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Unlocking the potential of cultivated seaweeds *Ecklonia radiata* and *Cladophora* sp. for sustainable future foods: nutritional value, fatty acid profile, and microbial safety

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Abstract. Marine macroalgae are increasingly recognized as valuable resources to develop sustainable functional foods due to their diverse biochemical compositions. Their cultivation has become an important sector in global aquaculture that aims to provide sustainable sources of biomass and expand their potential applications. However, biomass obtained from many emerging farming operations requires thorough evaluation of its nutritional profile. This study evaluated the nutritional composition of *Ecklonia radiata* and *Cladophora* sp. cultivated in Australian farms and their potential use in future food applications. To ensure the traceability and consistency of raw materials, analyses were conducted on total carbohydrate and protein content, saturated and monounsaturated fatty acids, omega-3 (e.g., eicosapentaenoic acid) and omega-6 profiles, α- and β-carotene content, and complete amino acid profiles. Microbiological assessments (standard plate counts for anaerobes, coliforms, *Salmonella*, mesophilic spores, yeasts, and molds) and heavy metal screenings (Sb, As, Cd, Cu, Pb, Hg, Se, Sn, and Zn) were also conducted. Among the most notable results, *E. radiata* and *Cladophora* sp. exhibited low total fat content (1.56% and 1.8%, respectively). *Ecklonia radiata* was distinguished by its high carbohydrate content (62.48%) and essential amino acids, such as lysine (718.52 mg·100 g^{-1}), along with elevated omega-3 levels (especially eicosapentaenoic acid [9.3%]) and acceptable microbiological quality. Conversely, *Cladophora* sp. stood out for its high ash (60.9%), β-carotene (180 µg·100 g^{-1}), and arginine (750 mg·100 g^{-1}) content. However, its lower microbiological quality and elevated heavy metal levels suggest the need for caution when using it as a component in functional foods. The nutritional differences between these species suggest their complementary potential, opening important opportunities for the development of future functional food applications based on seaweeds.

Key words: algae, dietary supplements, food bioproducts, health-promoting nutrients, nutritional profiling.

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Introduction

Seaweed species are widespread across coastal regions worldwide, from tropical to temperate to polar areas (Sarkar et al. 2016). These species are considered the macroalgae of the millennium due to their social, economic, and environmental benefits (Sultana et al. 2023). Seaweeds have attracted increasing commercial interest due to their wide range of applications, including as biochemical raw materials (e.g., agar, alginate, and carrageenan) and in dyes, foods, enzymes, medicines, feed, fertilizers, cosmetics, textiles, and various biotechnological products. Much of their utility is due to their sophisticated metabolic machinery, which enables them to produce diverse primary and secondary metabolites with important biological functions (Jeeva et al. 2012).

Seaweed cultivation has become increasingly common in coastal communities as a source of subsistence income (Agyarko 2017). In 2022, global aquaculture production reached a historic record of 36.5 million t (wet weight) of algae (including seaweeds and microalgae), valued at US$17 billion, with an average annual growth rate of 5.8% (FAO 2024). Although the global production of algae has more than tripled in the last 20 years, it is still dominated (86%) by Asian countries, in particular China (58%) (FAO 2024). To meet future food demand, seaweed aquaculture must expand beyond Asia into high-potential regions. This expansion will create opportunities to diversify the sector through the cultivation of native and endemic species with strong commercial potential (Biancacci et al. 2022). Indeed, species occupying lower trophic levels, such as algae, constitute 17% of total aquaculture production and offer substantial opportunities to notably improve the sustainability of the global aquatic food supply (FAO 2024, Vijayaram et al. 2024).

Seaweed farming has been increasingly recognized as a sustainable practice given that it acts as a carbon sink, absorbing CO_2 from seawater and contributing to the mitigation of ocean acidification and the protection of marine ecosystems (Duarte et al. 2017, Kim and Kim 2024, Maulana and Rosariawari 2024) while also supporting large-scale climate change mitigation efforts (Yong et al. 2022). Seaweed aquaculture has great potential to remove N and P from coastal ecosystems, contributing to the reduction of eutrophication by removing excess nutrients from water bodies and improving water quality. However, its role in targeted nutrient assimilation has been little appreciated or explored (Racine et al. 2021). In addition, seaweed cultivation can help protect coastal areas by dampening wave energy and reducing physical damage from storms (Behera et al. 2022). Furthermore, offshore seaweed farms have the potential to complement terrestrial agriculture and play a notable role in enhancing the global food supply. Current models estimate that utilizing just 1% of suitable ocean space for seaweed farming could provide 2–14% of the global food supply (Van Oort et al. 2023).

Although global seaweed aquaculture has grown exponentially over the past 4 decades, Australia is struggling to overcome its reliance on wild harvesting to meet industrial demands (Steven et al. 2020). However, the country has favorable environmental and regulatory conditions (e.g., high water quality and an extensive coastline), as well as broad market potential in sectors such as food, feed, fertilizers, nutraceuticals, pharmaceuticals, and novel polymers. In particular, South Australia has been identified as one of the most promising regions globally for the sustainable development of this industry. Recent reports have estimated that the sector could reach US$75 million in gross production value and generate 1,200 direct jobs by 2025, with projections of over US$1 billion in gross production value and 9,000 jobs by 2040, especially in temperate coasts and offshore areas (Theuerkauf et al. 2019, Visch et al. 2023).

Recent studies on functional ingredients derived from seaweeds have highlighted brown seaweeds as an abundant source of nutraceuticals and diverse bioactive compounds (Alloyarova et al. 2024). Among the most prominent are sulfated polysaccharides (e.g., fucoidan), phenolic compounds (e.g., phlorotannins), and carotenoids (e.g., fucoxanthin). Additionally, brown seaweeds provide polyunsaturated fatty acids (PUFAs), including omega-3 fatty acids, as well as bioactive peptides (Holdt and Kraan 2011). These bioactives have been associated with a broad spectrum of biological activities, including antioxidant, anti-HIV, antifungal, anticancer, antidiabetic, antimicrobial, anticoagulant, antiviral, antitumor, anti-inflammatory, immunomodulatory, gastric protective, and cholesterol- and lipid-lowering effects (Charoensiddhi et al. 2015, Thuy et al. 2015, Admassu et al. 2018, Dos Santos et al. 2024a, b).

The Golden Kelp (*Ecklonia radiata*) is widely distributed in the Southern Hemisphere, occurring mainly on subtidal rocky reefs between 27°S and 48°S, and is considered the most abundant macroalga in Australian waters, contributing substantially to coastal biomass productivity (Steinberg and Kendrick 1999, Wernberg et al. 2019). Despite its ecological dominance, this species remains underexplored for higher-value applications, with most biomass still directed to low-value uses such as fertilizers and animal feed (Charoensiddhi et al. 2015). Studies have reported the presence of biomolecules of interest in *E. radiata*, including alginate, fucoidan, and phlorotannins (Lorbeer et al. 2017, Shrestha et al. 2021, Abdel-Latif et al. 2022), while recent advances in hatchery-based cultivation have stimulated interest in its sustainable aquaculture (Praeger et al. 2022).

In parallel, many species of the genus *Cladophora*, which comprises more than 183 macroscopic green algae species, are ecologically and economically important and exhibit high tolerance to variable environmental conditions (Hayakawa et al. 2012, Nutautaitė et al. 2021). These algae are characterized by their high content of carbohydrates, minerals, and proteins and have been investigated for applications in food, feed, fertilizers, and energy production, positioning *Cladophora* species as promising candidates for aquaculture and nutritional use (Srimaroeng et al. 2015, Lawton et al. 2017, Munir et al. 2019, Michalak and Messyasz 2021).

