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Sea Vegetables

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Abstract

Sea vegetables or seaweeds have a long tradition in Asian cuisine. In Western countries, including Turkey, seaweed consumption is generally limited to sushi and other imported Asian dishes. However, seaweeds are well recognized for their richness in several nutrients such as carbohydrate, fiber, protein, lipid, and minerals. The migration of Asian population across the world has promoted the discovery of new ingredients from seaweeds and has given courage to the creation of new dishes by chefs in restaurants. Among the seaweeds traditionally consumed by Asian population, *Ulva*, *Laminaria*, and *Porphyra* are well-known species. Seaweed polysaccharides, such as agar, alginate, and carrageenan, are widely used in the food industry as clarifying, gelling, emulsifying, stabilizing, thickening, and flocculating agents in various food products such as ice cream, yogurt, candy, meat product, beverages, etc. The production of plant protein concentrates (PCs) is of growing interest to the food industry. Recently, PCs were also extracted from three edible green seaweed species of *Enteromorpha* or *Ulva*. Seaweed contains a wide array of nutritional compounds also possessing several functional properties that may lead to many dish and food preparation innovations. For example, a green seaweed, *Ulva*, may be used with or in the replacement of other commonly used vegetables to promote healthy food.

Keywords: algae, polysaccharide, proteins, fiber composition, minerals

1. Introduction

Algae, including micro-algae and macro-algae or seaweeds, constitute the primary producers in the aquatic food chain. Algae sustain the production of a hundred million tons per year of marine fisheries and a large portion of the aquaculture production, securing a stable human food supply. The annual seaweed production both from nature and aquaculture farms was 28.4 million tons in 2014, and 96% of seaweeds is produced by aquaculture with the value of 6.4 billion US dollar in 2013 [23]. About 40% of the seaweed production in 2014 represents seaweeds

traditionally eaten in Japan. In 2014, 7.7 million of tons of Kombu (*Saccharina japonica*), 2.4 million tons of Wakame (*Undaria pinnatifida*), and 1.8 million tons of Nori (*Porphyra* sp.) which is particularly used dried in sushi preparation were produced [23]. Among the seaweeds, 13% have been used for the production of hydrocolloids (polysaccharides), such as agar, alginate or alginic acid, and carrageenan, while 75% are used for food, and the remaining (12%) are used by agriculture industry [34].

There has been a long traditional use of algae, especially seaweeds or sea vegetables, as food in Pacific and Asian countries for several centuries. In Pacific countries such as Indonesia, the Philippines, Maori of New Zealand, and Hawaii and Asian countries such as China, Japan, and Korea, seaweeds have long been consumed in a variety of dishes such as raw salads, soups, cookies, meals, and condiments [56]. In Iceland, Wales, France, as well as the Canadian and US Maritimes, there exists a traditional consumption of seaweed-based foods which varies in importance depending between country and regions but which is overall less prominent than in Asia [12].

The increase of vegetable consumption, including seaweeds, has been promoted to exert health benefits during Inuit childhood and life course [32, 43]. Thus, it is possible to see many cooking books incorporating recipes using “sea vegetables” in many countries around the world. And, more recently there has been a strong movement in European countries to introduce sea plants into the European cuisine. With the current trend for consumers, as “natural” food sources, marine plants receive an increasing acceptance [56].

All these advantages, together with available modern technologies and the proximity of European and Asian markets, encourage the development of sustainable seaweed cultivation for a variety of profitable end-products, such as protein, vitamins, minerals, phycocolloids, pigments, etc. In Turkey, algae cultivation is limited to micro-algae production in fish hatcheries. However, natural resources necessary for commercial seaweed cultivation, such as diversity of seaweed species, clean water, sunlight, and coastlines, are abundant. For example, in Turkey, more than 1000 seaweed species have been identified and species of *Porphyra*, *Gracilaria*, juvenile *Laminaria*, *Cystoseira*, *Sargassum*, and *Ulva* being particularly abundant [14]. In the overall Turkish population, the consumption of algae as a food is mostly limited to traditional algal cuisine from Asia [45, 84].

Seaweeds are well known for their abundance in several nutrients as dietary fibers, minerals (i.e., iodine), and certain vitamins (i.e., B12) and also contain numerous proteins/peptides, polyphenols, and polyunsaturated fatty acids (omega-3) [10]. A diet rich in seaweed in Asian countries has been consistently associated with a low incidence of cancers [13], and other potential health benefits of seaweeds have been reported, including cardioprotective, neuroprotective, and anti-inflammatory effects as well as beneficial impacts on gut function and microbiota [13]. These results not only strongly support the use of seaweeds in functional food development but also promote new utilization in food products and in the kitchen of consumers.

The objective of this chapter is to review the main uses of whole seaweeds in food formulations, including *Ulva*, and the interest of using some components such as seaweed polysaccharides and PCs as ingredients that could play roles in food as well as some nutritional attributes of seaweeds.

