Journal of Applied Phycology
https://doi.org/10.1007/s10811-023-03114-9

RESEARCH

# Fatty acid composition of different morphological structures in the sub-Antarctic kelps *Macrocystis pyrifera* (L.) C. Agardh and *Lessonia flavicans* Bory of the Magellan Ecoregion: Nutritional and biomedical potentials

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Received: 25 April 2023 / Revised: 23 September 2023 / Accepted: 28 September 2023


## Abstract

The sub-Antarctic Magellan Ecoregion is a unique biogeographic area located at the southern tip of South America, which has exceptional marine flora and high endemism. Along the coastline, the ochrophytes *Macrocystis pyrifera* and *Lessonia flavicans* form vital underwater forests that serve as critical habitats, providing shelter, food and breeding grounds for a diverse marine organisms. These algal species are also important components used in the food industry and biomedicine, due to their high lipid, amino acid and fiber content. In this study, we investigated the intra-thallus variation of fatty acids among the different morphological structures (fronds, stipes and holdfast) of *M. pyrifera* and *L. flavicans* collected in Rinconada Bulnes during spring, 2021. The stipes of *M. pyrifera* (3.73 ± 1.73%) and the fronds of *L. flavicans* (3.35 ± 0.97%) both exhibited high lipid content. Saturated fatty acids were highest in the holdfast of *M. pyrifera* (37.82 ± 0.06%) followed by the fronds of *L. flavicans* (34.30 ± 0.10%). Notably, monounsaturated fatty acids showed higher levels en the holdfast of *L. flavicans* (46.45 ± 0.19%) followed by the stipes of *M. pyrifera* (43.04 ± 0.08%). The fronds of both *M. pyrifera* (32.38 ± 0.26%) and *L. flavicans* (28.89 ± 0.23%) showed high levels of polyunsaturated fatty acids. These findings provide valuable insight into the intra-thallus variation of fatty acids in different morphological structures of *M. pyrifera* and *L. flavicans*, highlighting their potential nutritional and biomedical importance as the most representative kelps in the Magellan region.

**Keywords** Phaeophyceae · Fatty acids profile · *Macrocystis* thallus · *Lessonia* thallus · Kelp uses · Biomedical potential, Magellan region

## Introduction

Macroalgae increasingly have shown great potential over the years due to their multiple uses and applications, ranging from everyday life to large-scale industries (Ganesan et al. 2019). They contain a significant amount of phycocolloids (e.g. agar, carrageenans and alginates), which are widely used in the food, cosmetic, pharmaceutical and biotechnological industries (Kelly and Brown 2000; Mansilla et al. 2012; Wan et al. 2019; Leandro et al. 2020; Pereira et al. 2021). Several studies demonstrate the benefits of macroalgae as nutraceuticals due to their significant lipid, amino acid and fiber content (Harnedy and FitzGerald 2013; Flachs et al. 2014; Astorga-España et al. 2017; Athyros et al. 2018; Husni 2018; Afonso et al. 2019; Cikoš et al. 2020), and their potential applications in human health to fight pathologies of high prevalence and public health impact such as cancer, stroke, hypertension, type II diabetes, gastrointestinal disorders, osteoporosis, immune disorders, arthritis and influenza, among others (Mendis and Kim 2011; Collins et al. 2016; Quitral et al. 2019; Do-Amaral et al. 2020).

The sub-Antarctic Magellan Ecoregion (47°-56°S; 71°-73°W) of Chile has unique environmental conditions due to its location at the southern tip of South America (Rozzi et al. 2012). The diverse and abundant flora and fauna in this region may be due to the presence of various oceanographic gradients (influenced by the Pacific, Atlantic and Southern Oceans) and substrate types (e.g. sandy beaches, terraces, boulders and pebbles). This region is exposed

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to seasonal changes in abiotic parameters including temperature, salinity, photoperiod and solar radiation, which play a significant role in shaping the ecosystem (Dayton 1985; Silva and Calvete 2002; Ojeda et al. 2014). The high environmental heterogeneity of this region allows the occurrence of a benthic marine flora with high endemism, which hosts the largest reserves of submerged brown alga forests, with a predominance of the species *Lessonia flavicans* Bory, *Lessonia searlesiana* Asensi and de Reviers, *Durvillaea antarctica* (Chamisso) Hariot and *Macrocystis pyrifera* (L.) C. Agardh (Mansilla et al. 2020; Marambio et al. 2020) The last two species have wide dominance and extension, with populations parallel to the coast (30–45 m wide, Mansilla and Ávila 2011). They are considered as ecosystem engineers, forming habitats that provide shelter, food and breeding places for different species of great biological and economic importance in these sub-Antarctic environments (Ramírez 2010; Mansilla and Ávila 2011; Marambio et al. 2020).

Sub-Antarctic macroalgae are exposed to environmental stressors characteristic of high latitudes such as cold temperature, which induces the biosynthesis of unsaturated fatty acids in macroalgae. This is a mechanism of acclimatization to low temperatures (Khotimchenko and Yakovleva 2005; Koch et al. 2016; Barkina et al. 2020; Ho et al. 2021; Chemello et al. 2022). Environmental stress triggers alterations in several physiological processes, generating an increase in reactive oxygen species (ROS); lethal increase in ROS promotes "signaling molecules" originating defensive genes and adaptive responses. These adaptive strategies allow toleration of environmental stress through a set of antioxidant enzymes and metabolites such as polyunsaturated fatty acids (PUFA). These compounds contribute to controlling cellular levels of ROS and minimizing the detrimental effects of oxidative stress, preserving the cellular redox state and homeostasis of organisms, thus controlling internal conditions in the face of environmental changes (Kumar et al. 2014; Chemello et al. 2022).

The lipid composition of macroalgae has attracted considerable interest recently, due to their high PUFA content, particularly α-linolenic (18:3n -3), stearidonic (18:4n-3), arachidonic (20:4n-6) and eicosapentaenoic (20:5n-3) acids, which are essential dietary components in humans and animals (Kendel et al. 2015; Da Costa et al. 2019; Do-Amaral et al. 2020). These PUFA also possess antimicrobial, antiviral, anti-inflammatory and antitumor properties (Kendel et al. 2015; Da Costa et al. 2019; Do-Amaral et al. 2020; Saini et al. 2021; Kargın and Bilgüven 2022) and play a crucial role in the prevention of cardiovascular disease, osteoarthritis and diabetes (Marinho et al. 2015; Da Costa et al. 2019; Pereira et al. 2021; Rocha et al. 2022; Healy et al. 2023). Macroalgae have been suggested as potential candidates for PUFA supply, showing higher concentrations than those found in terrestrial vegetables (Marinho et al. 2015).

Several studies have explored the variation of fatty acids in brown macroalgae, particularly intra-thallus variation. Khotimchenko and Kulikova (2000) analyzed the fronds (upper, middle and lower) of *Saccharina japonica* and reported elevated levels of PUFA (n-6) in the lower zone (29.8 ± 1.5%) and PUFA (n-3) in the upper zone (30.7 ± 2.1%) of the frond. Gosch et al. (2015a) conducted a seasonal study over a year, examining intra-thallus variation between sections (end, middle and base) of the species *Spatoglossum macrodontum*. They observed consistently high levels of PUFA in all sections of the species, with a peak in June (~ 40%), while the basal section exhibited higher monounsaturated fatty acids (MUFA) (32.16 ± 0.43%) in September. Gosch et al. (2015b) explored the seasonal and intra-thallus fatty acid variation of the species *Dictyota bartayresii* and *Dictyopteris australis* in frond sections (upper and lower; terminal, middle and basal, respectively), finding a slight increase from the upper to lower sections of *D. bartayresii*, with high levels of MUFA (~ 30.5%) in summer and PUFA (~ 37.2%) in winter. In the case of *D. australis*, they showed a pattern of increasing MUFA from the terminal to the basal Sect. (27.3 ± 10.4%) in summer, whereas PUFA did not show an intra-thallus variation pattern and high levels were observed in the middle Sect. (42.8 ± 3.4%) in winter. Schmid and Stengel (2015) investigated five species of Laminariales (*Alaria esculenta, Laminaria digitata, Laminaria hyperborea, Saccharina latissima* and *Saccorhiza polyschides*) and three species of Fucales (*Ascophyllum nodosum, Fucus serratus* and *Himanthalia elongata*). They observed a pattern of intra-thallus variation with decreasing MUFA content (from the ends of the fronds towards the holdfast) in the Laminariales species with high levels in *L. hyperborea* (29.3 ± 2.2%), while an opposite distribution pattern was evident (from the holdfast towards the end of the fronds) for PUFA, with high levels in *L. digitata* (55.5 ± 1.4%). No distinct distribution pattern was observed in the Fucales species, but high levels of MUFA (45.4 ± 1.3%) and PUFA (54.6 ± 0.9%) were found at the fronds ends of *A. nodosum* and *H. elongata*, respectively.

Previous studies conducted at lower latitudes (27° S) of Chile explored fatty acid variation in the brown macroalgae *M. pyrifera* and *D. antartica* (Ortiz et al. 2006, 2009). However, only Ortiz et al. (2006) specifically investigated the intra-thallus variation in *D. antartica* (in fronds and stipes), reporting high levels of MUFA (38.11 ± 0.12%) and PUFA (34.42 ± 1.90%) in fronds compared to stipes (29.21 ± 1.13% and 29.23 ± 2.20%, respectively). Several studies in the Magellan region have analyzed fatty acids in *M. pyrifera,*

*D. antarctica* and *L. flavicans* (Mansilla and Ávila 2011; Astorga-España and Mansilla 2014; Astorga-España et al. 2017; Santos et al. 2019). However, none of these studies addressed the intra-thallus variation in the most representative kelps of the region.