Considering the complete processing cycle of seaweeds, from cultivation to the final product, it is evident that the current increase in global seaweed production remains insufficient to meet the growing demand for biomass (Pai et al. 2025). This demand is driven by the wide range of both conventional and emerging applications in this rapidly expanding sector (Duarte et al. 2017). However, beyond production volume, a key challenge lies in the data on the nutritional composition and safety of cultivated seaweed biomass intended for food applications (Ali et al. 2025). In this context, the quality and specific characteristics of seaweed biomass, including its nutritional profile and microbiological and chemical safety, must be carefully evaluated.

In the present study, we selected 2 seaweed species that are widely recognized for their abundance and currently cultivated in Australia. Our aim was to map their nutritional profiles (i.e., total fat, saturated fat, ash, carbohydrates, energy, protein, α-carotene, and β-carotene), certain metabolic profiles (i.e., fatty acids and amino acids), microbiological safety, and heavy metal content. This work contributes to understanding and valorizing the cultivated *E. radiata* and *Cladophora* sp. and emphasizes their nutritional and functional potential. The results provide valuable early-stage insights into the composition and safety of *E. radiata* and *Cladophora* sp. and support their use in food products and bioproduct development.

MATERIALS AND METHODS

Algae sample

Ecklonia radiata dry biomass was acquired from Auskelp Pty Ltd (Wonboyn, Australia) as part of Eden 1 Project, which encompasses a 200-ha area dedicated to cultivating this species. This project represents the first commercial-scale seaweed farm in the coastal waters of New South Wales. The proposed lease site is located 23 km southwest of Eden, in Disaster Bay, bordered to the north by Greencape Lighthouse.

Cladophora sp. biomass was sourced from the Tassal Group (Hobart, Tasmania, Australia), the largest vertically integrated seafood producer in Australia, and collected from the Proserpine Farm (northern Queensland, Australia) on 7 October 2024, dehydrated, and vacuum-sealed. At Proserpine Farm, the seaweed was cultivated in 7 of 12 sedimentation tanks, which naturally improved water quality while producing a secondary commercial crop.

The *Cladophora* sp. biomass was dehydrated to reduce moisture content and enhance stability, vacuum sealed for storage, and rehydrated to a standardized moisture level prior to analysis. The samples were then vacuum sealed again to preserve integrity and ensure analytical reproducibility. To enable direct comparisons across species, the *E. radiata* values were converted from fresh weight to dry weight (DW) using a conversion factor. The moisture content of the *E. radiata* samples, which was determined by oven-drying at 60 °C until constant weight was achieved, was 87.2%, indicating that the biomass was predominantly water. This moisture content was used to calculate the fresh-to-dry weight conversion factor (7.81), which was applied in subsequent analyses. Figure 1 summarizes the sampling origin, cultivation sites, and the analytical workflow adopted for the compositional and safety assessment of *E. radiata* and *Cladophora* sp. biomass.

Biochemical and nutraceutical analyses

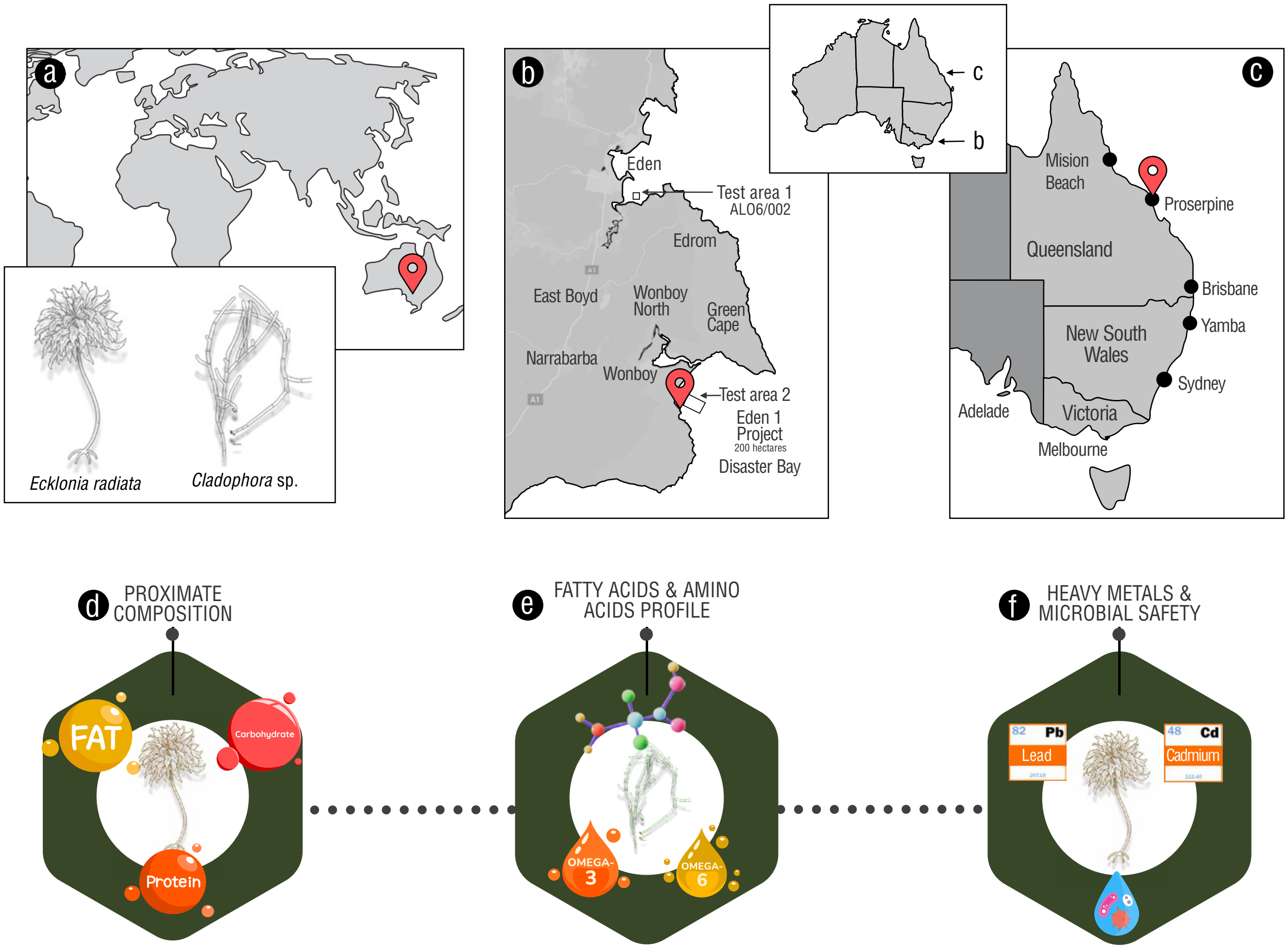
The biochemical and nutraceutical analyses of the seaweed biomass were conducted by the National Measurement Institute (NMI; Port Melbourne, Australia). The methods were certified by the National Association of Testing Authorities (NATA), Australia, and conducted under accreditation standards (ISO/IEC 17025). The samples were received by NMI in September 2024, assigned a unique NMI sample identification code, and prepared in accordance with in-house NMI protocols specific to each analytical procedure.

Proximate composition analysis

Moisture content was determined by the gravimetric method (in-house NMI method VL298), which quantifies water loss upon drying. Protein content was measured using the Kjeldahl nitrogen method (6.25×) (in-house NMI method VL299). Ash content was determined using the gravimetric method (in-house NMI method VL286), and carbohydrate and energy content were determined by energy calculation (Atwater factors) (in-house NMI method VL412). Fat content was determined using the Mojonnier extraction method (limit of detection $< 0.2 \cdot 100\ g^{-1}$) (in-house NMI method VL302).

