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Seaweeds: A traditional ingredients for new gastronomic sensation

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ABSTRACT

Seaweeds have a long tradition in Asian cuisine. In Canada and US, seaweed consumption is mostly limited to sushi and other imported Asian dish. However, seaweeds are well recognized for their richness in several nutrients such as fiber, protein and minerals. But what is limiting seaweed and seaweed derived ingredients utilization in home cooking? Finding fresh seaweeds within inland cities is one limiting step but also the seaweed marketing need to propel the image that seaweed are not only nutritive but can bring flavor and texture in cuisine dish. With the rise of TV cooking shows, blogs and online recipes hosted by several renowned chefs, it is now time to bring seaweed in the spotlight. The aim of this review is to look at seaweeds to support a wider use in culinary applications for their nutritional contribution but also from a sensory perspective.

Contents

1. Introduction

Globally, 96% of the harvested seaweeds are produced by aquaculture which had an economic value of 6.4 billion US dollar in 2013 (FAO, 2016a). The annual macroalgae harvest from wild and cultivated crops was 28.4 million tons in 2014 (FAO, 2016b). This is a

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rise of 43% compared to 2010 where 19.9 million of tons of seaweeds were harvested. Forty percent of the global harvest in 2014 represent seaweeds traditionally eaten in Japanese culture (Fig. 1). 7.7 million of tons of Kombu (*Saccharina japonica*) and 2.4 million tons of Wakame (*Undaria pinnatifida*), two brown seaweeds, were harvested in 2014 (FAO, 2016b). Additionally, 1.8 million tons of Nori (*Porphyra* sp.), particularly used dried in sushi preparation, were harvested (FAO, 2016b). Among the harvested seaweeds, 13% have been used for the production of hydrocolloids (polysaccharides) such as: agar, alginate and carrageenan while 75% are used for food (Hardouin, Bedoux, Burlot, Nyvall-Collén, & Bourgougnon, 2014). The remaining (12%) are used for agriculture.

In Pacific (Indonesia, Philippines, Maori of New Zealand, Hawaii) and Asian cultures (China, Japan, Korea), seaweeds have long been consumed in a variety of dishes such as raw salads, soups, cookies, meals and condiments (McHugh, 2003; Yuan, 2007). In Iceland, Wales, France as well as the Canadian and U.S. 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 (Chopin, 2015; Yuan, 2007). For example, in the Canadian Arctic, more than 210 species have been identified (Archambault et al., 2010), kelp (Laminariales) and rockweeds (Fucales) being particularly abundant (Sharp, Allard, Lewis, Semple, & Rochefort, 2008; Tamigneaux & Johnson, 2016). These brown seaweeds, together with red seaweeds (Palmariales), have once been a part of the traditional diet of native peoples of the coast of St. Lawrence and Nunavik in Canada (Blanchet & Rochette, 2008; Kuhnlein & Turner, 1991; Wein, Freeman, & Makus, 1996) but this cultural habit has been lost with the modern food offer. The increase of vegetable consumption, including seaweeds, has been promoted in these populations, to exert health benefits during Inuit childhood and life-course (Gagné et al., 2012; Johnson-Down & Egeland, 2010). In the overall Canadian population, the consumption of algae as a food is mostly limited to traditional algal cuisine from Asia (Winberg, 2011).

Seaweeds are well known for their abundance in several nutrients as dietary fibers, minerals (e.g., iodine) and certain vitamins (e.g., B12) and also contain numerous proteins/peptides, polyphenols and polyunsaturated fatty acids (omega-3) (Cardoso, Pereira, Seca, Pinto, & Silva, 2015). A diet rich in seaweed in Asian countries has been consistently associated with a low incidence of cancers (Cian, Drago, de Medina, & Martínez-Augustin, 2015), 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 (Cian et al., 2015; Liu, Banskota, Critchley, Hafting, & Prithiviraj, 2015). These results strongly support the use of seaweeds in functional food development but also to promote new utilization in food products and in the kitchen of consumers. In this paper, we will review the main uses of whole seaweeds and the interest of using some components as ingredients that could play roles on textural or sensory properties of food as well as some nutritional attributes.

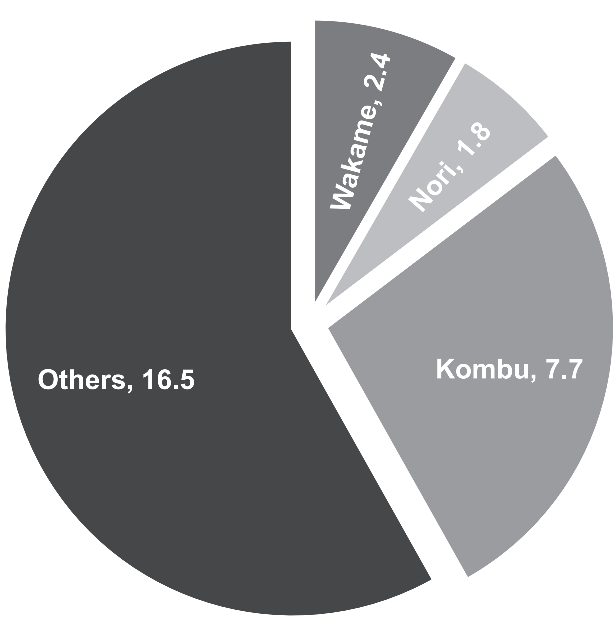

Fig. 1. Global production of wild and cultivated macroalgae in 2014 in million of tons.

