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Chemical composition and nutrient profiles of nine red macroalgae species

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Abstract

Nine red macroalgae (*Amphiroa rigida, Gracilaria bursa-pastoris, Gracilaria gracilis, Grateloupia torture, Jania rubens, Laurencia obtusa, Laurencia pyramidalis, Liagora viscida, and Pterocladiella capillaries*) were collected from coastal waters of Türkiye, and their proximate, fatty acid, soluble carbohydrate, and mineral profiles were investigated in the present study. According to the results, the crude protein content of the samples was between 4% and 23.8%, and four of the samples (*G. turuturu, L. obtusa, L. pyramidalis,* and *P. capillacea*) contained more than 10% protein. The crude lipid content of all the samples was below 1.6%, and the total carbohydrate content was between 38.3% and 76.9%. The macroalgae samples were generally richer in saturated fatty acids, palmitic acid being the most abundant, whereas *G. gracilis* had the highest content of unsaturated fatty acids (55.8%). All samples exhibited high contents of myo-inositol or glucose. Also, the samples generally had a good composition of minerals. Still, the heavy metal (i.e., Pb and Cd) content of *Gracilaria gracilis* was higher (59.6 µg/kg, $P < 0.05$) than those of the other algae samples. This study provides valuable insight into the chemical composition and fatty acid, mineral, and soluble carbohydrate profiles of *Amphiroa rigida, Gracilaria bursa-pastoris, Gracilaria gracilis, Grateloupia turuturu, Jania rubens, Laurencia obtusa, Laurencia pyramidalis, Liagora viscida,* and *Pterocladiella capillacea* from Türkiye.

Keywords Carbohydrates, Fatty acids, Mineral profile, Proximate composition, Red macroalgae

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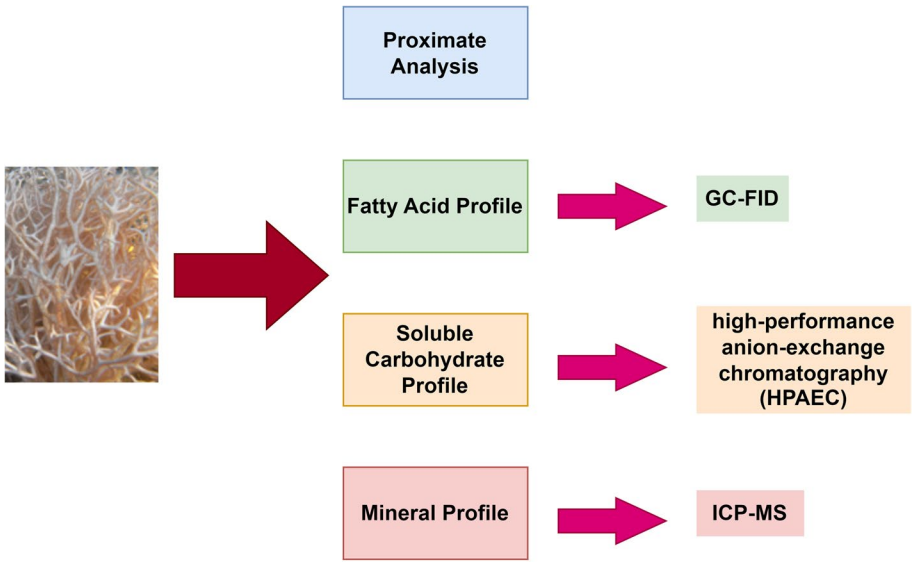
Graphical Abstract



Introduction

Recently, the interest in alternative and sustainable protein sources is growing to meet the demand for food due to the increasing popularity of non-meat products among consumers (Tso et al. 2021). Animal-based foods are considered non-sustainable, as livestock production requires more land use and produces more greenhouse emissions and carbon footprint compared to non-meat sources (Henchion et al. 2017; van Zanten et al. 2016).

Algae have been suggested as suitable alternatives to protein sources (Chronakis & Madsen 2011). They can have comparable or superior nutritional quality, amino acid composition, and functional properties compared to conventional protein sources (Chronakis & Madsen 2011; Fleurence 1999). However, these properties can change significantly among different species of algae (Makkar et al. 2016).

Macroalgae have generally higher mineral content than terrestrial plants due to their ability to accumulate these elements from the environment (Afonso et al. 2021; Usda 2001). Although the lipid content of macroalgae is low, they have higher amounts of essential fatty acids, which are crucial for human health, than terrestrial plants (Peñalver et al. 2020). The chemical composition profile of macroalgae varies due to the impact of many factors, such as geographical origins, maturity, and seasonal and environmental conditions (Peñalver et al. 2020). Furthermore, macroalgae contain both soluble and insoluble carbohydrates. Sugars (e.g., sucrose, fructose, glucose) and sugar alcohols (e.g., mannitol, myoinositol) are important metabolites with antioxidant and osmoregulatory properties, responsible for the resistance of the algae cell wall against variations in the salinity of the medium (Baweja et al. 2016). Therefore, these valuable compounds have great potential for supplementation in functional food applications (Ismail et al. 2020).

Macroalgae can be utilized in the sustainable production of functional food products due to their excellent bioactive composition (Garcia-Vaquero & Hayes 2016). The mineral content of macroalgae is a critical aspect, as they have widely been regarded as alternative food products (Circuncisão et al. 2018). However, the mineral profile of macroalgae can include heavy metals, which could be toxic to humans when consumed (Circuncisão et al. 2018).