Fatty acid and amino acid profiles

The fatty acid profile was determined by gas chromatography with flame ionization detection (GC-FID) (in-house NMI method VL289). Briefly, the seaweed samples were extracted using a methanol-chloroform mixture, followed by methylation with sodium methoxide. Fatty acid methyl esters were analyzed by GC-FID (7890A GC; Agilent, Santa Clara, USA), and fatty acids were identified by comparing their retention times with those of certified reference standards (Stone et al. 2022). Additionally, α- and β-carotene content were determined by the spectrophotometry (in-house NMI method VL292). The quantification of 18 amino acids (alanine, arginine, aspartic acid, glutamic acid, glycine, histidine, hydroxyproline, isoleucine, leucine, lysine, methionine, phenylalanine, proline, serine, taurine, threonine, tyrosine, and valine) was performed by hydrolyzing the samples in 6 M HCl, followed by ultra-performance liquid chromatography coupled with photodiode array detection and tandem mass spectrometry (UPLC-PDA-MS/MS) using amino acid standards (in-house NMI method VL450) (Stone et al. 2022, Camperio et al. 2025).



- Moisture: Gravimetric method (NMI method VL298)
- Fat: Mojonnier extraction method (NMI method VL302)
- Protein: Kjeldahl nitrogen method (6.25×) (NMI method VL299)
- Ash: Gravimetric method (NMI method VL286)
- Carbohydrates: Calculation method (NMI method VL412)
- Energy: Calculation method (NMI method VI412)

- Fatty acid profile: Gas chromatography with flame ionization detection (GC-FID) (NMI method VI289)
- α- and β-carotene content: Spectrophotometric method (NMI method VI292)
- Amino acid profile (18 types*): Ultra-performance liquid chromatography coupled with photodiode array detection and tandem mass spectrometry (UPLC-PDA-MS/MS) using amino acid standards (NMI method VL450)

- Heavy metals (Sb, As , Cd, Cu, Pb, Hg, Se, Sn, and Zn): Inductively coupled plasma-mass spectrometry (ICP-MS) (NMI method NT2-46)
- Total coliforms: Most probable number (MPN) (NMI method VM1.09C)
- Anaerobic bacteria (30 °C): Plate count (NMI method VM1.22A)
- Yeasts and molds: Plate count (NMI method VM1.28A)
- Mesophilic spores (30 °C): Plate count (NMI method VM1.22C)
- *Salmonella* spp.: Enzyme-linked fluorescent assay (ELFA) (NMI method VM1.20B)

Figure 1. Sample origin, analytical procedures, and compositional evaluations of *Ecklonia radiata* and *Cladophora* sp. Location of the cultivation farm and sample collection site in Australia under the Green Light Accelerator Program (**a**). *Ecklonia radiata* samples obtained from Eden Project 1 (test area 1 or 2) operated by Auskelp Pty Ltd (Wonboyn, Australia) (**b**). *Cladophora* sp. was collected from Proserpine Farm (Queensland, Australia), operated by Tassal Group (Hobart, Tasmania, Australia), on 7 October 2024 (**c**). Proximate composition analyses performed according to standardized methods of the National Measurement Institute (NMI; Port Melbourne, Australia), including moisture (%), fat (%), protein (%), ash (%), carbohydrates (% difference), and energy ($\text{kJ}\cdot 100\ \text{g}^{-1}$ or $\text{kcal}\cdot 100\ \text{g}^{-1}$) (**d**). Fatty acid (% of total fatty acids) and amino acid ($\text{mg}\cdot 100\ \text{g}$ dry weight $[\text{DW}]^{-1}$) profiles and carotenoid ($\mu\text{g}\cdot 100\ \text{g}^{-1}$) content obtained using standardized NMI methods (**e**). Heavy metals (Sb, As, Cd, Cu, Pb, Hg, Se, Sn, and Zn) ($\text{mg}\cdot\text{kg}^{-1}$ DW) were quantified using obtained using standardized NMI methods. The microbiological safety analysis assessed total coliforms, anaerobic bacteria, yeasts, molds, mesophilic spores, and *Salmonella* spp. (**f**). All analyses were performed following certified NMI laboratory standards, ensuring traceability and compliance with national testing authority requirements.

Analysis of heavy metals and microbial safety

The heavy metal analysis (Sb, As, Cd, Cu, Pb, Hg, Se, Sn, and Zn) was conducted by NMI using inductively coupled plasma-mass spectrometry (ICP-MS), according to the in-house NMI method NT2-46. Briefly, samples were homogenized and digested using nitric acid and hydrochloric acid. After digestion, the samples were diluted with Milli-Q water (Millipore, Burlington, USA) and further diluted as required prior to ICP-MS analysis (Taylor 2023). Microbial contaminants were assessed using the following methods. The total coliform count was obtained via the most probable number method (in-house NMI method VM1.09C); a standard plate count was performed to evaluate anaerobic bacteria at 30 °C (in-house NMI method VM1.22A); yeasts and molds were quantified on DRBC agar and reported as CFU·g^{-1} (in-house NMI method VM1.28A); the mesophilic spore count was performed at 30 °C (in-house NMI method VM1.22C). *Salmonella* spp. detection was conducted using the enzyme-linked fluorescent assay (ELFA) method (VM1.20B).

Table 1. Proximate composition (g·100 g^{-1} dry weight [DW]) and carotenoid content (µg·100 g^{-1}) of *Ecklonia radiata* and *Cladophora* sp. biomass.

Component	*Ecklonia radiata*	*Cladophora* sp.
Total fat	1.56	1.80
Saturated fat	0.78	0.90
Ash	27.34	60.90
Carbohydrates	62.48	20.00
Energy (kJ·100 g^{-1})	1,250.00	590.00
Proteins	10.16	11.10
β-carotene (µg 100 g^{-1})	<5.00	180.00
α-carotene (µg·100 g^{-1})	<5.00	<5.00

RESULTS

Nutritional composition

Ecklonia radiata and *Cladophora* sp. exhibited low levels of total fat (1.56% and 1.8%, respectively) and saturated fat (0.78% and 0.9%, respectively). Ash content was notably higher in *Cladophora* sp. (60.9%) than in *E. radiata* (27.34%). The carbohydrate fraction was higher in *E. radiata* (62.48%) than in *Cladophora* sp. (20%). In terms of bioactive compounds, *Cladophora* sp. stood out for its β-carotene content (180 µg·100 g^{-1}), which was absent in *E. radiata* (Table 1). Considering the sum of the remaining components (fat, ash, and carbohydrates), protein content was estimated to be 10–11% in both species.

Amino acid composition

Protein content was calculated to be 10.16% (DW) in *E. radiata* and 11.1% DW in *Cladophora* sp. After adjusting for DW, *E. radiata* contained 3,155 mg·100 g^{-1} DW of essential amino acids (EAAs), mainly lysine, threonine, and leucine, and 4,524 mg·100 g^{-1} DW of non-essential amino acids (NAAs), primarily glutamic acid, aspartic acid, and alanine. In comparison, the total content of EAAs and NAAs in *Cladophora* sp. was 3,555 mg·100 g^{-1} DW and 5,690 mg·100 g^{-1} DW, respectively, with arginine, lysine, and leucine identified as key EAAs and glutamic acid, aspartic acid, and alanine dominating the NAA profile (Fig. 2).

The analysis of the EAA and NAA composition in *E. radiata* and *Cladophora* sp. revealed distinct and complementary biochemical profiles. *Ecklonia radiata* contained higher levels of EAAs, such as lysine (718.52 mg·100 g^{-1} DW), leucine (554.51 mg·100 g^{-1} DW), and threonine (593.56 mg·100 g^{-1} DW), which are essential for protein synthesis, the maintenance of muscle and connective tissues, metabolic balance, and immune system support, giving the species a protein profile of high nutritional value (Wunderle et al. 2024). On the other hand, *Cladophora* sp. showed high arginine content (750 mg·100 g^{-1} DW), whereas this amino acid was not detectable in *E. radiata*. In addition, *Cladophora* sp. contained higher concentrations of the NAAs glutamic acid (1,800 mg·100 g^{-1} DW) and aspartic acid (1,300 mg·100 g^{-1} DW).

