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Dried Seaweeds Available in the United Kingdom Market Are a Potential Source of n-3 Polyunsaturated Fatty Acids

Agnieszka Jaworowska [1,*], Aliza Murtaza [2] and Joshua Boateng [2]

[1] Division of Medicine, Faculty of Medical Sciences, University College London, London WC1E 6BT, UK
[2] School of Science, Faculty of Engineering and Science, University of Greenwich, Medway ME4 4TB, UK; a.murtaza@greenwich.ac.uk (A.M.); j.s.boateng@gre.ac.uk (J.B.)
* Correspondence: a.jaworowska@ucl.ac.uk

Abstract

To address the increasing global demand for eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), novel and sustainable sources are required. Seaweeds have been identified as promising alternative sources of these fatty acids (FAs). This study evaluated the FA profiles of dry, commercially available seaweeds in the United Kingdom, including *Porphyra* spp., *Palmaria palmata*, *Himanthalia elongata*, *Laminaria digitata*, *Saccharina japonica*, *Undaria pinnatifida*, *Sargassum fusiforme* and *Fucus vesiculosus*. FA identification was performed by gas chromatography. The highest content of polyunsaturated FAs (PUFAs) was observed in *U. pinnatifida*, accounting for 67.68% of the total FAs (TFAs). EPA represented 33.34% of TFA content in Rhodophyta and 7.13% in Ochrophyta. EPA was the dominant FA in *Porphyra* spp., comprising 38.91% of TFAs (1064.40 mg/100 g dry weight). A higher content of EPA was also found in *P. palmata* (32.18%), *L. digitata* (13.76%), and *U. pinnatifida* (13.00%). DHA content was consistently lower than that of EPA, with the highest proportion observed in *P. palmata* (0.27% of TFAs). *U. pinnatifida, P. palmata* and *Porphyra* spp. appear to be the most promising seaweed species for providing n-3 long-chain PUFAs in human diets.

Keywords: Docosahexaenoic acid; Eicosapentaenoic acid; lipids; n-3 polyunsaturated fatty acids; *Palmaria palmata*; *Porphyra* spp. seaweeds; *Undaria pinnatifida*

1. Introduction

Lipids are a vital component of a healthy diet and are mostly consumed as triacylglycerols esterified with three FAs, which constitute over 95% of food lipids [1]. FAs are classified as saturated, monounsaturated, and polyunsaturated, depending on the number of double bonds [1]. PUFA, especially long-chain polyunsaturated n-3 FA (n-3 LC-PUFA), including EPA and DHA, have been shown to exhibit a variety of health benefits, including anti-inflammatory, antihypertensive, anticancer, antioxidant and insulin-sensitizing properties [2]. n-3 LC-PUFAs are also essential for proper development and healthy aging [3] and their intake is associated with a reduced risk of cardiovascular disease, diabetes, cancer, Alzheimer's disease, dementia and depression [4].

Due to the significant role of these FAs in human health, nutritional requirements have been established for EPA and DHA. In the UK, the Scientific Advisory Committee on Nutrition (SACN) recommends consuming two portions (140 g per portion) of fish per week, with at least one portion being oily fish, to achieve a daily intake of 450 mg of n-3 LC-PUFA [5], which aligns with global recommendations [6]. However, the average

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worldwide consumption of EPA and DHA is below 200 mg/day [7], with the exception of in Iceland, Norway, Finland, South Korea and Japan [8]. For example, EPA and DHA intakes among American adults were only 89 mg/day [7] and around 50 mg/day in the UK [9]. EPA and DHA can be derived from alpha-linolenic acid (ALA), but the conversion rate in humans is at a 1% level in infants and considerably lower in adults [10,11]. Therefore, intake of preformed EPA and DHA directly from food sources is the recommended way to ensure proper levels of these FAs in the body [9].

EPA and DHA are almost exclusively found in aquatic organisms, with fish and fish oil being the main food sources in the human diet [12]. However, fish consumption remains below the recommended level in many countries [9], for example, in the UK, only around 16% of the population meets oily-fish recommendations [7]. A number of studies have demonstrated that vegetarians and vegans have significantly lower plasma concentrations of DHA and EPA when compared to omnivores [13].

In addition, the seafood sector faces many challenges as a sustainable source of n-3 LC-PUFAs, including climate change and disasters, water scarcity, pollution and biodiversity loss [14]. It has been estimated that the current gap between supply and demand for EPA and DHA to meet the recommended intake is between 0.4 and 1.0 million tons per year and will further increase with a growing population [9]. Similarly, Salem at al. [15] assessed that the total global availability of EPA/DHA for human consumption represents only about 15% of the recommended intake. Furthermore, Lofstedt et al. [6] reported that dietary recommendations for fish consumption in Europe were satisfied by national net seafood supplies in only 13 out of the 31 countries analyzed. Concerns have been raised about the overexploitation of wild fish stocks and the environmental impacts of aquaculture, and it is predicted that with current rates of fishing, global fish supply could collapse by 2048 [6,16]. In addition, it has been reported that the content of n-3 LC-PUFA in farmed fish is considerably lower than in wild varieties [9]. Therefore, oily fish alone can only satisfy a small proportion of global needs for EPA and DHA and the sustainability of food production systems when developing dietary recommendations needs to be considered. To meet the increasing global demand for LC-PUFAs, there is an urgent need to identify alternative, affordable, acceptable and sustainable EPA and DHA sources.

Seaweeds have emerged as promising plant-based sources of EPA and DHA [17]. Over the past decade, global interest in seaweed cultivation and its application in human nutrition and health has grown significantly [18]. Seaweed lipids have been shown to have antibacterial, antiviral, antifungal, antioxidant, antitumor and anti-inflammatory activity [17,19]. Furthermore, regular seaweed consumption has been associated with a lower risk of hypertension, cardiovascular disease, type 2 diabetes, and some cancers [20,21]. In contrast to terrestrial plants, seaweed can synthesize EPA and DHA, with notable reported EPA content (1–21%) and DHA content (2 and 17%) of the total FAs, depending on the taxonomic group [17].

Importantly, seaweed does not require freshwater, fertilizers, or arable land and thus can be cultivated sustainably with a low carbon dioxide footprint [22]. Seaweeds might advance the goals of the Sustainable Blue Economy, the initiative aiming to facilitate economic growth through sustainable use of ocean resources, [23] and can contribute towards the achievement of the sustainable development goals (SDGs), including SDG 2 (zero hunger), SDG 3 (good health and well-being) and SDG 14 (life below water) [22,24]. The United Nations SDGs are a set of 17 goals developed to achieve a sustainable future for the planet [25]. Additionally, replacement of fish oil with seaweed in aquaculture feed has been proposed as a promising strategy for developing more sustainable aquaculture systems capable of supporting a growing global population [23].

Lipid content and composition vary considerably both across and within seaweed species [17] and are influenced by a number of factors, such as the geographical region, season and environmental conditions, with temperature being one of the most significant contributors [26]. This variability means that some species may be a richer source of n-3 LC-PUFAs than others and understanding these differences is key to identifying optimal candidates for human consumption. While the FA profiles of fresh wild-harvested seaweed have been studied, the lipid composition of dried seaweed products directly available to consumers remains largely underexplored. Due to their high moisture content, seaweeds are perishable and drying can extend their shelf life; however, drying can also affect the nutritional composition of seaweed [27]. Most of the macroalgae used as food is dried [28]; thus, there is a need to assess their FA profile to inform dietary recommendations or develop functional ingredients. To the best of our knowledge, this is the first study to analyze the FA composition of dried seaweed products commercially available and commonly consumed in the UK market and to assess their potential as a source of n-3 PUFAs, especially EPA and DHA, in the human diet.

2. Materials and Methods

2.1. Seaweed Samples

A total of 46 dried seaweed products were sourced between January 2023 and January 2024 across the UK from small ethnic stores, supermarkets, online shops and directly from UK-based seaweed producers. All seaweed products were stored in their original packaging, protected from light and heat, and analyzed within their stated shelf lives, as indicated by the expiration dates on the packaging. It should be noted that this study evaluated commercial products rather than strictly biological replicates of seaweed species.

