has remained steady at 1.2 tons annually for the past decade. This stagnation is due to the lack of suitable areas and the need for a large workforce in these countries (FAO, 2005, 2018). However, with the consumer market expanding 5% annually, there is an increasing demand for innovation and development in production practices. This overview shows the economic potential of Nori species and includes perspectives for their use for global food security (Leandro *et al.*, 2020).

Historically, the seaweed industry in Brazil has been based on the harvesting of natural seaweed beds (Simioni; Hayashi; Oliveira, 2019; Soriano *et al.*, 2016). This practice still persists in several coastal communities in northeastern Brazil, where species from *Gracilaria* and *Hypnea* genera are cultivated for agar and carrageenan (Andrade *et al.*, 2020; Sousa; Moura; Marinho-Soriano, 2012). However, in the 1990s, this activity declined due to the overexploitation of this resource. More sustainable practices, such as seaweed cultivation, have since supported the growth of algae production in Brazil (Soriano *et al.*, 2016). Promising results from projects cultivating of *Kappaphycus alvarezii* in southern and southeastern Brazilian states demonstrate the country's substantial potential as a seaweed biomass producer (Hayashi; Reis, 2012; Obando *et al.*, 2022; Pellizzari; Reis, 2011; Rudke; Andrade; Ferreira, 2020). Despite the growth in the algaculture sector, Brazil remains a net importer of seaweed, including varieties used in human consumption (such Nori, kombu, wakame) and their derivatives (Pellizzari; Reis, 2011; Soriano *et al.*, 2016). According to data from the consultation platform of the Ministério do Desenvolvimento, Indústria, Comércio e Serviços (MDIC), Brazil imported a high biomass of algae (around 616 t) for human consumption (including wakame, kombu and Nori) (BRASIL, 2024). Although not specified, it is believed that most of the imported are Nori products, given their widely used in Japanese cuisine in Brazil. The primary ports for these imports are located in the states of São Paulo (53.38%), Paraná (21.85%), and Santa Catarina (8.07%) (Figure 3). Additionally, the top exporters are in China (46.4%), South Korea (20.9%) and Singapore (14.7%).

In exploratory research on the commercialization of Nori seaweed sheets in the Brazilian market (Supplementary data), it was observed that a wide range of international brands offer Nori products for Japanese cuisine. These include well-known names such as Sukina®, Mac®, Fukumatsu®, Kenko (Sakura®), Yakisushinori®, Edomae®, Karui®, Manmaru®, Takaokaya, and Maki. However, it is important to note that only a few brands specify the particular species of algae in their product descriptions. Packaging sizes varies between 25 g to 140 g, offering various options for consumers. Most of these products originate from Asian countries, particularly China, which aligns with literature on the production of *Porphyra*, *Pyropia*, and *Neopyropia* seaweeds. We also registered products imported from South Korea, and Japan. Additionally, the price per kilogram varies considerably, ranging from R$ 310.00 to R$ 1328.00, indicating a high market value and suggesting significant potential for growth in this segment.

Regarding the cultivation of Nori species in Brazil, research has primarily been conducted at laboratory scale (Obando *et al*., 2022; Pereira *et al.*, 2020; Urrea-Victoria *et al.*, 2022). A recent cultivation laboratory study explored how nitrate content influences the growth rate, concentration of photosynthetic pigments, and concentration of secondary metabolites in *Pyropia var. brasiliensis* (Pereira *et al.*, 2020). Although studies have confirmed the presence of Nori

Figure 3 - Data on algae imports for human consumption in Brazil, highlighting the primary purchasing states. The figure was created using public data from the Ministério do Desenvolvimento, Indústria, Comércio e Serviços (Brazil, 2024)



species in Brazil (Milstein *et al.*, 2015), no attempts have been made to develop commercial cultivation of these species (Simioni; Hayashi; Oliveira, 2019). This highlights the potential for commercial exploitation of these algae in Brazil. Furthermore, cultivating Nori in Brazil has the potential to contribute to achieving Sustainable Development Goals (SDGs) 2 (Zero Hunger), 12 (sustainable production and consumption), and especially SDG 14 (Life Below Water) (Spillias *et al.*, 2022).