2. Seaweed utilization in food formulation

The recent popularity of sushi and Asian cuisine in Western countries has stimulated the seaweed economy. The migration of Asian population across the world has promoted the discovery of new ingredients from seaweeds and has fuelled the creation of new dishes by chefs in restaurants. Among the macroalgae traditionally consumed by Asian population, *Ulva*, *Laminaria* and *Porphyra* (Atlas & Bartha, 1998) are well known. Table 1 displays the seaweed species used in Asian cuisine. These are grouped under three seaweed phylum: *Chlorophyta* (green), *Ochrophyta* (brown) and *Rhodophyta* (red) based on their pigmentation. Species such as Wakame or Kombu requires cooking to overcome their chewy texture while others can be eaten raw (Nori and sea lettuce) (Mouritsen, 2009). The valorization of seaweed as sea vegetables generally involves drying or salting processing treatments. Seaweed drying is one of the primary step to allow transportation. They are either sun dried, air dried or dehydrated by salt addition (Fleurence, 2016; Venugopal, 2011). Seaweed can also be macerated with specific enzymes to improve protein bioaccessibility through hydrolysis of dietary fibers resistant to human digestion but this process hasn't reach any commercial application yet (Fleurence, 1999a, 2016). Fermentation by lactic acid bacteria was also reported but the growth was dependent of the seaweed species (presence of fermentable carbohydrates such as laminaran) and heating treatment applied prior to the inoculation step (Gupta, Abu-Ghannam, & Scannell, 2011). All these processing treatments are likely to affect seaweed's nutrients but to our knowledge, there is a limited number of studies describing their impact. More research may provide useful information to promote their usage in innovative dish and food preparation.

While seaweeds have been consumed traditionally in several countries, there is a current buzz regarding algae derived food product. Food navigator USA has launched an algae special edition newsletter in August 2016 (http://www.foodnavigator-usa.com/feature/news-by-month/08/2016) highlighting several new products from seaweeds and their derivatives (vegan egg, algae oil, etc.). Although most products were derived from microalgae, it shows that consumers are more thrilled to use these products in their kitchen. A recent survey of XTC database, a qualitative worldwide database indexing innovative food products on the market, reported several new food products containing macroalgae launched in 2015–2016 (Table 2, (XTC, 2016)). Seaweed crips, milk-based powder preparation enriched with seaweeds, seaweed biscuits, seaweed instant mashed potatoes, seaweed tagliatelle and *Wakame* salad were among the list. Also, in the literature several studies were conducted regarding the addition of seaweed ingredients/powder in several food formulations (reviewed in (Cardoso et al., 2015; Mahadevan, 2015)). In most studies, the goal was to develop new functional food but none the less, the functional

Table 1
Seaweed traditionally consumed as sea vegetable.

Phyllum	Seaweed species	Common names
Brown *Ochrophyta*	*Alaria esculenta*	Daberlocks, Bladderlocks, Edible Kelp, Honeyware, Wing Kelp, Bladderlochs, Tangle, Henware, Murlins, Dabberlocks, Stringy Kelp, Horsetail kelp, Fruill, Rufaí, Láracha, Láir bhán, Sraoilleach, Láir, Essebarer Riementang, Marinkjarni, Chigaiso
	Himanthalia elongata	**Sea Spaghetti,** Sea thong, Thongweed, Buttonweed, Sea Haricots, Thong Weed
	Hizikia fusiformis	**Hijiki,** Hai tso, Chiau tsai, Hai ti tun, Hai toe din, Hai tsao, Hoi tsou, Nongmichae
	Laminaria digitata	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
	Laminaria japonica *Saccharina japonica*	**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
	Undaria pinnatifida	**Wakame,** Qun dai cai, Sea mustard, Precious sea grass, Miyok, Miyeouk
Green *Chlorophyta*	*Ulva lactuca*	**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
Red *Rhodophyta*	*Chondrus crispus*	**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, Irisches moos, Muschio Irlandese, Musgo-gordo, Botelho, Botelha, Cuspelho, Musgo, Limo-folha, Musgo gordo, Folha-de-alface, Condrus, Karragener
	Palmaria palmata	**Dulse**, Dillisk, Dillesk, Crannogh, Water Leaf, Sheep Dulse, Dried dulse, Shelldulse, Duileasc, Creathnach, Saccha, Sol, Darusu, Sou Sol, Botelho-comprido, Sea grass, American dulse, Dillisc, Sheep's weed, Sea devil, Horse seaweed, Creannach
	Porphyra umbilicalis *Porphyra yezoensis* *Porphyra tenera*	**Nori,** Laverbread, Purple laver, Sloak, Slook, Laver, Tough, Chishima-kuronori, Folhuda

Adapted from Guiry and Guiry (2016). Commonly used names are bold.