The analyzed samples represented two seaweed phyla: Rhodophyta (red seaweed): *Porphyra* spp. (Nori, n = 4) and *Palmaria palmata* (Dulse, n = 7); and Ochrophyta (brown seaweed): *Himanthalia elongata* (Sea spaghetti, n = 6), *Laminaria digitata* (Kelp, n = 5), *Saccharina japonica* (Kombu, n = 4), *Undaria pinnatifida* (Wakame, n = 9), *Sargassum fusiforme* (Hijiki, n = 5) and *Fucus vesiculosus* (Bladderwrack, n = 5). The seaweed species were selected based on their global production for human consumption [28], availability and popularity in the UK.

According to the information on the packaging, the seaweeds were harvested in China, South Korea, Japan, Scotland, England, Ireland, France, Spain and Portugal. Details regarding seaweed processing, harvest season and the precise location of harvesting were not available. All analyses were conducted by an external food-testing laboratory accredited by the United Kingdom Accreditation Service (UKAS).

2.2. Lipid Extraction

Lipids were extracted following acid hydrolysis with hydrochloric acid with approximately 3 g of dried seaweed sample used for lipid extraction. First, the samples were heated for 60 min at 75−80 °C with 3M hydrochloric acid, then cooled and filtered. The residue was washed and dried for one and a half hours in an air oven at 100 °C. The dried residue underwent a six-hour extraction with light petroleum; the solvent was evaporated and the residue dried for one and a half hours in an air oven at 100 °C. The lipid content was measured gravimetrically [29] and the lipid extraction was done in triplicate.

2.3. Fatty Acid Analysis

The extracted FAs were converted to their FA methyl esters (FAMEs) through transmethylation of lipid extracts. The samples were saponified and methylated directly in a microwave solvent-extraction system. Firstly, potassium hydroxide (2.5%) in methanol was

added and the reaction vessels were heated. The reaction vessels were then removed from the spindle wheel and cooled until they had reached room temperature. Subsequently, methylation was conducted by adding 5% acetyl chloride to the methanol solution. The resulting FAMEs were extracted with n-hexane and a saturated sodium chloride solution. For the analysis of the FAMEs, 1 µL of the esterified sample was injected into a gas chromatograph coupled with a flame ionization detector [30]. A SLB-IL111 (100 m × 0.25 mm, 0.20 µm) capillary column was used for the FAME separation. The temperatures of the injector and FID detector were set to 250 °C and 270 °C, respectively, while the carrier gas was helium with a flow rate of 1.0 mL/min. The content of individual FAs and lipid classes were reported as a relative percentage of the total FA methyl esters (%TFAs) and/or in mg/100 g dry weight (dw) samples. The values were averaged over three injections of each duplicate extract.

2.4. Nutritional Quality of Lipids

The nutritional quality of seaweed lipids was evaluated based on the FA profiles. The n-6/n-3 ratio, PUFA/saturated FA (SFA), EPA + DHA, and nutritional quality indices, including atherogenic index (AI, Equation (1)), thrombogenic index (TI, Equation (2)), hypocholesterolemic/hypercholesterolemic ratio (H/H, Equation (3)) were calculated as follows [31]:

$$AI = [C12{:}0 + (4 \times C14{:}0) + C16{:}0]/(\sum UFA) \quad (1)$$

$$TI = (C14{:}0 + C16{:}0 + C18{:}0)/[(0.5 \times \Sigma MUFA) + (0.5 \times \Sigma n - 6\ PUFA) + (3 \times \Sigma n - 3\ PUFA) + (n - 3/n - 6)] \quad (2)$$

$$H/H = (cis\text{-}C18{:}1 + \Sigma PUFA)/(C12{:}0 + C14{:}0 + C16{:}0) \quad (3)$$

UFA—unsaturated FA.
MUFA—monounsaturated FA.

2.5. Statistical Analysis

All analytical data measurement was conducted in triplicate and the mean value of the replicates was used for the statistical analysis; all statistical comparisons are based on independent commercial samples. The data were analyzed using SPSS version 29.0 (SPSS Inc., Chicago, IL, USA), and $p < 0.05$ was considered statistically significant. All variables were checked for normality of distribution using histograms, Kolmogorov–Smirnov and Shapiro–Wilk tests before the analyses. All results are presented as a median with an interquartile range (25th and 75th percentiles) due to their nonparametric distribution. The differences in FA content between the seaweed species were analyzed with the Kruskal–Wallis and Dunn's tests. The Mann–Whitney U test was applied to evaluate the differences in FA profile between Rhodophyta and Ochrophyta. Principal component analysis (PCA) was performed using XLSTAT to examine the distribution of FAs across the analyzed seaweed species. The FA data matrix included all FA values as shown in Table 1, except for dodecanoic acid (C12:0), pentadecanoic acid (C15:0), heptadecanoic acid (C17:0), arachidic acid (C20:0), behenic acid (C22:0), lignoceric acid (C24:0), myristoleic acid (C14:1), pentadecenoic acid (C15:1), ecosadienoic acid (C22:2) and eicosatrienoic acid (C20:3) due to their insignificant amounts and/or lack of correlation with the data matrix. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy for the PCA model was 0.712 and Bartlett's test of sphericity was statistically significant ($p < 0.001$). The n-6/n-3 ratio, EPA + DHA and the nutritional quality indices (AI, TI, H/H) were calculated for each seaweed sample and reported as medians (Q25 and Q75) for each species and phyla.

3. Results

The total fat content and FA composition varied significantly ($p < 0.05$) across all analyzed seaweed species (Table 1). Overall, the total lipid content was relatively low, ranging from 1.03 g/100 g in *P. palmata* to 3.20 g/100 g dw in *Porphyra* spp., with brown seaweeds characterized by slightly higher average lipid levels (1.58 g/100 g dw) than red algae (1.47 g/100 g dw).

In general, red algae showed a significantly higher ($p < 0.05$) content of SFAs (48.54% of TFAs) than brown seaweed (33.54% of TFAs) (Figure 1). Among the species studied, *P. palmata* had the highest SFA content (58.40% of TFAs). On the other hand, brown seaweeds were richer in MUFA than red algae (20.37 vs. 9.96% of TFAs; $p < 0.05$), with *F. vesiculosus* showing the highest MUFA concentration (29.13% of TFAs). PUFAs were the dominant FAs in all analyzed species, except *P. palmata* (33.31% of TFAs) and *S. fusiforme* (33.80% of TFAs). The highest PUFA content was observed in *U. pinnatifida* (63.05% of TFAs).