The rise in chronic diseases over recent decades is a global concern, impacting the quality of life and exerting a significant economic burden on both public and private health systems (Crespo et al. 2020). According to the Chilean Ministry of Health, the Magellan region faces high rates of prevalent diseases like type 2 diabetes mellitus, obesity and hypertension. In fact, 13.4% of the region´s population (total population 166,533, National Health Survey, 2016–2017) have been diagnosed with hypertension, and an estimated additional 13% are likely unaware of their condition (Fernandez 2019). Data from the National Health Survey (2016–2017), reveal that 80.2% of the population in Magellan suffers from obesity, attributed to a sedentary lifestyle, high meat consumption and low intake of fruits and vegetables, partly due to the adverse climatic conditions and isolation inherent to a remote and extreme region. However, the Magellan region possesses untapped potential that offers and ideal opportunity to address these prevalent diseases among the local population. The abundant macroalga populations in sub-Antarctic ecosystems, thriving in harsh environmental conditions with constant low temperatures, low irradiance and extended photoperiods, represent a vital source of biomolecules, particularly with high concentration of fatty acids. Understanding these biomolecules is essential for future biomedical research and their potential incorporation into a healthy diet.

Owing to the environmental extremes found in high latitudes, such as permanent low temperatures, it is anticipated that the sub-Antarctic kelps *M. pyrifera* and *L. flavicans* will exhibit higher levels of unsaturated fatty acids compared to other low latitude macroalgae. The aim of this study is to assess the fatty acid concentration in the different morphological structures (fronds, stipes and holdfast) of these two significant kelp species from the sub-Antarctic Magellan Ecoregion, given their potential applications in biomedicine.

## Materials and methods

**Field sampling** Twelve adult individuals (6 individuals for both *M. pyrifera* and *L. flavicans*) were collected at Rinconada Bulnes, Puerto del Hambre (53°35'47.76" S; 70°56'08.52" W), located south of Punta Arenas, Chile (Fig. 1) during spring of 2021. For each species, the collected individuals ranged from 1 - 1.5 m in length. All samples were transported through a seawater cooler to the Laboratory of Antarctic and sub-Antarctic Marine Ecosystems (LEMAS) at the University of Magellan. Upon arrival at the laboratory, the samples were carefully separated by structure (fronds, stipes and holdfast), followed by washing with distilled water to remove epiphytes and seawater from the thallus according Schmid et al. (2018). Subsequently, 300 g of fresh biomass was collected from each thallus structure. The collected samples were then frozen at -80 °C and subsequently lyophilized at -50 °C. For lipid extraction, 30 g of dried biomass per structure of each species was used.

**Lipid extraction** For lipid extraction, 3.0 g of lyophilized samples were used (n = 9 for *M. pyrifera* and n = 9 for *L. flavicans*) following the method described by Bligh and Dyer (1959). Each thallus structure (n = 3 for both species) was ground through a motor-driven mill (Thomas Scientific) and weighed in 150 mL beakers. Lipids were extracted by adding 10 mL chloroform, 20 mL methanol and 8 mL distilled water in proportions $CHCl_3$:$CH_3OH$:$H_2O$ (1:2:0.8). The mixture was homogenized for 3 min using an Ultra-Turrax disperser (IKA T25, USA) and the homogenate was filtered under vacuum through Whatman No.1 filter paper. The samples were re-extracted using the same procedure to recover as much extract as possible. The filtrate was transferred to a 100 mL graduated cylinder where its volume was measured and the missing amounts of chloroform and water were immediately added to reach the ratio $CHCl_3$:$CH_3OH$:$H_2O$ (2:2:1.8). After phase separation and clarification for 10 min, the chloroform phase containing the lipids was extracted using a Pasteur pipette and transferred to a pre-weighed 250 mL flask. The chloroform was evaporated using a vacuum rotary evaporator for 20 min at 45 °C, and the solvents were completely removed under a nitrogen gas stream. The total lipid content was measured gravimetrically and stored in hermetically sealed tubes containing a mixed chloroform: methanol solvent solution with 0.01% butylated hydroxytoluene (BHT) in a nitrogen atmosphere. The tubes were kept in the dark at -80 °C.

**Fatty acid esterification** The dried lipid extracts were transformed into fatty acid methyl esters (FAME) using the method of Metcalfe et al. (1966), with some modifications to simplify the weighing. Specifically, 20 mg of the sample was weighed in screw-capped test tubes, and 1.5 mL 0.50 M methanol-sodium hydroxide was added. The tubes were tightly stoppered, vortexed, and heated at 100 °C for 5 min. After cooling to room temperature, 2.0 mL of 14% boron trifluoride ($BF_3$) in methanol (Supelco, USA) was added and the tubes were capped, vortexed, and block heated at 100 °C for 30 min which was followed by the addition of hexane (1.0 mL) and vortex mixing for 30 seg. To facilitate phase extraction, 5.0 mL saturated NaCl was added to the mixture. The solution was centrifuged, and the hexane layer was transferred to a second tube. The methanol–water phase was

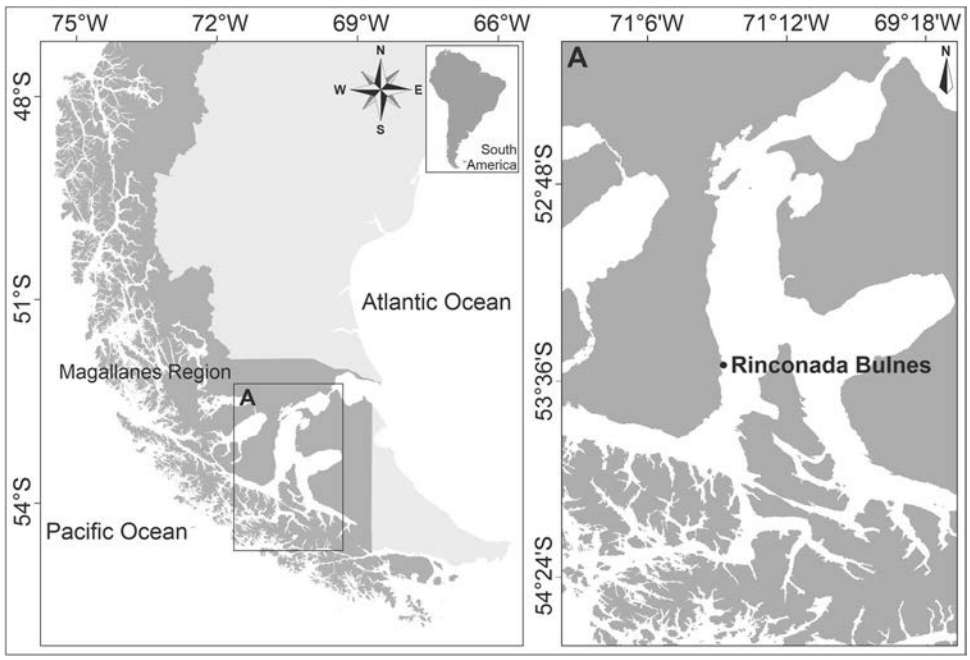


**Fig. 1** Sampling site of *M. pyrifera* and *L. flavicans* individuals in Rinconada Bulnes (53°35'47.,76″S; 70°56'08.52″W), Magellan region, Chile

extracted again with 1.0 mL hexane. The hexane extracts were combined and concentrated to 1 mL under a nitrogen stream before gas chromatographic analysis.

**Gas chromatographic analysis** The analysis was carried out using an Agilent model 7890B gas chromatograph equipped with an autosampler and a flame ionization detector. The identification of methyl ester fatty acids was performed by comparing their retention times on the Agilent HP-88 column (60 m × 0.25 mm × 0.20 µm) with the retention times of high-purity 37-component FAME MIX standards (Sigma Aldrich, USA). A flow split injection system with a 50:1 vent ratio was used; the carrier gas ($H_2$) flow rate was 1 mL $min^{-1}$. The injector temperature was 250 °C, and the detector temperature was 280 °C. The oven temperature program started at 120 °C for 5 min, followed by a ramp of 3 °C $min^{-1}$ to 220 °C, which was then maintained for 5 min.

## Data analysis

Statistical analysis was performed at 95% confidence level ($p = 0.05$) using STATISTICA software version 7.1. A factorial analysis of variance (ANOVA) was performed to compare the lipid composition between the factors (species, structure, species-structure) of *M. pyrifera* and *L. flavicans*. When the results were significant ($p < 0.05$), a Tukey test was performed to verify the significant difference between them. The non-parametric Kruskal–Wallis test (Siegel and Castellan 1988) was used to compare the means of multiple variables, investigating the differences in fatty acids among the structures (fronds, stipes and holdfast) of each macroalga species. This test was chosen due to its ability to handle data without assuming a normal distribution (Kruskal and Wallis 1952), (STATISTICA software, version 7.1). To explore the relationships between the structures (fronds, stipes and holdfast) of *M. pyrifera* and *L. flavicans* and the fatty acid composition, Principal Component Analysis (PCA) (Jolliffe 1986) was employed with the 'factoextra' package in R v4.2.0 (R Development Core Team 2022). A two-way permutational analysis of variance (PERMANOVA) (Anderson 2001) was utilized to assess the differences in fatty acid composition between the macroalga species and their structures (fronds, stipes and holdfasts). PERMANOVA calculated the Euclidean dissimilarity distance between observations pairs using non-transformed data and 9999 permutations. All factors were treated as fixed (Galloway et al. 2012), and the homogeneity of the multivariate dispersion was tested using the PERMDISP function, yielding non-significant results (Anderson and Walsh 2013). Multivariate analysis was conducted using PRIMER 6 v6.1.13 software with the PERMANOVA + v1.0.3 add-on package (Clarke and Gorley 2006) (PRIMER-E, Ltd., UK).