Knowledge of the proximate, carbohydrate, and fatty acid compositions of macroalgae is necessary before their utilization in the development of food products. The mineral profile is also essential, as they can contain toxic metals. Thus, the objective of this study was to evaluate the proximate compositions, lipid profiles, soluble carbohydrates, and mineral profiles of the nine red macroalgae (*Amphiroa rigida, Gracilaria bursa-pastoris, Gracilaria gracilis, Grateloupia turuturu, Jania rubens, Laurencia obtusa, Laurencia pyramidalis, Liagora viscida, Pterocladiella capillacea*) collected from the Marmara, Aegean, and Mediterranean coasts of Türkiye. The selection of nine red macroalgae species in our study was based on a

strategic approach to encompass a diverse representation of macroalgae found along the coasts of Türkiye. Each species was chosen for its prevalence in these coastal regions and potential relevance to the local ecosystem. The aim was to provide a comprehensive overview of the proximate compositions, lipid profiles, soluble carbohydrates, and mineral profiles within this specific geographical context. This is the first study in the literature that reports the mineral, soluble carbohydrates, fatty acids, and proximate profiles of *L. pyramidalis* to the best of our knowledge.

Materials and methods

Material

A fatty acid methyl ester (FAME) standard mixture (37 components) and the carbohydrate standards were obtained from Supelco (Bellefonte, PA, USA) and Santa Cruz Biotechnology (Dallas, TX, USA), respectively. All other chemicals were obtained from Merck (Darmstadt, Germany).

Collection and preparation of the samples

The red macroalgae samples (*A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea*) were collected in 2019 (between May and August). The pictures of the samples and map of sampling locations are provided in Fig. 1. Also, the list of the collected nine macroalgae and their locations are listed in Table 1. After the delivery of the samples to the laboratory, they were washed, dried, and ground into small particles (< 500 µm) using a laboratory-type grinder (Waring 8011 EB Blender, Cole-Parmer, Vernon Hills, IL, USA) in the laboratory. Visual appearance of the samples is given in ground form in Figure S.1 as a supplementary document. All samples were stored at -20 °C in plastic pouches until further analysis.

Table 1 Macroalgae samples and their sampling locations

Macroalgae	Sampling site	Coordinate
Amphiroa rigida	Antalya	36°52′19.18"N 30°42′59.11"E
Gracilaria bursa-pastoris	Çanakkale	40°14′27.03"N 26°32′29.74"E
Gracilaria gracilis	Çanakkale	40°1′35.90"N 26°19′49.49"E
Grateloupia turuturu	Yalova	40°43′41.56"N 29°29′59.55"E
Jania rubens	Antalya	36°31′33.93"N 30°33′8.64"E
Laurencia obtusa	Çanakkale	40°19′1.80"N 26°13′6.21"E
Laurencia. pyramidalis	Çanakkale	40°19′1.80"N 26°13′6.21"E
Liagora viscida	Antalya	36°31′33.93"N 30°33′8.64"E
Pterocladiella capillacea	Antalya	36°52′21.98"N 30°42′56.07"E

Proximate analysis

In the analytical assessment of the samples, total nitrogen content was determined using the Kjeldahl method, a widely recognized technique in analytical chemistry. To estimate total protein content, the total nitrogen amount was multiplied by a conversion factor of 6.25, following the established protocol outlined by the Association of Official Analytical Chemists (AOAC 1995). The Soxhlet method was employed to ascertain the total lipid content of the samples. This method, described by Mohammadpour et al. (2019), involves the extraction of lipids from the samples using a solvent extraction system, providing