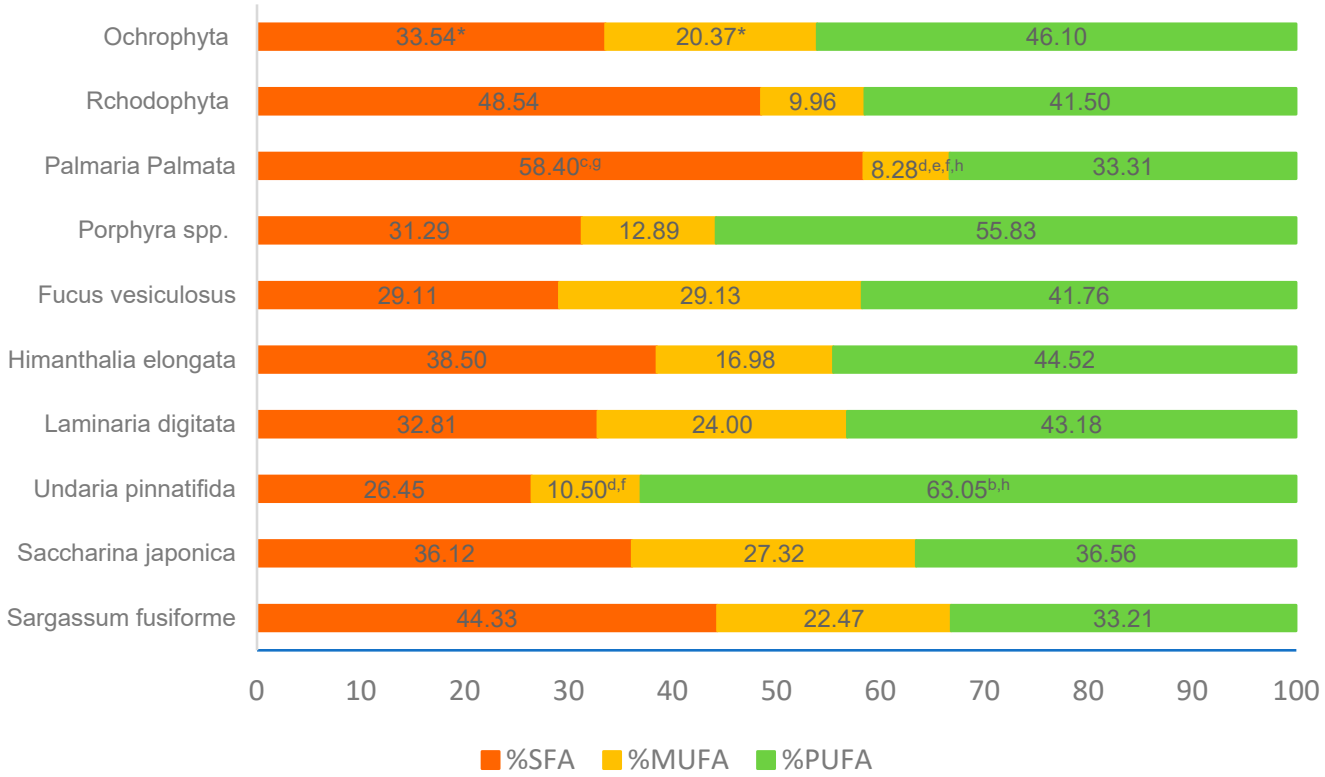


Figure 1. Proportion (%) of the different types of FAs, i.e., SFA, MUFA and PUFA in the seaweed analyzed. * Significant difference between phyla (Mann–Whitney U test, $p < 0.05$); significant difference between seaweed species (Dunn's tests with Bonferroni adjustment, $p < 0.05$): [a] *Porphyra* spp.; [b] *Palmaria palmata*; [c] *Fucus vesiculosus*; [d] *Himanthalia elongata*; [e] *Laminaria digitata*; [f] *Saccharina japonica*; [g] *Undaria pinnatifida*; [h] *Sargassum fusiforme*.

Red algae were characterized by significantly lower ($p < 0.05$) n-6 PUFA levels than brown seaweed (2.36 vs. 19.66% of TFAs) and significantly higher ($p < 0.05$) n-3 PUFA levels (28.20 vs. 18.99% of TFAs) (Table 1).

Table 1. FA composition (% of total FAs and/or g/100 g dw for the total lipids) of the seaweeds analyzed. Data is presented as medians and interquartile (25th and 75th) percentiles.

FA	**Rhodophyta** ***n* = 11**	***Palmaria palmata*** ***n* = 7**	***Porphyra* spp.** ***n* = 4**	**Ochrophyta** ***n* = 35**	***Fucus vesiculosus*** ***n* = 6**	***Himanthalia elongata*** ***n* = 6**	***Laminaria digitata*** ***n* = 5**	***Undaria pinnatifida*** ***n* = 9**	***Saccharina japonica*** ***n* = 4**	***Sargassum fusiforme*** ***n* = 5**
C12:0 (Lauric acid) (%)	0.06 (0.02–0.07)	0.07 (0.06–0.10) [a]	0.02 (0.02–0.03)	0.05 (0.05–0.06)	0.05 (0.05–0.07) [a,b]	0.05 (0.05–0.05) [a,b]	0.05 (0.05–0.05)	0.06 (0.04–0.11)	0.04 (0.03–0.05)	0.06 (0.02–0.07)
C14:0 (Myristic acid) (%)	9.33 (0.37–12.17)	11.32 (9.33–14.19)	0.37 (0.26–1.26) [b,c]	5.51 (4.40–10.54)	10.89 (10.65–11.56)	5.86 (4.77–6.80)	5.94 (5.20–13.20)	3.58 (2.01–4.34) [b,c]	6.98 (5.41–9.99)	4.98 (4.89–5.44)
C14:1 (Myristoleic acid) (%)	0.27 (0.02–0.51)	0.50 (0.27–0.55) [a]	0.02 (0.02–0.02)	0.19 (0.12–0.23)	0.14 (0.13–0.19)	0.22 (0.14–0.25)	0.21 (0.20–0.39)	0.24 (0.10–0.32)	0.09 (0.03–0.19)	0.09 (0.08–0.18)
C15:0 (Pentadecanoic acid) (%)	0.24 (0.14–0.32)	0.28 (0.25–0.42)	0.14 (0.04–0.14) [c,e,h]	0.35 (0.27–0.46)	0.40 (0.35–0.44)	0.27 (0.22–0.31)	0.41 (0.34–0.60)	0.27 (0.21–0.32)	0.34 (0.23–0.55)	0.49 (0.45–0.54)
C15:1 (Pentadecenoic acid) (%)	0.04 (0.02–0.07)	0.07 (0.06–0.07) [a]	0.02 (0.02–0.02)	0.05 (0.03–0.05)	0.03 (0.03–0.05)	0.05 (0.05–0.05)	0.05 (0.05–0.05)	0.05 (0.04–0.06)	0.04 (0.03–0.05)	0.03 (0.02–0.06)
C16:0 (Palmitic acid) (%)	36.60 (26.54–44.84) *	41.41 (34.02–52.62)	27.27 (25.83–34.45)	23.51 (15.00–29.48)	14.48 (13.53–16.74) [b,h]	26.54 (24.39–32.22)	22.41 (16.37–24.61)	14.94 (12.91–25.41) [b,h]	23.79 (19.56–29.10)	34.63 (32.28–38.24)
C16:1 (Palmitoleic acid) (%)	0.69 (0.36–0.73) *	0.69 (0.64–1.10)	0.28 (0.14–0.62) [c,g,h]	1.44 (1.16–3.33)	1.31 (1.13–1.46)	1.28 (0.99–1.51)	3.27 (1.99–4.13)	1.00 (0.45–1.50) [c]	2.62 (1.41–4.19)	4.62 (4.22–4.99)
C17:0 (Heptadecanoic acid) (%)	0.09 (0.06–0.15) *	0.14 (0.10–0.19)	0.05 (0.04–0.08)	0.15 (0.11–0.26)	0.34 (0.09–0.41)	0.14 (0.11–0.18)	0.14 (0.09–0.19)	0.15 (0.10–0.70)	0.21 (0.14–0.41)	0.23 (0.11–0.25)
C17:1 (Heptadecenoic acid) (%)	0.10 (0.02–0.12) *	0.11 (0.10–0.13)	0.02 (0.02–0.02) [d]	0.27 (0.03–0.55)	0.03 (0.03–0.47)	0.49 (0.32–0.64)	0.54 (0.18–0.73)	0.51 (0.12–1.29)	0.16 (0.03–0.39)	0.03 (0.01–0.12)
C18:0 (Stearic acid) (%)	1.19 (0.89–1.65) *	1.54 (1.10–1.70)	0.92 (0.71–1.14)	0.74 (0.50–1.11)	0.75 (0.36–0.99)	0.48 (0.42–0.57) [b,f]	0.75 (0.52–1.03)	1.06 (0.51–1.58)	1.68 (1.27–4.25)	0.69 (0.53–0.99)
C18:1 (Oleic acid) (%)	4.50 (3.35–5.54) *	4.57 (3.81–5.54) [c,e,f]	3.93 (2.94–5.57) [c,e,f]	14.18 (10.85–19.86)	28.63 (17.05–33.43)	14.20 (12.92–16.38)	18.13 (15.74–24.85)	8.45 (5.23–10.71) [c]	24.90 (20.08–26.9)	11.37 (10.59–12.01)
C18:2 (Linoleic acid) (%)	1.30 (0.88–2.27) *	1.00 (0.77–1.30) [c,f,g]	2.37 (2.24–3.69) [c]	6.44 (4.92–7.81)	8.87 (7.81–9.54)	5.37 (4.93–6.21)	6.13 (4.45–7.45)	7.26 (5.47–7.73)	7.31 (6.92–8.58)	4.30 (4.19–4.37) [c]
C18:3 (γ-Linolenic acid) (%)	0.25 (0.21–0.33) *	0.22 (0.16–0.25) [f,g]	0.37 (0.31–0.41)	0.52 (0.41–1.13)	0.48 (0.45–0.52)	0.41 (0.29–0.48)	0.54 (0.46–0.80)	1.13 (0.69–1.49)	2.93 (1.93–3.62)	0.22 (0.16–0.31) [f,g]