2. Seaweed utilization in food formulation

The recent popularity of sushi and Asian cuisine in Western countries, including Turkey, has stimulated the seaweed economy. The migration of Asian population across the world has promoted the discovery of new ingredients from seaweeds and has given courage to the creation of new dishes by chefs in restaurants. Among the seaweeds traditionally consumed by Asian population, *Ulva*, *Laminaria*, and *Porphyra* [1] are well-known species in addition to the other species used in Asian cuisine (**Table 1**). Species such as Wakame or Kombu requires cooking to overcome their chewy texture, while others can be eaten raw such as Nori and sea lettuce [59]. The valorization of seaweed as sea vegetables generally involves drying or salting processing treatments. Seaweed drying is one of the primary steps to allow their storage and transportation. They are either sun dried, air-dried, or dehydrated by salt addition [29, 87]. Seaweed can also be macerated with specific enzymes to improve protein bioaccessibility through hydrolysis of dietary fibers resistant to human digestion, but this process has not reached any commercial application yet [26, 29]. However, there are some recent studies on *Ulva lactuca* that is fermented with specific

Seaweed species	Common names
<i>Alaria esculenta</i>	Dabberlocks, Bladderlocks, Edible Kelp, Honeyware, Winged Kelp, Bladderlocks, Tangle, Henware, Murlins, Stringy Kelp, Horsetail kelp, Fruill, Rufaí, Láracha, Láir bhán, Sraoilleach, Láir, Essebarer Rientang, Marinkjarni, Chigaiso
<i>Himanthalia elongata</i>	Sea Spaghetti, Sea thong, Thongweed, Buttonweed, Sea Haricots, Thongweed
<i>Hizikia fusiformis</i>	Hijiki, Hai tso, Chiau tsai, Hai ti tun, Hai toe din, Hai tsao, Hoi tsou, Nongmichae
<i>Laminaria digitata</i>	Tangle, Sea girdles, Tangle tail, Wheelbangs, Sea wand, Sea ware, Sea Tangle, Horsetail Kelp, Kelp, Strap wrack, Oarweed, Oar weed, Horsetail tangle, Sea Girdle, Coirrleach, Screadhbhuidhe, Coirleach, Ribíní, Feamnach dhubh, Leathrach
<i>Laminaria japonica</i> or with its new name <i>Saccharina japonica</i>	Kombu, Hai Dai, Hai Tai, Kunpu, Royal Kombu, Makombu, Shinori-Kombu, Hababiro-Kombu, Oki-Kombu, Uchi Kombu, Moto-Kombu, Minmaya-Kombu, Ebisume, Hirome, Umiyama-Kombu, Hoiro-kombu, ae tae, Tasima
<i>Undaria pinnatifida</i>	Wakame, Qun dai cai, Sea mustard, Precious sea grass, Miyok, Miyeouk
<i>Ulva lactuca</i>	Sea lettuce, Tahalib, Hai Tsai, Shih shun, Haisai Kun-po, Kwanpo, Lettuce laver, Green Laver, Sea Grass, Thin stone brick, Chicory sea lettuce, Meersalat, Aosa, Klop-tsai-yup, Alface-do-mar, Luche, Luchi, Havssallat
<i>Chondrus crispus</i>	Irish Moss, Iers mos, Carragheen, Carragheen Moss, Dorset weed, Pearl Moss, Sea Moss, Sea Pearl Moss, Jelly Moss, Rock Moss, Gristle Moss, Curly Moss, Curly Gristle Moss, Carrageen, Carraghean, Carrageenin, Punalevä-laji, Cruibín chait, Carraigín, Cosáinín carriage, Irischmoos, Irishes moos, Muschio Irlandese, Musgo-gordo, Botelho, Botelha, Cuspelho, Musgo, Limo-folha, Musgo gordo, Folha-de-alface, Condrus, Karragener
<i>Palmaria palmata</i>	Dulse, Dillisk, Dillesk, Crannogh, Water Leaf, Sheep Dulse, Dried dulse, Sheldulse, Duileasc, Creathnach, Saccha, Sol, Darusu, Sou Sol, Botelho-comprido, Sea grass, American dulse, Dillisc, Sheep's weed, Sea devil, Horse seaweed, Creannach
<i>Porphyra umbilicalis</i> , <i>Porphyra yezoensis</i> , <i>Porphyra tenera</i>	Nori, Laverbread, Purple laver, Sloak, Slook, Laver, Tough, Chishima-kuronori, Folhuda

Table 1. Seaweed traditionally consumed as sea vegetable [69].