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CONCLUSION

In this review, we discuss comprehensive studies on the composition and nutritional properties of Nori species (*Porphyra, Pyropia,* and *Neopyropi*a). Nori algae are excellent sources of essential nutrients such as carbohydrates, lipids (including PUFAs), proteins, minerals and secondary metabolites with biological properties beneficial to human health. These attributes make Nori algae promising candidates as functional food ingredients, with applications extending in both human and animal nutrition, as well as in various industrial sectors. Furthermore, Nori algae have significant market potential, with large-scale cultivation already taking place worldwide. Continuous research aimed at further understanding and harnessing the nutritional benefits of Nori seaweed, along with studies focused on cultivating these resources in Brazil, could pave the way for its integration into a variety of food products. This would also create favorable conditions for expanding algaculture in the country. Given Brazil's rich biodiversity, it is well-positioned to strengthen its presence in the global Nori aquaculture sector, while contributing to

Brazilian food security in alignment with the United Nations Sustainable Development Goals goals (SDGs).

REFERENCES

AINSA, A. *et al*. Influence of seaweeds on the quality of pasta as a plant-based innovative food. **Foods**, v. 11, n. 16, p. 2525, 2022.

ANDRADE, H. *et al*. Seaweed production potential in the Brazilian Northeast: a study on the Eastern coast of the state of Rio Grande do Norte, RN, Brazil. **Sustainability**, v. 12, n. 3, p. 780, 2020.

ANDRADE, M. E. *et al*. Development and consumer acceptance of gluten-free pasta enriched with Pyropia columbina seaweed. Physical, textural and nutritional properties. **Revista Española de Nutrición Humana y Dietética**, v. 26, e1510, 2022. DOI:10.14306/renhida.26. S1.1510. Suplemento 1.

ARAKAKI, N. *et al*. Biochemical and nutritional characterization of edible seaweeds from the Peruvian coast. **Plants**, v. 12, n. 9, p. 1795, 2023.

ASTORGA-ESPAÑA, M. *et al.* Nutritional properties of dishes prepared with sub-Antarctic macroalgae: an opportunity for healthy eating. **Journal of Applied Phycology**, v. 29, p. 2399-2406, 2017.

BESEDNOVA, N. *et al*. Algae polyphenolic compounds and modern antibacterial strategies: current achievements and immediate prospects. **Biomedicines**, v. 8, n. 9, 2020.

BHATIA, S. *et al*. Novel algal polysaccharides from marine source: porphyran. **Pharmacognosy Reviews**, v. 2, n. 4, p. 271, 2008.

BIANCAROSA, I. *et al*. Amino acid composition, protein content, and nitrogen-to-protein conversion factors of 21 seaweed species from Norwegian waters. **Journal of Applied Phycology**, v. 29, p. 1001-1009, 2017.

BITO, T. T. F.; WATANABE, F. Bioactive compounds of edible purple laver *Porphyra* sp. (*Nori*). **Journal of Agricultural and Food Chemistry**, v. 65, n. 49, p. 10685-10692, 2017.

BRASIL. Ministério do Desenvolvimento, Indústria, Comércio e Serviços. **Estatísticas de comércio exterior do Brasil**. 2024. Disponível em: https://comexstat.mdic.gov.br/pt/home. Access at:19 mar. 2024.

BRASPAIBOON, S. *et al.* Ultrasound-assisted alkaline extraction of proteins in several algae and their nutritional characteristics. **International Journal of Food Science & Technology**, v. 57, n. 9, p. 6143-6154, 2022.

BURTIN, P. Nutritional value of seaweeds. **Electronic Journal of Environmental, Agricultural and Food Chemistry**, v. 2, n. 4, p. 498-503, 2003.

CAI, J. *et al*. **Seaweeds and microalgae**: an overview for unlocking their potential in global aquaculture development. Rome: FAO, 2021.

CAO, J. *et al*. *Porphyra* species: a mini-review of its pharmacological and nutritional properties. **Journal of Medicinal Food**, v. 19, n. 2, p. 111-119, 2016.

CHERRY, P. *et al*. Risks and benefits of consuming edible seaweeds. **Nutrition Reviews**, v. 77, n. 5, p. 307-329, 2019. DOI: 10.1093/nutrit/nuy066.

COSTA, E. *et al.* High-resolution lipidomics of the early life stages of the red seaweed *Porphyra dioica*. **Molecules**, v. 23, n. 1, p. 187, 2018.

COTAS, J. *et al.* Seaweed phenolics: rom extraction to applications. **Marine Drugs**, v. 18, n. 8, p. 384, 2020.

CUELLAR-BERMUDEZ, S. P. *et al*. Extraction and purification of high-value metabolites from microalgae: essential lipids, astaxanthin and phycobiliproteins. **Microbial Biotechnology**, v. 8, n. 2, p. 190-209, 2015.

DAWCZYNSKI, C.; SCHUBERT, R.; JAHREIS, G. Amino acids, fatty acids, and dietary fiber in edible seaweed products. **Food Chemistry**, v. 103, p. 891-899, 2007.

