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Review

Seaweed proteins: biochemical, nutritional aspects and potential uses

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Seaweeds are traditionally used in human and animal nutrition. Their protein contents differ according to the species and seasonal conditions. Little information is available on the nutritional value of algal proteins and, especially, on the compounds that decrease their digestibility. This paper is a short review of the biochemical and nutritional aspects associated with seaweed proteins. Some perspectives on the potential uses of algal proteins for the development of new foods or additives for human or animal consumption are also discussed. © 1999 Elsevier Science Ltd. All rights reserved.

The annual global aquaculture production of marine algae is 6.5×10^6 tonnes (fresh products) [1]. This marine resource is mainly exploited for food additive and sea vegetable production. In Asian countries, seaweeds are often consumed as marine vegetables. Japanese people are the main consumers with an average of 1.6 kg (dry weight) per year *per capita* [2].

In Europe, algae, more particularly the brown seaweeds, are traditionally used for the production of additives (e.g. alginates) or meal for animal nutrition [3]. In most cases, the seaweeds are used in human or animal foods for their mineral contents or for the functional properties of their polysaccharides. Seaweeds are rarely promoted for the nutritional value of their proteins.

Protein content

The protein content of seaweeds differs according to species. Generally, the protein fraction of brown seaweeds is low (3–15% of the dry weight) compared with that of the green or red seaweeds (10–47% of the dry weight) [4,5]. Except for the species *Undaria pinnatifida* (wakame) which has a protein level between 11 and 24% (dry weight), most brown seaweeds industrially exploited (*Laminaria digitata, Ascophyllum nodosum, Fucus vesiculosus and Himanthalia elongata*) have a protein content lower than 15% (by dry weight) (Table 1). In some green seaweeds such as the species belonging to the genus *Ulva*, the protein content can represent between 10 and 26% (dry weight) of the plant. For instance, the species *Ulva pertusa,* which is frequently consumed under the name of "ao-nori" by the Japanese people, has a high protein level between 20 and 26% (dry product) [2] (Table 1). Higher protein levels were recorded for the red seaweeds such as *Porphyra tenera* (47% of dry mass) or *Palmaria palmata* (35% of dry mass) [5,6] (Table 1). These algae, known under the names of "nori" and "dulse", respectively, have protein levels higher than those found in high-protein pulses such as soybean.

The protein content of marine algae also depends on the seasonal period. An annual monitoring of protein level from *Palmaria palmata* (Dulse) collected on the French Atlantic coast showed that the protein content of this algae can vary between 9 and 25% (dry weight) [7]. Higher protein levels were observed during the end of the winter period and spring whereas lower amounts were recorded during the summer months [7] (Fig. 1). The seasonal variation of the algal protein content was also reported for various species such as *Laminaria digitata* or *Ulva lactuca* [8,9].

Amino acid composition

The amino acid composition of seaweeds has been frequently studied and compared to that of other foods such as eggs or soybean. For most seaweeds, aspartic and glutamic acids constitute together a large part of the amino acid fraction. In *Fucus sp.* (brown seaweeds), Munda reported that these two amino acids can represent between 22 and 44% of the total amino acids [12]. In the green seaweeds, the level of these two amino acids can represent up to 26 and 32% of the total amino acids

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Table 1. Protein levels in some seaweeds used by the food industry

Seaweed species or genus	*Palmaria palmata* [6,7]	*Porphyra tenera* [3,10]	*Ulva lactuca* [11,13]	*Ulva pertusa* [5,10]	*Laminaria digitata* [3]	*Fucus sp.* [12]	*Ascophyllum nodosum* [12,13]
Protein (in % of dry mass)	8–35	33–47	10–21	20–26	8–15	3–11	3–15

of the species *Ulva rigida* and *Ulva rotundata*, respectively [14]. However, the glutamic and aspartic acid levels seem to be lower in red seaweed species such as *Palmaria palmata* and *Porphyra tenera* (14 and 19% of the total amino acids, respectively) [2,3]. With respect to the high protein algae (e.g. *Palmaria sp.*, *Porphyra sp.*, *Ulva* sp.), the comparison of their amino acid composition with those of other food proteins (soybean, eggs) allows us to obtain a first estimate of the nutritional value of seaweed proteins. For the species *Palmaria palmata*, leucine, valine and methionine are well represented in the essential amino acid fraction. The average levels of these amino acids are close to those generally reported for ovalbumin. On the other hand, isoleucine and threonine contents are similar to those recorded for leguminous proteins (Table 2). Except for histidine content, the essential amino acid profile of *Porphyra tenera* seems to be relatively close to those of leguminous plants (Table 2). The amino acid composition of *Ulva pertusa* shows that valine, leucine and lysine are the main essential amino acids present. Histidine, which is an essential amino acid for children, is present at a similar level to leguminous and egg proteins (Table 2).