Table 1. *Cont.*

FA	Rhodophyta *n* = 11	*Palmaria palmata* *n* = 7	*Porphyra* spp. *n* = 4	Ochrophyta *n* = 35	*Fucus vesiculosus* *n* = 6	*Himanthalia elongata* *n* = 6	*Laminaria digitata* *n* = 5	*Undaria pinnatifida* *n* = 9	*Saccharina japonica* *n* = 4	*Sargassum fusiforme* *n* = 5
C18:3 (α-Linolenic acid) (%)	0.36 (0.11–0.52) *	0.44 (0.37–0.69) [d,g]	0.09 (0.04–0.15) [d,g,h]	7.43 (4.65–7.81)	5.40 (3.70–8.00)	9.52 (7.82–10.66)	6.30 (3.88–7.73)	11.37 (6.91–12.20)	2.54 (1.95–3.43)	8.14 (7.63–8.53)
C18:4 (Stearidonic acid) (%)	0.28 (0.18–0.61) *	0.46 (0.28–0.75) [g]	0.15 (0.05–0.21) [e,g]	6.09 (2.90–9.91)	1.54 (0.48–7.36)	5.65 (4.22–9.46)	9.25 (3.80–13.77)	22.24 (11.40–25.05)	5.05 (2.78–6.55)	2.90 (1.58–3.38)
C20:0 (Arachidic acid) (%)	0.07 (0.02–0.13) *	0.12 (0.07–0.14) [f,g]	0.02 (0.02–0.03) [f,g]	0.43 (0.32–0.61)	0.27 (0.17–0.39)	0.40 (0.28–0.44)	0.51 (0.28–0.59)	0.61 (0.46–0.95)	0.78 (0.48–1.02)	0.46 (0.30–0.51)
C20:2 (Eicosadienoic acid) (%)	0.06 (0.03–1.09)	0.04 (0.02–0.06) [a,c,h]	1.12 (1.07–1.21)	0.16 (0.13–0.30)	0.71 (0.51–0.99)	0.13 (0.11–0.13)	0.22 (0.13–0.57)	0.12 (0.11–0.16)	0.15 (0.05–0.74)	0.25 (0.22–0.30)
C20:4 (Arachidonic acid) (%)	1.30 (0.95–4.97) *	1.12 (0.74–1.30) [d,g]	6.45 (4.81–15.68)	13.35 (9.68–15.51)	9.17 (4.94–13.83)	15.86 (13.47–16.31) [c]	9.91 (9.23–11.20)	13.74 (12.69–16.89)	11.35 (8.51–15.05)	12.90 (10.20–14.09)
C20:3 (Eicosatrienoic acid) (%)	0.03 (0.00–0.09) *	0.03 (0.00–0.09) [c]	0.02 (0.02–0.09)	0.19 (0.11–0.29)	0.29 (0.18–0.33)	0.22 (0.16–0.30)	0.19 (0.04–0.25)	0.14 (0.12–0.27)	0.06 (0.03–0.07)	0.20 (0.15–0.35)
C22:0 (Behenic acid) (%)	0.06 (0.02–0.35)	0.28 (0.06–0.44)	0.02 (0.02–0.03) [d,h]	0.12 (0.05–0.06)	0.14 (0.06–0.17)	0.78 (0.48–0.99)	0.07 (0.05–0.13)	0.05 (0.05–0.08)	0.06 (0.03–0.06) [d,h]	0.90 (0.67–1.12)
C20:5 (Eicos-apentaenoic acid) (%)	33.33 (19.71–43.06) *	32.18 (16.90–42.12) [h]	38.91 (30.01–47.22) [f,h]	7.12 (4.74–12.99)	8.48 (7.04–11.40)	7.78 (5.33–10.06)	13.76 (5.24–14.54)	13.00 (6.55–15.21)	5.01 (3.72–8.94)	4.21 (3.45–4.61)
C22:1 (Erucic acid) (%)	0.77 (0.58–1.07) *	0.77 (0.58–1.08) [c]	0.80 (0.70–1.54) [c]	0.07 (0.06–0.09)	0.05 (0.03–0.07)	0.08 (0.07–0.10)	0.07 (0.06–0.20)	0.07 (0.05–0.09)	0.05 (0.03–0.08)	0.09 (0.05–0.16)
C24:0 (Lignoceric acid) (%)	0.38 (0.03–0.47)	0.46 (0.38–0.55) [d]	0.02 (0.02–0.05) [b,d]	0.10 (0.05–0.51)	0.12 (0.03–0.42) [c]	0.64 (0.49–0.86) [f]	0.07 (0.05–0.20)	0.10 (0.06–0.12)	0.05 (0.03–0.09)	0.52 (0.26–0.64)
C22:5 (Docos-apentaenoiccid) (%)	0.06 (0.03–0.17) *	0.13 (0.06–0.18) [c]	0.03 (0.02–0.08)	0.05 (0.03–0.05)	0.03 (0.03–0.05)	0.05 (0.05–0.05)	0.06 (0.05–0.05)	0.06 (0.04–0.05)	0.04(0.03–0.05)	0.03 (0.02–0.06)
C22:6 (Docosa-hexaenoic acid) (%)	0.24 (0.03–0.34)	0.27 (0.24–0.41)	0.02 (0.02–0.09)	0.05 (0.03–0.05)	0.03 (0.03–0.05)	0.05 (0.05–0.05)	0.06 (0.05–0.21)	0.05 (0.04–0.06)	0.04 (0.03–0.05)	0.03 (0.02–0.06)
Total n-3 (%)	28.20 (18.83–42.50) *	27.58 (13.59–36.09)	38.01 (29.21–46.09)	18.98 (12.64–26.05)	14.72 (11.73–23.58) [a,b]	22.07 (15.77–25.84)	25.80 (10.57–30.95)	41.79 (20.65–46.84)	11.46 (8.02–18.70)	13.79 (12.30–15.19)

Table 1. *Cont.*

FA	**Rhodophyta** ***n* = 11**	***Palmaria palmata*** ***n* = 7**	***Porphyra* spp.** ***n* = 4**	**Ochrophyta** ***n* = 35**	***Fucus vesiculosus*** ***n* = 6**	***Himanthalia elongata*** ***n* = 6**	***Laminaria digitata*** ***n* = 5**	***Undaria pinnatifida*** ***n* = 9**	***Saccharina japonica*** ***n* = 4**	***Sargassum fusiforme*** ***n* = 5**
Total n-6 (%)	2.36 (1.94–12.17) *	2.04 (1.70–2.36) [c,d,g,h]	13.68 (10.92–21.63)	19.66 (15.12–21.44)	21.10 (20.24–22.10)	20.44 (17.44–21.52)	14.08 (12.58–17.08)	20.27 (16.15–23.27)	21.24 (19.29–23.56)	15.86 (13.30–17.64)
Total Lipids (g/100 g dw)	1.47 (0.87–2.80)	1.03 (0.61–1.47) [a,g]	3.20 (2.42–3.67)	1.58 (1.27–2.17)	1.60 (1.49–1.84)	1.92 (1.24–2.20)	1.42 (0.85–2.50)	2.42 (1.79–3.19)	1.31 (0.85–1.93)	1.12 (0.90–1.37)

n—Number; * Significant difference between phyla (Mann–Whitney U test, $p < 0.05$); significant difference between seaweed species (Dunn's tests with Bonferroni adjustment, $p < 0.05$): [a] *Porphyra* spp.; [b] *Palmaria palmata*; [c] *Fucus vesiculosus*; [d] *Himanthalia elongata*; [e] *Laminaria digitata*; [f] *Saccharina japonica*; [g] *Undaria pinnatifida*; [h] *Sargassum fusiforme.*