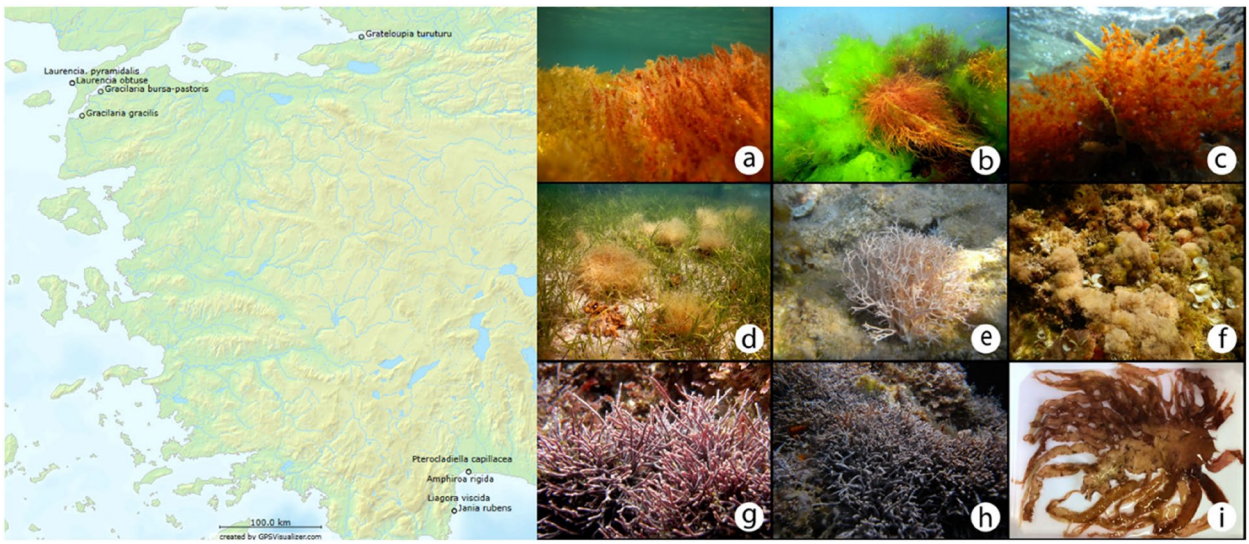


Fig. 1 Map of the sampling locations and visual appearance of macroalgae. **a** *Laurencia pyramidalis*, **b** *Gracilaria gracilis*, **c** *Laurencia obtusa*, **d** *Gracilaria bursa-pastoris*, **e** *Liagora viscida*, **f** *Jania rubens*, **g**-**h** *Amphiroa rigida*, **i** *Grateloupia turuturu* (Photography by Dr. Emine Şükran Okudan)

a precise measurement of the total lipid content. The assessment of total ash and moisture contents was conducted by the methodologies stipulated by AOAC (1995). These procedures involve incineration to determine the mineral content (ash) and drying to establish the moisture content of the samples.

Moreover, the total carbohydrate content was calculated with a comprehensive approach. The remaining percentage represents the total carbohydrate content by subtracting the cumulative values of lipid, protein, ash, and moisture from 100.

Fatty acid profile

The fatty acid composition analysis of the macroalgae samples was conducted through chromatographic methods, specifically following the procedure outlined by IOC (2015). Fatty acid methyl esters were then analyzed using a gas chromatograph coupled with a flame ionization detector (GC-FID) (Agilent 7820A, Agilent Technologies Inc., Palo Alto, CA, USA). The analytical approach and parameters employed in this process adhered to the method described by Uluata et al. (2021). This methodological consistency ensures the reliability and reproducibility of the fatty acid composition results obtained from the macroalgae samples.

Soluble carbohydrate profile

The soluble carbohydrate compositions of the samples were analyzed as described by Pfetzing et al. (2000) with some modifications. A 10 mg of the macroalgae sample was added with 3 mL of ultra-pure water and agitated for 4 h at 80 °C, the aliquots of the supernatant were taken and kept at -18 °C until analysis. The analysis used a high-performance anion-exchange chromatography (HPAEC) (Dionex ICS-5000, Dionex Corporation, Sunnyvale, CA, USA) with a PA-200 and a guard column coupled with an electrochemical ED40 detector in integrated amperometric mode. The separation of myoinositol, mannitol, glucose, fructose, and sucrose was performed using a binary gradient method for 30 min at a flow rate of 0.40 mL/min at 25 °C: 0% solvent B for 3 min, up to 12% solvent B until 15 min, down to 0% again in 12 min minutes, and so on, where solvent A was 600 mM NaOH, and B was 100 mmol/L NaAc in solvent A.

Mineral profile

The mineral profiles of the macroalgae samples were investigated using inductively coupled plasma mass spectrometry (ICP-MS). 0.2 g of each sample was added with 10 mL of 65% HNO_3 in a vessel tube, and the tubes were kept open-top for 15–20 min under a fume hood. Then, the samples were incinerated in a microwave combustion system (Mars 5 Microwave Accelerated Reaction System, CEM Corporation, Charlotte, NC, USA) under specified conditions (Temperature: 200 °C, Ramp: 15:00 mm: ss, Pressure: 800 psi, Power: 900–1800 W) (Gunn 2014). Then, the samples were filtered using 0.45 µm syringe filters, and the mineral compositions were determined using an ICP-MS instrument (Agilent Company, Santa Clara, CA, USA). A 2% HNO_3 solution was used as the blank. The identification was performed using a calibration curve prepared using equal concentrations of the heavy metals (Ahamad et al. 2017; Pilarczyk et al. 2013).

Statistical analysis

All samples underwent a triple replication to ensure the robustness and reliability of the data. The collected data were subjected to statistical analysis using the Minitab 16 software developed by Minitab LLC (State College, PA, USA). The statistical evaluation was performed through analysis of variance (ANOVA). Tukey's multiple comparisons test was employed to discern differences between the samples, and statistical significance was determined at a confidence level of 95% ($P < 0.05$).

Result and discussion

Proximate composition

The total lipid, crude protein, moisture, ash, and carbohydrate compositions of the macroalgae samples were significantly different, as demonstrated in Table 2. The protein content of the samples ranges between 3.95% and 23.85% on a dry basis. The protein content of *P. capillacea* was the highest, approximately 6.0-, 5.8-, and 5.2-folds greater than that of *A. rigida, J. rubens,* and *L. viscida*, respectively ($P < 0.05$). The *G. bursa-pastoris, G. gracilis, G. turuturu, L. obtusa, L. pyramidalis,* and *P. capillacea* samples also had a higher protein content compared to *A. rigida, J. rubens,* and *L. viscida* ($P < 0.05$). Also, the lipid contents of *L. obtusa* (1.53%) and *L. viscida* (1.19%) were the greatest and significantly higher than that of the other macroalgae samples ($P < 0.05$). The lipid content of *L. prymidalis* was also higher than that of *A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu,* and *J. rubens* ($P < 0.05$). In addition, the samples' ash, moisture, and total carbohydrate contents ranged between 6.69%- 56.05%, 1.16% -9.50%, and 38.33%- 76.88%, respectively. The ash content of *J. rubens* (56.5%) and *A. rigida* (51.11%) was higher than that of the rest of the samples ($P < 0.05$), but their moisture, protein, and lipid contents were the lowest ($P < 0.05$).