Fatty acid composition

The analysis of the fatty acid profile revealed that *E. radiata* had higher saturated fatty acid content (61%), which was mainly composed of butyric acid (C4:0, 37%), palmitic acid (C16:0, 14%), myristic acid (C14:0, 5%), stearic acid (C18:0, 3.5%), and arachidic acid (C20:0, 1.4%), than *Cladophora* sp. In contrast, *Cladophora* sp. contained 47% saturated fatty acids, which were dominated by palmitic acid (31%) and myristic acid (11%), with butyric acid (0.3%) and stearic acid (3.2%) present in smaller proportions. The monounsaturated fatty acid (MUFA) fraction in *E. radiata* accounted for 18% of all fatty acids and was mainly composed of oleic acid (C18:1, 12%) and palmitoleic acid (C16:1, 4%). *Cladophora* sp. presented higher MUFA content (28%) than *E. radiata*, with oleic acid (13%), vaccenic acid (C18:1 trans, 9.3%), and palmitoleic acid (5.4%) as the major components.

PUFAs accounted for 21% of fatty acids in *E. radiata*, with strong contributions from the omega-3 fatty acids eicosapentaenoic acid (EPA) (C20:5 ω-3, 9.3%) and stearidonic acid (C18:4 ω-3, 2.9%) and the omega-6 fatty acids linoleic acid (C18:2 ω-6, 3.1%), eicosadienoic acid (C20:2 ω-6, 2.8%), and docosadienoic acid (C22:2 ω-6, 3.2%). In *Cladophora* sp., PUFAs accounted for 24% of fatty acids, although with markedly lower EPA content (1%) than in *E. radiata*. Instead, linoleic (9.1%) and eicosadienoic (9.5%) acids were the predominant polyunsaturated components. Finally, *E. radiata* displayed a lipid profile highly enriched in omega-3 fatty acids (omega-3 [89%] vs. omega-6 [12%]), whereas the distribution between omega-3 (13%) and omega-6 (10%) fatty acids in *Cladophora* sp. was more balanced (Fig. 3).

Heavy metal levels and microbiological analysis

The analysis of trace elements revealed clear differences in bioaccumulation between *E. radiata* and *Cladophora* sp. (Table 2). *Cladophora* sp. showed extremely high Cd (63.0 mg·kg^{-1}), Cu (11.0 mg·kg^{-1}), and Zn (37.0 mg·kg^{-1}) levels compared to those in *E. radiata*. In contrast, *E. radiata* presented a markedly higher Pb concentration (32 mg·kg^{-1}) than that of *Cladophora* sp.

Microbiological quality differed considerably between the *E. radiata* and *Cladophora* sp. biomass. *Ecklonia radiata* showed lower microbial loads, with a standard plate count of 30 CFU·g^{-1} under anaerobic conditions, whereas the standard plate count of *Cladophora* sp. was 10,000 CFU·g^{-1}. The quantity of mesophilic spores was also lower in *E. radiata* (10 CFU·g^{-1}) than in *Cladophora* sp. (7,200 CFU·g^{-1}). Yeast and mold counts were <100 CFU·g^{-1} and 100 CFU·g^{-1} in *E. radiata*, respectively, whereas *Cladophora* sp. presented counts of 3,000 CFU·g^{-1} and 500 CFU·g^{-1}, respectively (Table 3). The biomass of both species tested negative for *Salmonella* (not detected) and coliforms, indicating compliance with basic safety standards. *Ecklonia radiata* presented better microbiological quality compared to that of *Cladophora* sp., with substantially lower counts of mesophilic spores, yeasts, molds, and anaerobic bacteria.

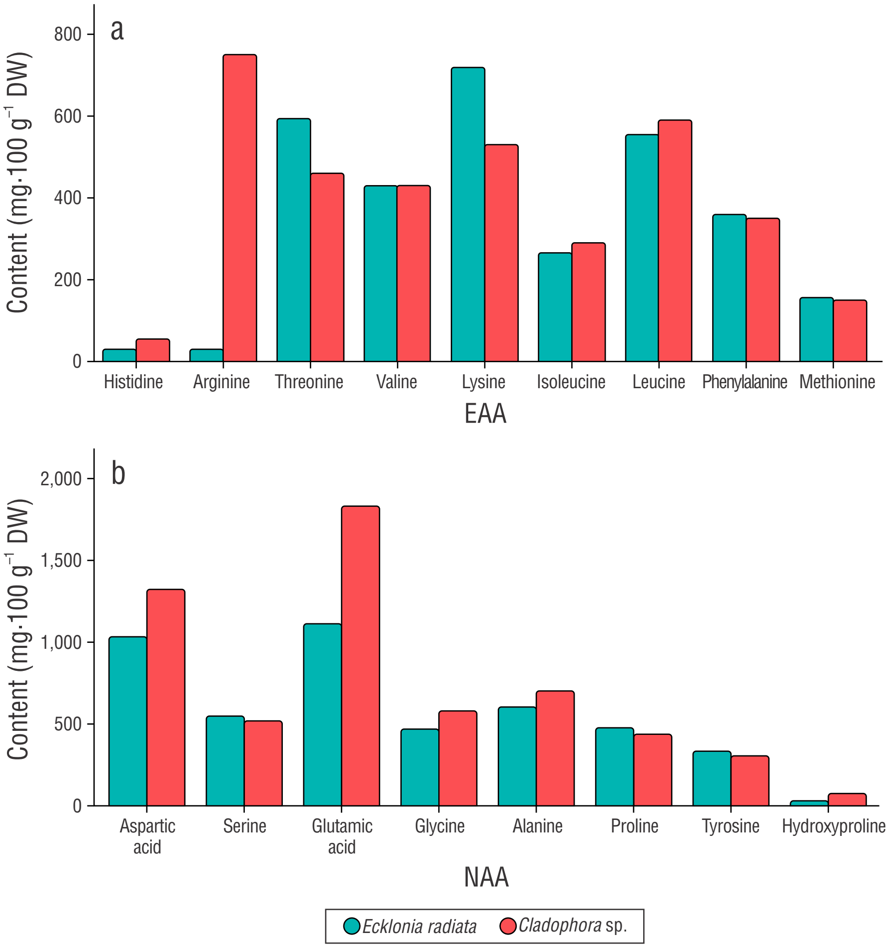


Figure 2. Amino acid profiles of *Ecklonia radiata* and *Cladophora* sp. Essential amino acids (EAA) (**a**); non-essential amino acids (NAA) (**b**). Values (mg·100 g^{-1} dry weight [DW]) correspond to analytical compositional determinations. Overall, both species exhibit diversified amino acid profiles, with higher levels of glutamic acid and aspartic acid among the NAAs, and lysine and leucine among the EAAs.

Discussion

Seaweeds have been recognized for their nutritional potential due to their diverse and species-specific biochemical compositions, which exhibit distinct profiles of proteins, carbohydrates, lipids, minerals, and bioactive compounds that determine their suitability for different food and functional applications (Marques et al. 2021). For example, Marques et al. (2021) evaluated commercial seaweed blends in Europe and reported protein contents ranging from 17.79% to 26.61% DW and carbohydrate contents between 39.47% and 47.37% DW. It is clear that seaweed blends can be excellent nutritional alternatives (Marques et al. 2021). Specifically, the protein content in *E. radiata* has been found to range from 5.6% to 7.6% DW (Nepper-Davidsen et al. 2023), while values have been found to range from 14.45% to 26.55% DW in *Cladophora* species (Messyasz et al. 2015). Our results fall within or close to these reported ranges, considering potential variations related to methodology, environmental factors, and seasonal dynamics. Although this study did not evaluate seaweed blends, nutritional potential was assessed at the species level to provide a general understanding of the specific nutritional profiles of *E. radiata* and *Cladophora* sp.

The results showed that *E. radiata* and *Cladophora* sp. exhibited complementary characteristics in terms of functional carbohydrate, amino acid, and lipid profiles. If the objective is to provide high levels of protein, then each species has a limited capacity when considered individually. However, a blend of *E. radiata* and *Cladophora* sp. could strategically balance nutritional properties. Accordingly, future research should assess blends of these species to determine whether their distinct nutritional attributes translate into a more balanced overall profile.