## Results

The lipids composition was significantly different between the structures for each species ($p < 0.05$, Online Resource 1). In the case of *M. pyrifera*, the values were found to be more concentrated in the stipes (3.73 ± 1.73%), followed by the fronds (2.74 ± 0.70%) and the holdfast (1.38 ± 0.08%). On the other hand, the lipid composition of *L. flavicans* increased in the following order: holdfast (1.26 ± 0.15%), stipes (2.27 ± 0.66%), fronds (3.35 ± 0.97%), (Online Resource 2).

The three thallus structures of *M. pyrifera* displayed similar percentages (35.09 ± 0.11%; 35.77 ± 0.28%; 37.82 ± 0.06%) of total saturated fatty acids (SAFA), while the highest percentages of MUFA were found in the stipe (43.04 ± 0.08%) and the holdfast (41.65 ± 0.21%), nearly doubling the percentage obtained in the fronds (26.46 ± 0.10%). Fronds exhibited the highest percentage of PUFA (32.38 ± 0.26%), followed by stipes (21.99 ± 0.17%) and holdfasts (18.24 ± 0.17%), (Fig. 2a). The total SAFA of *L. flavicans* was higher in fronds (34.30 ± 0.10%) and holdfasts (32.01 ± 0.19%) than in stipes (27.59 ± 0.06%), while the total percentage of MUFA was highest in the holdfast (46.45 ± 0.19%), similar to that found in stipes (43.64 ± 0.04%), and twice the concentration found in fronds (29.46 ± 0.13%). The total percentage of PUFA was higher in fronds (28.89 ± 0.23%) and stipes (27.71 ± 0.05%) than in holdfasts (18.39 ± 0.21%), (Fig. 2b). A total of 16 fatty acids, including 6 saturated, 3 monounsaturated and 8 polyunsaturated fatty acids, were identified in the different thallus structures of *M. pyrifera* and 14 fatty acids; 5 saturated, 4 monounsaturated, and 5 polyunsaturated fatty acids were found in its thallus structures of *L. flavicans* (Table 1 and Figs. 3 and 4).

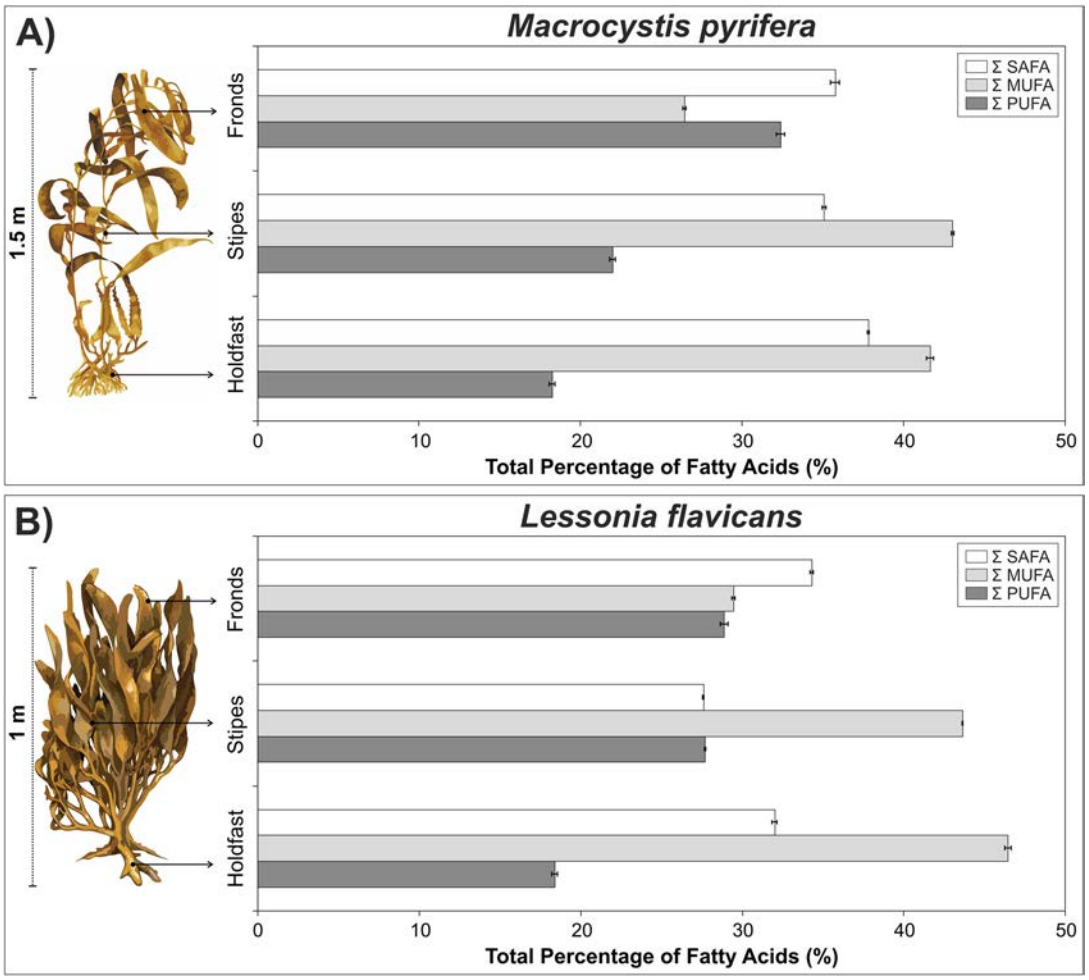


**Fig. 2** Total percentage (%) of saturated, monounsaturated and polyunsaturated fatty acids of **A**) *M. pyrifera* and **B**) *L. flavicans* (fronds, stipes and holdfast), in Rinconada Bulnes (53°35'47,76″S; 70°56'08,52″W), Magellan region, Chile (n = 9 for *M. pyrifera* and n = 9 for *L. flavicans*). Data are given as percentage of total fatty acid content and are presented as mean values of triplicate samples ± SD

**Table 1** Percentage profile (%) of saturated, monounsaturated and polyunsaturated fatty acids in *M. pyrifera* and *L. flavicans* (fronds, stipes and holdfast), Magellan region, Chile. (n = 9 for *M. pyrifera* and n = 9 for *L. flavicans*). Data are given as percentage of total fatty acid content and are presented as mean values of triplicate samples ± SD. (-) Not detected

| Fatty acids | Chemical formulae | Percentage fronds (mean ± SD) | | Percentage stipes (mean ± SD) | | Percentage holdfast (mean ± SD) | |
|---|---|---|---|---|---|---|---|
| | | *M. pyrifera* | *L. flavicans* | *M. pyrifera* | *L. flavicans* | *M. pyrifera* | *L. flavicans* |
| Tridecanoic acid | C13:0 | 1.26 ± 0.01 | - | - | - | - | - |
| Myristic acid | C14:0 | 11.50 ± 0.05 | 7.13 ± 0.02 | 14.55 ± 0.06 | 4.69 ± 0.01 | 14.54 ± 0.12 | 5.30 ± 0.2 |
| Pentadecanoic acid | C15:0 | 1.02 ± 0.34 | - | - | - | 0.24 ± 0.34 | 0.80 ± 0.01 |
| Palmitic acid | C16:0 | 20.82 ± 0.09 | 26.05 ± 0.09 | 18.55 ± 0.06 | 20.48 ± 0.02 | 20.74 ± 0.16 | 23.83 ± 0.12 |
| Palmitoleic acid | C16:1n-7 | 2.82 ± 0.01 | 2.21 ± 0.01 | 2.69 ± 0.01 | 4.40 ± 0.00 | 3.99 ± 0.01 | 4.98 ± 0.08 |
| Stearic acid | C18:0 | 0.56 ± 0.01 | 1.05 ± 0.00 | 1.04 ± 0.02 | 1.00 ± 0.00 | 1.28 ± 0.02 | 1.01 ± 0.00 |
| Oleic acid | C18:1n-9c | 11.44 ± 0.06 | 11.44 ± 0.04 | 22.03 ± 0.05 | 13.07 ± 0.00 | 23.27 ± 0.18 | 22.55 ± 0.10 |
| Linolelaidic acid | C18:2n-6t | 0.21 ± 0.30 | - | - | - | - | - |
| Linoleic acid | C18:2n-6c | 4.33 ± 0.01 | 4.10 ± 0.05 | 4.30 ± 0.06 | 6.14 ± 0.06 | 4.45 ± 0.04 | 7.71 ± 0.04 |
| Arachidic acid | C20:0 | 0.63 ± 0.00 | - | 0.88 ± 0.02 | 1.42 ± 0.05 | 1.05 ± 0.00 | 0.97 ± 0.01 |
| Linolenic acid | C18:3n-3 | 5.69 ± 0.03 | 5.53 ± 0.02 | 3.35 ± 0.01 | 4.04 ± 0.00 | 2.23 ± 0.04 | 1.57 ± 0.01 |
| Octadecatetraenoic acid | C18:4n-3 | 9.42 ± 0.04 | 6.59 ± 0.06 | 3.80 ± 0.06 | 5.16 ± 0.05 | 2.32 ± 0.02 | 1.96 ± 0.13 |
| γ-Linolenic acid | C18:3n-6 | - | - | - | 0.92 ± 0.01 | - | 1.82 ± 0.01 |
| 8,11,14-cis-Eicosatrienoic acid | C20:3n-6 | 0.79 ± 0.01 | - | 1.40 ± 0.13 | - | 1.45 ± 0.16 | - |
| Arachidonic acid | C20:4n-6 | 0.63 ± 0.02 | 1.78 ± 0.06 | 1.33 ± 0.02 | - | 0.69 ± 0.12 | - |
| 5,8,11,14,17-cis-Eicosapentanoic acid | C20:5n-3 | 10.13 ± 0.02 | 10.89 ± 0.38 | 7.10 ± 0.10 | 11.44 ± 0.00 | 5.99 ± 0.06 | 5.34 ± 0.05 |
| Eicosatetraenoic acid | C20:4n-3 | 1.18 ± 0.03 | - | 0.72 ± 0.05 | - | 1.12 ± 0.10 | - |
| 11-cis Eicosanoic acid | C20:1n-9 | - | - | - | 2.83 ± 0.03 | - | 2.90 ± 0.02 |
| Erucic acid | C22:1n-9 | 12.13 ± 0.03 | 15.74 ± 0.07 | 18.27 ± 0.04 | 23.36 ± 0.01 | 14.25 ± 0.04 | 16.09 ± 0.25 |
| Omega 3 | Σ*n*-3 | 26.42 ± 4.57 | 23.01 ± 4.41 | 14.97 ± 2.73 | 20.65 ± 4.34 | 11.65 ± 2.16 | 8.87 ± 1.98 |
| Omega 6 | Σ*n*-6 | 5.96 ± 1.57 | 5.88 ± 1.58 | 7.02 ± 1.59 | 7.06 ± 2.29 | 6.59 ± 1.64 | 9.52 ± 2.88 |