Table 2
Example of seaweed utilization in several worldwide food products.

Products	Seaweed	Company	Country	Website
Seaweed crips	NA	Annie Chun's	USA	https://anniechun.com/anniechun-seaweed-crisps/
Milk-based powder preparation enriched with seaweeds	*Fucus, Ascophyllum, Laminaria*	Spécialités SUPPLEX	France	http://supplex.fr/gamme-bio/43-supplex-cao-bio.html
Seaweed biscuits	NA	Bio-Darma	Spain	http://www.bio-darma.com/en/cookies-with-seaweed/#composition
Seaweed instant mashed potatoes	*Dulse*	Supersec	France	https://supersec.com/en/products/seaweed/sp/algapurare/
Seaweed tagliatelle	*Himanthalia elongata*	Seamore	Netherlands	http://seamorefood.com/?v=3e8d115eb4b3
Seaweed tartare	*Ulva, Palmaria, Himanthalia elongata*	Auchan	France	NA

NA: information not available.

properties of seaweed extracts may also enhance the food palatability. For example, beef patty texture was improved by the addition of *Wakame* powder (3%) (López-López, Cofrades, Yakan, Solas, & Jiménez-Colmenero, 2010) while a small addition of seaweed in pasta has reduced the cooking loss (Prabhasankar, Ganesan, & Bhaskar, 2009a) without alteration of the sensory attributes (Prabhasankar et al., 2009b). This trend is also observed in the beer industry where sugar kelp is use to enhance the malty taste (www.huffingtonpost.com/2014/07/24/seaweed-beer_n_5614794.html). The following section will provide information on how seaweeds may be used to creating innovative dish.

2.1. Sensory contribution of seaweeds

Marine macroalgae are unique. They can provide texture and flavor to food, two outstanding characteristics that may open up to new culinary innovation. In 2014, a new cookbook featuring seaweeds was published with the collaboration of 19 Australian chefs (Tinellis, 2014). Appetizers, main courses, desserts and even cocktails recipes were proposed. They included the list of the suppliers which are located worldwide in order to promote seaweed utilization. In Canada, Acadian Seaplants has commercialized dried Hana Tsunomata™ (*Chondrus crispus*) along with gastronomic recipes from renowned chef. All these gastronomic recipes are just the beginning of the culinary innovation that seaweed can initiate.

2.1.1. Flavoring attributes

One of the most known traditional seaweed based soup/broth in Japan is *dashi*. It is made with Kombu (*Saccharina japonica*) and other ingredients such as fermented bonito (*katsuobushi*) and shitake mushrooms cooked in boiling water. Many variations in the preparation and in the ingredients were reported depending on the geographic localization resulting in different sensory profiles. Its common utilization started during the Edo period (1603–1868) and a recent survey revealed that *dashi* is still used almost every day in Japanese households (Osawa, 2012). It is in *dashi* that umami taste was first discovered in 1908. This taste is mainly attributed to a specific amino acid, glutamate (glutamic acid). Other molecules such as guanylate and inosinate respectively found in dried bonito and shitake mushrooms were also associated to the umami taste (Ninomiya, 2015). Therefore, the glutamate (glutamic acid) content of seaweed may be the foundation for developing new sensory characteristic and enhancing the umami taste in several food product. The proportion of this amino acid varies according to the seaweed species (section 3.2) which may alter the intensity of the umami taste. *Dashi* made with Dulse (*Palmaria palmata*) contained around 40 mg/100 g of glutamate while with Kombu, 145 mg/100 g was found (Mouritsen, Williams, Bjerregaard, & Duelund, 2012). Dulse seaweeds or its resulting *dashi* were used in dishes as ice cream, fresh cheese and bread as examples of non-traditional food product with umami flavor. In this study, no information was provided on the nutritional gain or if the textural properties of these new food were altered. This open gap may lead to interesting research projects linking food and culinary sciences.