Both *E. radiata* and *Cladophora* sp. exhibited low total lipid content (<1.56% and 1.8% DW, respectively), which was slightly higher or within the range reported for commercial seaweed blends in Europe (0.55–1.50% DW) (Marques et al. 2021). This aligns with the typical biochemical profile of macroalgae, in which lipids represent a minor fraction of dry biomass. Despite the low quantity, seaweed lipids have been recognized for their high quality and enrichment of bioactive long-chain PUFAs, including *n*-3 and *n*-6 fatty acids, which have beneficial effects on cardiovascular health (Schmid et al. 2014).

Ash content serves as an indirect indicator of the total mineral load in seaweed biomass, reflecting the proportion of inorganic nutrients relative to organic matter (Beacham et al. 2019). In this context, *Cladophora* sp. exhibited high ash content (60.9% DW), which fell within or exceeded the typical range reported for commonly consumed seaweeds. For example, the ash content of the green seaweeds studied by Barot et al. (2019) ranged from 20 ± 0.2% to 50 ± 0.5%, which constitutes a remarkably high mineral load that is characteristic of species from freshwater or estuarine environments, where the bioaccumulation of dissolved minerals is often intensified (Rybak et al. 2012).

In contrast, *E. radiata* presented an ash content of 27.34% DW, which is consistent with the standard range reported for brown macroalgae such as Badderlocks (*Alaria esculenta*; 33.0% DW) (Schiener et al. 2015) and Bladderwrack (*Fucus vesiculosus*; 25.5% DW) (Neto et al. 2018). However, this value is slightly higher than the range reported by Nepper-Davidsen et al. (2023) for *E. radiata* (16.2–25.1% DW, *n* = 72), likely reflecting site-specific environmental conditions, seasonal variation, or methodological differences in sampling and processing.

Protein content has been fount to range from 5% to 47% DW (Thiviya et al. 2022), with the species analyzed in the present study falling within the lower range (10–11% DW) (Table 1). A recent study with *E. radiata* collected in New Zealand reported a protein content of 7.1% (Hrstich-Manning and Aguirre 2025). The protein content in *Cladophora glomerata* has been found to vary depending on the analytical method used. Manivannan et al. (2009) reported 20.38% protein in *C. glomerata* using the Biuret method, whereas Akköz et al. (2011) reported 14.13% protein using the Kjeldahl method. Nutautaitė et al. (2021) showed that the crude protein content in *C. glomerata* was considerably variable (19.2–24.2% DW) depending on the biomass source. These variations highlight the importance of the analytical method, as well as species-specific traits and environmental conditions, in determining the protein content in seaweeds.

Seaweed proteins are a source of all EAAs and NAAs and contain particularly high levels of glycine, alanine, arginine, proline, glutamic acid, and aspartic acid (Černá 2011). In addition, seaweeds contain amino acids like valine, leucine, isoleucine, and taurine, which may exhibit antioxidant properties (El-Beltagi et al. 2022). Amino acids are essential for synthesizing hormones and low molecular weight nitrogenous compounds, both of which play important biological roles (El-Beltagi et al. 2022). It is important to highlight that the protein content in seaweed varies widely depending on the species, season, and geographic location, and can reach up to 45% DW in some cases (Mouritsen et al. 2019).

Assessing the amino acid profile of seaweed biomass is a fundamental step from nutritional, sensory, and functional perspectives. From a nutritional standpoint, the amino acid profile is necessary for evaluating the protein quality of food, particularly the presence and proportion of EAAs required for human metabolism (Calvez et al. 2024). Amino acid analysis is especially relevant in light of the growing demand for more sustainable food alternatives (Marques et al. 2021), such as seaweeds, which are increasingly recognized as promising protein sources, particularly as diets shift toward those with lower environmental impact.

In the present study, *Cladophora* sp. exhibited higher L-arginine content compared to that of *E. radiata*. L-arginine plays essential biological roles and is involved in protein biosynthesis, immune response modulation, and the urea cycle. It is also a key precursor in the synthesis of nitric oxide, an important endogenous vasodilator associated with beneficial

Table 2. Trace element concentrations in *Ecklonia radiata* and *Cladophora* sp. samples. Results are expressed in mg·kg^{-1} dry weight (DW) and were determined by inductively coupled plasma mass spectrometry (ICP-MS). The elements analyzed were Sb, As, Cd, Cu, Pb, Hg, Se, Sn, and Zn.

Element	*Ecklonia radiata*	*Cladophora* sp.
Sb	<0.01	<0.02
As	3.20	4.00
Cd	0.37	63.00
Cu	0.61	11.00
Pb	32.00	5.70
Hg	<0.01	<0.01
Se	<0.05	0.73
Sn	<0.02	0.22
Zn	2.80	37.00

effects on cardiovascular and immune function (Gambardella et al. 2020). Glutamic acid and aspartic acid emerged as the predominant amino acids in *Cladophora* sp. and *E. radiata*, highlighting their potential biological and functional relevance. Both amino acids act as excitatory neurotransmitters in the central nervous system and play crucial roles in synaptic transmission and neuronal communication (Qu et al. 2023). Aspartic acid actively participates in the synthesis of other amino acids and in the production of cellular energy, while glutamic acid is essential for cognitive processes such as learning and memory (Zhang et al. 2008). Additionally, glutamic acid contributes to sensory characteristics and is directly responsible for umami flavor, which is associated with increased palatability in foods (Ghirri and Bignetti 2012). These results suggest that *E. radiata* is a more suitable protein source for essential amino acid supplementation, whereas *Cladophora* sp. presents a biofunctional profile suited to metabolic, neuromodulatory, and sensory applications and is a potential functional source of arginine. For this reason, *Cladophora* sp. can be incorporated into mixtures with other seaweeds or complementary ingredients to improve the nutritional profile and sensory characteristics of the final product.

Using seaweeds as a protein source in aquatic feeds is challenging, primarily due to their low EAA concentrations rather than their overall protein quality (Maehre et al. 2014). Thus, seaweeds present limitations as protein sources for monogastric animal diets, especially when compared to conventional sources such as corn and soybean. Another restrictive factor is their high moisture content (64.9–94.0%), which requires additional fresh biomass to achieve the same levels of dry matter obtained with terrestrial ingredients (Wan et al. 2019). Nevertheless, various studies have highlighted the benefits of including seaweeds in fish diets, with positive effects on palatability, digestibility, immunity, functionality, and growth performance (Glencross 2020, Ngoepe et al. 2024). Černá (2011) confirmed that compared to standard proteins, seaweed proteins (like plant proteins) are not complete proteins, as they contain low amounts of some amino acids.

In addition to nutritional value, the content of free and protein-bound amino acids directly influences the organoleptic properties of foods, especially the development of flavors such as umami. This aspect was investigated in detail by Mouritsen et al. (2019), who analyzed 20 different species from 12 genera of brown algae consumed worldwide, including *Nereocystis*, *Macrocystis*, *Laminaria*, *Saccharina*, *Undaria*, *Alaria*, *Postelsia*, *Himanthalia*, and *Ecklonia* (formerly *Eisenia*). When analyzing the amino acid profile of *Ecklonia bicyclis*, a clear predominance of NAAs over EAAs was observed in diversity and total concentration. Among the NAAs, alanine, glycine, and proline stood out, constituting the largest fraction of the total content and contributing to sensory properties, particularly sweet and mild notes. Glutamic acid, also an NAA, was detected and is associated with umami flavor.

In a recent study, spatiotemporal variation in the composition of amino acids in *E. radiata* biomass was quantified using samples collected at 12 sites in the North Island of New Zealand and from samples collected monthly from one site over one year ($n = 138$) (Nepper-Davidsen et al. 2023). The results revealed that glutamic acid and aspartic acid were the most abundant, collectively accounting for more than 30% of the total. Their levels ranged from 1.0–1.7% and 0.7–1.0% of dry biomass, respectively, indicating a protein profile of high nutritional value, especially in cellular metabolism and in the generation of umami-type flavors (Nepper-Davidsen et al. 2023).