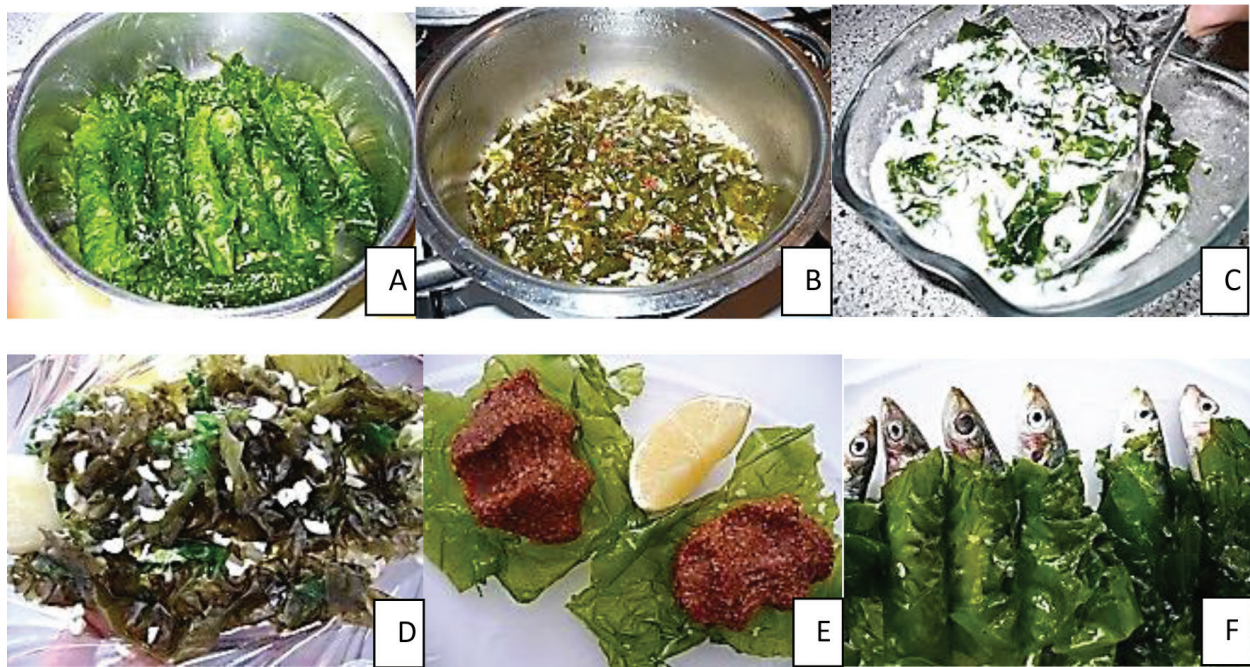
enzymes to improve protein bioaccessibility resistant to fish digestion [78]. During fermentation the growth of lactic acid bacteria was dependent on the seaweed species, the presence of fermentable carbohydrates such as laminaran, and the heating treatment applied prior to the inoculation step [33]. All these processing treatments are likely to affect seaweed's nutrients but to our knowledge, there are a limited number of studies describing their impact. More research may provide useful information to promote their usage in innovative dish and food preparation.

A green seaweed sea lettuce or *Ulva* is used in Scotland, where it is added to soups or used in salads, and today in Japan, where it is used in making sushi also with a red seaweed Nori or *Porphyra*. In Turkey, in the formulation of innovative seaweed dishes and food preparation samples, traditional mezze recipes belong to some vegetables replaced with *Ulva* (freshly harvested with 22.42% protein, dry weight) [84]. The seaweed dishes were prepared according to traditional recipes of stuffed grape leaves, spinach with rice, lamb's lettuce salad, *Salicornia* mezze, spicy tartare meatballs, and fresh sardines in grape leaves [3].

2.1. Food formulations of *Ulva*

The preparation of stuffed *Ulva* spp. for six servings according to the stuffed grape leave recipe started with soaking 225 g rice in warm and salted water for 10 min, followed by draining and rinsing. To prepare the filling, two onions were finely chopped, and two cloves of garlic were softened in two tablespoons of olive oil and a little butter. Then, one not quite full tablespoon of sugar, two tablespoons of currants soaked in water, and two tablespoons of pine nuts were added and cooked for 2–3 min. Next, one-half teaspoon of ground allspice, one-half teaspoon of ground cinnamon, and one-half teaspoon of ground cloves, salt, and freshly ground black pepper were added, and the mixture was covered with just enough water and brought to a boil. It was simmered for 10–15 min at reduced heat until the water was almost absorbed. Then, it was mixed with herbs (bunch of fresh parsley, dill, and mint) with a fork; the pan was covered and left for 5 min. The rice still had a bite to it. *Ulva* spp. were placed on the bottom of a wide pan. The rest of the *Ulva* spp., 24–30 pieces replacing a similar number of vine leaves in the original recipe, was laid on a flat surface, and a spoonful of the rice mixture was placed in the middle of each *Ulva*. The near end of each *Ulva* was folded over the mixture, and the side was flapped to seal it in and rolled up. The stuffed *Ulva* rolls were arranged in the pan, tightly packed. The cooking liquid—including 150 mL water, two tablespoons of olive oil, and two tablespoons of lemon juice—was poured over the rolls. A plate was placed on top to prevent them from unraveling, and the pan was covered with a lid. The liquid part was brought to a boil; then, the heat was reduced and cooked gently for 1 h. Finally, the rolls were left to cool in the pan and served cold with wedges of lemon (**Picture 1A**).