Other taste can also be obtained with specific seaweeds species. Some species as *Laminaria* or *Saccharina* are rich in the sugar alcohol, mannitol (up to 30%) (Reed, Davison, Chudek, & Foster, 1985). When seaweeds are soaked in hot water, significant amount of mannitol may be released in the broth and subsequently be used in different food product providing a sweet taste without the calories (Jamieson, 2011). In aged and dried Kombu, mannitol and glutamate (under the form of monosodium glutamate) may precipitate at the surface of the seaweed (Mouritsen et al., 2012). These white crystals should not be removed before the *dashi* preparation since it may enhance the umami and sweet flavor in the broth. The combination of mannitol with glutamate may open up to different flavoring profiles depending on the proportion of each compounds. Also, different seaweed combination should be tested to obtain different flavor/texture. Observation made by chefs showed that palatability of low fat food was improved by umami flavors (Ninomiya, 2015). Other volatile compounds such as aldehyde derived from fatty acids, bromophenol, dimethyl sulfoxide, etc. are also found in seaweed and can contribute to food flavoring (Ferraces-Casais, Lage-Yusty, Rodríguez-Bernaldo de Quirós, & López-Hernández, 2013; Venugopal, 2008). However, those compounds may be altered by the seaweed processing steps such as storage condition (LePape, Grua-Priol, & Demaimay, 2002) and drying (Michel, Priol, Galaup, & Demaimay, 1997) suggesting that some aromas could be specifically produced using the appropriate seaweed dish preparation.

Recently, edible seaweed for taste enhancement and salt replacement was investigated. One patented product available on the market, AlgySalt® (http://setalg.com/en/seaweed/13-algysalt.html), a clean label ingredient from *Laminaria japonica* aiming to reduce salt in food formulation was found (Chaude, Cossic, Guillot, Le Ker, & Vimont, 2015). This seaweed contains high proportion of K which is a good substitute for Na in food formulation at low dose (<30% NaCl substitution).

2.1.2. Texture and palatability

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 Ireland, *Chondrus crispus* also known as Irish moss, is a seaweed species containing carrageenan, a gelling and thickening agent. It is traditionally used in many recipes such as seafood chowder or Irish moss pudding. Under its purified form, carrageenan is used by the food industry. The next section will highlight how purified ingredients can be used to enhance food texture.

2.1.2.1. Algal 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 3. Their structural characteristics and the condition in which they are used governed their thickening, gelling, etc. functionality due to polysaccharide-polysaccharide interactions. In this review, the structure-function relationship will not be detailed and readers are referred to several exhaustive documents (Helgerud, Gåserød, Fjæreide, Andersen, & Larsen, 2009; Imeson, 2009a, 2009b; Stephen, Phillips, & Williams, 2006). Some examples will be provided for the main polysaccharides used in the food industry.

Agar and carrageenans are both found within red algae. Agar is mostly extracted from *Gelidium* and *Gracilaria* (McHugh, 2003) and their cell wall holds up to 30% (Freilepelegrin, Robledo, & Garciareina, 1995) and 20% (Santelices & Doty, 1989) respectively. Agar structure is made of alternating D-galactose and L-galactose units (Table 3) (Lahaye & Rochas, 1991; Murano, 1995; Stanley, 2006). It also contains (3,6)-anhydrogalactose rings and small amounts of sulfate groups (<4.5%) (Imeson, 2009a; Murano, 1995). 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 3). 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 (Boral, Saxena, & Bohidar, 2008; Wang, Zhang, & Zhang, 2013). One of agar gels characteristics is its in-mouth juiciness caused by the gel syneresis during mastication (Nussinovitch & Hirashima, 2013). Agar gels are currently part of many traditional Japanese food. *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 (Nussinovitch & Hirashima, 2013; Stanley, 2006). 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* (Bixler & Johndro, 2000; McHugh, 2003). 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 3). 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)-anydro-D-galactose ring units prevents λ-carrageenan gelation. 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) (Imeson, 2009b). It is also sometimes used in combination with κ-carrageenan to favor the formation of creamy gels (ex: puddings and cream desserts) (Imeson, 2000). Kappa- and ι-carrageenans forms gels at concentration varying between 0.5 and 3% and upon cooling at temperature ranging from 40 to 60 °C in presence of cations such as Ca or K (Whistler & BeMiller, 1997). Gels are thermally reversible at temperature up to 75 and 80 °C for respectively κ- and ι-carrageenans and are stable at room temperature (Imeson, 2000). They are 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 (Moe, Draget, Skjåk-Braek, & Smidsrød, 1995; Whistler & BeMiller, 1997). 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* (Helgerud et al., 2009; McHugh, 2003). 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

Table 3
Seaweed polysaccharides structure and functionality.

Polysaccharide	Seaweed phyllum	Main structure	Mw (kDa)	Solubility	Gelling condition and properties	Functional properties
Food grade polysaccharide						
Agar	Rhodophyta	(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	Ochrophyta	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	Rhodophyta	(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	Ochrophyta	D-Mannitol monomers	n/a	nd	n/a	Sweetener, Low glycemic index
None-food grade polysaccharide						
Fucoidan	Ochrophyta	α-(1,3) and α-(1,4)-L-fucose <22% sulfate groups	6.8–1600	nd	None	None
Ulvan	Chlorophyta	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.

firm and rigid gel (Draget, SkjakBraek, & Smidsrod, 1997). Alginate is used as a thickening agent in ice cream, ketchup, mayonnaise, sauces and purees (Moe et al., 1995; Whistler & BeMiller, 1997). 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 regulate water diffusion in food products (Helgerud et al., 2009). The pastries fruit filling is often covered of an alginate film to prevent cake moistening.