DUARTE, C. M.; BRUHN, A.; KRAUSE-JENSEN, D. A. Seaweed aquaculture imperative to meet global sustainability targets. **Nature Sustainability**, v. 5, n. 3, p. 185-193, 2022.

FAO. **Fishery statistics**: aquaculture production. Rome, 2005. Disponível em: https://www.fao.org/fishery/en/publication/70809. Access at: 19 mar. 2024.

FAO. The global status of seaweed production, trade and utilization. **Globefish Research Programme**, v. 124, 2018. Disponível em: https://www.fao.org/in-action/globefish/publications/details-publication/en/c/1154074/. Acesso em: 19 mar. 2024.

FERREIRA, M. *et al*. Potential of red, green and brown seaweeds as substrates for solid state fermentation to increase their nutritional value and to produce enzymes. **Foods**, v. 11, n. 23, e3864, 2022. DOI: https://doi.org/10.3390/foods11233864.

FREITAS, M. V. *et al.* Primary composition and pigments of 11 red seaweed species from the center of Portugal. **Journal of Marine Science and Engineering**, v. 10, n. 1168, p. 1-23, 2022.

GAILLARD, C. *et al*. Amino acid profiles of nine seaweed species and their in situ degradability in dairy cows. **Animal Feed Science and Technology**, v. 241, p. 210-222, 2018.

GARCÍA-CASAL, M. N. *et al*. High iron content and bioavailability in humans from four species of marine algae. **The Journal of Nutrition**, v. 137, n. 12, p. 2691-2695, 2007.

GOMES, L. *et al.* Seaweeds' pigments and phenolic compounds with antimicrobial potential. **Biomolecular Concepts**, v. 13, n. 1, p. 89-102, 2022.

GUEDES, A. C.; AMARO, H. M.; MALCATA, F. X. Microalgae as sources of carotenoids. **Marine Drugs**, v. 9, p. 625-644, 2011.

HAYASHI, L.; REIS, P. Cultivation of the red algae *Kappaphycus alvarezii* in Brazil and its pharmacological potential. **Revista Brasileira de Farmacognosia**, v. 22, p. 748-752, 2012.

HUANG, D. *et al*. Analysis of environmental factors affecting the quality of *Neopyropia yezoensis* cultivated in the Yellow Sea. **Journal of Marine Science and Engineering,** v. 11, p. 428, 2023. Disponível em: https://doi.org/10.3390/jmse11020428. Acesso em: 29 out. 2024.

HWANG, E. S.; DO THI, N. Effects of extraction and processing methods on antioxidant compound contents and radical scavenging activities of laver (*Porphyra tenera*). **Preventive Nutrition and Food Science**, v. 19, n. 1, p. 40, 2014.

IOANNOU, E.; ROUSSIS, V. Natural products from seaweeds. *In*: OSBOURN, A. E.; LANZOTTI, V. (ed.). **Plant-derived natural products**. New York, USA: Springer US, p. 51-81, 2009.

ISAKA, S. *et al*. Antioxidant and anti-inflammatory activities of porphyran isolated from discolored *Nori* (*Porphyra yezoensis*). **International Journal of Biological Macromolecules**, v. 74, p. 68-75, 2015.

JAGANATH, I. B.; CROZIER, A. Dietary flavonoids and phenolic compounds. *In*: FRAGA, C. G. **Plant phenolics and human health**: biochemistry, nutrition, and pharmacology. [*S. l.*]: John Wiley & Sons, p. 1-50, 2010.

KAVALE, M. G. *et al.* Food value of *Pyropia vietnamensis* (Bangiales, Rhodophyta) from India. **Indian Journal of Geo-Marine Sciences**, v. 47, p. 402-408, 2018.

KAZLOWSKA, K. *et al.* Anti-inflammatory properties of phenolic compounds and crude extract from Porphyra dentata. **Journal of Ethnopharmacology**, v. 128, n. 1, p. 123-130, 2010.

LEAL, M. C. *et al*. Biogeography and biodiscovery hotspots of macroalgal marine natural products. **Natural Product Reports**, v. 30, n. 11, p. 1380-1390, 2013.

LEANDRO, A. *et al*. Compostos bioativos de algas candidatos para a indústria de alimentos e a segurança alimentar global. **Research, Society and Development**, v. 9, n. 10, e3469108094, 2020.

LEMOINE, Y.; SCHOEFS, B. Secondary ketocarotenoid astaxanthin biosynthesis in algae: a multifunctional response to stress. **Photosynthesis Research**, v. 106, p. 155-177, 2010.