The preparation of *Ulva* spp. with rice according to a spinach with rice recipe for four to six servings started with frying one chopped onion with three to four cloves of garlic and one tablespoon of olive oil. Then, one glass of rinsed rice was added into the pan with some salt and black pepper and cooked for 2–3 min. Five hundred grams chopped fresh *Ulva*, instead of 500 g finely chopped fresh spinach, was added into the rice mixture, covered with just enough water, and brought to a boil. It was simmered for 10–15 min at reduced heat until the water was almost absorbed. The pan was then covered and left for 5 min (**Picture 1B**).



Picture 1. (A) Stuffed *Ulva*, (B) *Ulva* with rice, (C) *Ulva* salad, (D) sea lettuce *Ulva* mezze, (E) spicy tartare meatballs with *Ulva* spp., and (F) fresh sardines in *Ulva*.

In the preparation of *Ulva* salad according to a lamb's lettuce salad recipe for four to six servings, 500 g chopped fresh *Ulva* was used instead of 500 g lamb's lettuce. The chopped *Ulva* spp. were placed in a salad bowl, tossed in a little olive oil and lemon juice, and seasoned with salt and freshly ground black pepper. Two to three tablespoons of soft hick yogurt were mixed with two cloves of crushed garlic and added to the bowl; the mix was tossed well and served (**Picture 1C**).

In the preparation of *Ulva* mezze according to a *Salicornia* mezze recipe for four to six servings, 500 g chopped fresh *Ulva* was replaced with 500 g of *Salicornia*. The chopped *Ulva* spp. were placed in a salad bowl, tossed in a little olive oil and lemon juice, and seasoned with salt and freshly ground black pepper. Two cloves of crushed garlic were also added to the bowl; the mix was tossed well and served (**Picture 1D**).

Spicy tartare meatballs were prepared with *Ulva* spp. instead of lettuce leaves for four to six servings. Two hundred twenty-five grams of boiled bulgur was squeezed and allowed to cool (about 30 min), then put in a bowl with 225 g minced lamb or beef meat, and kneaded well (slapping it against the side of the bowl until well mixed). Two finely chopped onions, six finely chopped cloves of garlic, and two tablespoons of concentrated tomato purée were then kneaded into the mixture, followed by one teaspoon of red pepper, one-half teaspoon of roasted red pepper, one-half teaspoon of ground chili pepper, one-half teaspoon of ground coriander, one-half teaspoon of ground cumin, one-half teaspoon of ground allspice, one-half teaspoon of ground cinnamon, one-half teaspoon of ground cloves, one-half teaspoon of ground fenugreek, a little chopped parsley, and salt. The mixture was kneaded thoroughly for 20–30 min. Small portions of the mixture were then shaped into balls, indented with a finger, and arranged on a bed of parsley (**Picture 1E**).

***Ulva* was replaced with grape leaves in a dish filled with fresh sardines.** For four to six servings, 20–30 fresh sardines were wrapped in 25–30 *Ulva* spp., leaving the sardine heads peeping out. They were packed tightly in the base of a wide saucepan. Two tablespoons of olive oil, juice of one lemon, two crushed cloves of garlic, salt, and freshly ground black pepper were mixed to taste and poured over the sardines. A plate was placed directly on top of the sardines, the pan was covered, and it was cooked gently for 5–8 min. The dish was served hot or left to cool and sprinkled with salt or lemon juice (**Picture 1F**).

As it was seen, seaweeds contribute in a food either if they are used as a whole or through the numerous ingredients that have been produced from various species. In Turkey, *Hypnea musciformis* also known as Crozier weeds is a red seaweed species containing carrageenan, a gelling and thickening agent. Under its purified form, carrageenan is used by the food industry. Again, *Gracilaria gracilis* or *Gracilaria verrucosa* is a red seaweed species containing agar, a gelling and thickening agent. Under its purified form, agar is used by the food industry. *Cystoseira* spp. and *Sargassum vulgare* are brown seaweeds containing alginate or alginic acid with other important agents as well used by food industry.

2.2. Seaweed polysaccharides

Purified polysaccharides, such as agar, alginate, and carrageenan, are widely used in the food industry as clarifying, gelling, emulsifying, stabilizing, thickening, and flocculating agents in various food products such as ice cream, yogurt, candy, meat product, beverages, etc. The main structure and the functionality of polysaccharides extracted from seaweeds are presented in **Table 2**.

