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Comparison of nutritive chemistry of a range of temperate seaweeds

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Abstract

Eleven species of macroalgae (including four species from commercially important genera) were analysed for moisture, ash, fat, protein, neutral detergent fibre, crude fibre, calorific value, and calcium content. At the extremes of the nutritional values, *Corallina officinalis* had low calorific value (2.7 ± 0.3 MJ kg^{-1}), high ash content ($77.8 \pm 0.2\%$ dw), low protein ($6.9 \pm 0.1\%$ dw) and high calcium content (182 ppm); whereas the exploited *Porphyra* sp. had high calorific value (18.3 ± 1.8 MJ kg^{-1}), low ash content ($9.3 \pm 0.2\%$ dw), high protein ($44.0 \pm 1.2\%$ dw) and low calcium content (19.9 ppm). The other species considered had intermediate values, but tended to be more similar to *Porphyra* than to *Corallina*. When possible our data were also compared with those of other workers; they were found to be broadly similar.

Keywords: Seaweeds; Ash; Protein; Fibre; Calorific value; Calcium

1. Introduction

In 2003, it was estimated that approximately 1 millions tonnes of wet seaweed were harvested in 35 countries as a source of food; as sources of agar, alginate and carrageenan; as a fertilizer; as fuel; and, for use in cosmetics annually (McHugh, 2003). However, it is as a dietary supplement that seaweed has had the longest and perhaps most significant use. Seaweed has been an important dietary component since at least the fourth century in Japan and the sixth century in China (McHugh, 2003). Recently, both these and other countries, such as the Republic of Korea, the United States of America, South America, Ireland, Iceland, Canada and France have significantly increased the consumption, production and marketing of seaweeds (McHugh, 2003). As demand has increased, natural stocks have been unable to meet market requirements, and now more than 90% of seaweed that is used commercially is cultivated (McHugh, 2003). Seaweeds are a valuable food source as they contain protein, lipids, vitamins and minerals (Norziah & Ching, 2000; Sánchez-Machado, López-Cervantes, López-Hernández, & Paseiro- Losada, 2004; Wong & Cheung, 2000). Seaweeds are not only a useful food source to humans, whole plants and seaweed mixes have been used in animal nutrition (Chapman & Chapman, 1980; Indergaard & Minsaas, 1991; Ventura & Castanon, 1998) and fish feed (McHugh, 2003). However, very few of the world's available seaweed species are used commercially. This may be because they cannot be harvested or cultivated on a commercially viable scale, or because their composition simply makes them unsuitable.

This study aims to compare aspects of the nutritional composition of seaweeds from genera that are traditionally used in the food industry with other (currently not exploited) commonly occurring temperate macroalgae. The data will also be compared with available data on the same species reported by other workers.

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2. Materials and methods

2.1. Materials

Samples comprising of up to 15 individual plants of 11 species of algae (the commercially important *Ulva lactuca, Porphyra* sp., *Fucus serratus* and *Laminaria digitata*, and the unexploited *Cladophora rupestris, Ceramium* sp., *Polysiphonia* sp., *Dumontia contorta, Mastocarpus stellatus, Osmundea pinnatifida* and *Corallina officinalis*) were collected from Holbeck, North Yorkshire, UK (54°16′N, 0°25′W) and washed to remove all epifauna and epiphytes.

2.2. Nutrient analysis

Seaweeds were analysed for moisture content, ash content, fat content, protein content, fibre (neutral detergent fibre and crude fibre), and calorific value. Although the authors recognise that other components of seaweed (e.g. amino acids, soluble fibre, fatty acids and vitamins) play an important role in the human diet, this study focuses on a range of general nutritional components as outlined above. For all analyses (with the exception of moisture content) algal material was dried in an oven at 100 °C for 24 h and ground into a fine powder prior to use. Each analysis was replicated three times.

2.2.1. Moisture content

Percentage dry matter of fresh algal material was measured using Oxford and Ohaus moisture balances.