Protein digestibility

The main studies the *in vitro* digestibility of algal proteins were performed from proteins extracted in strong alkaline conditions [2,3]. Their digestion is carried out by means of three enzymes, pepsin, pancreatin and pronase. The relative digestibility of algal proteins is generally expressed as a percentage of casein digestibility base (100%). In this context, the relative digestibility of alkali-soluble proteins from *Porphyra tenera* is higher than 70% in the presence of pronase and 56% with pepsin and pancreatin [2]. The *in vitro* digestibility of alkali-soluble proteins from *Ulva pertusa* submitted to the action of pepsin or pancreatin or pronase is 17, 66 and 95%, respectively (Table 3). These results suggest a high digestibility of algal proteins when submitted to the action of pronase and moderate digestibility with other proteolytic systems tested. On one hand, these experimental data were obtained from a protein fraction already denatured by the extraction conditions. On the other hand, recent studies were performed from water or low-ionic buffer-soluble proteins extracted from the red seaweed *Palmaria palmata* [7] and *Ulva armoricana* [15]. The results obtained from *Palmaria palmata* showed that the algal proteins were more sensitive to the action of trypsin than to actions of human intestinal juice or chymotrypsin. The relative digestibility of water soluble proteins of *Palmaria palmata* to pepsin and pancreatin was estimated to be 56% [7]. This result is similar to that obtained from the alkali-protein fraction on *Porphyra tenera* which is another red seaweed with high protein content. The behaviour of *Ulva armoricana* proteins to the action of digestive enzymes seems to be different from that established for *Palmaria palmata*. The *Ulva* proteins appear effectively to be more sensitive to the action of human intestinal juice than to the action of trypsin or chymotrypsin [15]. In addition, the digestive activities of enzymes tested seem to differ according to the seasonal variation of glycoprotein content of *Ulva* species. In conclusion, the *in vitro* digestibility of algal proteins can differ according to the species and seasonal variations in antinutritional factor content. These compounds which limit the digestibility of algal proteins are either phenolic molecules or polysaccharides. The algal polysaccharides behave like soluble or insoluble fibres. Studies performed on brown algae show the strong inhibitory action of soluble fibres on *in vitro* pepsin activity and their negative effects on protein digestibility [16]. However, an enzymatic pre-treatment of algae, allowing the removal of polysaccharides, as already described for *Ulva pertusa*, *Undaria pinnatifida* [17] or

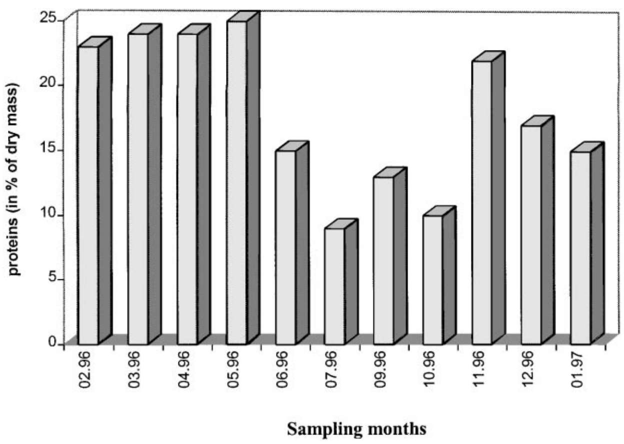

Fig. 1. Annual variation of protein content of *Palmaria palmata* (Dulse) samples collected on the French Atlantic coast (Belle-Ile).

Table 2. Amino acids composition of some seaweeds and traditions foods (in g amino acid/100 g protein)

Amino acids	*Ulva armoricana* (green seaweed) [15]	*Ulva Pertusa* (green seaweed) [2]	*Palmaria palmata* (red seaweed) [3,7]	*Porphyra tenra* (red seaweed) (2)	Leguminous plant [24]	Ovalbumin (2)
Histidine	1.2–2.1	4.0	0.5–1.2	1.4	3.8–4.0	4.1
Isoleucine	2.3–3.6	3.5	3.5–3.7	4.0	3.6	4.8
Leucine	4.6–6.7	6.9	5.9–7.1	8.7	7.3	6.2
Lysine	3.5–4.4	4.5	2.7–5.0	4.5	6.4–6.5	7.7
Methionine	1.4–2.6	1.6	2.7–4.5	1.1	1.2–1.4	3.1
Phenylalanine	5.0–7.1	3.9	4.4–5.3	3.9	2.4	4.1
Threonine	4.5–6.8	3.1	3.6–4.1	4.0	4.0	3.0
Tryptophan	—	0.3	3.0	1.3	1.6–1.9	1.0
Valine	4.0–5.2	4.9	5.1–6.9	6.4	4.5	5.4
Alanine	5.5–7.0	6.1	6.3–6.7	7.4	—	6.7
Arginine	4.3–8.7	14.9	4.6–5.1	16.4	13.0–14.0	11.7
Aspartic acid	6.0–11.8	6.5	8.5–18.5	7.0	4.7–5.4	6.2
Glutamic acid	11.7–23.4	6.9	6.7–9.9	7.2	6.4–6.7	9.9
Cysteine	—	—	—	—	1.1–1.3	—
Glycine	6.3–7.5	5.2	4.9–13.3	7.2	—	3.4
Proline	5.0–10.5	4.0	1.8–4.4	6.4	—	2.8
Serine	5.6–6.1	3.0	4.0–6.2	2.9	—	6.8
Tyrosine	4.4–4.7	1.4	1.3–3.4	2.4	2.3–2.6	1.8