Agar and carrageenans are both found within red algae. Agar is mostly extracted from *Gelidium* and *Gracilaria* [56], and their cell wall holds up to 30% [31] and 20% [73], respectively. Agar structure is made of alternating d-galactose and l-galactose units (**Table 2**) [48, 60, 79]. It also contains (3,6)-anhydrogalactose rings and small amounts of sulfate groups (<4.5%) [40, 60]. Agar forms stable gels upon cooling between 32 and 43°C and at concentrations varying from 0.5 to 2% over a wide range of pH (**Table 2**). The gels are odorless and tasteless since no cations are necessary to promote the gel formation, and they are stable at temperature up to 85°C. The gel strength is influenced by the polysaccharide concentration, the number of 3,6-anhydrogalactose rings, the molecular weight, and the rate of cooling [6, 88]. One of agar gel characteristics is its in-mouth juiciness caused by the gel syneresis during mastication [62]. Agar gels are currently part of many traditional Japanese foods. Yokan (agar jelly with red bean paste), Mitsumame (canned fruit salad with agar jelly), and Tokoroten (noodlelike agar gel) are some examples of the culinary applications of agar [62, 79]. Worldwide, agar is also used as an additive in numerous food products such as dairy, bakery, and canned meat/fish products. It is also found in soups, sauces, and beverages. Carrageenans are sulfated polysaccharides extracted from seaweed such as *Chondrus crispus*, *Kappaphycus alvarezii*, and *Eucheuma denticulatum* [5, 56]. The seaweed cell wall can contain up to 80% of polysaccharides. Carrageenan's structure depends on the number of sulfate groups and (3,6)-anhydro-d-galactose rings (**Table 2**). The structure of carrageenans controls its gelling properties, and this has an important impact for its utilization in food systems. For example, the absence of (3,6)-anhydro-d-galactose ring units prevents λ -carrageenan gelation.

Polysaccharide	Main structure	Mw (kDa)	Solubility	Gelling condition and properties	Functional properties
Food grade polysaccharides					
Agar	(1,3)- α -d-galactose, (1,4)- β -l-galactose, 3,6-anhydrogalactose ring, <4.5% sulfate groups	36–386	>85°C	0.5–2%; melting 85°C	Clarifying, gelling, stabilizing, and flocculating agent
Alginate or alginic acid	β -d-mannuronic acid (M), α -l-guluronic acid (G) linked in β -(1,4) or α -(1,4)	150–1700	Salt, ionic strength, and pH	0.5–2%; melting 85°C; Ca or Mg	Gelling, emulsifying, film-forming, stabilizing, and thickening agent
Carrageenan	(1,3)- α -d-galactose, (1,4)- β -l-galactose, 3,6-anhydrogalactose ring, 25–35% sulfate groups	300–600	ι - > 70°C κ - > 70°C λ - cold	0.5–3%; ι - Ca melting 50–80°C; κ - Ca or K melting 40–75°C; λ - n/a	Gelling, thickening, suspension, and stabilizing agent
Mannitol	D-Mannitol monomers	n/a	nd	n/a	Sweetener, low glycemic index
Nonfood grade polysaccharides					
Fucoidan	α -(1,3) and α -(1,4)-l-fucose, <22% sulfate groups	6.8–1600	nd	None	None
Ulvan	β -d-glucuronosyluronic acid-(1,4)- α -l-rhamnose 3-sulfate, α -l-iduronopyranosic acid-(1,4)- α -l-rhamnose 3-sulfate, 15–20% sulfate groups	150–2000	nd	1.6%; Cu ²⁺ and B ³⁺	None but potential gelling application

Mw, molecular weight; n/a, not applicable; nd, not determined.

Table 2. Seaweed polysaccharide structure and functionality [69].

Carrageenan may be found under three main structures influencing its gelling capacity. Lambda-carrageenan does not form gels but increases the solution viscosity to stabilize the overrun (whipped cream and shakes) or improve mouthfeel (pasteurized chocolate milk) [41]. It is also sometimes used in combination with κ -carrageenan to favor the formation of creamy gels (i.e., puddings and cream desserts) [39]. Kappa- and ι -carrageenans form gels at concentration varying between 0.5 and 3% and upon cooling at temperature ranging from 40 to 60°C in the presence of cations such as Ca or K [89]. Gels are thermally reversible at temperature up to 75 and 80°C for, respectively, κ - and ι -carrageenans and are stable at room temperature [39]. They are not only used in several water-based gelled desserts and cake frosting but also used in dairy products alone (flan, process cheese, sterilized chocolate, and evaporated milks) or in combination with other gums such as locust bean gum (cream cheese and ice cream). In brown seaweed, alginate may be isolated and found at concentrations up to 40% according to the seaweed species [57, 89].