Reports on amino acid profiles of *Cladophora* spp. are more frequent than those of *Ecklonia* spp. However, notable variability can occur among different species and between biomass samples of the same species, as demonstrated by Nutautaitė et al. (2021). The objective of their study was to evaluate the prospective use of freshwater *C. glomerata* as an alternative source of protein and other essential nutrients for animal feed. To achieve this, Nutautaitė et al. (2021) conducted a comprehensive chemical analysis of biomass samples collected from different locations to assess nutritional composition and potential applicability. The amino acid profile of *C. glomerata* revealed that the abundant amino acids were glutamic acid (14.16–19.50 g·kg^{-1}), aspartic acid (10.90–15.97 g·kg^{-1}), glycine (8.06–11.46 g·kg^{-1}), alanine (8.12–10.73 g·kg^{-1}), and leucine (9.64–12.01 g·kg^{-1}), which play essential roles in metabolism and contribute to taste properties such as umami and sweetness. Notably, EAAs, such as lysine (5.76–7.88 g·kg^{-1}), isoleucine (5.94–7.69 g·kg^{-1}), valine (8.39–10.42 g·kg^{-1}), and phenylalanine (6.37–8.50 g·kg^{-1}), were present in relevant amounts, supporting the nutritional value of the biomass, as they are essential in the human diet and play key roles in protein synthesis and metabolic functions.

Table 3. Trace element concentrations in *Ecklonia radiata* and *Cladophora* sp. samples. Results are expressed in mg·kg^{-1} dry weight (DW) and were determined by inductively coupled plasma mass spectrometry (ICP-MS). The elements analyzed were Sb, As, Cd, Cu, Pb, Hg, Se, Sn, and Zn.

Microbiological quality indicator	*Ecklonia radiata*	*Cladophora* sp.
Anaerobic bacteria	30 CFU·g^{-1}	10,000 CFU·g^{-1}
Coliforms	<1 MPN·g^{-1}	<1 MPN·g^{-1}
Salmonella spp.	ND	ND
Mesophilic spores	10 CFU·g^{-1}	7,200 CFU·g^{-1}
Yeasts	<100 CFU·g^{-1}	3,000 CFU·g^{-1}
Molds	100 CFU·g^{-1}	500 CFU·g^{-1}

In another study focused on *Cladophora vagabunda*, the amino acid profile was analyzed to investigate organic compounds that function as osmolytes and enable this intertidal alga to adapt to a wide range of salinity conditions (Rani 2007). The main amino acids identified were aspartate, glutamate, glycine, valine, lysine, histidine, arginine, and proline. Notably, aspartate and glutamate and EAAs (i.e., lysine, histidine, and arginine) exhibited a simultaneous increase in response to salinity stress. These findings further support the idea that environmental conditions can greatly influence the amino acid composition, highlighting the metabolic plasticity of *Cladophora* species in response to external stressors. Similarly, Pikosz et al. (2019) investigated the amino acid profile of *C. glomerata* and *Cladophora fracta* under chemical stress conditions to identify which amino acids showed notable variability and whether this variability reflected adaptive responses.

In *C. fracta* and *C. glomerata*, the most abundant amino acids were glutamic acid, aspartic acid, and leucine (Pikosz et al. 2019). In response to increasing concentrations of chemical exudates, notable accumulation of proline and tryptophan was observed, suggesting they play roles in stress mitigation (Pikosz et al. 2019). The relative abundance of amino acids in *C. fracta* followed the order of glutamic acid > aspartic acid > leucine > arginine > valine > alanine > glycine > lysine > threonine > serine > proline > phenylalanine > isoleucine > tyrosine > histidine > cysteine > methionine > tryptophan, whereas *C. glomerata* exhibited a similar pattern of glutamic acid > aspartic acid > leucine > arginine > valine > alanine > glycine > lysine > threonine > proline > serine > phenylalanine > isoleucine > tyrosine > histidine > cysteine > methionine > tryptophan (Pikosz et al. 2019). These patterns reinforce the dominant role of acidic amino acids in the protein profile of *Cladophora* species while highlighting the capacity of certain amino acids, such as proline and tryptophan, to act as biochemical markers of stress responses.

Messyasz et al. (2015) reported the amino acid profile of *C. glomerata* biomass, expressed as g·100 g^{-1} total protein. This study observed that glutamic acid and aspartic acid were the most abundant amino acids in samples collected from the lake environment. Additionally, the biomass was identified as a rich source of arginine, leucine, alanine, glycine, and valine, highlighting its potential nutritional value (Messyasz et al. 2015). It is worth noting that caution should be exercised when comparing data between different seaweed species and between samples of the same species from different regions or conditions, as the amino acid composition can vary greatly depending on the cultivation environment and the time of harvest.

Lipids in marine macrophytes are predominantly composed of phospholipids and glycolipids (Alghazeer et al. 2022). Low lipid levels of ~1–6% DW have been consistently reported across different taxa (Biris-Dorhoi et al. 2020, Alghazeer et al. 2022). In *E. radiata*, lipid content ranged from 0.1% to 1.6% DW (n = 72), following a unimodal seasonal pattern, with the highest levels observed in late austral spring to early summer and the lowest levels in austral autumn and winter (Nepper-Davidsen et al. 2023). Despite their low total lipid content, macroalgae are particularly rich in PUFAs, including long-chain PUFAs (Schmid et al. 2014). These bioactive compounds are widely recognized for their health-promoting properties, including anti-inflammatory, antioxidant, and potential anticancer activities (Coudray et al. 2021).

In the present study, *E. radiata* stood out for its high content of saturated fatty acids, especially butyric acid (37%), a short-chain fatty acid rarely recorded as abundant in macroalgae. From a functional point of view, butyric acid performs several important physiological functions, including providing an energy source for colon cells and regulating cell proliferation. It promotes intestinal development, maintains intestinal health and function, enhances the immune response, and has antitumor and antioxidant properties (Załęski et al. 2013). In addition, the notable content of EPA (9.3%), an essential omega-3 fatty acid, positions *E. radiata* as a valuable source of bioactive lipids for anti-inflammatory, cardioprotective, and neuroprotective applications. Previous studies have indicated that EPA intake may benefit neuropsychomotor development in children, improve attention in individuals with attention deficit and hyperactivity disorder, and reduce cortical thickness loss in patients with schizophrenia (Souto et al. 2022). In the elderly, EPA has been associated with greater cerebral oxygenation and a slowdown in brain mass loss in cases of dementia (Souto et al. 2022).

The high proportion of omega-3 in relation to omega-6 (89% vs. 12%) observed in *E. radiata* in the present study represents a relevant nutritional characteristic. The incorporation of macroalgae into the diet can notably contribute to the supply of omega-3 PUFAs, which are often deficient in Western diets that include reduced fish intake, the main source of these fatty acids, due to issues related to taste, cost, or the stability of the derived products (Mišurcová et al. 2011).