The results for omega-3 and omega-6 and in *M. pyrifera* revealed an increase in omega-3 levels from the holdfast (11.65 ± 2.16%), stipes (14.97 ± 2.73%) to the fronds (26.42 ± 4.57%), while omega-6 levels remained constant across all three structures within a similar range (6.59 ± 1.64%; 7.02 ± 1.59% and 5.96 ± 1.57%, respectively). The omega-6 levels of *L. flavicans* increased from the fronds (5.88 ± 1.58%), stipes (7.06 ± 2.29%) to the holdfast (9.52 ± 2.88%), while omega-3 levels decreased from the fronds (23.01 ± 4.41%), stipes (20.65 ± 4.34%) to the holdfast (8.87 ± 1.98%), (Table 1).

Each of the more abundant fatty acids in the structures of *M. pyrifera* accounted for 10% or more of the fatty acid profile. These fatty acids were C14:0 (11.50 ± 0.05%), C16:0 (20.82 ± 0.09%), C18:1n-9c (11.44 ± 0.06%), C20:5n-3 (10.13 ± 0.02%) and C22:1n-9 (12.13 ± 0.03%) in the fronds. In the stipes, they were C14:0 (14.55 ± 0.07%), C16:0 (18.55 ± 0.07%), C18:1n-9c (22.03 ± 0.05%), C22:1n-9 (18.27 ± 0.04%); in the holdfast they were C14:0 (14.54 ± 0.12%), C16:0 (20.74 ± 0.16%), C18:1n-9c (23.28 ± 0.18%), and C22:1n-9 (14.25 ± 0.04%) (Fig. 3, Table 1). The most representative acids in both the fronds and stipes of *L. flavicans* species were C16:0 (26.05 ± 0.09%; 20.48 ± 0.02%), C18:1n-9c (11.44 ± 0.04%; 13.07 ± 0.00%), C20:5n-3 (10.89 ± 0.38%; 11.44 ± 0.00%) and C22:1n-9 (15.74 ± 0.07%; 23.36 ± 0.01%), while in the holdfast they were C16:0 (23.83 ± 0.12%), C18:1n-9c (22.55 ± 0.10%) and C22:1n-9 (16.09 ± 0.25%), (Fig. 4 and Table 1).

Statistical analysis revealed significant differences in the fatty acid profile among the three *M. pyrifera* structures (Online Resource 3). In SAFA compounds, both stearic acid (C18:0) and arachidic acid (C20:0) exhibited significant differences ($p > 0.02$) between fronds and holdfasts, with higher values in holdfasts (1.27 ± 0.02% and 1.05 ± 0.00%, respectively). Significant differences in MUFA compounds ($p > 0.02$) were found for palmitoleic acid (C16:1n-7) between stipes (2.69 ± 0.01%) and holdfast (3.99 ± 0.01%), oleic acid (C18:1n-9c) between fronds (11.44 ± 0.06%) and

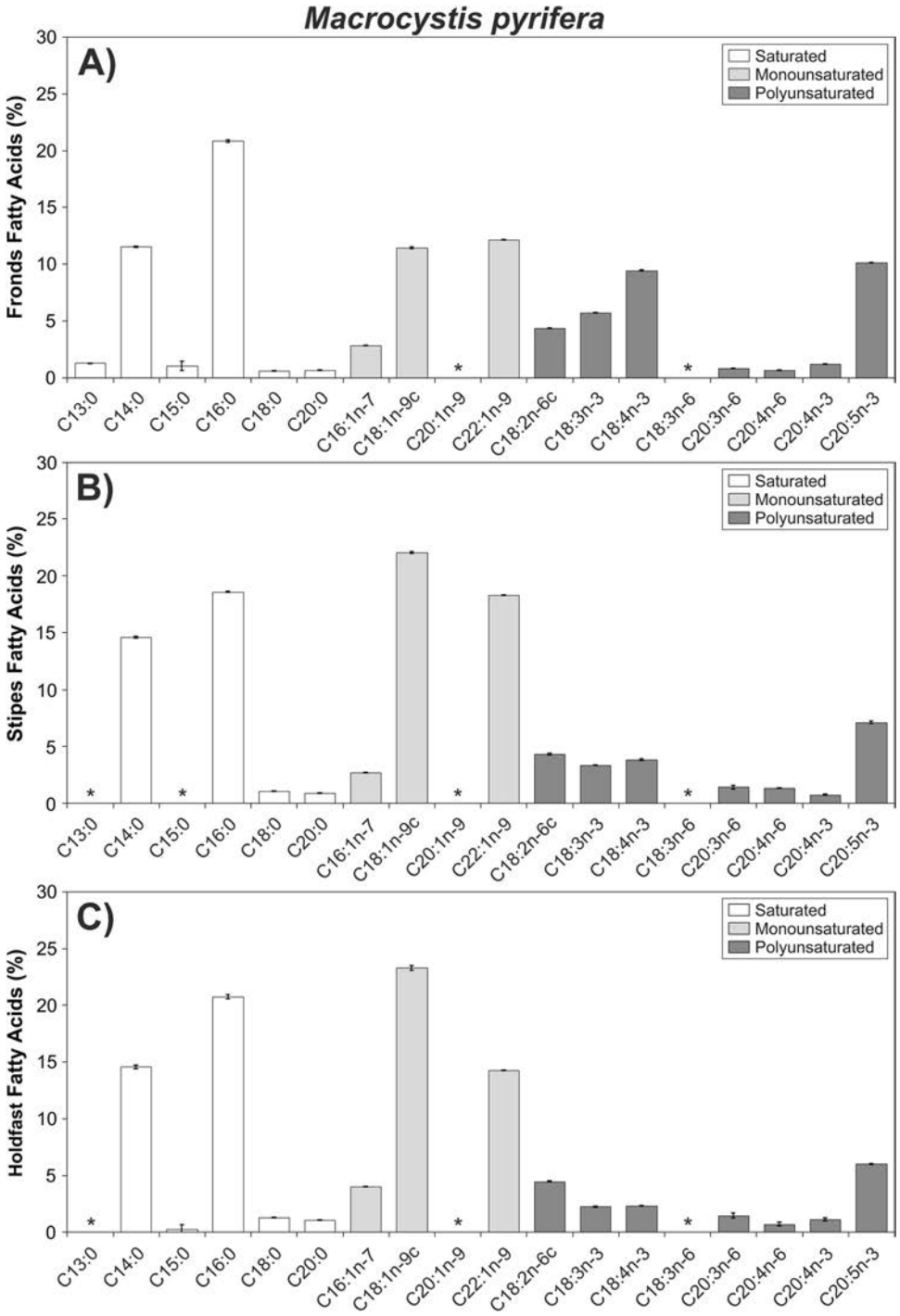


**Fig. 3** Percentage (%) of identified fatty acids (saturated, monounsaturated and polyunsaturated) from *M. pyrifera* **A**) fronds, **B**) stipes and **C**) holdfast, in Rinconada Bulnes (53°35'47.76″S; 70°56'08.52″W), Magellan region, Chile (n = 9 for *M. pyrifera* and n = 9 for *L. flavicans*). Data are given as percentage of total fatty acid content and are presented as mean values of triplicate samples ± SD. (*) Not detected

holdfast (23.27 ± 0.18%), and erucic acid (C22:1n-9) between fronds (12.13 ± 0.03%) and stipes (18.27 ± 0.04%). Significant differences ($p > 0.022$) were also observed between fronds and holdfast for PUFA compounds linolenic acid (C18:3n-3) (5.69 ± 0.03%; 2.23 ± 0.04%), octadecatetraenoic acid (C18:4n-3) (9.42 ± 0.04%; 2.32 ± 0.02%) and eicosapentaenoic acid (C20:5n-3) (10.13 ± 0.02%; 5.99 ± 0.06%).