2.2.2. Ash content

Two grams of dried algal material were added to a pre-weighed crucible and weighed, placed in a furnace at 400 °C for 4 h, cooled in a desiccator and reweighed. The ash content was determined using Eq. (1):

$$\%\text{ash} = \text{weight of ash}/\text{weight of sample} \times 100. \quad (1)$$

2.2.3. Fat content

Crude fat content was determined using the Soxtherm method. One hundred and forty millilitres of petroleum ether was poured over 5 g of algal material in an extraction thimble. The thimble was placed in a pre-weighed beaker containing anti-bumping granules and placed in a Soxtherm for 80 min, after which the beaker was dried in an oven, cooled and reweighed. The fat content of each sample was calculated using Eq. (2):

$$\%\text{crude fat} = ([\text{weight of dried beaker} + \text{fat}] - [\text{weight of dried beaker} + \text{granules}]/\text{weight of sample}) \times 100. \quad (2)$$

2.2.4. Protein content

Crude protein content was determined using the Kjeldahl method. One gram of algal material was digested in 15 ml of sulphuric acid in the presence of 2 kjeltec Ck catalyst tablets by placing in a turbosog fume scrubber for 1 h. Digestion was complete on production of a clear, coloured solution. After digestion, samples were analysed for nitrogen content by placing digested material into a Vapodest 33 distilling unit. The digested sample was then titrated against standard (0.1 M) hydrochloric acid until a colour change from blue to straw colour occurred. Nitrogen content was calculated using Eq. (3):

$$\%N = [14.01 \times (\text{ml titrant for sample} - \text{ml titrant for blank}) \times \text{molarity of acid}]/\text{weight of sample} \times 100. \quad (3)$$

The crude protein content was then calculated using Eq. (4):

$$\%\text{protein} = N \times 6.25 \text{ (protein factor specific to sample)}. \quad (4)$$

The average $\%N$ in plant proteins is 16%. The general conversion factor to convert N to protein is $100/16 = 6.25$.

2.2.5. Neutral detergent fibre

Neutral detergent fibre (NDF) was determined using fat-free samples. A half gram of algal material was placed in a fibre bag and boiled with 360 ml of neutral detergent solution for 30 min. One hundred and eighty millilitres of this hot neutral detergent solution was added to 180 ml of cold neutral detergent solution and 12 ml of amylase solution and boiled for a further 30 min. Fibre bags were then washed in four portions of hot, distilled water, patted dry and dried in an oven at 100 °C for 4 h, desiccated, cooled and weighed. They were then ashed in a furnace at 600 °C for 6 h, desiccated, cooled and reweighed. NDF content was determined using Eq. (5):

$$\%\text{NDF} = [(\text{beaker} + \text{residue weight} - \text{fibrebag weight}) - (\text{beaker} + \text{ash weight})/\text{sample weight}] \times 100. \quad (5)$$

2.2.6. Crude fibre

Crude fibre was determined using fat-free samples. One gram of algal material was placed in a fibre bag, boiled firstly with 360 ml of 0.128 M sulphuric acid for 30 min and then with 360 ml of 0.313 M hydrochloric acid for a further 30 min. Fibre bags were washed once with hot distilled water, once with 0.1 M hydrochloric acid and twice more with hot distilled water, patted dry and dried in an oven at 100 °C for 4 h, desiccated, cooled and weighed. They were then ashed in a furnace at 600 °C for 6 h, desiccated, cooled and reweighed. Crude fibre content was determined using Eq. (6):

$$\%\text{crude fibre} = [(\text{beaker} + \text{residue weight} - \text{fibrebag weight}) - (\text{beaker} + \text{ash weight})/\text{sample weight}] \times 100. \quad (6)$$

2.2.7. Calorific value

A half gram of algal material was placed in a bomb calorimeter (Parr 1351 calorimeter). A spike of benzoic acid was added to the samples of *C. officinalis* to aid ignition of the material.

2.3. Calcium content

Algal samples were also analysed for calcium content using atomic absorption spectrophotometry (AAS). Ashed algal samples were used and samples were prepared by weighing out the amount of ash obtained from 2 g of algae, to which 10 ml of concentrated acid mix (2 parts hydrochloric acid, 1 part nitric acid and 3 parts distilled water) was added. This solution was filtered and made up to 100 ml with distilled water. Two millilitres of lanthanum chloride was added to stabilise the calcium atoms. Hundred millilitres standard solutions of 1, 5, 10, 15, 20, 25, 50, 75 and 100 ppm were prepared using a calcium stock solution in nitric acid, distilled water and 2 ml of lanthanum chloride. Standard solutions were analysed in the AAS to prepare a calibration curve, against which the algal samples were compared to calculate calcium levels.