LIANG, Z. *et al.* The influence of ecological factors on the contents of nutritional components and minerals in laver based on open sea culture system. **Journal of Marine Science and Engineering**, v. 10, n. 7, e864, 2022. DOI: https://doi.org/10.3390/jmse10070864.

LIN, D. *et al.* An overview of plant phenolic compounds and their importance in human nutrition and management of type 2 diabetes. **Molecules**, v. 21, n. 10, p. 1374, 2016.

LOURENÇO, S. O. *et al.* Amino acid composition, protein content and calculation of nitrogen-to-protein conversion factors for 19 tropical seaweeds. **Phycological Research**, v. 50, p. 233-241, 2002.

LUTZ, M. *et al.* Roles of phenolic compounds in the reduction of risk factors of cardiovascular diseases. **Molecules**, v. 24, n. 2, p. 366, 2019.

MCHUGH, D. J. **A guide to seaweed industry**. Rome: FAO, 2003.

MILSTEIN, D. *et al*. Native or introduced? A re-evaluation of *Pyropia* species (Bangiales, Rhodophyta) from Brazil based on molecular analyses. **Journal of Phycology**, p. 37-45, 2015. DOI: 10.1080/09670262.2014.982202.

MILSTEIN, D.; OLIVEIRA, M. C. de. Molecular phylogeny of Bangiales (Rhodophyta) based on small subunit rDNA sequencing: emphasis on Brazilian *Porphyra* species. **Phycologia**, v. 44, n. 2, p. 212-222, 2005.

MISURCOVÁ, L. *et al.* Seaweed lipids as nutraceuticals. **Advances in Food and Nutrition Research**, v. 64, p. 339-355, 2011.

MURAYAMA, F. *et al*. Preparation of nori *Pyropia yezoensis* enriched with free amino acids by aging the culture with nori koji. **Chemistry and Biochemistry**, **Fisheries Science**, v. 86, p. 531-542, 2020.

NETO, R. T. *et al.* Screening of *Ulva rigida*, *Gracilaria* sp., *Fucus vesiculosus* and *Saccharina latissima* as functional ingredients. **International Journal of Molecular Sciences**, v. 19, p. 2987, 2018.

NHUI-GEN, Li *et al*. Analysis of nutrient composition and heavy metal content of *Porphyra haitanensis* in different sea areas of Fujian Province. **Journal of Fisheries Research**, v. 42, n. 5, p. 453-462, 2020.

NISIZAWA, K. *et al*. The main seaweed foods in Japan. **Hydrobiologia**, v. 151/152, p. 5-29, 1987.

OBANDO, J. M. C. *et al*. Current and promising applications of seaweed culture in laboratory conditions. **Aquaculture**, v. 560, p. 596-738, 2022.

PAIVA, L. *et al.* Edible Azorean macroalgae as source of rich nutrients with impact on human health. **Food Chemistry**, v. 164, p. 128-135, 2014.

PELLIZZARI, F.; REIS, R. P. Seaweed cultivation on the southern and southeastern Brazilian coast. **Revista Brasileira de Farmacognosia**, v. 21, n. 2, p. 305-312, 2011.

PEREIRA, D. T. *et al*. Effects of high nitrate concentrations on the germination of carpospores of the red seaweed *Pyropia acanthophora* var. *brasiliensis* (Rhodophyta, Bangiales). **Hidrobiologia**, v. 847, n. 1, p. 217-228, 2020.

REDDEN, H. *et al.* Changes in higher heating value and ash content of seaweed during ensiling. **Journal of Applied Phycology**, v. 29, p. 1037-1046, 2017.

ROCHA, P. *et al.* Seaweeds as valuable sources of essential fatty acids for human nutrition. **International Journal of Environmental Research and Public Health**, v. 18, n. 9, p. 4968, 2021.

RUDKE, A. R.; ANDRADE, C. J.; FERREIRA, S. R. S. *Kappaphycus alvarezii* macroalgae: an unexplored and valuable biomass for green biorefinery conversion. **Trends in Food Science & Technology**, v. 103, p. 214-224, 2020.

SANTOS, T. C. *et al.* Metabólitos bioativos e aplicações biotecnológicas de macroalgas do gênero *Sargassum*: uma revisão. **Revista Virtual de Química**, v. 15, n. 4, p. 741-758, 2023.

SEKAR, S.; CHANDRAMOHAN, M. Phycobiliproteins as a commodity: trends in applied research, patents and commercialization. **Journal of Applied Phycology**, v. 20, p. 113-136, 2007.