Statistical analyses also revealed significant differences among the three structures For *L. flavicans* (Online Resource 4). Significant differences in SAFA ($p = 0.02$) were observed between fronds and stipes for myristic acid (C14:0) (7.13 ± 0.02%; 4.69 ± 0.01%), palmitic acid (C16:0) (26.05 ± 0.09%; 20.48 ± 0.02%), stearic acid (C18:0) (1.05 ± 0.00%; 1.00 ± 0.00%) and

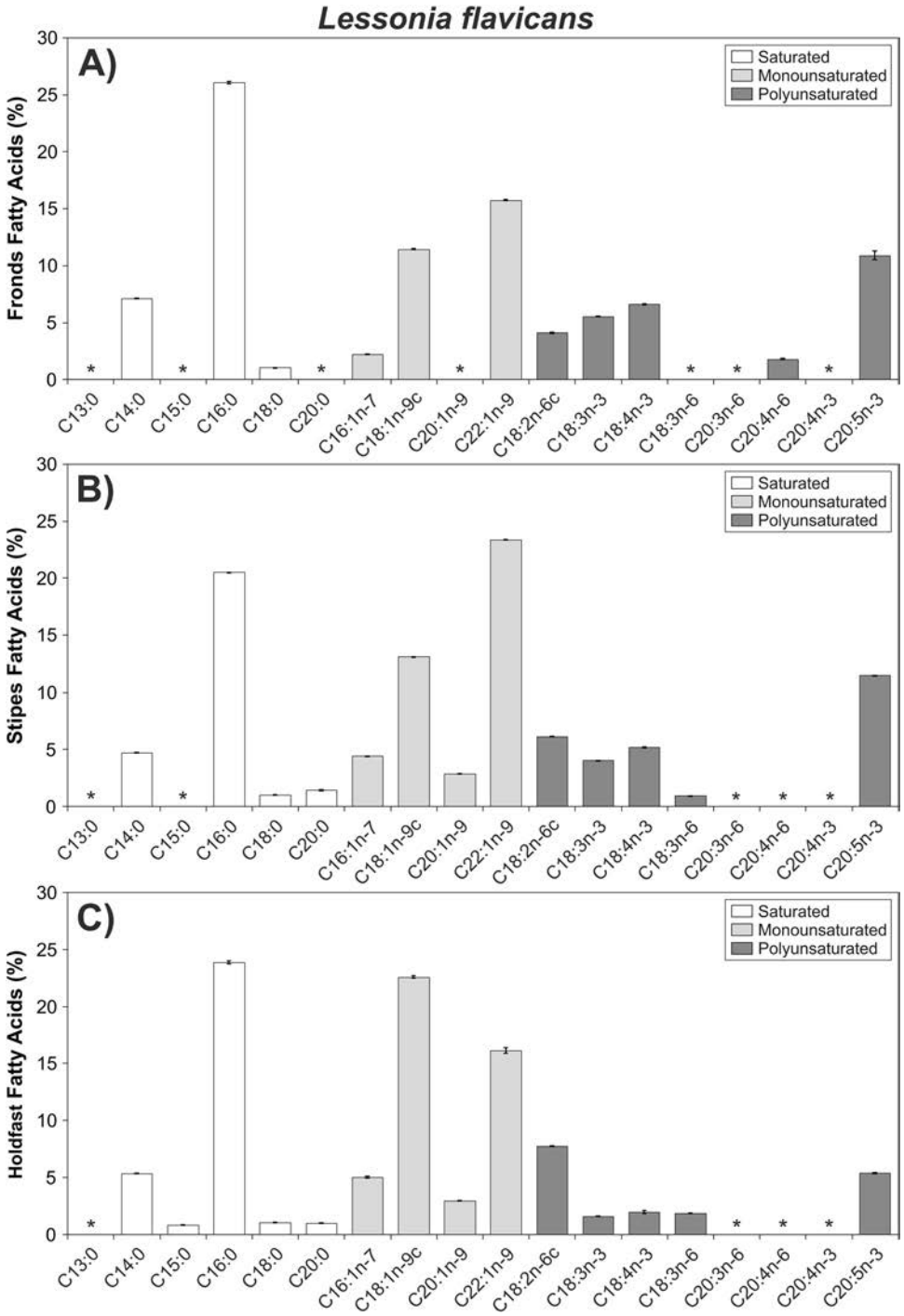


**Fig. 4** Percentage (%) of identified fatty acids (saturated, monounsaturated and polyunsaturated) from *L. flavicans* **A**) fronds, **B**) stipes and **C**) holdfast, in Rinconada Bulnes (53°35'47.76″S; 70°56'08.52″W), Magellan region, Chile (n = 9 for *M. pyrifera* and n = 9 for *L. flavicans*). Data are given as percentage of total fatty acid content and are presented as mean values of triplicate samples ± SD. (*) Not detected

arachidic acid (C20:0) (0.00 ± 0.00%; 1.42 ± 0.05%). For MUFA, significant differences ($p > 0.02$) were found between fronds and holdfast for palmitoleic acid (C16:1n-7) (2.21 ± 0.01%; 4.98 ± 0.08%), oleic acid (C18:1n-9c) (11.44 ± 0.04%; 22. 55 ± 0.10%) and erucic acid (C22:1n-9) (16.74 ± 0.07%; 16.09 ± 0.25%), respectively. Significant differences ($p > 0.02$) were also observed for eicosanoic acid (C20:1n-9) between fronds (0.00 ± 0.00%) and stipes (2.83 ± 0.03%). For PUFA, significant differences ($p > 0.02$) between fronds and holdfast were observed for linoleic acid (C18:2n-6c) (4.10 ± 0.05%; 7.71 ± 0.04%), linolenic acid (C18:3n-3) (5.53 ± 0.02%; 1.57 ± 0.01%), octadecatetraenoic acid (C18:4n-3) (6.59 ± 0.06%; 1.96 ± 0.13%) and γ-linolenic acid (C18:3n-6) (0.00 ± 0.00%; 1.82 ± 0.01%). A significant difference ($p > 0.02$) between stipes and holdfast was also found for eicosapentaenoic acid (EPA) (C20:5n-3) (11.44 ± 0.00%; 5.34 ± 0.05%).

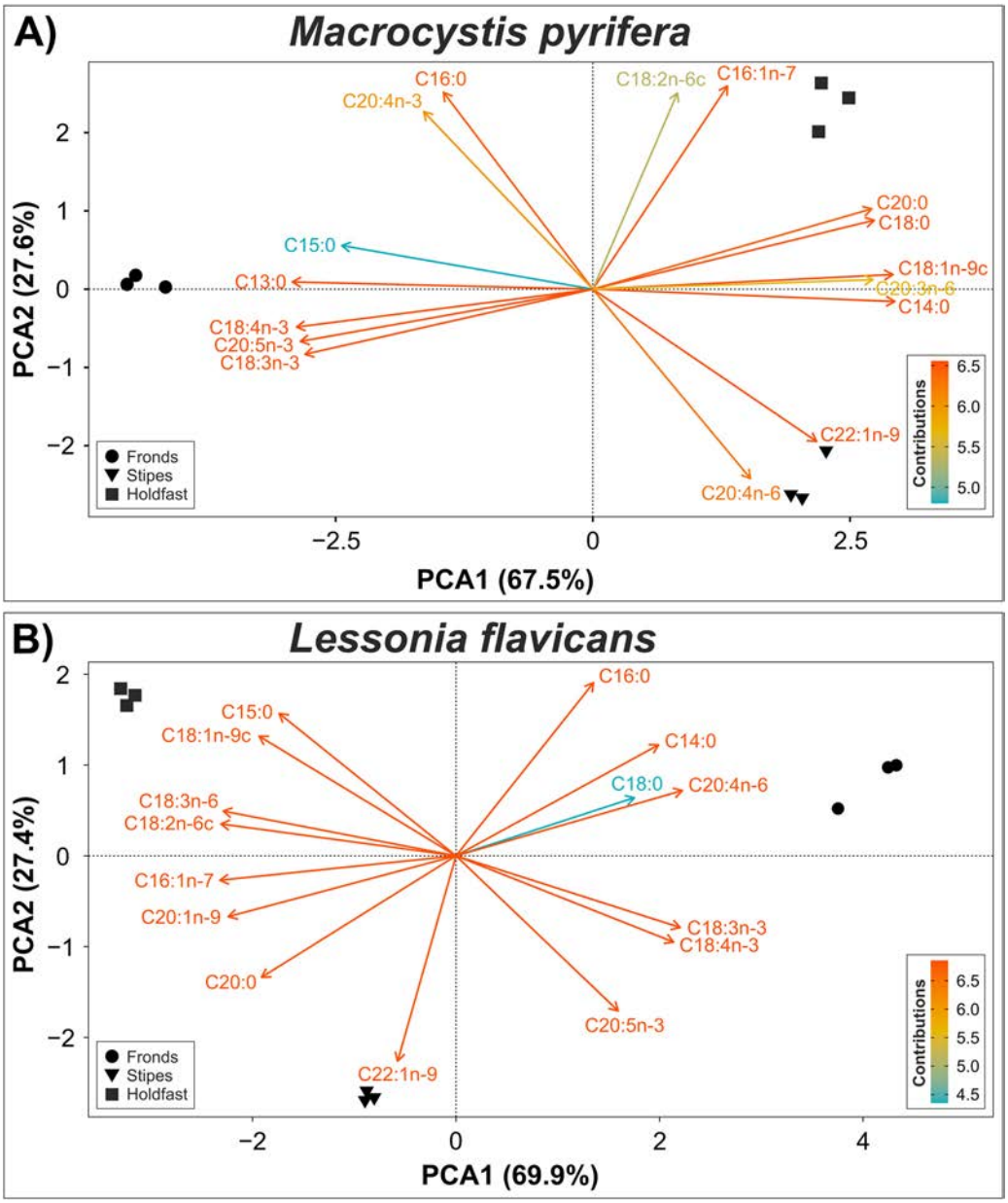


**Fig. 5** Principal Component Analysis (PCA) of identified fatty acids (saturated, monounsaturated and polyunsaturated) from **A**) *M. pyrifera* and **B**) *L. flavicans* (fronds, stipes and holdfast), in Rinconada Bulnes (53°35'47,76″S; 70°56'08,52″W), Magellan region, Chile