Saygili et al. (2022) reported similar lipid and protein contents in *A. rigida* and *J. rubens* collected from the Mediterranean coasts of Türkiye. Still, the authors measured lower ash contents compared to the present study. The total carbohydrate content of *G. bursa-pastoris* investigated in the present study was higher than

Table 2 Proximate compositions of the *A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea* samples (%)

Macroalgae	Protein	Lipid	Ash	Moisture	Carbohydrate
A. rigida	3.95 ± 0.09^{d}	0.19 ± 0.01^{c}	51.11 ± 1.82^{b}	1.89 ± 0.07^{d}	42.86 ± 1.70^{e}
G.bursa-pastoris	7.69 ± 0.85^{c}	0.22 ± 0.04^{c}	11.06 ± 1.45^{f}	4.015 ± 0.50^{c}	76.88 ± 2.81^{a}
G. gracilis	7.57 ± 0.57^{c}	0.19 ± 0.02^{c}	17.86 ± 0.25^{de}	7.87 ± 0.17^{b}	66.51 ± 0.17^{b}
G. turuturu	10.52 ± 0.22^{b}	0.27 ± 0.03^{c}	15.91 ± 0.39^{e}	7.00 ± 0.00^{b}	66.30 ± 0.63^{bc}
J. rubens	4.10 ± 0.38^{d}	0.33 ± 0.09^{c}	56.05 ± 0.22^{a}	1.19 ± 0.09^{d}	38.33 ± 0.00^{e}
L. obtusa	10.55 ± 0.72^{b}	1.53 ± 0.12^{a}	18.58 ± 0.34^{de}	9.56 ± 0.00^{a}	59.78 ± 0.92^{cd}
L. pyramidalis	12.24 ± 0.24^{b}	0.74 ± 0.00^{b}	20.16 ± 0.60^{d}	6.38 ± 0.50^{b}	60.48 ± 0.82^{bcd}
L. viscida	4.60 ± 0.03^{d}	1.19 ± 0.20^{a}	38.37 ± 0.45^{c}	1.80 ± 0.29^{d}	54.04 ± 0.14^{d}
P. capillacea	23.85 ± 0.10^{a}	0.47 ± 0.10^{bc}	6.69 ± 0.59^{g}	7.21 ± 0.35^{b}	61.78 ± 0.42^{bc}

Data are the mean of 2 replicates ± standard deviation. Values labeled with different superscript letters in each column are significantly different ($P < 0.05$)

that was reported in another study investigating the macroalgae collected from a fish farm in Israel. Still, the protein contents were similar (Korzen et al. 2016). The total protein content in *G. gracilis* collected from Italy was higher compared to the present study (Francavilla et al. 2013). The protein and lipid contents of *G. turuturu* were 2- and ninefold lower than that reported by Denis et al. (2010) in the samples collected from France, while the ash contents were similar to those of the present study. Moreover, El-Shenody et al. (2019) reported lower protein and carbohydrate content for *L. obtusa,* but the lipid content was similar to that was reported in the present study. On the other hand, Turan et al. (2015) reported similar protein and ash contents for the *L. obtusa* collected from Türkiye (Mediterranean Sea), but the authors observed approximately threefold lower carbohydrate content. In another study, the ash content of *L. viscida* from Spain ranged between 50%-80% on a dry basis (Sánchez et al. 2019). To the best of our knowledge, the approximate composition of *L. pyramidalis* was not reported before.

The proximate composition of the macroalgae samples exhibited variations compared to findings reported in previous studies on macroalgae sampled from different seas. These disparities are likely attributed to the geological location and season of sample collection. The carbohydrate and lipid content in algae is notably influenced by environmental factors, with light playing a primary role. The maximal carbohydrate and lipid content is associated with the peak growth phase of macroalgae (Perfeto 1998; Rosenberg & Ramus 1982; Torres et al. 2019). The dynamic interplay of geological and seasonal factors, including variations in light availability, contributes to the observed differences in the proximate composition of the macroalgae. Recognizing the impact of these environmental dynamics is crucial for contextualizing and interpreting the proximate composition variations observed in our study relative to findings from diverse geographical locations and collection periods.

Fatty acid profile

The fatty acid profiles of the nine red macroalgae (*A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea*) are demonstrated in Table 3. The total saturated fatty acid (SFA) content of *G. gracilis* (44.2%) was significantly the lowest among all samples, which ranged between 70.9% and 86.2% ($P < 0.05$). In contrast, *G. gracilis* was the highest in the mono- and polyunsaturated fatty acid contents compared to the other samples ($P < 0.05$). The nine red macroalgae's total mono- and polyunsaturated fatty acid contents ranged between 9.1%-26.8% and 1.4%- 29.0%, respectively. Also, gamma-linolenic acid (C18:3 n6) was detected only in *G. gracilis*, and no polyunsaturated fatty acid (18:2, 18:3) was detected in *J. rubens* samples.