Alginate is extracted from several brown algae including *Ascophyllum nodosum*, *Laminaria digitata*, *Laminaria hyperborea*, *Laminaria saccharina*, *Laminaria japonica*, *Ecklonia maxima*, *Macrocystis pyrifera*, *Lessonia nigrescens*, and *Lessonia trabeculata* [37, 56]. Alginate is a derivative of alginic acid, and it is found under the form of sodium, calcium, or magnesium alginate. It is composed of a mixture of β -D-mannuronic acid (M) and α -L-guluronic acid (G). These monomers are organized in segments containing MM, GG, or MG/GM blocks which are linked β -(1,4) for MG block or α -(1,4) in the case of GG block. The proportion of each segment affects the gelling properties of alginate. Alginate containing high amounts of GG blocks will lead to firm and rigid gel [20]. Alginate is used as a thickening agent in ice cream, ketchup, mayonnaise, sauces, and purees [57, 89]. The viscosity of the solution may be controlled by the addition of Ca. Alginate gelling property is useful in several food applications such as jams, puddings, and restructured food (chili found in green olives or onion rings made with onion powder). Its film-forming capacity reduces water loss and regulates water diffusion in food products [37]. The pastries fruit filling is often covered with an alginate film to prevent cake moistening.

The food industry in collaboration with polysaccharide suppliers has developed a thorough knowledge regarding the usage of algal polysaccharides in food products. However, the culinary usages might at some point be less known by chefs. Recently, the culinary use of those purified ingredients was reviewed in the book *Modernist Cuisine* [61]. The functional properties such as solubility, foaming, as well as gelation are potentialized and presented for culinary purposes. For example, agar gels may be used in terrine (appetizer), agar beads flavored with fruit or vegetable juices, Chantilly without cream, pasta, eggless mayonnaise, foams, etc. Alginate main usages in modern cuisine are under the form of moldable forms (spaghetti, beads, etc.). Propylene glycol alginate may also be used to produce eggless citrus curd [61]. The proper combination of κ - and ι -carrageenans allowed the formation of a dashi-flavored gel to coat cremini mushrooms [61]. Also, these polysaccharides may be used in combination to stabilize a beurre blanc sauce emulsion, processed cheese, etc.

Finally, other polysaccharides such as fucoidan and ulvan could potentially be interesting for culinary applications. Fucoidan is a sulfated polysaccharide mainly of L-fucose (>50%), and up to 10% of this polysaccharide was isolated in several brown seaweeds [42, 83]. Fucoidan is not used as a food ingredient in Turkey but is included in food as a nutraceutical in Asia [25]. This polysaccharide has no gelling or thickening capacity (Rioux et al., 2007) as compared to others such as alginate. However, when the whole brown seaweed Kombu or Wakame is consumed, substantial amount of fucoidan may be ingested and have beneficial effects in humans. Ulvan is a water-soluble polysaccharide found within green algae *Ulva* spp. The algae contains between 8 and 29% ulvan on dry basis [47]. Ulvan is mainly composed in L-rhamnose and D-glucuronic acid under the form of ulvanobiuronic acids A and B [46, 67]. Ulvan molecular weight ranges between 150 and 2000 kDa depending on the extraction method and seaweed species [64, 77, 91]. Ulvan possesses interesting gelling and viscosifying properties dictated by the amount of uronic acids that may be useful in food products [76, 77, 90]. Most recent studies were oriented toward biomedical applications [58, 86]. This polysaccharide could be of interest for new food application.

2.3. Seaweed protein concentrates (PCs)

The production of plant protein concentrates (PCs) is of growing interest to the food industry [81]. Recently, PCs were extracted from three edible green seaweed species of *Enteromorpha*

or *Ulva* and were investigated for their functional properties as functions of salt and pH [44]. The protein contents in the PCs varied from around 33 to 60%. In all three PCs, the minimum nitrogen solubility was observed at pH 4, and foaming capacity and stability were pH-specific. Also, PC of red alga *Kappaphycus* was extracted, and its functional properties were evaluated [81]. The PC contained around 62% proteins, and the results obtained in this investigation suggest great emulsion stability with oil extracted from *Jatropha*, a plant species of the Euphorbiaceae family native to Brazil. Although these results are promising, before considering these PCs as ingredients in food formulations, food-grade solvents have to be chosen during the extraction method avoiding chemical residues, which could be toxic [69]. Indeed, solvent choice influences potential applications of algal protein extracts in terms of human consumption [75].