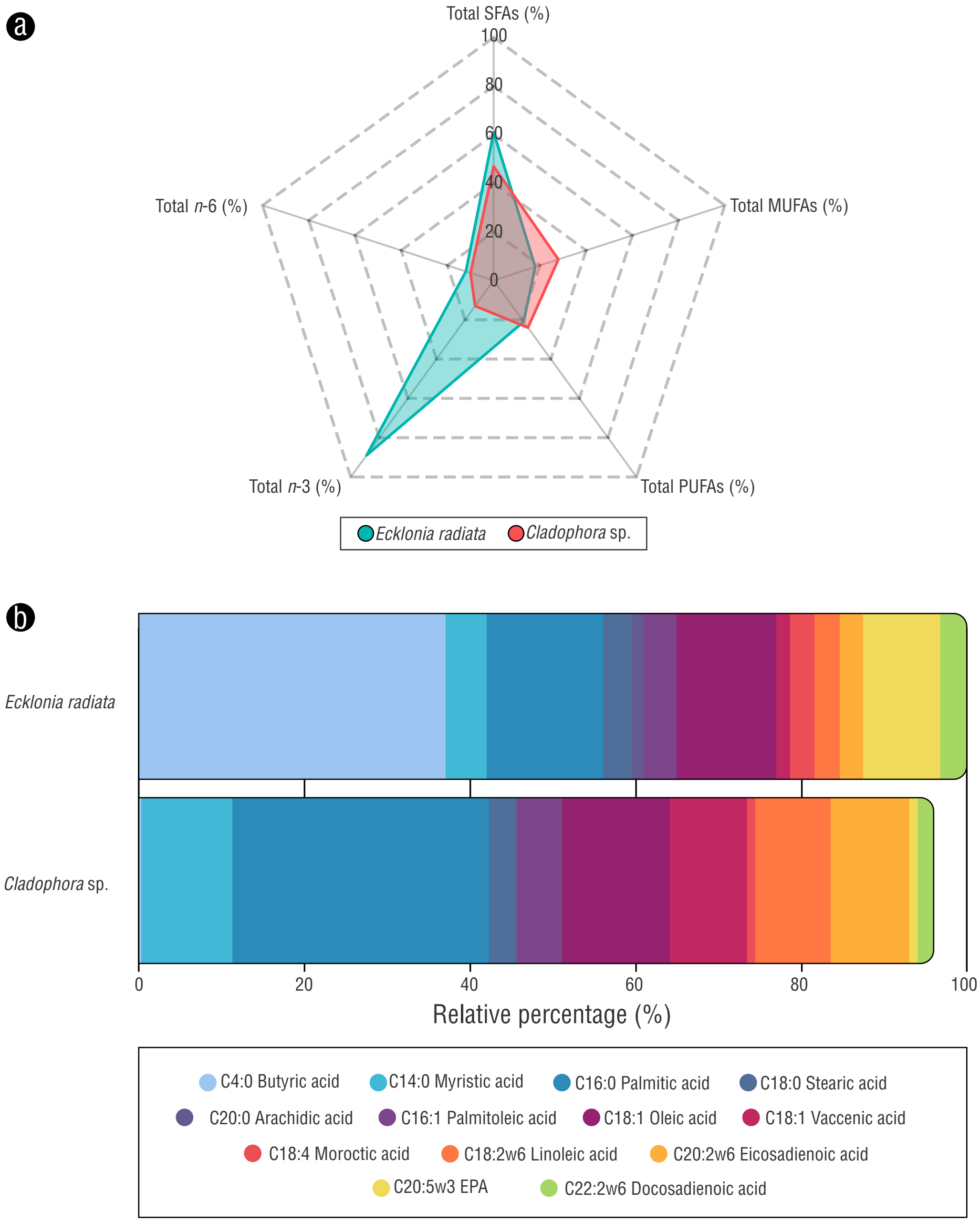


Figure 3. Fatty acid composition and lipid profile of *Ecklonia radiata* and *Cladophora* sp. Relative distribution of major lipid classes expressed as percentage of total identified fatty acids. The radar chart compares total saturated fatty acids (SFAs), total monounsaturated fatty acids (MUFAs), total polyunsaturated fatty acids (PUFAs), total omega-3 (*n*-3), and total omega-6 (*n*-6) in both species (**a**). Detailed fatty acid profile. The stacked bar chart shows the relative abundance of individual fatty acids, including C4:0 (butyric acid), C14:0 (myristic acid), C16:0 (palmitic acid), C18:0 (stearic acid), C20:0 (arachidic acid), C16:1 (palmitoleic acid), C18:1 (oleic acid), C18:1 (vaccenic acid), C18:4 (moroctic acid), C18:2 ω6 (linoleic acid), C20:2 ω6 (eicosadienoic acid), C20:5 ω3 (eicosapentaenoic acid [EPA]), and C22:2 ω6 (docosadienoic acid). All values are expressed on a dry weight (DW) basis and represent the relative percentage (%) of each fatty acid in relation to the total fatty acids identified in each species (**b**).

In *Cladophora* sp., the most important saturated fatty acid was palmitic acid, which acts as an energy source and is essential for the structure and functionality of cell membranes. In addition, palmitic acid has anti-inflammatory, antioxidant, and immunomodulatory properties (Wang et al. 2023). It is also noteworthy that the fraction of MUFAs in *Cladophora* sp. was more representative than in *E. radiata*, conferring a particularly interesting lipid profile. MUFAs have been associated with several health benefits, especially reducing cardiovascular risk, and diets rich in MUFAs have been found to decrease the need for insulin and to reduce plasma glucose and insulin levels in patients with type 2 diabetes (López-Miranda et al. 2006).

The relatively balanced proportion of omega-3 (13%) to omega-6 (10%) in this *Cladophora* sp. is a relevant nutritional characteristic. This lipid balance is close to the profiles considered ideal for diets aimed at preventing inflammatory and cardiovascular diseases. This balance reinforces the functional potential of this biomass, whether in the formulation of foods focused on metabolic and cardiovascular health or in the development of products aimed at skin health that require maintaining an adequate PUFA profile (Patel et al. 2022). It is also noteworthy that other functional fatty acids were detected in *Cladophora* sp., further reinforcing their nutritional relevance. For example, *trans*-vaccenic acid (9.3%), identified in *Cladophora* sp. in the present study, has been associated with beneficial metabolic and immunomodulatory properties in a previous study by Fan et al. (2023). This study demonstrated that *trans*-vaccenic acid can enhance CD8$^+$ T-cell function and anti-tumor immunity, highlighting its potential role in immune regulation and metabolic health (Fan et al. 2023). Although this fatty acid has been more commonly reported in animal-derived lipids, its occurrence has also been described in marine macroalgae (Marques et al. 2021).

Finally, it is worth emphasizing that the notable content of β-carotene present in *Cladophora* sp. (180 $\mu g \cdot 100\ g^{-1}$) in the present study further enhances its nutritional value. Carotenoids are one of the three main classes of antioxidants found in seaweeds, alongside vitamins and polyphenols (Jacobsen et al. 2019), and function as potent antioxidants, helping to protect cells against oxidative stress (Krinsky 2001). Additionally, carotenoids serve as precursors to vitamin A, which is vital for maintaining eye health, supporting immune function, and contributing to overall physiological well-being (Meléndez-Martínez 2019).

The uptake of trace and heavy metals by seaweeds is influenced by factors such as their presence in the environment and the intrinsic uptake capacity of the seaweed species (FAO 2022b). The results of the present study suggest variations in the accumulation of trace elements among the seaweed species, likely reflecting their distinct taxonomic characteristics, metabolic pathways, and ecological niches (Špoljarićе et al. 2021). The extremely high Cd concentration detected in *Cladophora* sp. (63.0 $mg \cdot kg^{-1}$) is particularly concerning. Recent research indicates that *C. fracta* exhibits a greater capacity to accumulate heavy metals, including Cd, compared to other green macroalgae (Yazılan and Taşkın 2024). This enhanced bioaccumulation ability has been attributed to the presence of specific functional groups in cell walls, which play a key role in binding Cd^{2+} ions. Furthermore, studies on *C. glomerata* have suggested that this species demonstrates a notable tolerance to elevated Cd concentrations, with the synthesis of stress-related compounds serving as biomarkers of oxidative stress (Celekli and Bulut 2020). These Cd levels may exceed the food safety limits established by various regulatory frameworks, raising concerns about the direct use of *C. glomerata* in food or feed applications without the implementation of appropriate decontamination strategies.