The most abundant SFA in all the samples was palmitic acid (C16:0), and the content of palmitic acid was between 33.4% (*G. gracilis*) and 69.2% (*A. rigida*) (Table 3). A comparable observation was documented by Heiba et al. (1997), highlighting palmitic acid as the predominant fatty acid in macroalgae samples collected from Qatari coasts. However, a contrasting profile was noted in *J. rubens*, where the saturated fatty acid (SFA) content was higher and its unsaturated fatty acid content was lower than the findings reported by El Maghraby and Fakhry (2015).

Besides, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) were not detected in the samples. Similar findings were reported before (Mehdipour et al. 2014; Wahbeh 1997). However, it is essential to acknowledge that the fatty acid composition of macroalgae is subject to numerous influencing factors, including geographical location, temperature, light exposure, nutrient

Table 3 Fatty acid compositions of the *A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea* samples (%)

Fatty acids	*A. rigida*	*G.bursa-pastoris*	*G. gracilis*	*G. turuturu*	*J. rubens*	*L. obtusa*	*L. pyramidalis*	*L. viscida*	*P. capillacea*
Capric acid (C10:0)	1.83 ± 0.02^{ab}	2.46 ± 0.14^{ab}	0.60 ± 0.08^{b}	nd	3.87 ± 0.03^{ab}	4.30 ± 2.02^{ab}	4.88 ± 0.45^{a}	2.65 ± 0.21^{ab}	3.71 ± 0.39^{ab}
Lauric acid (C12:0)	nd	1.59 ± 0.02^{a}	0.69 ± 0.02^{a}	1.29 ± 0.30^{a}	nd	3.18 ± 1.79^{a}	1.71 ± 0.33^{a}	1.849 ± 0.68^{a}	nd
Myristic acid (C14:0)	5.78 ± 0.29^{a}	9.71 ± 0.41^{a}	3.19 ± 0.07^{a}	5.41 ± 0.31^{a}	5.31 ± 0.22^{a}	5.78 ± 4.34^{a}	6.97 ± 0.42^{a}	9.51 ± 0.27^{a}	3.83 ± 0.15^{a}
Pentadecylic acid (C15:0)	1.06 ± 0.07^{a}	nd	0.42 ± 0.01^{a}	2.69 ± 1.13^{a}	1.77 ± 0.14^{a}	4.77 ± 3.46^{a}	1.18 ± 0.05^{a}	3.64 ± 0.21^{a}	nd
Palmitic acid (C16:0)	69.17 ± 2.22^{a}	63.10 ± 1.95^{ab}	33.35 ± 0.69^{c}	57.67 ± 3.63^{ab}	62.42 ± 2.83^{ab}	60.18 ± 1.14^{ab}	50.27 ± 1.48^{bc}	50.95 ± 8.05^{abc}	62.89 ± 0.66^{ab}
Stearic acid (C18:0)	2.65 ± 0.28^{a}	4.07 ± 0.44^{a}	5.94 ± 0.74^{a}	3.87 ± 0.41a	4.97 ± 0.47^{a}	4.58 ± 1.79^{a}	3.27 ± 1.01^{a}	6.17 ± 0.36^{a}	2.22 ± 0.47^{a}
Behenic acid (C22:0)	5.75 ± 1.09^{a}	nd	nd	nd	2.45 ± 0.27^{ab}	nd	1.43 ± 0.37^{b}	nd	3.50 ± 0.17^{ab}
Tricosylic acid (C23:0)	nd	nd	nd	nd	5.42 ± 1.25^{a}	nd	3.30 ± 0.01^{a}	nd	8.05 ± 1.58^{a}
Total SFA	86.24 ± 1.61^{a}	80.92 ± 2.04^{a}	44.19 ± 0.19^{b}	70.92 ± 1.49^{a}	86.20 ± 2.15^{a}	83.49 ± 1.81^{a}	73.00 ± 2.49^{a}	74.74 ± 7.99^{a}	84.20 ± 1.07^{a}
Pentadecenoic acid (C15:1)	nd	nd	nd	nd	2.36 ± 0.40^{a}	0.84 ± 0.00^{a}	1.89 ± 0.78^{a}	nd	2.09 ± 0.11^{a}
Palmitoleic acid(C16:1)	2.74 ± 0.15^{cd}	7.99 ± 0.15^{abc}	4.78 ± 0.24^{abcd}	8.73 ± 2.60^{ab}	3.06 ± 0.04^{cd}	5.15 ± 0.01^{abcd}	9.69 ± 1.01^{a}	4.12 ± 0.17^{bcd}	2.40 ± 0.58^{d}
Oleic acid (C18:1 n9)	6.39 ± 0.48^{b}	6.88 ± 0.75^{b}	22.02 ± 1.90^{a}	12.33 ± 0.55^{b}	8.39 ± 1.70^{b}	8.41 ± 0.40^{b}	8.50 ± 1.26^{b}	11.74 ± 3.63^{b}	7.66 ± 0.04^{b}
Total MUFA	9.13 ± 0.33^{c}	14.87 ± 0.60^{bc}	26.80 ± 1.65^{a}	21.07 ± 3.15^{ab}	13.80 ± 2.15^{bc}	13.98 ± 0.82^{bc}	20.08 ± 1.48^{ab}	15.86 ± 3.46^{bc}	12.15 ± 0.44^{bc}
cis-Linoleic acid (C18:2 n6)	4.63 ± 1.28^{b}	1.41 ± 0.95^{b}	26.79 ± 1.05^{a}	8.01 ± 1.66^{b}	nd	2.53 ± 0.99^{b}	2.88 ± 0.08^{b}	9.39 ± 4.53^{b}	3.65 ± 0.63^{b}
gamma-Linolenic acid (C18:3 n6)	nd	nd	2.22 ± 0.42	nd	nd	nd	nd	nd	nd
Total PUFA	4.63 ± 1.28^{b}	1.41 ± 0.95^{b}	29.01 ± 1.47^{a}	8.01 ± 1.66^{b}	nd	2.53 ± 0.99^{b}	2.88 ± 0.08^{b}	9.39 ± 4.53^{b}	3.65 ± 0.63^{b}