3. Nutritional contribution of seaweeds

Seaweed's main constituents vary according to the seaweed species, harvest location and time, wave exposition, and water temperature. Also, the methodology used to determine these constituents may differ which may explain why large variations are sometimes observed (Table 3). Seaweeds are rich in carbohydrates, and concentration up to 76% of the algae dry weight was reported. Also, an important proportion of proteins was quantified. *Ulva* sp. contains up to 44% of proteins based on the algae dry weight. The mineral content also reaches values as high as 55% that were found for *Ulva* sp. Generally, seaweed lipid content is relatively low (<5%) independently of the species.

3.1. Seaweed carbohydrates

Seaweed carbohydrates or polysaccharides are mostly found within the algae cell wall with exception of the storage polysaccharides which are located in the plastid. The seaweed cell wall (extracellular matrix) has an important structural role. It is a physical barrier against wave, ice,

Seaweed species	Polysaccharide (%)	Protein (%)	Lipid (%)	Ash (%)
<i>Ulva</i> sp.	15–65	4–44	0.3–1.6	26; 52–55
<i>Laminaria longicuris</i> or <i>Saccharina longicuris</i>	38–61	3–21	0.3–2.9	15–45
<i>Ascophyllum nodosum</i> and <i>Fucus vesiculosus</i>	42–70	1.2–17	0.5–4.8	18–30
<i>Undaria pinnatifida</i>	35–45	11–24	1–4.5	27–40; 14
<i>Sargassum</i> sp.	68	9–20	0.5–3.9	44
<i>Chondrus crispus</i>	55–66	6–29	0.7–3	21
<i>Porphyra</i> sp.	40–76	7–50	0.12–2.8	7–21
<i>Gracilaria</i> sp.	36; 62–63	5–23	0.4–2.6	8–29
<i>Palmaria palmata</i>	38–74	8–35	0.2–3.8	12–37

Values are expressed in percentage (%) of dry weight.

Table 3. Composition of different seaweed species [69].

and sun dehydration [65], but it also regulates many other functions such as solute accumulation, turgor, and cell growth [8, 68]. The main cell wall polysaccharides are agar and carrageenan (Rhodophyta), sulfated fucans and alginates (Ochrophyta), and cellulose and hemicellulose (Chlorophyta). Seaweeds within the Ochrophyta and Rhodophyta phyla also contain variable amounts of cellulose and/or hemicellulose according to the seaweed species [2, 18].

The storage carbohydrates are equivalent to the human glycogen and serve as the principal energy source [9]. According to the seaweed species, other small polysaccharides may be found within the chloroplast (laminaran and starch) or in the cytoplasm (floridean starch) [85]. Smaller solutes are found when seaweeds are grown under high salinity conditions. Mannitol, sucrose, floridoside, isofloridoside, and digeneaside were reported for some seaweed. They can serve as photosynthetic reserve or as osmoregulator [19, 68].

3.1.1. Seaweed fiber composition

Seaweeds are good sources of fibers since they contain valuable carbohydrates undigested by the human gastrointestinal track [69]. Dietary fibers, or fibers from food source, remain intact in the small intestine while they are partially or sometimes completely fermented by the gut microbiota [24]. The total dietary fiber within food may be found under two forms, such as soluble and insoluble, depending on the polysaccharide structure. Soluble fibers refer to polysaccharides that may be solubilized in water. They are known to increase the viscosity in the gastrointestinal track and are fermented by the microbiota. At the opposite, insoluble fibers have a bulking action and are rarely fermented [69]. Seaweeds with their high polysaccharide contents (**Table 2**) have interesting nutritional properties since their total dietary fiber may reach up to 38% (dry weight) according to the seaweed species [29]. Among them, some polysaccharides are already considered as valuable food ingredients and are, therefore, available on the market as purified polysaccharides such as agar, alginate, and carrageenan.

3.2. Seaweed proteins

Increasing world population and the consumer demand for healthy foods have driven the search for unconventional protein sources as ingredients to be incorporated in new high-value products [15, 52, 70]. Seaweeds have long been used in Asia as traditional foodstuffs [22]. Also, they have been recently promoted in the cuisine of several American and European countries and evaluated for the nutritional value of their proteins, which is mainly defined by their amino acid composition and digestibility [56]. Proteins are present in algae in a variety of forms and distributed in various cellular compartments. They are part of the intracellular components or the cell wall, are enzymes, or are bound to pigments and polysaccharides [80]. The protein content is variable according to the species, season, geographic distribution, population, cultivation conditions, and nutrient supply during growth phase [4, 17, 27, 36, 52, 54]. In general, the red and green species contain relatively high protein levels, with an average value of 4–50% (w/w) dry weight, compared to brown species, which contain between 1 and 29% (w/w) dry weight (**Table 3**) [35]. The protein concentrations of red species are comparable to those found in high-protein vegetables such as soybeans where proteins represent 35% of the dry weight [63]. A review of the nutrient composition of edible seaweeds has been reported comparing different protein contents of red, green, and brown species [66].