The food industry in collaboration with polysaccharides 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 were reviewed in the book *Modernist Cuisine* (Myhrvold, Young, & Bilet, 2011). 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 (Myhrvold et al., 2011). The proper combination of κ - and ι-carrageenans allowed the formation of a *dashi* flavored gel to coat crimini mushrooms (Myhrvold et al., 2011). 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 (Indegaard & Minsaas, 1991). Fucoidan is not used as a food ingredient in North America but is included in food as a nutraceutical in Asia (Fitton, Irhimeh, & Teas, 2008). This polysaccharide has no gelling or thickening capacity (Rioux, Turgeon, & Beaulieu, 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 (section 3.1.1). Ulvan is a water soluble polysaccharide found within green algae *Ulva* and *Entermorpha*. The algae contains between 8 and 29% ulvan on dry basis (Lahaye & Robic, 2007). Ulvan is mainly composed in L-rhamnose and D-glucuronic acid under the form of ulvanobiuronic acid A and B (Lahaye & Ray, 1996; Quemener, Lahaye, & Bobin-Dubigeon, 1997). Ulvan molecular weight ranges between 150 and 2000 kDa depending on the extraction method and seaweed species (Paradossi, Cavalieri, & Chiessi, 2002; Siddhanta, Goswami, Ramavat, Mody, & Mairh, 2001; Yamamoto, 1980). Ulvan is not authorized as a food ingredient in Canada and USA. However this polysaccharide possesses interesting gelling and viscosifying properties dictated by the amount of uronic acids that may be useful in food products (Shao, Qin, Han, & Sun, 2014; Siddhanta et al., 2001; Yaich et al., 2014). Most recent studies were oriented towards biomedical applications (Morelli, Betti, Puppi, & Chiellini, 2016; Venkatesan et al., 2015). This polysaccharide could be of interest for new food application.

2.1.2.2. Algal proteins. Studies on the functional properties of edible seaweed proteins, such as solubility, water/oil holding capacity, emulsifying activity, foaming ability and stability, viscosity, and gelation are limited. One microalgae protein concentrate (PC) was launched on the market (http://algavia.com/ingredients/proteins/). The ingredient is stable at acidic pH and the viscosity of the product remains constant up to 20% supplementation. But

Table 4
Composition[a] of different seaweed species based on their phylum.

	Chlorophyta (Green)	*Ochrophyta* (Brown)					*Rhodophyta* (Red)		
	Ulva	*Laminaria* and *Saccharina*	*Ascophyllum* and *Fucus*	*Undaria*	*Sargassum*	*Chondrus*	*Porphyra*	*Gracilaria*	*Palmaria*
Polysaccharide	15–65%	38–61%	42–70%	35–45%	4%; 68%	55–66%	40–76%	36%; 62–63%	38–74%
Protein	4–44%	3–21%	1.2–17%	11–24%	9–20%	6–29%	7–50%	5–23%	8–35%
Lipid	0.3–1.6%	0.3–2.9%	0.5–4.8%	1–4.5%	0.5–3.9%	0.7–3%	0.12–2.8%	0.4–2.6%	0.2–3.8%
Ash	11–26%; 52–55%	15–45%	18–30	27–40%	14%; 44%	21%	7–21%	8–29%	12–37%

[a] Adapted from Holdt and Kraan (2011) and Rioux and Turgeon (2015). Values are expressed in % of dry weight.

to our knowledge, no commercial macroalgae PC is been commercialized. Nonetheless, the production of plant PCs is of growing interest to the food industry (Suresh Kumar, Ganesan, Selvaraj, & Subba Rao, 2014). Recently, PCs were extracted from three edible green seaweed species of *Enteromorpha* and were investigated for their functional properties as functions of salt and pH (Kandasamy, Karuppiah, & Subba Rao, 2011). 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* (cultivated on the West coast of India) was extracted and its functional properties were evaluated (Suresh Kumar, Ganesan, Selvaraj, & Rao, 2014). 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. Indeed, solvent choice influences potential applications of algal protein extracts in terms of human consumption (Shannon & Abu-Ghannam, 2016).

3. Nutritional contribution of seaweeds

Seaweeds main constituents varies 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 4). Seaweeds are rich in carbohydrates (polysaccharides) and concentration up to 76% of the algae dry weight was reported. Also, 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% were found for *Ulva* sp. Generally, seaweed lipid content is relatively low (<5%) independently of the species. The next sections will briefly introduce each constituents.