Data are the mean of 2 replicates ± standard deviation. Values labeled with different superscript letters in each row differ significantly ($P < 0.05$)

nd Not detected

availability, and the algae's growth phase (Stefanov et al. 1988). Fatty acid compositions can also vary depending on the season (Polat & Ozogul 2013). The discrepancies observed between our samples and the literature can thus be attributed to the inherent variability introduced by these multifaceted factors. Recognizing and considering these influential variables are critical for a comprehensive understanding and accurate comparison of the fatty acid profiles of macroalgae across different studies and locations.

Soluble carbohydrate profile

Carbohydrate or polysaccharides in algae is usually found in three types: alginate, laminarin, and fucoidan (Ross et al. 2009). These polymers can be hydrolyzed into monosaccharides such as glucose and fructose (Parsa et al. 2018; Watanabe et al. 2006). Soluble carbohydrate compositions (myo-inositol, mannitol, glucose, fructose, and sucrose) of the nine macroalgae samples (*A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea*) are shown in Table 4. The myo-inositol content of *P. capillacea* (2.31 g/kg) was higher than those of all the other samples ($P < 0.05$), but it did not have mannitol, fructose, or sucrose. Mannitol was only noted in *G. turuturu* (0.01 g/kg). The myo-inositol contents of *A. rigida, L. obtusa, L. pyramidalis,* and *L. viscida* were below 0.15 g/kg and lower than the rest of the samples ($P < 0.05$). The glucose contents of the macroalgae samples ranged between 0.42 g/kg and 0.58 g/kg and were not significantly different from each other ($P > 0.05$) except that glucose was not detected in *A. rigida, G. gracilis, J. rubens,* and *L. viscida*. The fructose contents of *G. bursa-pastoris* and *G. turuturu* were lower than those of *L. viscida* and *L. obtusa* ($P < 0.05$). In addition, sucrose was detected in only *A. rigida, G. bursa-pastoris,*

Table 4 Soluble carbohydrate compositions of the *A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea* samples (g/kg)

Macroalgae	Myo-inositol	Mannitol	Glucose	Fructose	Sucrose
A. rigida	0.15 ± 0.04^{d}	-	-	0.16 ± 0.01^{ab}	0.21 ± 0.01^{ab}
G.bursa-pastoris	0.26 ± 0.01^{cd}	-	0.54 ± 0.11^{a}	0.05 ± 0.01^{b}	0.14 ± 0.03^{b}
G. gracilis	0.90 ± 0.15^{b}	-	-	0.21 ± 0.06^{ab}	-
G. turuturu	0.75 ± 0.13^{bc}	0.01 ± 0.00	0.43 ± 0.05^{a}	0.06 ± 0.01^{b}	0.15 ± 0.00^{ab}
J. rubens	0.57 ± 0.04^{bcd}	-	-	0.16 ± 0.08^{ab}	-
L. obtusa	0.12 ± 0.04^{d}	-	0.43 ± 0.16^{a}	0.26 ± 0.01^{a}	0.22 ± 0.01^{a}
L. pyramidalis	0.13 ± 0.04^{d}	-	0.42 ± 0.15^{a}	0.18 ± 0.05^{ab}	-
L. viscida	0.14 ± 0.05^{d}	-	-	0.30 ± 0.07^{a}	-
P. capillacea	2.31 ± 0.30^{a}	-	0.58 ± 0.05^{a}	-	-

Data are the mean of 2 replicates ± standard deviation. Values labeled with different superscript letters in each column differ significantly ($P < 0.05$)

G. turuturu, and *L. obtusa*. The sucrose content of *G. bursa-pastoris* was also significantly lower than that of *L. obtusa* ($P < 0.05$).

The variances observed in the composition of these red macroalgae species can be ascribed to distinctions in both algal sources and the growth environment. The carbohydrate content of wild macroalgae is known to exhibit considerable variability, influenced by environmental factors such as water salinity, temperature, nutrient availability, and light conditions (Marinho-Soriano et al. 2006; Zhang et al. 2020). These environmental parameters play a crucial role in shaping the macroalgae's metabolic pathways and biochemical processes, leading to notable differences in their carbohydrate profiles. As such, understanding the impact of these environmental factors is paramount for accurately interpreting and contextualizing the nutritional compositions of macroalgae in their natural habitats.