In all the seaweeds studied, (with the exception of *F. vesiculosus* and *Porphyra* spp.,) the single most abundant FA was palmitic acid (C16:0), accounting for over 30% of TFAs in *P. palmata* and *S. fusiforme*. Oleic acid (C18:1, n-9) was the dominant MUFA, with significantly higher ($p < 0.001$) concentrations in brown than red algae (14.18 vs. 4.50 of TFAs). C18:1, n-9 was the main FA found in *F. vesiculosus*, accounting for 28.63% of TFAs, and its concentration was significantly higher ($p < 0.05$) than in *P. palmata*, *Porphyra* spp., and *U. pinnatifida*. Higher levels of C18:1, n-9 were also found in *S. japonica* (24.60% of TFAs). The seaweeds studied were also a source of the essential PUFAs, including alpha-linolenic acid (ALA, C18:3, n-3) and linoleic acid (LA, C18:2, n-6). Red algae had significantly lower ALA and LA content than brown algae (0.36 vs. 7.43; $p < 0.05$ and 1.31 vs. 6.44% of TFAs; $p < 0.05$, respectively). *U. pinnatifida* was particularly rich in stearidonic acid (SDA, C18:4, n-3), with a concentration of 22.24% of TFAs. In contrast, other seaweed species showed much lower levels of this n-3 PUFA, ranging from 0.16% in *Porphyra* spp., and 9.25% of TFAs in *S. japonica*. EPA represented 33.33% of TFA content in Rhodophyta and 7.12% in Ochrophyta. EPA was the dominant FA in *Porphyra* spp., comprising 38.91% of TFAs (1064.40 mg/100 g dw). A higher level of EPA was also found in *P. palmata* (32.18%), *L. digitata* (13.76%) and *U. pinnatifida* (13.00%), but EPA levels were below 10% of TFAs in all other analyzed seaweed species. The DHA content was much lower than that of EPA, with the highest proportion observed in *P. palmata* (0.27% of TFAs) (Table 1). The main n-6 LC PUFA in all seaweeds analyzed was arachidonic acid (AA, C20:4, n-6), with its content significantly higher ($p < 0.05$) in brown seaweeds than red ones (13.35 vs. 1.30% of TFAs).

The nutritional quality indices were calculated based on the FA profiles of the analyzed seaweeds (Table 2). Statistically significant differences ($p < 0.05$) between seaweed species were observed for the n-6/n-3 ratio, AI, TI, H/H ratio, and EPA+DHA. The average n-6/n-3 ratio was low; 0.14 among the red seaweeds and 1.05 in brown seaweeds. The highest ratio was found in *S. japonica* (2.06) and the lowest in *P. palmata* (0.08). The AI and TI values were higher in Rhodophyta (1.34 and 0.63, respectively) than in Ochrophyta (0.81 and 0.14, respectively). *P. palmata* was characterized by the highest AI, TI and H/H values, which were related to the higher SFA content in this seaweed. The absolute amount of EPA+DHA was significantly higher ($p < 0.05$) in *Porphyra* spp., when compared to *S. fusiforme* and *S. japonica* (Table 2).

PCA was conducted using 14 FAs and described 81.27% of the total variability in seaweed FA composition. Principal component 1 (PC1) explained 57.40% of the variance, principal component 2 (PC2) explained 13.53%, and principal component 3 (PC3) explained 10.32% (Figure 2a). The variables with the greatest discriminatory power along the *x*-axis (PC1) were LA (0.259), ALA (0.633), SDA (0.639), AA (0.306), EPA (−0.214) and C22:1 (−0.446), while C14:0 (0.365), DHA (0.174) and C16:1 (0.206) were most discriminant along the *y*-axis (PC2) (Figure 2b). Species within Ochrophyta formed a distinct cluster (Group 1) and were clearly separated from Rhodophyta species (Group 2) (Figure 2a). Brown seaweeds were distinguished by their high content of C18 PUFAs, including ALA, GLA, LA, SDA and MUFAs, especially C18:1. On the other hand, red seaweeds were separated by higher concentrations of EPA and DHA, while *P. palmata* was clearly separated from *Porphyra* spp. All Ochrophyta species except *U. pinnatifida* clustered together, indicating similarities in their FA composition. *U. pinnatifida* was separated from other brown seaweeds by its high SDA content (Figure 2a).

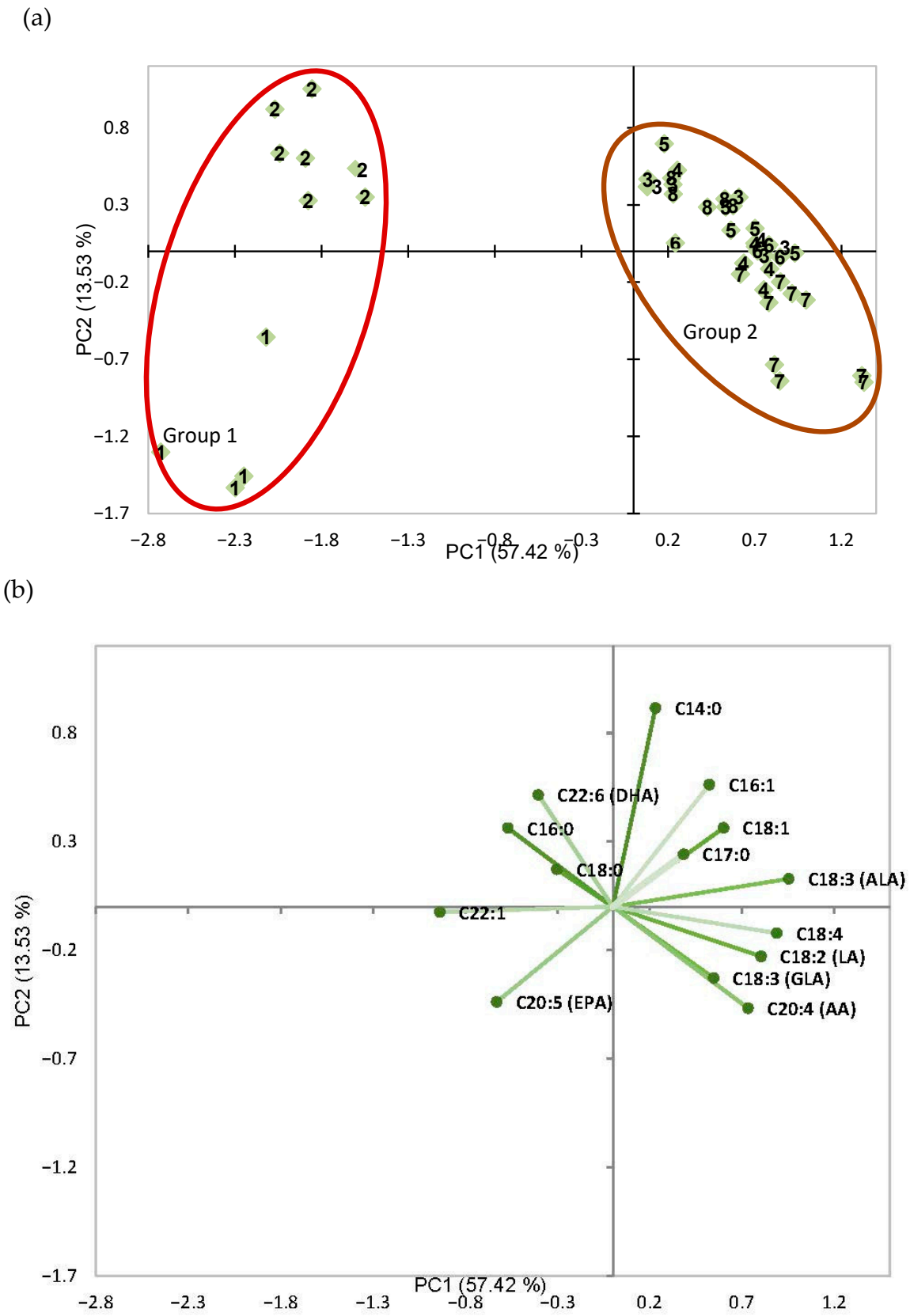


Figure 2. PCA biplot of the scores and factor loadings of the first and second principal components for the FA profiles of the analyzed seaweed samples. (**a**) Score plot, (**b**) factor loading plot. 1 *Porphyra* spp.; 2 *Palmaria palmata*; 3 *Fucus vesiculosus*; 4 *Himanthalia elongata*; 5 *Laminaria digitata*; 6 *Saccharina japonica*; 7 *Undaria pinnatifida*; 8 *Sargassum fusiforme*.