Table 3. Relative digestibility *in vitro* of alkali or water soluble proteins from seaweeds

Seaweed species	Pepsin % Digestibility*	Pancreatin % Digestibility*	Pronase % Digestibility*
Ulva pertusa [2] (green seaweed)	17.0	66.6	94.8
Undaria pinnatifida [2] (brown seaweed)	23.9	48.1	87.2
Porphyra tenera [2] (red seaweed)	56.7	56.1	78.4
Palmaria palmata [7] (red seaweed)	—	56.0	—

*Relative digestibility is expressed as a percentage compared with casein digestibility basis (100%).

Palmaria palmata [18] could be an alternative way to limit the influence of algal fibres as antinutritional factors.

In contrast with the *in vitro* situation, little information is available about the *in vivo* digestibility of algal proteins. According to Indegaard and Minsaas [3], experiments on seaweed protein digestibility *in vivo* (e.g. human and animal) did not give conclusive results.

Potential uses of algal proteins

With respect to their high protein level and their amino acid composition, the red seaweeds appear to be an interesting potential source of food proteins. In Europe, the development of novel foods such as functional foods could be a new possibility for the use of seaweeds, especially for the protein-rich species, in human nutrition. In addition, the Rhodophyceae contain a particular protein called phycoerythrin (PE) which is already used in biotechnology applications (dye in immunofluorescence reaction). At the moment, PE used for this particular application is obtained from the microalgae *Porphyridium cruentum* in which the pigment can represent up to 50% of the protein fraction [19]. The main problem in the use of PE as a food dye is the relative instability of this chromoprotein to heat and pH variations. However, studies are being performed to understand the physical conditions needed to improve the stability of PE, especially that extracted from *Palmaria palmata*. In association with this application, the use of enzymatic liquefaction of red seaweeds already described in the literature could be an alternative procedure to improve protein solubilization, especially PE, in mild conditions (Fig. 2) [18,20].

The use of algae with high protein levels in the production of foods for fish farmed by aquaculture could be another application of this marine plant resource. The beneficial effects of the *Porphyra* meal used as a food additive in the diet of red sea bream was described by Mustafa *et al*. [21]. The diet appeared to improve body weight gain and increased the triglyceride and protein deposition in muscle. Other positive effects concerning the use of seaweed in fish feed were reported. In these latter cases, the algae diet improved the resistance of fish to stress or diseases [22,23].

In conclusion, the seaweeds, especially the Chlorophyceae and the Rhodophyceae, could be a complementary

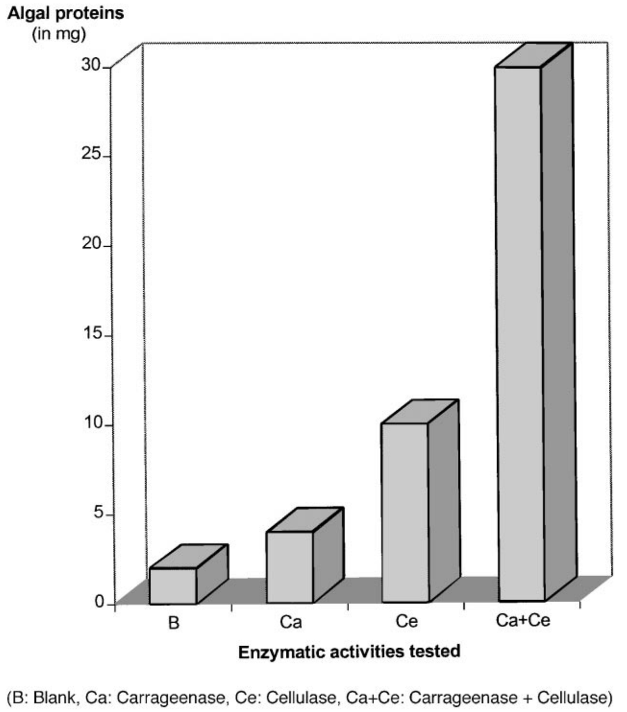

Fig. 2. Effect of polysaccharidases on the protein extraction from the red seaweed Chondrus crispus.

source of food proteins for human and animal nutrition. Their amino acid content is of nutritional interest but their protein digestibility *in vivo* is still poorly decribed. A biotechnological treatment of seaweeds by enzymatic degradation of algal fibres could be attempted to improve protein digestibility and, therefore, increase the nutritional value of these proteins. Independently, the red seaweeds could also be a potential source of food additives and especially food dye. The use of high level protein seaweeds in feed for fish farming seems to be a promising way for the utilization of this plant marine resource in Europe. This would also satisfy industrial needs which require a partial substitution of animal meal by plant meal in fish feed. This new requirement, which should enable improved exploitation of seaweeds in the western world, is a new challenge for research.

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