Mineral profile

It is known that some elements (i.e. Cd, Pb) are harmful to organisms even at trace levels. In contrast, others are essential micronutrients (i.e. Al, Mn, Fe, Cu, Zn, etc.) that can be toxic at specific concentrations (Stevenson & Cole 1999). Since trace elements persist in the environment and accumulate in tissues, they can enter the food chain, resulting in biomagnification at higher trophic levels; trace elements are considered a hazard to algal ecosystems (Chen et al. 2018; Rainbow 2007; Shabaka & Moawad 2021).

Table 5 Mineral compositions of the *A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea* samples

Minerals	*A. rigida*	*G.bursa-pastoris*	*G. gracilis*	*G. turuturu*	*J. rubens*	*L. obtusa*	*L. pyramidalis*	*L. viscida*	*P. capillacea*
Macro elements (mg/kg)									
K	0.49 ± 0.00^{f}	10.96 ± 0.13^{a}	7.42 ± 0.10^{b}	2.17 ± 0.03^{d}	0.50 ± 0.00^{f}	0.53 ± 0.00^{f}	0.79 ± 0.01^{f}	1.66 ± 0.02^{e}	3.24 ± 0.01^{c}
Mg	37.55 ± 0.63^{a}	3.31 ± 0.86^{e}	11.23 ± 0.20^{c}	10.16 ± 0.15^{c}	30.53 ± 0.38^{b}	8.82 ± 0.11^{d}	9.08 ± 0.15^{d}	3.73 ± 0.04^{e}	3.24 ± 0.04^{e}
Microelements (µg/kg)									
Al	$302{,}23 \pm 5{,}92^{d}$	47.75 ± 0.89^{h}	$142{,}38 \pm 4{,}09^{f}$	$234{,}66 \pm 1{,}94^{e}$	$97{,}44 \pm 2{,}17^{g}$	1384.90 ± 3.78^{a}	708.67 ± 9.24^{b}	403.23 ± 5.43^{c}	$296{,}93 \pm 5{,}89^{d}$
Mn	$281{,}49 \pm 5{,}47^{a}$	24.68 ± 0.31^{cd}	$25{,}55 \pm 0{,}43^{cd}$	$31{,}94 \pm 0{,}32^{bc}$	$34{,}06 \pm 0{,}57b^{c}$	36.50 ± 0.25^{bc}	21.93 ± 0.32^{d}	15.97 ± 0.18^{d}	$41{,}93 \pm 0{,}68^{b}$
Fe	$2052{,}95 \pm 44{,}75^{a}$	305.56 ± 4.37^{e}	$813{,}96 \pm 20{,}68^{c}$	$407{,}3 \pm 4{,}10^{d}$	$310{,}7 \pm 3{,}23^{de}$	1709.84 ± 16.48^{b}	778.29 ± 20.63^{c}	754.62 ± 9.36^{c}	$247{,}1 \pm 5{,}44^{e}$
Ni	$170{,}31 \pm 0{,}81^{a}$	1.08 ± 0.01^{e}	$5{,}30 \pm 0{,}14^{d}$	$1{,}87 \pm 0{,}04^{e}$	$19{,}01 \pm 0{,}36^{b}$	10.77 ± 0.16^{c}	9.79 ± 0.44^{c}	18.72 ± 0.14^{b}	$8{,}51 \pm 0{,}196^{c}$
Cu	$32{,}79 \pm 0{,}44^{b}$	2.04 ± 0.09^{b}	$1423{,}4 \pm 28{,}43^{a}$	$6{,}64 \pm 0{,}03^{b}$	$4{,}16 \pm 0{,}16^{b}$	8.30 ± 0.17^{b}	19.00 ± 0.40^{b}	6.56 ± 0.13^{b}	$17{,}96 \pm 0{,}41^{b}$
Zn	$107{,}72 \pm 2{,}16^{b}$	18.56 ± 0.52^{c}	$804{,}5 \pm 22{,}42^{a}$	$102{,}59 \pm 1{,}18^{b}$	$17{,}46 \pm 0{,}58^{c}$	21.67 ± 0.22^{c}	18.85 ± 0.37^{c}	12.28 ± 0.28^{c}	$13{,}87 \pm 0{,}34^{c}$
Se	$5{,}19 \pm 0{,}10^{a}$	3.22 ± 0.09^{d}	$3{,}81 \pm 0{,}11^{bc}$	$3{,}56 \pm 0{,}10^{c}$	$0{,}43 \pm 0{,}01^{e}$	0.56 ± 0.02^{c}	4.34 ± 0.11^{b}	0.34 ± 0.01^{e}	$5{,}59 \pm 0{,}08^{a}$
Ag	$21{,}98 \pm 0{,}21^{a}$	1.84 ± 0.06^{d}	$2{,}33 \pm 0{,}036^{cd}$	$3{,}49 \pm 0{,}09^{b}$	$2{,}19 \pm 0{,}05^{cd}$	2.66 ± 0.09^{c}	4.15 ± 0.16^{b}	3.46 ± 0.06^{b}	1,90 ± 0,04 cd
Heavy metals (µg/kg)									
Cd	$0{,}83 \pm 0{,}01^{a}$	0.06 ± 0.00^{g}	$0{,}14 \pm ,004^{e}$	$0{,}05 \pm 0{,}00^{g}$	$0{,}14 \pm 0{,}00^{e}$	0.28 ± 0.01^{c}	0.32 ± 0.00^{b}	0.09 ± 0.00^{f}	$0{,}17 \pm 0{,}00^{d}$
Pb	$6{,}45 \pm 0{,}17^{c}$	0.74 ± 0.02^{d}	$59{,}49 \pm 1{,}638^{a}$	$1{,}21 \pm 0{,}02^{d}$	$9{,}72 \pm 0{,}10^{b}$	1.96 ± 0.03^{d}	2.61 ± 0.06^{d}	1.38 ± 0.04^{d}	$1{,}35 \pm 0{,}06^{d}$