3.1. Carbohydrates

Seaweed 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, sun dehydration, etc. (Percival, 1979) but it also regulates many other functions such as solute accumulation, turgor, cell growth, etc. (Brownlee, 2002; Reed, 2010). The main cell-wall polysaccharides are: agar and carrageenan (*Rodophyta*), sulfated fucans and alginates (*Ochrophyta*) and cellulose and hemicellulose (*Chlorophyta*). Seaweeds within the *Ochrophyta* and *Rhodophyta* phylum also contain variable amounts of cellulose and/or hemicellulose according to the seaweed species (Barsanti & Gualtieri, 2014; Cronshaw, Myers, & Preston, 1958).

The storage carbohydrates are equivalent to the human glycogen and serve as the principal energy source (Busi, Barchiesi, Martín, & Gomez-Casati, 2014). According to the seaweed species, other small polysaccharides may be found within the chloroplast (laminaran and starch) or in the cytoplasm (floridean starch) (Usov, 2011). Smaller solutes are found when seaweeds are grown under high salinities conditions. Mannitol, sucrose, floridoside, isofloridoside and digeneaside were reported for some seaweed. They can serve as photosynthetic reserve or as osmoregulator (Dittami et al., 2011; Reed, 2010).

3.1.1. Fiber composition and bioactivity

Seaweeds are good sources of fibers since they contain valuable carbohydrates undigested by the human gastrointestinal track. Dietary fibers (refers to fibers from food source) remain intact in the small intestine while they are partially or sometimes completely fermented by the gut microbiota (FAO/WHO, 2013). The total dietary fiber within food may be found under two forms: soluble and insoluble depending on the polysaccharides 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. Seaweeds with their high polysaccharide contents (Table 4) have interesting nutritional properties since their total dietary fiber may reach up to 38% (dry weight) according to the seaweed species (Fleurence, 2016). 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. Floridoside, isofloridoside, digeneaside and laminaran will not be discussed in this review paper since no/few potential food application were reported. However, they contribute to the amount of dietary fiber found within seaweed (up to 18% for laminaran) and they can have a small impact on the nutritional properties of the whole seaweed plant. Others like fucoidan, mannitol and ulvan have potential application as seen previously as food ingredients or as natural health product (natural amylase inhibitor). Multiple bioactivities such as anticoagulant, antitumoral, anti-thrombosis, anti-inflammatory, and antiviral activities were reported for fucoidan (Ale, Mikkelsen, & Meyer, 2011; Bedoux, Hardouin, Burlot, & Bourgougnon, 2014; Fedorov, Ermakova, Zvyagintseva, & Stonik, 2013; Vo & Kim, 2013; Wijesinghe & Jeon, 2012). *In vitro* studies revealed interesting capacity of fucoidan to regulate the glycemic index by inhibiting α-amylase and α-glucosidase activity, two enzymes involved in starch digestion (Kim, Rioux, & Turgeon, 2014). Antioxidant activity was also reported for several fucoidan fraction (Lim et al., 2014) for use as a natural ingredient in food.

3.2. Proteins

Increasing world population and the consumer demand for healthy foods has driven the search for unconventional protein sources as ingredients to be incorporated in new high-value products (Cole, de Nys, & Paul, 2015; Marinho, Holdt, & Angelidaki, 2015a; Rosegrant & Cline, 2003). Seaweeds have long been used in Asia as traditional foodstuffs (FAO, 2014). 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 (McHugh, 2003). 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 (Stengel, Connan, & Popper, 2011). The protein content is variable according to the species, season, geographic distribution, population, cultivation conditions and nutrient supply during growth phase (Beaulieu, Sirois, & Tamigneaux, 2016; Connan, Deslandes, & Gall, 2007; Fleurence, 1999b; Harnedy, Soler-Vila, Edwards, & FitzGerald, 2014; Marinho et al., 2015a; Martínez & Rico, 2002). 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 4) (Harnedy & FitzGerald, 2011). 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 (Pangestuti & Kim, 2015). A review of the nutrient composition of edible seaweeds has been reported comparing different protein contents of red, green and brown species (Pereira, 2011). Seaweed proteins display a profile of essential amino acids, which is equivalent to other food proteins such as legumes or eggs (Fleurence, 2004) and their levels are comparable to those of the FAO/WHO requirements of dietary proteins (Pangestuti & Kim, 2015). Algal proteins usually contains most amino acids particularly glycine, alanine, arginine, proline, and glutamic and aspartic acids (Cerna, 2011). 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 (Pangestuti & Kim, 2015) 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 (Dumay & Morançais, 2016). 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 (Holdt & Kraan, 2011). Seaweeds contain a proportion of free amino acids including taurine, alanine, amino butyric acid, omithine, citrulline, and hydroxyl-proline. Numerous seaweed species also contain unusual amino acids among those, mycosporine-like amino acids (MAAs) known as demonstrating antioxidant properties (Harnedy & FitzGerald, 2011; Yuan, Westcott, Hu, & Kitts, 2009).