Due to the significant statistical differences observed, a Principal Component Analysis (PCA) was conducted to examine the clustering of the fatty acids detected in the different structures of *M. pyrifera* and *L. flavicans*. For *M. pyrifera*, PCA1 and PCA2 explained 95.1% of the total variance in the observed variables. The analyses revealed a positive relationship between the fatty acid C13:0 and fronds, C16:1n-7 and holdfasts, and C22:1n-9 and C20:4n-6 with the stipes. The other fatty acids (C16:0, C20:4n-3, C15:0, C18:4n-3, C20:5n-3, C18:3n-3, C18:2n-6c, C20:0, C18:0) exhibited a mixed interaction between the components (PCA1 and PCA2). The fatty acids C18:1n-9c, C20:3n-6 and C14:0 showed a prominent cluster in the first component (PCA1), but with a mixed interaction between stipes and holdfast. The C15:0 fatty acid had the lowest contribution (approximately 5.0) compared to the other fatty acids analyzed (Fig. 5a). PCA1 and PCA2 explained 97.3% of the total variance in the samples of *L. flavicans*. The analyses revealed a positive relationship between the fatty acids C14:0; C20:4n-6 and the fronds, C15:0; C18:1n-9c, the holdfast and C22:1n-9 the stipes. Fatty acid C16:0 showed mixed interactions between fronds and holdfast, while C18:2n-6c, C18:3n-6,

**Table 2** Permutational Multivariate Analysis of Variance (PERMANOVA) showing differences in fatty acid composition between macroalgae species (*M. pyrifera* and *L. flacivans*) and their structures (fronds, stipes and holdfast). Analyses are based on Euclidean distance matrix, type III sum of squares, fixed effects and 9999 permutations. Abbreviations: df, Degrees of freedom; MS, Mean squares

| Factor | df | MS | Pseudo-F | p-value |
|---|---|---|---|---|
| Algae | 1 | 488.47 | 2721.3 | 0.0001 *** |
| Structure | 2 | 434.84 | 2422.5 | 0.0001 *** |
| Algae × Structure | 2 | 93.465 | 520.7 | 0.0001 *** |
| Residuals | 12 | 0.1795 | | |

(*) Indicates significant values at a confidence level of 95% ($p < 0.05$)

C16:1n-7, C20:1n-9 and C20:0 showed mixed interactions between holdfast and stipes. Fatty acids (C20:4n-3, C18:4n-3, C20:5n-3 and C18:3n-3) showed mixed interactions between stipes and fronds. Fatty acid C18:0 had the lowest contribution (4.5) to the components (Fig. 5b).

PERMANOVA was conducted to assess the variation in fatty acid composition within each macroalgae species and to determine significant differences between their thallus structures. The results indicated significant differences ($p > 0.0001$) in fatty acid composition between macroalga species (*M. pyrifera* and *L. flavicans*), between structures (fronds, stipes, and holdfast) and between species and structure (*M. pyrifera* and *L. flavicans*; fronds, stipes, and holdfast) (Table 2).

## Discussion

The fatty acid composition in the fronds, stipes, and holdfast of the sub-Antarctic kelps *Macrocystis pyrifera* and *Lessonia flavicans* showed significant variation, particularly in monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA). While saturated fatty acids (SAFA) had similar levels between structures in both *M. pyrifera* and *L. flavicans*, MUFA exhibited a pattern of increasing concentration from fronds (26.46 ± 0.10%; 29.46 ± 0.13%) to stipes (43.04 ± 0.08%; 43.64 ± 0.04%) and holdfast (41.65 ± 0.21%; 46.45 ± 0.19%) for both macroalga species. Conversely, PUFA showed a decreasing pattern from fronds (32.38 ± 0.26%; 28.89 ± 0.23%) to stipes (21.99 ± 0.17%; 27.71 ± 0.05%) and holdfast (18.24 ± 0.17%; 18.39 ± 0.21%) for both species. Similar patterns of variation in fatty acid concentrations were described for *Saccharina japonica* by Khotimchenko and Kulikova (2000), who observed elevated levels (30.7 ± 2.1%) of PUFA (n3) in the upper zone of fronds. Similarly, Gosch et al. (2015a) observed high levels of MUFA in the basal zone (32.16 ± 0.43%) of the fronds of *S. macrodontum*, and Gosch et al. (2015b) reported an increase in MUFA from the ends towards the base of *D. bartayresii*, with high levels (~ 30.45%). Finally, Schmid and Stengel (2015) also observed a pattern of increased PUFA from the holdfast towards the fronds in Laminariales species, with high levels (55.5 ± 1.4%) in *L. digitata*. A well-differentiated distribution of PUFA concentrations in the different morphological structures of the thallus is evident in all these studies.

In contrast to other studies with *M. pyrifera* (Schmid et al. 2018, 2020; Biancacci et al. 2022) and *Lessonia corrugata* (Schmid et al. 2018), where high concentrations of PUFA were found, our results showed high levels of MUFA but low levels of PUFA. According to studies by Schmid et al. (2020) in laboratory culture, under two nitrate conditions (5 µM and 80 µM) and three temperatures (6, 17 and 24 °C), and by Biancacci et al. (2022) in marine culture lines at two sites with existing aquaculture concessions off the coast of Tasmania, Australia; these studies suggest that elevated PUFA levels may be induced by both the effects of salmon farming and the high nutrient conditions created there, which could lead to increase fatty acid concentrations in macroalgae. The Magellan kelp populations used in this study come from an area with little anthropogenic influence, therefore the fatty acid composition of the macroalgae studied is not influenced by farming systems that generate high nutrient conditions capable of inducing changes in fatty acid composition.

The environmental factors temperature, light, salinity, pH and nutrient availability, as well as habitat conditions, have been reported as parameters that regulate the fatty acid composition of macroalgae (Khotimchenko et al. 2002; Gosch et al. 2015a; Schmid and Stengel 2015; Schmid et al. 2018; Biancacci et al. 2022), resulting in different ranges of survival and adaptability (Schmid and Stengel 2015; Gerasimenko and Logvinov 2016). Variations in fatty acids in different structures of macroalgae are likely related to the morphological, functional and physiological differentiation of these structures, which play roles in growth, photosynthesis and energy storage (Gosch et al. 2015a). This differentiation may lead to a greater number of double bonds (PUFA) for the electron transport activity of the photosystems, especially at low temperatures (Sanina et al. 2008). Apical fronds are meristems with greater photosynthetic capacity compared to the basal structure (holdfast), whose primary function is to support and fix the substrate (Gosch et al. 2015a, b). Vega and Toledo (2018) reported that the chemical composition of macroalgae (proteins, carbohydrates, lipids and fibers) may increase during cold periods, as macroalgae need to enhance their nitrogen fixation rate for reproduction and growth. Macroalgae have to utilize energy to maintain their physiological processes during warm periods, resulting in a loss of nitrogen reserves. Oceanographic parameters have also been described as factors influencing phenotypic plasticity and variation in the chemical composition of macroalgae (Schmid and Stengel 2015; Vega and Toledo 2018).

The fatty acid profiles of *M. pyrifera* and *L. flavicans* exhibited high levels of certain MUFA in all their structures, particularly oleic acid (C18:1n-9c) and erucic acid

(C22:1n-9), especially in the stipes and holdfast. The fatty acid EPA (eicosapentaenoic acid) also stood out in the PUFA profile, despite the low concentrations found. EPA (C20:5n-3) was prominently present in *M. pyrifera* and *L. flavicans* fronds, with significantly higher levels in *L. flavicans* stipes. MUFA and PUFA have been shown to have beneficial effects on human health, including protection against insulin resistance (Mantilla-Mora et al. 2021), improved cardiovascular and coronary health, and improved cognitive performance in children (Cikoš et al. 2020). The high content of MUFA found in *M. pyrifera* and *L. flavicans* supports their role in the following: i) a protective mechanism against insulin resistance by altering cell membrane fluidity, modulating the regulation of transcription factors and influencing the expression of genes related to energy metabolism (Mantilla-Mora et al. 2021); ii) a regulator of lipid membrane fluidity under stress conditions (such as low temperatures), achieved through the expression of genes involved in the control of loacclimatization (Santos et al. 2017); and iii) an important component of a diet that reduces the risk of cardiovascular disease (Lomartire et al. 2021).

The balance between omega-6 and omega-3 fatty acids is of paramount importance for humans, particularly considering the increasing prevalence of processed foods, which reduce omega-3 levels and elevate omega-6 content in the diet, leading to potential effects on health (Melby 2019). The optimal omega-6/omega-3 ratio advocated by the pharmaceutical industry to combat common diseases is believed to range from 1:1 to 4:1 (Melby 2019; Santos et al. 2019). In the present study, a remarkable omega-6/omega-3 ratio of 1:1 was identified in the holdfast of *L. flavicans*, a brown macroalga endemic to the Magellan region.

The sub-Antarctic Magellan Ecoregion holds significant potential for biomedical applications at both regional and national levels. This potential is underscored by the utilization of specific macroalgal biomolecules that have demonstrated noteworthy outcomes in the field of biomedicine. These include: i) Investigation into the antitumor properties of lipid extracts derived from *Mazzaella laminarioides*, showing promising effects on bladder cancer cells (Do-Amaral et al. 2020); ii) The utilization of carrageenan sourced from *Gigartina skottsbergii* as a molecular tool for the early detection of SARS-CoV-2 (Zank et al. 2023) and iii) Ongoing preliminary research, as part of Fabio Méndez's PhD thesis, exploring the impact of lipid extracts from *M. pyrifera* and *L. flavicans* on glucose metabolism. This study encompasses both in vivo research utilizing *Caenorhabditis elegans* models and in vitro investigations using SH-SY5Y neuronal cells.

A novel opportunity emerges to exploit the resource species sustainably, with potential applications in A) healthy food—incorporating *M. pyrifera* into new food recipes can contribute to promoting a balanced diet in local communities and reduce the risk of obesity within health centers, as demonstrated preliminarly in Astorga-España and Mansilla (2014) and B) nutraceuticals—*M. pyrifera* and *L. flavicans* can be utilized in the form of pills, capsules or syrups, with various beneficial effects including antibacterial, antiviral, anti-inflammatory, anticoagulant and antithrombotic properties.