SHIN, D. M. *et al.* Seasonal variation in the dietary fiber, amino acid and fatty acid contents of *Porphyra yezoensis.*

Korean Journal of Fisheries and Aquatic Sciences, v. 46, n. 4, p. 337-342, 2013.

SIMIONI, C.; HAYASHI, L.; OLIVEIRA, M. C. Seaweed resources of Brazil: what has changed in 20 years? **Botanica Marina**, v. 62, n. 5, p. 433-441, 2019.

SORIANO, J. *et al.* Growth, development, yield and harvest index of two diverse rice cultivars in different water regimes and soil textures. **International Journal of Agronomy and Agricultural Research (IJAAR)**, v. 8, n. 2, p. 82-94, 2016. Disponível em: https://www.researchgate.net/publication/317427152. Acesso em: 11 set. 2024.

SOUSA, F. E. S. de; MOURA, E. A.; MARINHO-SORIANO, E. Use of geographic information systems (GIS) to identify adequate sites for cultivation of the seaweed *Gracilaria birdiae* in Rio Grande do Norte, Northeastern Brazil. **Revista Brasileira de Farmacognosia**, v. 22, p. 868-873, 2012.

SPILLIAS, S. *et al*. Expert perceptions of seaweed farming for sustainable development. **Journal of Cleaner Production**, v. 368, e133052, 2022.

STACK, J. *et al*. Seasonal variation in nitrogenous components and bioactivity of protein hydrolysates from *Porphyra dioica*. **Journal of Applied Phycology**, v. 29, p. 2439–2450, 2017. Disponível em: https://doi.org/10.1007/s10811-017-1063-0. Acesso em: 29 out. 2024.

SULTANA, F. *et al.* Seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment: a review. **Aquaculture and Fisheries**, v. 8, n. 5, p. 463-480, 2023.

TIBBETTS, S. M.; MILLEY, J. E.; LALL, S. P. Nutritional quality of some wild and cultivated seaweeds: Nutrient composition, total phenolic content and in vitro digestibility. **Journal of Applied Phycology**, v. 28, n. 6, p. 3575-3585, 2016.

TIWARI, B. K.; TROY, D. J. **Seaweed sustainability: food and nonfood applications**. [*S. l.*]: Academic Press, p. 1-6, 2015.

TRINDADE, S. S. *et al*. **Prospecção de compostos bioativos nas macroalgas *Bifurcaria bifurcata*, *Cystoseira tamariscifolia* e *Sargassum muticum***. Dissertação (Mestrado em Bioquímica) – Universidade de Aveiro, 2016.

TSUGE, K. *et al*. Dietary effects of porphyran from *Porphyra yezoensis* on growth and lipid metabolism of Sprague-Dawley rats. **Food Science and Technology Research**, v. 10, n. 2, p. 147-151, 2007.

URREA-VICTORIA, V. *et al*. Antioxidant potential of two Brazilian seaweeds in response to temperature: *Pyropia spiralis* (red seaweed) and *Sargassum stenophyllum* (brown seaweed). **Journal of Experimental Marine Biology and Ecology**, v. 549, p. 151-706, 2022.

VENKATRAMAN, K. L.; MEHTA, A. Health benefits and pharmacological effects of *Porphyra* species. **Plant Foods for Human Nutrition**, v. 74, p. 10-17, 2019.

XU, L. *et al*. Physiological responses of *Sargassum fusiforme* seedlings to high-temperature stress. **Regional Studies in Marine Science**, v. 62, 2022.

XU, N. *et al*. Nutrient enrichment improves growth and food quality of two strains of the economic seaweed *Pyropia haitanensis*. **Frontiers in Marine Science**, seção Aquatic Physiology, v. 7, 2020. Disponível em: https://doi.org/10.3389/fmars.2020.544582. Acesso em: 29 out. 2024.

YANG, L. *et al*. Redefining *Pyropia* (Bangiales, Rhodophyta): four new genera, resurrection of *Porphyrella* and description of *Calidia pseudolobata* sp. nov. from China. **Journal of Phycology**, v. 56, p. 862–879, 2020.

ZARAGOZANO, J. F.; ASÍN, J. F. Valoración nutricional y económica de la utilización de algas. **Revista Española de Estudios Agrosociales y Pesqueros**, v. 253, p. 37-64, 2019.

ZHANG, Q. *et al.* The structure of a sulfated galactan from *Porphyra haitanensis* and its in vivo antioxidant activity. **Carbohydrate Research**, v. 339, p. 105-111, 2004.

ZHONGZHONG, L.; JIANGUANG, L.; HUASHI, G. Progress on chemical constituents and biological activities of *Porphyra*. **Period Ocean University China**, v. 39, p. 47-51, 2009.