Table 2. Calculated nutritional indices (n-6/n-3, DHA, EPA, DHA+EPA, AI, TI and H/H) obtained for the different seaweed samples. Data presented as median and interquartile (25th and 75th) percentile.

	Rhodophyta ***n* = 11**	***Palmaria pamata*** ***n* = 7**	***Porphyra* spp.** ***n* = 4**	**Ochrophyta** ***n* = 35**	***Fucus vesiculosus*** ***n* = 6**	***Himanthalia elongata*** ***n* = 6**	***Laminaria digitata*** ***n* = 5**	***Undaria pinnatifida*** ***n* = 9**	***Saccharina japonica*** ***n* = 4**	***Sargassum fusiforme*** ***n* = 5**
n-6/n-3	0.14 (0.06–0.28)	0.08 (0.06–0.14) [c,f,h]	0.41 (0.23–0.66)	1.05 (0.71–1.43)	1.47 (0.90–1.90)	0.95 (0.79–1.09)	0.56 (0.54–1.50)	0.56 (0.37–1.13)	2.06 (1.39–2.43)	1.15 (1.06–1.16)
DHA (mg/100 g dw)	2.52 (0.69–3.39)	2.69 (2.25–3.39) [h]	0.71 (0.59–3.15)	0.72 (0.54–1.11)	0.54 (0.48–0.87)	0.96 (0.62–1.10)	1.12 (0.73–1.22)	1.00 (0.58–1.63)	0.53 (0.30–0.87)	0.39 (0.18–0.64)
EPA (mg/100 g dw)	611.10 (138.22–978.84) *	235.68 (109.02–611.10)	1064.40 (816.89–1570.09) [f,h]	120.12 (58.29–187.96)	130.08 (103.41–197.97)	121.08 (91.85–179.37)	183.18 (155.12–187.97)	242.60 (109.20–426.89) [b]	70.72 (55.92–78.84)	39.06 (29.93–54.43)
DHA+EPA (mg/100 g dw)	614.65 (141.62–982.80) *	238.20 (109.20–614.65)	1066.66 (818.40–1570.79) [f,h]	121.17 (59.01–189.74)	130.56 (103.92–198.85)	122.08 (92.45–180.41)	183.89 (156.24–189.75)	243.61 (110.35–428.03) [b]	71.16 (56.22–79.71)	39.24 (30.30–54.98)
AI	1.34 (0.42–2.34) *	1.94 (1.34–3.76) [a,g]	0.40 (0.37–0.63)	0.81 (0.60–0.91)	0.83 (0.80–0.87)	0.78 (0.65–1.07)	0.67 (0.61–0.86)	0.38 (0.25–0.63) [h]	0.83 (0.73–0.98)	0.98 (0.87–1.16)
TI	0.63 (0.10–1.40) *	1.03 (0.63–2.29) [a,g]	0.10 (0.07–0.15)	0.14 (0.09–0.25)	0.14 (0.09–0.19)	0.13 (0.10–0.29)	0.14 (0.13–0.18)	0.05 (0.03–0.11) [h]	0.22 (0.15–0.37)	0.29 (0.24–0.42)
H/H	1.17 (0.58–2.11) *	0.78 (0.38–1.17) [c,g]	2.25 (1.53–2.46)	2.26 (1.54–2.63)	2.64 (2.38–2.77)	1.92 (1.42–2.19)	2.28 (2.27–2.57)	4.24 (2.14–5.42)	1.91 (1.69–2.19)	1.18 (0.95–1.24) [c,g]

n—Number; * Significant difference between phyla (Mann–Whitney U test, $p < 0.05$); significant difference between seaweed species (Dunn's tests with Bonferroni adjustment, $p < 0.05$): [a] *Porphyra* spp.; [b] *Palmaria palmata*; [c] *Fucus vesiculosus*; [d] *Himanthalia elongata*; [e] *Laminaria digitata*; [f] *Saccharina japonica*; [g] *Undaria pinnatifida*; [h] *Sargassum fusiforme.*

4. Discussion

Similarly to previous studies, the total lipid content in the seaweeds analyzed was relatively low, ranging from 1.03 g in *P. palmata* to 3.20 g/100 g dw in *Porphyra* spp. However, Sánchez-Machado et al. [32] reported lower levels of lipids in *U. pinnatifida* 1.05 g/100 g, *Porphyra* spp. 1.03 g/100 g and *H. elongata* 0.97 g/100 collected from the Iberian coast. On the other hand, Susanto et al. [33] found that *U. pinnatifida* (5.8 g/100 g) and *S. fusiforme* (4.8 g/100 g) from Japan had lipid concentrations approximately two and five times higher, respectively, than those observed in this study. Dawczynski et al. [34] also reported higher levels of total lipids in dried, commercially available *U. pinnatifida* products (4.5 g/100 g), but the lipid levels in *S. fusiforme* (1.4 g/100 g) and *Porphyra* spp. from Japan and Korea (2.8 g/100 g) were comparable to those recorded in our study. Interestingly, they reported significantly lower levels of total lipids in dried *Porphyra* spp. harvested in China (1.0 g/100 g) [34]. Seasonal variation, environmental conditions, and temperature might play an important role in the observed variation in lipid content in seaweed [35]. Indeed, *P. palmata* harvested in the Forillon region of Quebec, Canada, exhibited significantly lower lipid content in autumn (October) compared to summer (June) (1.65 g/100 g vs. 3.65 g/100 g, $p < 0.05$, respectively) [36]. Similarly, the total lipid content in *U. pinnatifida* fluctuated throughout its growing season between July and December [37]. Furthermore, higher lipid levels were reported in *Ulva* spp. and *U. pinnatifida* samples collected from the cooler waters off the Brittany coast in France, compared to those from the warmer Portuguese shores [38,39]. Additionally, the observed variability of the lipid content within and between seaweed species may be attributed to different lipid extraction procedures [40].

The PCA indicated a clear discrimination of seaweeds according to FA profile, grouping species of the same phylum together. However, despite the observed trend by phylum, it was evident that there are still differences in the FA composition between species belonging to the same phylum. This highlights the considerable variability in lipid metabolism and accumulation across macroalgal species. In addition, the FA composition of the analyzed seaweeds varied widely, even within the same species. Similar to total lipid content, the lipid profile of seaweeds is a distinctive and characteristic feature of each seaweed, influenced by the environmental conditions in which the algae grow [38]. While FA types and lipid classes are species-specific, their relative proportions can vary significantly depending on external factors, including temperature, light, and nutrient availability [39,41]. The increase in content of PUFAs is a key component of macroalgal adaptation to cold-water conditions that allows the regulation of membrane fluidity and thylakoid membrane functioning [26,42]. These variations can lead to distinct lipid profiles within the same species, with shifts in FA composition that are particularly important for human nutrition. The observed significant variability of FA composition within seaweed species may indicate different cultivation conditions, including geographical location, harvest season, nutrient availability, and different post-harvest processing methods. However, the lack of information on the seaweed packaging made it impossible to investigate the impact of these factors on the FA profile of the investigated seaweeds.