2.4. Data analysis

Data were analysed using principle components analysis (PCA), to identify the variables important in separating the algal species by nutritional composition. Prior to PCA percentage data were arc-sine transformed (James & McCulloch, 1990) and the data set was examined for outliers (Pallant, 2001). Bartlett's test of sphericity was performed to determine if the matrices in the data set contained adequate correlation coefficients (greater than 0.3) (Tabachnick & Fidell, 2001). The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was also performed, to test for significance of correlations within the data matrices (Tabachnick & Fidell, 2001). The factors within the analysis were not correlated (determined by running an oblique rotation and examining the factor correlation matrix for correlations of 0.32 and above) and so data were subjected to orthogonal Varimax rotation (Tabachnick & Fidell, 2001). Two PCAs were performed. The first included all algal species and all nutrient variables. After interpretation of these results *C. officinalis* was found to form a discrete out-group. A second PCA of all nutrients was therefore carried out with the exclusion of *C. officinalis* to permit further elucidation of the relationships between the other species. All PCAs were performed using the SPSS version 11.5 for Windows statistical package.

3. Results and discussion

The nutritional composition of the seaweeds considered in this study are reported in Table 1. The table also presents data previously reported in the literature, where such data are available it would appear that our data are broadly similar to them. The eight nutritional variables for all algal species were subjected to PCA. Data screening of transformed nutrient data prior to PCA identified no outliers in the variables. Bartlett's test of sphericity was significant (all species: $\chi^2_{28} = 285.288$, $P < 0.001$; excluding *C. officinalis*: $\chi^2_{28} = 155.154$, $P < 0.001$). The KMO measure of sampling adequacy was 0.616 for all species ($P < 0.05$), thus indicating factor analysis was appropriate. When *C. officinalis* was excluded, the KMO measure of sampling adequacy was 0.474 ($P > 0.05$), which is lower than the recommended KMO value of 0.6 (Tabachnick & Fidell, 2001). However, coupled with the significant Bartlett's test for these data it was considered appropriate to proceed with factor analysis.

PCA revealed the presence of three components with eigenvalues exceeding 1, which accounted for 85.8% of the total variance (Table 2). Inspection of the screeplot (not presented) showed a clear break after the second component, so two components were retained for further investigation (Pallant, 2001). The factor loadings of the eight nutrient variables for all algal species on the first two components, and their communalities are shown in Table 3. The two factor extraction explained a total of 72.9% of the variance (see Table 3 for the % explained by each component). The main nutrients loading on component 1 were calorific value and ash content, whereas fat loaded strongly on component 2 (Table 3).

The plot of the regression factor scores for the first two principle components (Fig. 1) showed that most of the separation of the data points occurred across the first principle component axis, with some separation across the second principle component axis. Data points for *C. officinalis* were strongly displaced along the first principle components axis (Fig. 1), which suggests that this species has a different nutritional composition, which is likely to be caused by its relatively low calorific value and high ash content (Table 1). Along the second principle components axis, data points for *M. stellatus* were displaced (Fig. 1), which could be due to its relatively high fat content and low calcium content (Table 1).

As *C. officinalis* displaced strongly across the first principle component axis, PCA was performed excluding this species in order to permit further elucidation of the variation that exists between the other species considered. This analysis also produced three components with eigenvalues exceeding 1, accounting for 81.3% of the total variance (Table 4). Inspection of the screeplot (not presented) showed a clear break after the fifth component, however, as only three components had eigenvalues over 1 it was decided to retain three components for further investigation. The factor loadings of the eight nutrient variables for ten algal species (excluding *C. officinalis*) on the first three components, and their communalities are shown in Table 5. The three factor extraction explained a total of 70.2% of the variance (see Table 5 for the % explained by each component). The main nutrients loading on component 1 were calcium content and ash content, whereas