Seaweed proteins display a very good profile of essential amino acids, which is equivalent to other food proteins such as legumes or eggs [28], and their levels are comparable to those of the FAO/WHO requirements of dietary proteins [63]. Algal proteins usually contain most amino acids particularly glycine, alanine, arginine, proline, and glutamine and aspartic acids [11]. Both aspartic and glutamic acids are abundant in most seaweed species (brown, red, and green), and they exhibit interesting features in flavor development. Hence, glutamic acid is the main component in the taste sensations of umami [63], and the average proportion is higher in brown seaweed (153 mg/g proteins) compared to the red (117 mg/g proteins) and green (119 mg/g proteins) seaweeds [21]. In comparison with other protein-rich food sources, seaweeds are limited by lysine, threonine, tryptophan, and sulfur amino acids (cysteine and methionine), even though their levels are generally higher than those found in vegetables and cereals [38]. Seaweeds contain a proportion of free amino acids including taurine, alanine, amino butyric acid, ornithine, citrulline, and hydroxyproline. Numerous seaweed species also contain unusual amino acids among those, mycosporine-like amino acids (MAAs) known as demonstrating antioxidant properties [35].

3.3. Seaweed lipids

Seaweeds contain relatively low levels of lipids (1–5%) when compared to other plant seeds such as soy and sunflower, but majority of those lipids are polyunsaturated fatty acids (PUFAs) [50, 51]. PUFA's health benefits are well documented for fish, and seaweeds may also provide a sustainable source of these compounds. Algal PUFAs are under the form of ω -3 fatty acids such as eicosapentaenoic acid (EPA, C20:5) or docosahexaenoic acid (DHA, C22:6). EPA and DHA may both be metabolized from α -linolenic acid (ALA, C18:3), an essential fatty acid not only synthesized by humans but also found in seaweeds. Red seaweeds can contain up to 50% of EPA, while much lower levels were found in brown species [30]. Amounts of ω -6 fatty acids such as arachidonic acid (ARA, C20:4) are also found in seaweeds, and their levels are equivalent to the proportion of ω -3 with an ω -6/ ω -3 ratio that is ranging from 0.1 to 1.5 [16, 50]. This is particularly interesting since a balanced ω -6/ ω -3 ratio was associated to a decreased risk of mortality. Readers are referred to recent review papers discussing the health benefits of algal PUFAs for more details [7, 10].

The lipid content and fatty acid composition of seaweeds vary by species, geographical location, season temperature, salinity, and light intensity [72]. Based on the fatty acid composition and potential health benefits such as anti-inflammatory activity, seaweed species could be selected for cultivation toward food and health markets [55]. The lipid characterization of cultivated seaweeds during a year-round could contribute to a better control in aquaculture settings in order to identify the best harvest time for the choice of lipid quantity and quality. For example, PUFAs are made up more than half of the fatty acids with a maximum in July for *Saccharina latissima* cultivated in Denmark [53]. In addition, the *Saccharina latissima* species presents a better source of PUFAs compared to traditional vegetables, such as cabbage and lettuce.

The growing interest in PUFA-rich lipids from seaweeds for incorporation into foods has led to look for alternative extraction techniques with higher yields together with food grade solvent uses. As a result, the highest levels of PUFAs were obtained by the extraction with ethanol [74]. Seaweeds are also generally tested after food processing (drying, canning, etc.), due to its possible detrimental effect on fatty acid levels [72].

3.4. Seaweed minerals

The mineral content of seaweed is of great importance since up to 45% of the algal dry mass may be found (**Table 3**) [71, 82]. The values varied according to the seaweed species, seasonal variation, harvest time, and location [49]. Seaweed contains several mineral elements required in human nutrition such as Na, K, Ca, Mg, Fe, Zn, Mn, and Cu. For example, 948 and 2782 mg/100 dry weight of Ca were found, respectively, for *Gracilaria salicornia* and *Ulva lactuca*. These values are much higher than the one found in terrestrial plants such as spinach (851 mg/100 dry weight), broccoli (503 mg/100 dry weight), and cabbage (369 mg/100 dry weight) [82]. Their elevated amount in I content is one important feature of seaweeds. Holdt and Kraan [38] have reviewed that the distribution within several seaweed species including *Laminaria* sp. contains up to 8000 times of the recommended daily value.

4. Conclusions

Seaweed contains a wide array of nutritional compounds also possessing several functional properties that may lead to many dish and food preparation innovations. For example, seaweeds may be used with or in the replacement of other commonly used vegetables to promote healthy food. Until now only few applications have been taking profit of both attributes, and this should be more deeply exploited in the future. Collaboration with creative chefs can increase the visibility and acceptance of this resource by offering recipes or dishes where seaweeds are displayed. Future work connecting culinary and food science may support the usage of seaweeds not only at home but also in food products.

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