3.2.1. *Protein digestibility, bioavailability and bioactivity*

Protein digestibility is an important factor to consider in the evaluation of the protein nutritional value and of algal food quality. Most studies on algal protein digestibility have been performed using *in vitro* gastrointestinal models simulating the digestion by means of enzymes combination such as pepsin, pancreatin (mixture of protease, lipase, and amylase) and pronase similar to those in a human body (Cian, Caballero, Sabbag, González, & Drago, 2014; Fleurence, 2004; Maehre, Edvinsen, Eilertsen, & Elvevoll, 2015; Marrion et al., 2005; MišurCoVá, KráčMar, KLeJduS, & VaCeK, 2010; Rafiquzzaman, Kim, Kim, Nam, & Kong, 2013; Wong & Cheung, 2001; Yabuta, Fujimura, Kwak, Enomoto, & Watanabe, 2010). The relative digestibility of algal proteins is then referred to the digestibility of casein (100%) (Fleurence, 2004). Some authors reported that the *in vitro* protein digestibility of red seaweeds (*Hypnea charoides* and *Hypnea japonica*) was slightly higher than that of green seaweed (*Ulva lactuca*) (Wong & Cheung, 2001). Generally, brown seaweeds (*Eisenia bicyclis*, *Hizikia fusiformis*, *Undaria pinnatifida*) showed the poorest protein digestibility in comparison with other red species (*Palmaria palmata*, *Porphyra tenera*) (MišurCoVá et al., 2010). Though, the algal protein digestibility is mostly variable according to the species and can be limited by the level of protein glycosylation and the presence of polysaccharides, dietary fibers, lectins and phenolic compounds undergoing seasonal variations (Fleurence, 1999b, 2004; Galland-Irmouli et al., 1999; Goni, Valdivieso, & Gudiel-Urbano, 2002; Wong & Cheung, 2001). Therefore, processes based on an enzymatic treatment to remove polysaccharides of seaweeds could increase the accessibility or digestibility of the algal proteins and thus improve the nutritional value of some seaweeds (Fleurence, 2016; Fleurence, Chenard, & Luçcon, 1999). Other methods, such as physical processes (e.g. grounding, heating, and microwave) and fermentation of algae by fungi could limit the impact of some components on nutritional quality of proteins. For example, after physical treatment of *Palmaria palmata*, the digestibility improvement was related to the elimination of soluble molecules such as xylan and mineral salts while the improvement observed after fermentations seemed due to the degradation of insoluble fibers (Marrion, Schwertz, Fleurence, Gueant, & Villaume, 2003).

Bioaccessibility of bioactive compounds from red seaweeds have been investigated to develop functional snacks. Enzymatic digestions were performed on an expanded maize product added with *Porphyra columbina* and both ACE inhibitors and antioxidants activities were detected after the treatment (Cian et al., 2014). Interestingly, this snack added with algae supply bioaccessible and bioactive compounds and holds promising potential as future industrial production of functional foods.

The algal proteins that have been studied most are those from the class of phycobiliproteins (phycoerythrin, phycocyanins and allophycocyanins) and lectins, two main known groups of functionally active proteins (Pangestuti & Kim, 2011). Phycobiliproteins are a family of relatively stable and greatly soluble fluorescent proteins present in red seaweeds. These proteins play a biological role in collecting light and, through fluorescence resonance energy transfer, which is implied in the photosynthesis (Pangestuti & Kim, 2015). Phycobibliproteins from microalgae (*Spirulina*) are used as food dyes, cosmetics and as fluorescent markers in biomedical research (Stengel et al., 2011). Lectins have been isolated from red and green seaweeds (Pangestuti & Kim, 2015) and exhibit affinity for carbohydrates and glycoproteins as well as participate in many biological processes like intercellular communication. Lectins have the capacity to inhibit the growth of marine *Vibrio* strains (Liao, Lin, Shieh, Jeng, & Huang, 2003) and also possesses potential antiviral, anti-inflammatory, anticancer and anti-HIV activities (Chojnacka, Saeid, Witkowska, & Tuhy, 2012). In addition, several recent studies have revealed that enzymatic hydrolysis of seaweed extracts generates a new range of peptides with various biological activities which may be expressed during protein extract digestion (Harnedy & FitzGerald, 2011). Bioactive peptide sequences from *Palmaria palmata* proteins ribulose-1,5-diphosphate carboxylase/oxygenase (Rubisco, enzyme) and pigments (allophycocyanin, phycocyanin, phycoerythrin) have been identified (Bondu et al., 2015). Other bioactive peptides have been identified in algal protein hydrolysates such as both antihypertensive renin inhibitory peptides (Fitzgerald, Aluko, Hossain, Rai, & Hayes, 2014a; Fitzgerald et al., 2012), correlated to both photosystem I and II proteins, and dipeptidyl peptidase (DPP) IV inhibitory peptides (Harnedy, O'Keeffe, & FitzGerald, 2015). A study demonstrated that the health value of bread was increased through the addition of a seaweed renin inhibitory *Palmaria palmata* protein hydrolysate (Fitzgerald et al., 2014b) showing that bioactive peptides from seaweeds are valuable components. Beaulieu, Bondu, Doiron, Rioux, and Turgeon (2015) have extracted antibacterial peptides from the brown seaweed *Saccharina longicruris* and the identified peptides were associated to proteins precursors similar to ubiquitin, leucine rich repeat protein, histone, and a ribosomal structure, which are part of the innate immune defense of the seaweed. Other bioactivities such as ACE inhibitor (Qu et al., 2010; Suetsuna, 1998a, 1998b), cardioprotective (Harnedy & FitzGerald, 2013), antidiabetes (Harnedy & FitzGerald, 2013), antioxidant (Heo, Park, Lee, & Jeon, 2005; Je et al., 2009) were found.