Table 1
Nutritional composition of 11 species of macroalgae

Species	Moisture	Ash	Protein[a]	Fat	Crude fibre	NDF	Calorific value	Calcium
Cladophora rupestris	68.5 ± 2.7 59[c]	16.8 ± 0.6 55[d]	29.8 ± 0.6	1.0 ± 0.4	24.7 ± 0.5	45.7 ± 6.1	15.9 ± 0.3	49.0
Ceramium sp.	87.4 ± 1.5	27.1 ± 0.5	31.2 ± 0.5	0.6 ± 0.3	5.1 ± 1.3	33.7 ± 2.3	14.4 ± 0.06	95.1
Polysiphonia sp.	77.2 ± 2.2 86.3[c]	19.2 ± 0.1 31[c]	31.8 ± 0.2	0.05 ± 0.0 7	4.3 ± 0.6	52.8 ± 19.5	16.1 ± 0.1	104
Ulva lactuca	79.6 ± 2.6 78[f] 10.6[i] 79.6[j]	17.8 ± 0.1 13–22[f] 21.3[i] 23.6[j] 21[c] 20[d]	29.0 ± 0.1 15–25[f] 10–21[h] 7.06[i]	0.5 ± 0.03 0.6–0.7[f]	2.8 ± 0.7	32.9 ± 0.1	15.7 ± 0.1	53.7
Porphyra sp.	77.1 ± 4.4 86[f]	9.3 ± 0.2 8–16[f] 21[k] 12[d] 19.07[m]	44.0 ± 1.2 33–47[f] 28.29[k] 24.11[m] 30–50[l]	0.7 ± 0.09 0.7[f]	1.1 ± 0.6	33.5 ± 0.6	18.3 ± 1.8	19.9
Dumontia contorta	87.7 ± 0.6	17.8 ± 0.1	31.7 ± 0.4	0.12 ± 0.2	2.0 ± 0.2	34.3 ± 0.3	15.6 ± 0.06	51.6
Mastocarpus stellatus	64.9 ± 3.9	15.6 ± 0.2	25.4 ± 0.2	3.0 ± 4.8	1.8 ± 0.5	16.6 ± 0.8	15.5 ± 0.06	38.7
Osmundea pinnatifida	86.4 ± 3.7	32.3 ± 0.3	27.3 ± 0.1	4.3 ± 6.38	6.5 ± 1.7	25.6 ± 0.4	13.6 ± 0.2	89.1
Fucus serratus	81.1 ± 3.0	18.6 ± 0.3	17.4 ± 0.2 3–11[e]	1.8 ± 0.3	16.0 ± 0.8	26.2 ± 2.8	15.5 ± 0.1	44.26
Laminaria digitata	86.1 ± 0.3 73–90[f]	23.6 ± 2.2 21–35[f] 33[b] 37.6[k]	15.9 ± 0.4 8–15[f] 9.3[b] 10.7[k]	0.5 ± 0.3 1–2[f]	7.7 ± 1.6	16.6 ± 0.5	13.0 ± 0.3	73.4
Corallina officinalis	31.5 ± 3.7	77.8 ± 1.2 80[g]	6.9 ± 0.1 6.1[g]	0.3 ± 0.2	8.3 ± 3.2	9.4 ± 3.5	2.7 ± 0.3	182

All values are expressed as mean % dry weight ±SD, except calorific value (MJ kg^{-1} ± SD) and calcium content (ppm).

[a] Estimated using $N \times 6.25$ as a conversion factor, though this may over-estimate protein content, especially if samples contain high levels of non-protein nitrogen (Salo-Väänänen & Koivistoinen, 1996; Crossman et al., 2000). For each species, values in the first row were obtained during this study. Other values have been referenced from the literature as a comparison.

[b] Averaged from Black (1950).
[c] Paine and Vadas (1969).
[d] Carefoot (1973).
[e] Munda (1977).
[f] Indergaard and Minsaas (1991) and references therein.
[g] Foster and Hodgson (1998).
[h] Fleurence (1999) and references therein.
[i] Wong and Cheung (2000).
[j] Lamare and Wing (2001).
[k] Rupérez and Saura-Calixto (2001).
[l] McHugh (2003).
[m] Sánchez-Machado et al. (2004).

Table 2
Eigenvalues and % of total variance for the first three principle components extracted from PCA using nutritional data for all algal species

Component	Eigenvalues	% of Variance	Cumulative %
1	4.542	56.8	56.8
2	1.292	16.2	72.9
3	1.034	12.9	85.8

NDF and protein loaded strongly on component 2, and crude fibre on component 3 (Table 5).

The plot of the regression factor scores for the first two principle components (Fig. 2) showed that most of the separation of the data points occurred across the first principle component axis, with some separation across the second principle component axis. Data points for *Porphyra* sp.

Table 3
Post extraction communalities and factor loadings of the eight nutrient variables for all algal species for the first two principle components with orthogonal Varimax rotation

Variable	Communalities	Rotated first component	Rotated second component
Calorific value	0.980	0.955	
Ash	0.956	−0.921	0.306
Protein	0.843	0.884	
NDF	0.775	0.784	0.384
Moisture	0.617	0.782	
Calcium	0.861	−0.777	0.468
Fat	0.847		−0.872
CF	0.988		0.361
%Variance		55.2	17.7

NB only loadings above 0.3 are displayed.