Copper and Zn are essential micronutrients and exhibited higher concentrations in *Cladophora* sp. than in *E. radiata* in the present study (11.0 $mg \cdot kg^{-1}$ and 37.0 $mg \cdot kg^{-1}$, respectively). Although elevated, these levels fall within the ranges commonly reported for green macroalgae (Laib 2012) and may contribute positively to the nutritional value of the seaweeds when consumed within safe limits. Michalak et al. (2018) demonstrated that *Cladophora* biomass enriched with trace elements through biosorption can serve as a valuable feed additive, partially replacing conventional inorganic salts. Similarly, Michalak et al. (2011) reported that a biosorption-enriched mixture of *Ulva prolifera* and *Cladophora* sp. biomass with Cu(II), Zn(II), Co(II), Mn(II), and Cr(III), when incorporated into the diet of laying hens, led to increased egg concentrations of these elements and improved quality characteristics, including yolk color, shell thickness, and egg weight, as well as hen body weight.

Lead was markedly higher in *E. radiata* (32 $mg \cdot kg^{-1}$) than in *Cladophora* sp. (5.7 $mg \cdot kg^{-1}$). This suggests species-specific mechanisms of metal uptake or differences in habitat exposure, considering that brown algae (Phaeophyceae) often have a higher affinity for certain heavy metals, such as Pb, due to the presence of alginates, which are known metal chelators (Jung et al. 2009). Despite this, the Pb content in *E. radiata* exceeded the limits typically established for food-grade materials in some jurisdictions, which may limit its application in food or nutraceuticals without purification. Mercury and Sb were below the detection limit in both species ($<0.01\ mg \cdot kg^{-1}$), which is a positive result considering the high toxicity associated with these elements. Selenium and Sn were detected only in *Cladophora* sp., with Se (0.73 $mg \cdot kg^{-1}$) potentially offering beneficial antioxidant properties within safe intake limits, while Sn (0.22 $mg \cdot kg^{-1}$) remained low and likely poses no health risk.

Microbiological monitoring of seaweed samples is essential to ensure the safety and quality of products intended for human consumption or for use as ingredients in supplements and nutritional products (Lytou et al. 2021). Seaweed is a natural raw material that is susceptible to contamination at various stages, including harvesting, transportation, processing, and storage. The excessive presence of microorganisms, such as pathogenic bacteria, coliforms, yeasts, and fungi, may be related to inadequate handling practices during these stages or to the quality of the water where the seaweed is harvested (Løvdal 2021). This type of microbial contamination can pose notable health risks to consumers, including foodborne illnesses, infections, and allergic reactions (Wu et al. 2022).

Despite the differences in total microbial load, the absence of *Salmonella* and coliforms in *Cladophora* sp. and *E. radiata* suggests that their biomass met basic microbiological safety standards for non-pathogenic contamination under the tested conditions. However, the higher microbial counts observed in *Cladophora* sp. may require additional processing steps, such as drying, sterilization, or preservation, to ensure product safety and quality for potential industrial applications.

A joint FAO (2022a) report highlighted that heavy metals, (particularly As and Cd), microbiological hazards (e.g., *Salmonella* spp.), and excessive I levels are key food safety concerns associated with seaweed products. Therefore, strict monitoring and control are regulatory obligations and essential measures that must be taken to protect consumers and ensure that seaweeds and seaweed-based products are safe and suitable for human consumption. In addition, continuous monitoring is recommended to support traceability and facilitate the identification of failures in production processes, allowing timely corrective actions to mitigate contamination risks.

Biosafety and sanitary management based on good practices, disease prevention, and the responsible use of antimicrobials are essential for sustainable aquaculture. The implementation of these management measures requires national strategies, cooperation among stakeholders, and alignment with international standards (FAO 2025). Importantly, many of these risks can be mitigated through good cultivation practices, such as selecting low-contamination sites, conducting regular environmental monitoring, and applying controlled harvesting and post-harvest processes (FAO 2022a). In open-sea culture systems, timely water quality monitoring is essential for site selection to prioritize areas with low levels of heavy metals or, when feasible, to implement multitrophic strategies to help mitigate existing contaminants. In land-based culture systems (e.g., *Cladophora* cultivated in sedimentation tanks), similar attention must be given to the quality of the seawater source used for cultivation. In both systems, controlled harvesting and post-harvest handling remain critical to ensure product safety. Regarding microbiological contamination, the establishment of good handling practices and hygiene protocols is necessary to prevent cross-contamination, particularly from operators, thereby reducing the risk of introducing and spreading microorganisms along the production chain (FAO, WHO 2022b).

From a sustainability perspective, seaweed cultivation and valorization represent a strategic pathway for expanding aquatic food systems while reducing environmental pressure on terrestrial resources (Biris-Dorhoi et al. 2020). Beyond their well-documented ecosystem services, such as carbon sequestration, nutrient bioremediation, and coastal protection, the chemical profiles validated in this study reinforce their relevance within a sustainable bioeconomy framework (Duarte et al. 2017, Racine et al. 2021). The predominance of bioactive amino acids, essential nutrients, and functional compounds in *E. radiata* and *Cladophora* sp. highlights their dual role as environmentally efficient biomass sources and high-value biochemical reservoirs. Thus, the integration of their validated chemical composition with scalable aquaculture practices supports a climate-positive production model capable of delivering food ingredients with reduced ecological footprint (Koroma et al. 2025). In this context, the sustainable exploitation of these species transcends mere biomass production, positioning them as potential strategic resources for environmentally responsible innovation in the food sector.

CONCLUSIONS

The nutritional and biochemical analysis of *E. radiata* and *Cladophora* sp. revealed distinct but potentially complementary profiles, demonstrating their suitability as sustainable raw materials for the development of functional foods. On one hand, *E. radiata* exhibited a high carbohydrate content and a balanced, high-quality amino acid composition that was particularly rich in lysine, leucine, and threonine, combined with a lipid profile enriched in omega-3 fatty acids, especially EPA. Additionally, *E. radiata* presented good microbiological quality, making it a safer candidate for direct incorporation into food products. On the other hand, *Cladophora* sp. was characterized by an exceptionally high ash content, substantial β-carotene concentration, and an elevated arginine level. However, its higher microbial load and the accumulation of certain heavy metals require careful processing and quality control to mitigate potential risks in food applications. Given that both species exhibited valuable nutritional attributes and certain constraints, particularly the higher contaminant levels observed in *Cladophora* sp., blended formulations could represent a possible pathway to optimize their nutritional benefits, enhance functional properties, and promote the sustainable production of food ingredients.

At the same time, the results obtained in the present study may serve as useful guidance for producers and industry stakeholders, particularly regarding cultivation conditions, biomass quality monitoring, and post-harvest processing practices. These findings can inform improvements in cultivation management, contamination monitoring, and processing strategies, strengthening the applied relevance of the work, especially in ensuring the safety and quality of seaweed biomass intended for human or animal consumption.

Our findings highlight the nutritional potential of both species and their distinct nutritional attributes and represent a first step toward the exploration of their possible use in the food sector. Although our results did not directly evaluate mixtures of the algae, they suggest the potential strategic use of both species in synergistic blends that may optimize nutritional benefits, enhance functional properties, and promote the sustainable production of food ingredients. Nevertheless, dedicated studies assessing the nutritional profile of formulated blends are required to confirm whether their complementary characteristics and safety effectively translate into improved overall value and application potential.

DECLARATIONS

Supplementary Material

This work does not include supplementary material.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization: JMCO, LJGE, TCS, JPCO, FSS (equal); Data curation and Formal analysis: JMCO; Funding acquisition: LJGE, JMCO, TCS, JPCO, FSS; Investigation: LJGE, JMCO, TCS; Methodology: JMCO, TCS, LJGE, JPCO, FSS; Project administration: LJGE, JMCO; Resources: JMCO, TCS, LJGE (lead), GWB, LPM (supporting); Supervision: JMCO, LJGE; Validation: JMCO, LJGE, TCS, MVRS; Visualization: JMCO; Writing–original draft: JMCO; Writing–review & editing: JMCO, TCS, MVRS,GWB, LPM.

Data availability

The data for this study are available from the corresponding author by reasonable request.

Artificial intelligence (AI) tools

The authors, who are responsible for this work, employed AI tools to perform grammar checks.

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