Data are the mean of 2 replicates ± standard deviation. Values labeled with different superscript letters in each row differ significantly ($P < 0.05$)

The mineral compositions of nine macroalgae (*A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea*) are shown in Table 5. The Mg content of *A. rigida* was measured as 37.56 mg/kg and, significantly higher than that of the other samples ($P < 0.05$). *A. rigida* also demonstrated higher Mn, Fe, Ni, Ag, and Cd contents compared to the other macroalgae samples ($P < 0.05$). Still, its K content (0.49 mg/kg) was lower than the other samples except for that of *J. rubens*, *L. obtusa* and *L. pyramidalis* ($P < 0.05$). In addition, Cu and Zn were higher in *G. gracilis* than the other macroalgae ($P < 0.05$). Also, Al was the highest in *L. obtusa* among the samples ($P < 0.05$). On the other hand, the heavy metal content of *G. gracilis* was the highest ($P < 0.05$), and it contained 59.49 µg/kg Pb and 0.14 µg/kg Cd. The lowest amount of Cd was detected in *G. turuturu* (0.05 µg/kg) and *G. bursa-pastoris* (0.06 µg/kg) ($P < 0.05$), whereas Pb was the lowest in *G. bursa-pastoris* (0.74 µg/kg) ($P < 0.05$).

Based on the findings, it is evident that all examined samples boast substantial mineral content, suggesting their potential as valuable sources for mineral supplementation in human nutrition. Notably, the focus on the most studied elements in Mediterranean macroalgae—Cd, Pb, Cu, and Zn—aligns with the investigations of Sánchez-Quiles et al. (2017). Drawing parallels to related studies conducted by Bonanno and Orlando-Bonaca (2018) and Malea et al. (2015), Cd concentrations varied significantly among red macroalgae species. *G. gracilis* exhibited the lowest amount (< 0.01 mg/kg), while *J. rubens* displayed the highest (16.9 mg/kg). Similarly, Pb levels ranged from a minimum in *G. gracilis* (< 0.01 mg/kg) to a maximum in *J. rubens* (617 mg/kg) (Bonanno & Orlando-Bonaca 2018; Malea et al. 2015). The potential health risks associated with elevated levels of heavy metals, such as Pb and Cd, have been well-documented (Nagajyoti et al. 2010; War Naw et al. 2020; Wasi et al. 2013). Consequently, it is imperative to consider heavy metal contamination in macroalgae. In the current study, *G. gracilis* exhibited the highest total amounts of Cd and Pb (59.63 µg/kg), surpassing the levels found in *J. rubens* (9.86 µg/kg) and *A. rigida* (7.28 µg/kg) when compared to other samples ($P < 0.05$). It is worth noting that the observed heavy metal contamination in the macroalgae is intricately linked to the environmental pollution and industrial activity levels at their respective sampling locations (Chakraborty & Owens 2014; Chakraborty et al. 2014; War Naw et al. 2020).

Conclusions

The chemical and nutrition profiles are essential parameters for selecting macroalgae to be used in the formulations of new or functional food products. The proximate, fatty acid, soluble carbohydrate, and mineral profiles of *A. rigida, G. bursa-pastoris, G. gracilis, G. turuturu, J. rubens, L. obtusa, L. pyramidalis, L. viscida,* and *P. capillacea* collected from the coasts of Türkiye were evaluated. Most of the samples contained reasonable amounts of crude protein and were low in lipid content. In general, all the samples demonstrated good fatty acid and mineral compositions. Myo-inositol and glucose were the most abundant soluble carbohydrates detected in the samples. Moreover, *G. gracilis* had the highest unsaturated fatty acid content, whereas its heavy metal content was also increased. The results of this study will contribute to the literature with valuable information on the nine red macroalgae from Türkiye. Our future research endeavors are strategically designed to delve deeper into the multifaceted potential applications of macroalgae, particularly in the dynamic landscape of innovative and functional food product development. For instance, species rich in omega-3 fatty acids can be utilized in supplements for cardiovascular and cognitive health. Protein-rich varieties are valuable for plant-based protein powders. Polysaccharides from brown algae offer prebiotic benefits for gut health, while compounds from red algae contribute to food texture and stability. Additionally, bioactive compounds in macroalgae show promise in pharmaceuticals and as sustainable packaging materials. By expanding our investigations, we aim to achieve a more profound and comprehensive understanding of the intricate roles macroalgae can play in shaping the next generation of nutritional products.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
AY supervised the study and administered the project. AY and BÖ conceptualized and designed the study. EŞO collected the macroalgae samples and visualized. ZM, CS, ED, ENA and EŞO analyzed the samples. CK performed the data analysis. CK and ZM were involved in the preparation of the original draft of the study. AY, CK and BÖ contributed to the revision and editing of the manuscript. All authors read and approved the submitted version.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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