Higher levels of SFAs, exceeding 30% of the TFAs, were found in all the analyzed seaweeds, with the exception of *F. vesiculosus* and *U. pinnatifida.* C16:0 was the most abundant FA in *P. palmata*, *S. fusiforme*, *L. digitata*, and *H. elongata*. These results are consistent with previous findings by Sánchez-Machado et al. [32] who reported C16:0 levels of 45.44% in *P. palmata*. On the other hand, C16:0 levels in *F. vesiculosus* and *U. pinnatifida* were much lower and did not exceed 15% of the TFA fraction. These algae were also characterized by a lower proportion of SFAs. Similar findings were found in previous studies, with C16:0 concentrations ranging from 11.51% to 16.90% [32,34,37] and SFAs from

15.41% to 20.39% in *U. pinnatifida's* lipid fraction [32,34,37]. Consistent with our results, Dawczynski et al. [34] reported 30.8% of C16:0 acid and 35.7% of SFAs in the lipid fraction of dried, commercially available *Porphyra* spp. from Japan and Korea, but slightly higher contents in seaweed harvested in China, 37.1% and 44.5% of the TFAs, respectively. In contrast, Sánchez-Machado et al. [32] reported much higher contents of C16:0 and SFAs in dried *Porphyra* spp., comprising 64.95% and 63.19% of the TFAs, respectively. These differences can be related to the type of *Porphyra* species studied, for example, Lopes et al. [43] reported a C16:0 content of 23.3% and SFAs of 37.5% of the TFAs in *P. diocica* and Montone et al. [44] found 6.9% and 8.8% of the TFAs comprised these, respectively, in *P. umbilicalis.*

In all the seaweeds analyzed, MUFAs represented the smallest proportion of all FAs, with the exception of *F. vesiculosus*. The lipid fraction of *F. vesiculosus* contained 29.13% of MUFAs, with C18:1 being the dominant FA, accounting for 28.63% of TFAs. These results are consistent with previous studies that have identified C18:1 as the main FA of *F. vesiculosus*, with its content notably higher than in other seaweed species [41,43,45,46]. Across all the seaweed species examined, C18:1 was the most abundant MUFA, followed by palmitoleic acid (C16:1), while other MUFAs were present at levels below 1% of TFAs. This pattern aligns with earlier research [34,44,46], with only a few seaweed species showing slightly higher levels, approximately 2–3%, of myristoleic acid (C15:1), eicosenoic acid (C20:1), erucic acid (C22:1) or nervonic acid (C24:1) [46,47].

Most importantly, from a nutritional point of view, all of the seaweeds contained a high proportion of PUFA, ranging from 33.21% in *S. fusiforme* to 63.05% of TFAs in *U. pinnatifida* of TFAs. The main n-3 PUFAs identified in the seaweeds were SDA, ALA and EPA, while AA and LA were the major n-6 PUFAs identified. The total PUFA content was similar in Rhodophyta and Ochrophyta, comprising approximately 40% of TFAs, though Rhodophyta was characterized by significantly higher levels of total n-3 and lower levels of total n-6 when compared to brown seaweeds ($p < 0.05$). Interestingly, Premarathna et al. [48] observed higher accumulation of n-3 PUFAs in brown seaweeds. In the red seaweeds, C20 PUFAs were more abundant than C18 PUFAs, whereas in brown seaweeds, the proportions of these two classes were almost equal, a trend also noted in previous reports [32,49].

Consistent with earlier findings [28,46], our results revealed substantial variations in PUFA composition among different seaweed species. Red seaweeds, including *P. palmata* and *Porphyra* spp. had a lower content of LA, ALA and AA compared to brown seaweed species. In addition, PCA revealed a distinct lipid specificity of those two examined red seaweeds; with *P. palmata* discriminated from other seaweed species by C18:0 and DHA, while *Porphyra* spp. Was discriminated by exceptionally high levels of EPA. Many lines of evidence, including randomized controlled trials and case–control and cohort studies, indicate that both EPA and DHA are essential for proper development and growth, including brain function, as well as reducing incidence and mortality from a number of noncommunicable diseases [4,12,50]. Currently, fish and fish oil represent the main dietary sources of these LC n-3 PUFAs. However, rising global demand for fish-derived EPA and DHA may soon outpace supply due to overfishing and climate change. Therefore, it is necessary to look for new sustainable alternatives that can fulfill the growing demand for EPA and DHA [9].

DHA levels were generally low in all the seaweeds analyzed, with the highest concentration observed in *P. palmata* (0.27% of TFAs). One of the main n-3 LC-PUFA was EPA, with the highest content found in *P. palmata* and *Porphyra* spp., 32.18 and 38.91% of TFAs, respectively. Higher concentrations of EPA were reported in *P. palmata* samples collected from the French Brittany coast and a Portuguese aquaculture producer, with levels of 46.6% and 51% of TFAs, respectively [43,51]. In contrast, *P. palmata* powder from

controlled organic cultivation in Ireland contained only 11.28% EPA and 23.26% PUFAs [52]. Mouritsen et al. [53] highlighted significant variation in EPA and PUFA content in *P. palmata* depending on geographical location and storage duration of harvested seaweeds, which may contribute to PUFA degradation. Seasonal variation may also play a role, for example, *P. palmata* harvested in May had 54.2% PUFAs and 46.8% EPA, compared to 37.6% PUFA and 25.1% EPA in samples collected in October [54]. Similarly high levels of PUFAs and EPA were also observed in *Porphyra* spp., in line with previous studies. Commercially available dried *P. umbilicalis* from Spain contained 36.31% EPA, representing 71.60% of the total n-3 PUFAs [55]. However, lower EPA levels were reported in dried *Porphyra* spp. originating from Japan and Korea (20.9%) and from China (10.4%). It is worth noting that all *Porphyra* spp. samples analyzed in this study were harvested in Galicia, Spain.

In contrast, EPA levels were lower in Ochrophyta, with the highest content found in *U. pinnatifida*, at 13.00%, and *L. digitata*, at 3.76%, of TFAs. The main LC- PUFA in the studied brown seaweeds, except *U. pinnatifida*, was AA. Consistent with earlier studies [32,55,56], *U. pinnatifida* was distinguished by very high levels of PUFAs (67.68% of TFAs), including LA, ALA and AA. Similar to other seaweeds, significant seasonal fluctuation of PUFA content was also observed in *U. pinnatifida*, with higher accumulation of n-3 PUFAs in winter and n-6 PUFAs in summer [37,57]. PCA showed clear separation of *U. pinnatifida* from all other brown seaweed species, with its distinctive feature being a high concentration of SDA, aligning with the findings of earlier studies [34,37]. SDA is a nutritionally significant n-3 PUFA that is a metabolic intermediate in the conversion of ALA to EPA and DHA. Because SDA bypasses the first rate-limiting step controlled by delta-6-desaturase in endogenous FA desaturation, it is more efficiently converted to EPA than ALA [58]. Khan et al. [59] observed that SDA isolated from *U. pinnatifida* significantly decreased phorbol 12-myristate 13-acetate-induced mouse ear inflammation by reducing edema, erythema and blood flow.

In addition to the FA composition of food, it is also important to consider the balance between different FAs to evaluate the impact of dietary fat on cardiovascular health. Therefore, several nutritional indices based on the FA profile of foods have been proposed, with AI and TI being the most commonly used [31]. AI indicates the potential of dietary fat to promote atherosclerosis by assessing the proportion between proatherogenic (C12:0, C14:0 and C16:0) and antiatherogenic (sum of UFAs) fat. TI characterizes the thrombogenic potential of FAs by evaluating the relationship between pro-thrombogenic (SFAs) and anti-thrombogenic FAs (MUFAs, n-6 and n-3 PUFAs) [31]. In line with the findings from previous studies, we reported very low AI and TI values in the seaweeds analyzed, especially in *U. pinnatifida* and *Porphyra* spp., indicating that seaweed consumption can be beneficial to cardiovascular health. Similarly, all the seaweeds exhibited low n-6/n-3 ratios, with the highest value of 1.5 observed in *L.* digitata. In contrast, Western diets are characterized by excessive n-6 PUFA intake and insufficient n-3 consumption, especially EPA and DHA, resulting in the n-6/n-3 ratio as high as 20:1, which has been associated with the development of a number of chronic diseases [60]. Interestingly, the sum of EPA and DHA in some of the dried seaweeds studied, such as *U. pinnatifida* and *P. palmata*, was comparable to the levels reported in fresh fish [31,61]. Moreover, the concentration of EPA+DHA found in dried *Porphyra* spp. was two to seven times higher than that found in fresh sea bass, turbot and sea bream [61].