Finally, this study is the first to compare the fatty acid composition between morphological structures (holdfast, stipes, and fronds) in two highly representative macroalga species from the sub-Antartic Magellan Ecoregion. The region and the country must intensify efforts in bioprospecting for molecules in sub-Antarctic macroalgae to combat prevalent diseases in a remote natural laboratory with low anthropogenic impact.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10811-023-03114-9.

**Acknowledgements** The present study is part of the thesis of FM, a student of the Doctoral Program in "Antarctic and Subantarctic Sciences" at the University of Magellan, Punta Arenas, Chile. The acknowledgments go to: I) Funding from the National Agency for Research and Development (ANID)/ Scholarships Program/ Chilean National Doctorate/2020—Folio 21202059. II) Funding from the Cape Horn International Center (CHIC) Project ANID/BASAL FB210018. III) Center of Excellence in Biomedicine of Magallanes (CEBIMA), Punta Arenas, Chile. IV) Millennium Science Initiative Program – ICN2021_002, and V) Facilities and equipment kindly provided by the University of Magellan (UMAG), specifically the Laboratory of the Faculty of Sciences, Department of Agricultural and Aquaculture Sciences, and the Laboratory of Antarctic and Subantarctic Marine Ecosystems (LEMAS) at the University of Magallanes, Punta Arenas, Chile.

**Authors' contributions** F.M., wrote the main manuscript text, sample analysis, prepared figures. A.R., sample analysis. F.B., prepared figures. P.G., wrote the main manuscript text. M.F., wrote the main manuscript text. J.Z., wrote the main manuscript text. N.I., wrote the main manuscript text. A.M., wrote the main manuscript text. All authors reviewed the manuscript.

**Funding** The present study had financial and logistic support from: I) Funding from the National Agency for Research and Development (ANID)/ Scholarships Program/ Chilean National Doctorate/2020—Folio 21202059. II) Funding from the Cape Horn International Center (CHIC) Project ANID/BASAL FB210018. III) Center of Excellence in Biomedicine of Magallanes (CEBIMA), Punta Arenas, Chile. IV) Millennium Science Initiative Program – ICN2021_002, and V) Facilities and equipment kindly provided by the University of Magellan (UMAG), specifically the Laboratory of the Faculty of Sciences, Department of Agricultural and Aquaculture Sciences, and the Laboratory of Antarctic and Subantarctic Marine Ecosystems (LEMAS) at the University of Magallanes, Punta Arenas, Chile.

**Data availability** Data are available from the corresponding author upon reasonable request.

## Declarations

**Competing interests** The autors declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

## References


Afonso NC, Catarino MD, Silva A, Cardoso SM (2019) Brown macroalgae as valuable food ingredients. Antioxidants 8:365

Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. Austral Ecol 26:32–46

Anderson MJ, Walsh DC (2013) PERMANOVA, ANOSIM, and the Mantel test in the face of heterogeneous dispersions: what null hypothesis are you testing? Ecol Monogr 83:557–574

Astorga-España MS, Mansilla A (2014) Sub-Antarctic macroalgae: opportunities for gastronomic tourism and local fisheries in the Region of Magallanes and Chilean Antarctic Territory. J Appl Phycol 26:973–978

Astorga-España MS, Mansilla A, Ojeda J, Marambio J, Rosenfeld S, Mendez F, Ocaranza P (2017) Nutritional properties of dishes prepared with sub-Antarctic macroalgae - an opportunity for healthy eating. J Appl Phycol 29:2399–2406

Athyros VG, Doumas M, Imprialos KP, Stavropoulos K, Georgianou E, Katsimardou A, Karagiannis A (2018) Diabetes and lipid metabolism. Hormones 17:61–67

Barkina MY, Pomazenkova LA, Chopenko NS, Velansky PV, Kostetsky EY, Sanina NM (2020) Influence of warm-acclimation rate on polar lipids of *Ulva lactuca*. Russ J Plant Physiol 67:111–121

Barzkar N, Jahromi ST, Poorsaheli HB, Vianello F (2019) Metabolites from marine microorganisms, micro, and macroalgae: Immense scope for pharmacology. Mar Drugs 17:464

Biancacci C, Visch W, Callahan DL, Farrington G, Francis DS, Lamb P, McVilly A, Nardelli A, Sanderson JC, Schwoerbel J, Hurd CL, Evans B, Macleod C, Bellgrove A (2022) Optimisation of at-sea culture and harvest conditions for cultivated *Macrocystis pyrifera*: yield, biofouling and biochemical composition of cultured biomass. Front Mar Sci 9:951538

Bligh EG, Dyer WJ (1959) A rapid method for total lipid extraction and purification. Can J Biochem Physiol 37:911–917

Britton D, Schmid M, Noisette F, Havenhand JN, Paine ER, McGraw CM, Revill AT, Virtue P, Nichols PD, Mundy CN, Hurd CL (2020) Adjustments in fatty acid composition is a mechanism that can explain resilience to marine heatwaves and future ocean conditions in the habitat-forming seaweed *Phyllospora comosa* (Labillardière) C. Agardh. Glob Chang Biol 26:3512–3524

Chemello S, Signa G, Mazzola A, Ribeiro Pereira T, Sousa Pinto I, Vizzini S (2022) Limited stress response to transplantation in the Mediterranean macroalga *Ericaria amentacea*, a key species for marine forest restoration. Int J Environ Health Res 19:12253

Cikoš AM, Čož-Rakovac R, Šubarić D, Jerković I, Ačkar Đ (2020) Macroalgae in the food industry - opportunities and challenges. Power Eng 15:14–19

Clarke KR, Gorley RN (2006) PRIMER v6: User Manual/Tutorial (Plymouth Routines in Multivariate Ecological Research). PRIMER-E, Plymouth

Collins KG, Fitzgerald GF, Stanton C, Ross RP (2016) Looking beyond the terrestrial: the potential of seaweed derived bioactives to treat non-communicable diseases. Mar Drugs 14:60

Crespo R, Alvarez C, Hernandez I, García C (2020) A spatially explicit analysis of chronic diseases in small areas: a case study of diabetes in Santiago, Chile. Int J Health Geogr 19:1–13

Da Costa E, Domingues P, Melo T, Coelho E, Pereira R, Calado R, Abreu MA, Domingues MR (2019) Lipidomic signatures reveal seasonal shifts on the relative abundance of high-valued lipids from the brown algae *Fucus vesiculosus*. Mar Drugs 17:335

Dayton P (1985) Ecology of kelp communities. Annu Rev Ecol Syst 16:215–245

Do-Amaral CCF, Pacheco BS, Segatto NV, Paschoal JDF, Santos MAZ, Seixas FK, Pereira CMP, Astorga-España MS, Mansilla A, Collares T (2020) Lipidic profile of sub-Antarctic seaweed *Mazzaella laminarioides* (Gigartinales, Rhodophyta) in distinct developmental phases and cell cytotoxicity in bladder cancer. Algal Res 48:101936

Fernandez MJ (2019) Hipertensión Arterial en poblaciones especiales. Curso, Hospital Clinico Magallanes y Sociedad Médica, Punta Arenas, Chile

Flachs P, Rossmeisl M, Kopecky J (2014) The effect of n-3 fatty acids on glucose homeostasis and insulin sensitivity. Physiol Res 63:S93

Galloway AWE, Britton-Simmons KH, Duggins DO, Gabrielson PW, Brett MT (2012) Fatty acid signatures differentiate marine macrophytes at ordinal and family ranks. J Phycol 48:956–965

Ganesan AR, Tiwari U, Rajauria G (2019) Seaweed nutraceuticals and their therapeutic role in disease prevention. Food Sci Hum Wellness 8:252–263

Gerasimenko N, Logvinov S (2016) Seasonal composition of lipids, fatty acids pigments in the brown alga *Sargassum pallidum*: The potential for health. Open J Mar Sci 6:498

Gosch BJ, Paul NA, de Nys R, Magnusson M (2015a) Seasonal and within-plant variation in fatty acid content and composition in the brown seaweed *Spatoglossum macrodontum* (Dictyotales, Phaeophyceae). J Appl Phycol 27:387–398

Gosch BJ, Paul NA, De Nys R, Magnusson M (2015b) Spatial, seasonal, and within-plant variation in total fatty acid content and composition in the brown seaweeds *Dictyota bartayresii* and *Dictyopteris australis* (Dictyotales, Phaeophyceae). J Appl Phycol 27:1607–1622

Harnedy PA, FitzGerald RJ (2013) In vitro assessment of the cardioprotective, anti-diabetic and antioxidant potential of *Palmaria palmata* protein hydrolysates. J Appl Phycol 25:1793–1803

Healy LE, Zhu X, Pojić M, Sullivan C, Tiwari U, Curtin J, Tiwari BK (2023) Biomolecules from macroalgae-nutritional profile and bioactives for novel food product development. Biomolecules 13:386

Ho M, McBroom J, Bergstrom E, Diaz-Pulido G (2021) Physiological responses to temperature and ocean acidification in tropical fleshy macroalgae with varying affinities for inorganic carbon. ICES J Mar Sci 78:89–100

Husni A (2018) Therapeutic potential of seaweed polysaccharides for diabetes mellitus. In: Maiti S (eds) Seaweed Biomaterials. IntechOpen, Riejeka, pp 27–45

Jolliffe IT (1986) Principal Component Analysis. Springer, Berlin, p 487

Kargın H, Bilgüven M (2022) Microalgae-macroalgae based nutraceuticals and their benefits. Curr Trends Nat Sci 11:232–246