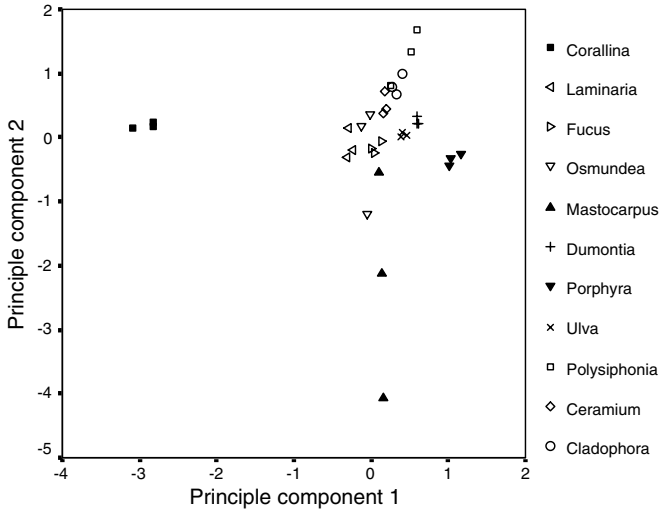

Fig. 1. PCA of transformed nutrient data for all algal species. Scores of the first two principle components are plotted. Algal species are used as markers.

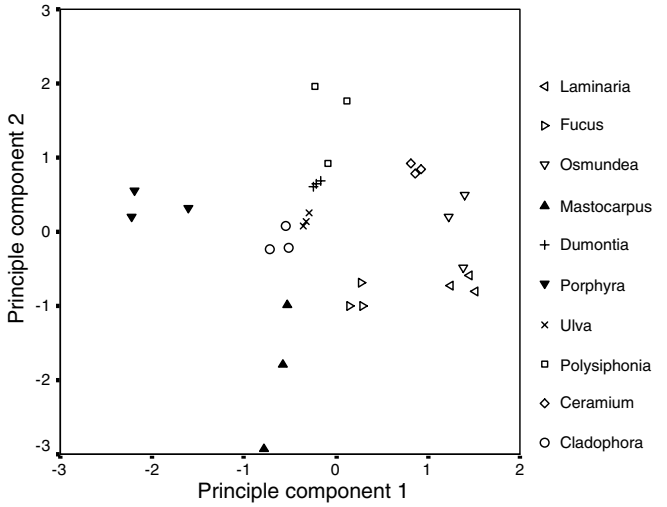

Fig. 2. PCA of transformed nutrient data for 10 algal species, excluding *C. officinalis*. Scores of the first two principle components are plotted. Algal species are used as markers.

Table 4
Eigenvalues and % of total variance for the first three principle components extracted from PCA using nutritional data for 10 algal species (excluding *C. officinalis*)

Component	Eigenvalues	% of Variance	Cumulative %
1	3.260	40.8	40.8
2	1.988	24.9	65.6
3	1.256	15.7	81.3

Table 5
Post extraction communalities and factor loadings of the eight nutrient variables for 10 algal species (excluding *C. officinalis*) for the first three principle components with orthogonal Varimax rotation

Variable	Communalities	Rotated first component	Rotated second component	Rotated third component
Calcium	0.783	0.949		
Ash	0.882	0.880		
Calorific value	0.910	−0.729	0.573	
NDF	0.869		0.915	
Protein	0.810		0.782	−0.465
CF	0.937			0.982
Fat	0.558			
Moisture	0.755			
%Variance		30.6	23.7	16.0

NB only loadings above 0.3 are displayed.

were strongly displaced along the first principle component axis (Fig. 2), which suggests that this species has a different nutritional composition. This displacement is likely to be caused by its relatively low ash content, high calorific value and low protein content (Table 1). Along the second principle component axis, data points for *Polysiphonia* sp. were displaced (Fig. 2), which could be due to its relatively low fat content and high NDF content (Table 1). Data points for *M. stellatus* were also displaced along the second principle component axis (Fig. 2), as reported above for Fig. 1.

Of the species that showed obvious differences in nutritional composition (Figs. 1 and 2), three of them are not currently commercially viable (*C. officinalis, M. stellatus* and *Polysiphonia* sp). The low calorific value and high ash content of *C. officinalis* are likely to be due to the presence of calcium carbonate in the thallus of this species (Steneck & Watling, 1982). In contrast to *C. officinalis, Porphyra* sp., which has a foliose thallus, had a high calorific value and low ash content. These two species illustrate the range of nutritional values for the seaweeds studied. *C. officinalis* had a low protein and high calcium content, whereas *Porphyra* had a high protein and low calcium content (Table 1).

The individual nutritional components of the remaining algal species (both commercial and non-commercial species) generally fell within the range of *Corallina* and *Porphyra*, suggesting there is limited variability between species. It is most likely that it is the relative abundance of a combination of nutritional components for a given species alongside its availability, ease of cultivation and harvesting that results in its commercial value as a food source.

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