Despite the relatively high EPA content in some of the seaweeds studied, such as *U. pinnatifida*, *P. palmata*, and *Porphyra* spp. they still cannot be considered the only dietary source of LC n-3 PUFAs due to their low total lipid content. To achieve the lowest recommended daily intake of 250 mg of EPA and DHA [62], proposed by the European Food Safety Authority, an individual would have to consume approximately 25 g of *Porphyra* spp. or 100 g of *U. pinnatifida* or *P. palmata*. In comparison, the amounts of sea bass, dentex,

turbot, and sea bream would be 61 g, 21 g, 167 g, and 78 g, respectively [61]. To meet the UK recommendations of 450 mg of EPA and DHA per day [5], the intake of *Porphyra* spp. will need to increase to 42 g and *U. pinnatifida* or *P. palmata* intake to 189 g. However, due to the high accumulation of iodine and potentially toxic elements (PTEs; e.g., cadmium, mercury, arsenic, lead), it is advised to limit seaweed intake to a few grams daily [63–66]. It is worth noting that levels of iodine and PTEs significantly differ between seaweed species, with higher concentrations reported, for example, in *Laminaria* spp., and lower concentrations found in *Porphyra* spp. [53,67]. In addition, their levels can be significantly affected by food preparation and cooking methods. Stévant et al. [68] reported that blanching (45 °C) using salt water reduced the iodine content in *Saccharina latissima* to levels that are considered safe for food applications. Importantly, this method also provided good nutrient retention, with no loss of FAs observed. The levels of cadmium, mercury, and arsenic in *Pyropia* spp. could be reduced by 80.8–83.0% and iodine by 90.1% by using ultrasonic treatment [69]. The effects of different seaweed preparation and cooking methods on iodine, heavy metal and PUFA levels therefore need to be further explored.

Incorporation of seaweed as a functional ingredient in innovative food products might offer a promising strategy to increase the intake of LC-PUFAs and enhance the n-6/n-3 FA ratio in Western diets. It was reported that the addition of 5.6% of dried *H. elongata*, *U. pinnatifida* or *P. umbilicalis* to low-salt meat emulsion model systems enhanced n-3 PUFA content and reduced the n-6/n-3 PUFA ratio [70]. Prabhasankar et al. [71] found that pasta with 10% of *U. pinnatifida* added had an n-6/n-3 ratio reduced from 1:15.2 to 1:3.4. However, adding 5.5% of dried *H. elongata* to low-fat frankfurters produced only a minor change in their FA profile, which might be related to the low lipid content in seaweed and the small amount added [72]. In contrast, frankfurters enriched with the microalga *Schizochytrium* sp. oil were characterized by high n−3 LC-PUFA contents [72]. This suggests that incorporation of seaweed into food products might require lipid extraction; therefore, the development of efficient, cost-effective extraction methods with the application of food-grade solvents is needed. Recent studies showed that ethyl acetate and ethanol offer a promising approach for efficient extraction of PUFA-rich lipid extracts from macroalgae [73,74]. It also needs to be considered that the use of seaweed as an ingredient in the food industry often requires dehydration before further processing. n-3 LC-PUFA in the presence of oxygen, light, heat, and prooxidants are highly prone to oxidation, which may decrease their nutritional value [75]. Therefore, the lipid profile of seaweed, especially the content and composition of PUFAs, might be affected by the drying method [47,76]. Freeze-drying promoted the highest retention of unsaturated FAs in *Sargassum hemiphyllum* and *Sargassum oligocystum* [47,76]. However, it was also observed that concentrations of nutrients and bioactive compounds, including FAs, are influenced not only by the drying method but also by seaweed species used, with no single drying procedure identified as consistently superior for all species [76,77]. In addition, Harrysson et al. [78] observed that storage conditions of dried *Porphyra umbilicalis* and *Ulva fenestrate* induced loss of PUFAs, including EPA. Dried seaweed products stored at room temperature in light and semi-light conditions lost almost all their PUFAs during 370 days of storage, with a lower PUFA degradation observed when stored in the dark. Surprisingly, oven-drying was superior to freeze-drying for maintaining the nutritional quality of *P. umbilicalis* and *U. fenestrate* lipids during storage [78]. Schmid et al. [73] found that PUFA loss in freeze-dried *Laminaria digitata* and *P. palmata* can be significantly reduced if seaweeds are stored at 4 °C and may be prevented at −20 °C. Importantly, no oxidation of PUFAs was observed in the scones after heating the dough with added *U. pinnatifida* at 190 °C for 30 min [79]. In contrast, boiling of *Ulva lactuca* resulted in a substantial reduction in MUFA and PUFA levels [80].

Our results indicate that *U. pinnatifida*, *P. palmata*, and *Porphyra* spp. are the most promising seaweed species for providing n-3 LC-PUFAs in human diets, particularly EPA. *U. pinnatifida* and *Porphyra* spp. are among the five seaweed species that account for 98% of current global seaweed production and are key macroalgae for human consumption. These species have been consumed in Asia for centuries and have recently become a popular food ingredient in Europe [28]. In contrast, *P. palmata* is associated with long-lasting dietary traditions in Europe and North America and is one of the most popular seaweed species among Western consumers [81]. Asia accounts for 97% of global seaweed production, and Europe contributes only 0.8% [82]. However, the European algae sector has considerable potential for the development of the seaweed industry due to the large availability of cultivation areas and favorable environmental conditions [82]. To increase lipid accumulation, especially n-3 LC-PUFA content in seaweeds, the development of cultivation methods by the manipulation of environmental conditions and genetic engineering might be explored. Importantly, seaweed cultivation requires fewer resources than terrestrial plants or animal agriculture, consequently offering a sustainable, low-carbon alternative to conventional n-3 LC-PUFA sources [22]. At the same time, seaweed farming and processing create employment opportunities that support and stimulate local economic growth [22]. Seaweeds also absorb excess carbon dioxide, nitrogen and phosphorus, which may help to reduce ocean eutrophication and acidification [82].

This study has several limitations. Although the FA profile of commercially available seaweed products was evaluated, the effects of preparation and cooking methods on FA content were not assessed. In addition, insufficient packaging information prevented analysis of the impact of geographical region, harvesting season, and environmental conditions on the FA profile of the seaweeds analyzed. Furthermore, the bioavailability of FAs may differ from the measured total FA levels. Finally, the unequal number of seaweed samples per species could reduce the power of statistical analysis.

5. Conclusions

Our results indicate that dried, commercially available seaweed products may be a promising, sustainable plant-based source of n-3 LC-PUFAs, especially EPA, in the human diet. Furthermore, all of the seaweeds exhibited low n-6/n-3 FA ratios and can be potentially used as a functional ingredient to increase the intake of n-3 PUFA and improve the n-6/n-3 FA ratio in Western diets. However, elevated levels of iodine and heavy metals in seaweeds currently limit their safe consumption and may hinder their broader application as a PUFA source. Future research is needed to optimize the environmental conditions of seaweed cultivation, including salinity, temperature, season and nutrient availability to produce seaweeds with desirable FA profiles, particularly by increasing EPA and DHA while reducing iodine and heavy metal content. Additionally, studies on the effects of drying methods on PUFA retention, oxidative stability and digestibility, as well as the development of efficient, cost-effective lipids extraction and purification methods with the application of food-grade solvents, are warranted.

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