Kelly BJ, Brown MT (2000) Variations in the alginate content and composition of *Durvillaea antarctica* and *D. willana* from southern New Zealand. J Appl Phycol 12:317–324

Kendel M, Wielgosz-Collin G, Bertrand S, Roussakis C, Bourgougnon N, Bedoux G (2015) Lipid composition, fatty acids and sterols in the seaweeds *Ulva armoricana*, and *Solieria chordalis* from Brittany (France): An analysis from nutritional, chemotaxonomic, and antiproliferative activity perspectives. Mar Drugs 13:5606–5628

Khotimchenko, SV, Kulikova IV (2000) Lipids of different parts of the lamina of *Laminaria japonica* Aresch. Bot Mar 45:87–91

Khotimchenko SV, Vaskovsky VE, Titlyanova TV (2002) Fatty acids of marine algae from the Pacific coast of North California. Bot Mar 17–22

Khotimchenko SV, Yakovleva IM (2005) Lipid composition of the red alga *Tichocarpus crinitus* exposed to different levels of photon irradiance. Phytochemistry 66:73–79

Koch K, Thiel M, Hagen W, Graeve M, Gómez I, Jofre D, Hofmann LC, Tala F, Bischof K (2016) Short-and long-term acclimation patterns of the giant kelp *Macrocystis pyrifera* (Laminariales, Phaeophyceae) along a depth gradient. J Phycol 52:260–273

Kruskal WH, Wallis WA (1952) Use of ranks in one-criterion variance analysis. JASA 47:583–621

Kumar M, Kumari P, Reddy CRK, Jha B (2014) Salinity and desiccation induced oxidative stress acclimation in seaweeds. Adv Bot Res 71:91–123

Leandro A, Pereira L, Gonçalves AM (2020) Diverse applications of marine macroalgae. Mar Drugs 18:17
Lomartire S, Marques JC, Gonçalves AM (2021) An overview to the health benefits of seaweeds consumption. Mar Drugs 19:341
Mansilla A, Ávila M (2011) Using *Macrocystis pyrifera* (L.) C. Agardh from southern Chile as a source of applied biological compounds. Rev Bras Farmacogn 21:262–267
Mansilla A, Ávila M, Yokoya NS (2012) Current knowledge on biotechnological interesting seaweeds from the Magellan Region, Chile. Rev Bras Farmacogn 22:760–767
Mansilla A, Gérard K, Boo GH, Ramirez ME, Ojeda J, Rosenfeld S, Murcia S, Marambio J, Gonzalez-Wevar C, Calderon M, Boo SM, Faugeron S (2020) Populations of a new morphotype of corrugate *Lessonia* Bory in the Beagle Channel, sub-Antarctic Magellanic ecoregion: a possible case of on-going speciation. Cryptogam Algol 41:105–119
Mantilla-Mora G, Ángel-Martín A, Moreno-Castellanos N (2021) Effects of oleic (18:1n-9) and palmitic (16:0) fatty acids on the metabolic state of adipocytes. Rev Univ Ind Santander Salud 53:21009
Marambio J, Rosenfeld S, Rodríguez JP, Méndez F, Contador T, Mackenzie R, Goffinet B, Rozzi R, Mansilla A (2020) Siete nuevos registros de macroalgas para el archipiélago Diego Ramírez (56° 31'S): el valor del nuevo parque marino como sumidero de carbono y conservación de la biodiversidad subantártica. Ann Inst Patagon 48:99–111
Marinho GS, Holdt SL, Jacobsen C, Angelidaki I (2015) Lipids and composition of fatty acids of *Saccharina latissima* cultivated year-round in integrated multi-trophic aquaculture. Mar Drugs 13:4357–4374
Melby MB (2019) Characterization of fatty acids in marine macroalgae by GC-MS. MSc Thesis, Norwegian University of Life Sciences, Ås, 72 pp.
Mendis E, Kim S (2011) Present and future prospects of seaweeds in developing functional foods. Adv Food Nutr Res 64:1–15
Metcalfe LD, Schmetz AA, Pelka JR (1966) Rapid preparation of fatty acid esters from lipids for gas chromatographic. Anal Chem 38:514–515
Ministerio de Salud (2018) Informe Encuesta Nacional de Salud 2016–2017: Diabetes Mellitus. Santiago de Chile, 26 p. https://goo.gl/oe2iVt. Accessed 20 Mar 2022
Ojeda J, Rosenfeld S, Marambio J, Rozzi R, Mansilla A (2014) Patrones estacionales y espaciales de la diversidad de moluscos intermareales de bahía Róbalo, canal Beagle, Reserva de la Biosfera Cabo de Hornos, Chile. Rev Biol Mar Oceanogr 49:493–509
Ortiz J, Romero N, Robert P, Araya J, Lopez-Hernández J, Bozzo C, Navarrete E, Osorio A, Rios A (2006) Dietary fiber, amino acid, fatty acid and tocopherol contents of the edible seaweeds *Ulva lactuca* and *Durvillaea antarctica*. Food Chem 99:98–104
Ortiz J, Uquiche E, Robert P, Romero N, Quitral V, Llantén C (2009) Functional and nutritional value of the Chilean seaweeds *Codium fragile*, *Gracilaria chilensis* and *Macrocystis pyrifera*. Eur J Lipid Sci Technol 111:320–327
Pereira T, Horta A, Barroso S, Mendes S, Gil MM (2021) Study of the seasonal variations of the fatty acid profiles of selected macroalgae. Molecules 26:5807
Quitral V, Jofré MJ, Rojas N, Romero N, Valdés I (2019) Algas marinas como ingrediente funcional en productos cárnicos. Rev Chil Nutr 46:181–189
Ramírez ME (2010) Flora marina Bentónica de la región austral de Sudamérica y la Antártica. Ann Inst Patagon 38:57–71
R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online at: http://www.R-project.org (accessed April 01, 2023)
Rocha DH, Pinto DC, Silva A (2022) Macroalgae specialized metabolites: Evidence for their anti-inflammatory health benefits. Mar Drugs 20:789
Rozzi R, Armesto JJ, Gutiérrez JR, Massardo F, Likens GE, Anderson CB, Poole A, Moses KP, Hargrove E, Mansilla AO, Kennedy JH, Willson M, Jax K, Jones CG, Callicott JB, Kennedy JH (2012) Integrating ecology and environmental ethics: earth stewardship in the southern end of the Americas. Bioscience 62:226–236
Sanina NM, Goncharova SN, Kostetsky EY (2008) Seasonal changes of fatty acid composition and thermotropic behavior of polar lipids from marine macrophytes. Phytochemistry 69:1517–1527
Saini RK, Prasad P, Sreedhar RV, Akhilender NK, Shang X, Keum YS (2021) Omega-3 polyunsaturated fatty acids (PUFAs): Emerging plant and microbial sources, oxidative stability, bioavailability, and health benefits—A review. Antioxidants 10:1627
Santos MA, Colepicolo P, Pupo D, Fujii MT, de Pereira CM, Mesko MF (2017) Antarctic red macroalgae: a source of polyunsaturated fatty acids. J Appl Phycol 29:759–767
Santos MAZ, de Freitas SC, Berneira LM, Mansilla A, Astorga-España MS, Colepicolo P, de Pereira CMP (2019) Pigment concentration, photosynthetic performance, and fatty acid profile of sub-Antarctic brown macroalgae in different phases of development from the Magellan Region, Chile. J Appl Phycol 31:2629–2642
Santos MAZ, Berneira LM, Goulart NL, Mansilla A, Astorga-España MS, de Pereira CMP (2021) Rhodophyta, Ochrophyta and Chlorophyta macroalgae from different sub-Antarctic regions (Chile) and their potential for polyunsaturated fatty acids. Rev Bras Bot 44:429–438
Schmid M, Guihéneuf F, Stengel DB (2014) Fatty acid contents and profiles of 16 macroalgae collected from the Irish Coast at two seasons. J Appl Phycol 26:451–463
Schmid M, Stengel DB (2015) Intra-thallus differentiation of fatty acid and pigment profiles in some temperate Fucales and Laminariales. J Phycol 51:25–36
Schmid M, Kraft LG, van der Loos LM, Kraft GT, Virtue P, Nichols PD, Hurd CL (2018) Southern Australian seaweeds: a promising resource for omega-3 fatty acids. Food Chem 265:70–77
Schmid M, Fernández PA, Gaitán-Espitia JD, Virtue P, Leal PP, Revill AT, Peter D. Nichols PD, Hurd, CL (2020) Stress due to low nitrate availability reduces the biochemical acclimation potential of the giant kelp *Macrocystis pyrifera* to high temperature. Algal Res 47:101895
Siegel S, Castellan NJ Jr (1988) Nonparametric statistics for the behavioral sciences (2nd Ed.). Mcgraw-Hill, NY. 399 pp.
Silva N, Calvete C (2002) Características oceanográficas físicas y químicas de canales australes chilenos entre el golfo de Penas y el estrecho de Magallanes. CIMAR 2 Fiordos. Cienc Tecnol Mar 25:23–88
Vega JM, Toledo PH (2018) The chemical composition of *Lessonia berteroana* (ex *L. nigrescens*) in kelp harvest management and open access areas near Coquimbo, Chile. Lat Am J Aquat Res 46:258–267
Wan AH, Davies SJ, Soler-Vila A, Fitzgerald R, Johnson MP (2019) Macroalgae as a sustainable aquafeed ingredient. Rev Aquac 11:458–492
Zank PD, Cerveira MM, Santos VBD, Klein VP, Souza TTD, Bueno DT, Poletti T, Leitzke AF, Giongo JL, Carreño NLV, Mansilla A, Astorga-España MS, Pereira CMP, Vaucher RDA (2023) Carrageenan from *Gigartina skottsbergii*: a novel molecular probe to detect SARS-CoV-2. Biosensors 13:378

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