3.3. Lipids

Seaweeds contain relatively low levels of lipids (1–5%, Table 4) when compared to other plant seeds such as soy and sunflower, but majority of those lipids are polyunsaturated fatty acids (PUFAs) (MacArtain, Gill, Brooks, Campbell, & Rowland, 2007; Makkar et al., 2016). PUFAs 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 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 (Fleurence, Gutbier, Mabeau, & Leray, 1994). 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 is ranging from 0.1 to 1.5 (Colombo et al., 2006; MacArtain et al., 2007). This is particularly interesting since a balanced ω-6/ω-3 ratio was associated to a decreased risk of mortality (Simopoulos, 2008). Readers are referred to recent review papers discussing the health benefits of algal PUFAs for more details (Brown et al., 2014; Cardoso et al., 2015).

The lipid content and fatty acid composition of seaweeds vary by species, geographical location, season temperature, salinity, and light intensity (Sánchez-Machado, López-Cervantes, López-Hernández, & Paseiro-Losada, 2004). Based on the fatty acid composition and potential health benefits such as anti-inflammatory activity, seaweeds species could be selected for cultivation towards food and health markets (McCauley, Meyer, Winberg, Ranson, & Skropeta, 2015). 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 made up more than half of the fatty acids with a maximum in July for *Saccharina latissima* cultivated in Denmark (Marinho, Holdt, Jacobsen, & Angelidaki, 2015b). 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 solvents uses. As a result, highest levels of PUFAs were obtained by the extraction with ethanol (Schmid, Guihéneuf, & Stengel, 2016). Seaweeds are also generally tested after food processing (drying, canning, etc.), due to its possible detrimental effect on fatty acid levels (Sánchez-Machado et al., 2004).

3.4. Minerals

The mineral content of seaweed is of great importance since up to 45% of the algal dry mass may be found (Table 4) (Ruperez, 2002; Tabarsa, Rezaei, Ramezanpour, & Waaland, 2012). The values varied according to the seaweed species, seasonal variation, harvest time and location, etc. (Mabeau & Fleurence, 1993). 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) (Tabarsa et al., 2012). Their elevated amount in I content is one important features of seaweeds. Holdt and Kraan (2011) has reviewed the I distribution within several seaweed species and *Laminaria* sp. contains up to 8000 times the recommended daily value.

3.5. Phenolic components

Seaweed contains a valuable source of polyphenols. Values, expressed in gallic acid, ranging from 4 to 59 mg per gram of dry seaweed may be found (Tibbetts, Milley, & Lall, 2016). Catechins and flavoids were isolated in several species from brown, green and red algae *(Santoso, Yoshie, & Suzuki, 2002*; *Yoshie-Stark, Hsieh, & Suzuki, 2003)*. Phlorotannins are also phenolic compounds only found in brown seaweeds (Peng et al., 2015).

The phenolic compounds found in marine algae have strong antioxidant activity (Jiménez-Escrig, Jiménez-Jiménez, Pulido, & Saura-Calixto, 2001; Wang, Jónsdóttir, & Ólafsdóttir, 2009). Recently, their utilization in fish and fish products was reviewed in order to search for alternatives to synthetic antioxidant molecules to limit lipid oxidation (Maqsood, Benjakul, & Shahidi, 2013). In addition, polyphenols can interact with several proteins to limit their activity. Seaweed phenolic extracts can inhibits α-amylase and/or α-glucosidase, two enzymes regulating the glycemic index via starch digestion (Sharifuddin, Chin, Lim, & Phang, 2015).

4. Conclusions

Seaweed contains a wide array of nutritional compounds also possessing several functional properties that may lead to many culinary innovations. For example, seaweeds may be used as a flavoring agent to promote the umami taste or as a texturizing agent. 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 algae at home but also in food products.

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