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REVIEW

Minerals in edible seaweed: health benefits and food safety issues

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ABSTRACT

An adequate daily intake of minerals is essential for the prevention of chronic nutrition-related and degenerative diseases, including cancer, cardiovascular disease, and obesity. Seaweeds are marine aquatic vegetable that are rich in nutrients. They also have a natural and sustainable origin and clean and renewable sources when they come from marine aquaculture or controlled fisheries. Seaweeds have high nutritional value as a source of polyunsaturated fatty acids, proteins, carbohydrates, vitamins, and especially minerals. They are known for their high mineral content, which is gathered from seawater depending on the seasonal variation and the environment. Seaweeds are consequently rich in macro-elements and trace elements, with a mineral content at least 10 times higher than terrestrial plants and reaching 20-50% of its dry weight. Therefore, seaweeds can make an important contribution to the daily intake of minerals and are a promising source of essential minerals for functional food, food supplements, and nutraceuticals. The aim of the present review is to compare the contents of essential minerals (K, Ca, Na, P, Cu, Fe, Se, Mn, Zn, Mg, Cr, and I) as well as potential toxic minerals (Hg, Pb, Cd, As, and Al) in 14 main edible seaweeds that have availability of biomass from harvest and aquaculture. Another goal is to establish their safety in foods and contributions to the Recommended Dietary Allowance (RDA) and adequate intake (AI) values.

KEYWORDS
Seaweed; minerals; food safety; food composition; nutraceuticals

Introduction

Seaweeds are photosynthetic non-flowering plant-like organisms called macroalgae that live in the sea. They are classified into three major groups based on their dominant pigmentation: red (Rhodophyta), green (Chlorophyta), and brown (Phaeophyceae; phylum: Ochrophyta) (Yan et al. 1999; Beetul et al. 2016). Red seaweeds consist of about 6000 species and brown (phylum Ochrophyta, class Phaeophyceae) seaweeds consist of about 1750 species. Green seaweeds consist of about 1200 species (Yong, Chin, and FrancisRodrigues 2016). About 80% of total seaweed production is used for direct human consumption, and the remaining 20% is used in other foods, cosmetics, fertilizers, feed additives, and the medical industry (West, Calumpong, and Martin 2016). The global production of seaweeds comes from two sources: wild stocks and aquaculture (FAO 2016; West, Calumpong, and Martin 2016; Buschmann et al. 2017).

In 2017, the amount of harvested global wild stocks of aquatic plants (fresh waters and marine) was 1’047,201 tons (wet weight). Of this amount, only 73,901 tons came from freshwater, and the rest were seaweed. In the case of aquaculture, the world production in 2017 was 31’810,863 tons (wet weight), of which 99% was seaweed. For green edible seaweeds, the highest production in this year comes from aquaculture, particularly the seaweed *Capsosiphon fulvescens* (6,276 tons) followed by the seaweed known as “green laver” (*Monostroma nitidum*) with 6,159 tons from aquaculture and 674 tons from wild stocks. In the case of red edible seaweed, the genus *Porphyra/Pyropia* (known as “nori” or “purple laver”) had the highest production, with 2’563,048 tons obtained from aquaculture. For brown edible seaweeds, the highest production also comes from aquaculture, with “Japanese kombu” (*Saccharina* japonica, formerly Laminaria *japonica*) with the greatest production of 11’220,025 tons, followed by “Wakame” (*Undaria pinnafitida*) with 2’343,583 tons of total production (FAO 2018).

The genus of red algae genera *Kappahycus* and *Eucheuma* are of great importance for the production of carrageenan, with a production of 10’228,430 tons from aquaculture. The species *Gigartina skottsbergii* is also important in this respect, with 20,012 tons from wild harvest, along with the brown seaweed *Lessonia nigrescens*, which has a high production of 211,299 tons. None of these seaweeds are used for direct human consumption (FAO 2018). Globally, 12 groups of the most important edible seaweeds have been identified. Some of these have been identified at the species level, while in other cases, only the genus or species groups corresponding one or several common names have been identified (McHugh 2003). It has been reported that the number of seaweeds used for human consumption comprises 145 different species, of which 79 correspond to red seaweed, 38 are brown seaweeds, and 28 are green seaweeds (Pereira 2011). Recently, 33 seaweeds have been reported as

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

Table 1. Edible seaweed around the world with availability in relation to their production volumes from aquaculture and harvesting wild stock.

Scientific name	Common names	Reference	Division
1.*Caulerpa* spp.	Sea grapes or Green caviar	(McHugh 2003; Pereira 2011, 2016; Roy and Anantharaman, 2018)	Chlorophyta
2.*Codium fragile*	Dichotomous sponge tang or Shui-sung	(Pereira 2011, 2016)	Chlorophyta
3.*Ulva clathrata* (formerly Enteromorpha clathrata*)	Green nori	(MacArtain et al. 2007; Holdt and Kraan 2011)	Chlorophyta
4.*Monostroma nitidium*	Hitoegusa, Green laver	(McHugh 2003; Bast et al. 2009; Pereira 2016)	Chlorophyta
5.*Gracilaria* spp.	Ogo, Ogonori or Sea Moss, Pelillo	(Robledo and Freile Pelegrin 1997; McHugh 2003; Pereira 2011, 2016)	Rodophyta
6.*Palmaria palmata*	Dulse	(McHugh 2003; Teas et al. 2004; MacArtain et al. 2007; Pereira 2011, 2016; Rubio et al. 2017)	Rodophyta
7.*Porphyra tenera*	Nori	(Teas et al. 2004; Holdt and Kraan 2011; Pereira 2011; Rubio et al. 2017)	Rodophyta
8.*Porphyra/Pyropia* spp.	Nori or purple laver, Luche	(McHugh 2003; Teas et al. 2004; Dawczynski et al. 2007; MacArtain et al. 2007; Pereira 2011, 2016; Buschmann et al. 2017)	Rodophyta
9.*Laminaria digitata*	Kombu/Konbu	(Teas et al. 2004; MacArtain et al. 2007; Pereira 2011, 2016)	Phaeophyceae
10.*Saccharina japonica* (formerly *Laminaria japonica*)	Japanese kombu	(Holdt and Kraan 2011; Pereira 2016; Buschmann et al. 2017; Rubio et al. 2017)	Phaeophyceae
11. *Saccharina latissima* (formerly *Laminaria saccharina*)	Royal or sweet Kombu	(Pereira 2016; Roy and Anantharaman, 2018)	Phaeophyceae
12.*Macrocystis pyrifera*	Huiro, Giant kelp, Giant bladder kelp, kelp pepper	(Ortiz et al. 2009; Smith et al. 2010; Pereira 2016; Roy and Anantharaman, 2018)	Phaeophyceae
13.*Sargassum fusiforme***	Hoshi hiziki, Hijiki	(Yan et al. 1999; Teas et al. 2004; Pereira 2016; Buschmann et al. 2017; Roy and Anantharaman, 2018)	Phaeophyceae
14.*Undaria pinnatifida*	Wakame, Mekabu, Quandai-CAI	(Yan et al. 1999; McHugh 2003; Teas et al. 2004; Pereira 2011, 2016; Buschmann et al. 2017; Rubio et al. 2017; Roy and Anantharaman, 2018)	Phaeophyceae

Ulva and *Enteromorpha* reported as same genera (Hayden et al. 2003; MacArtain et al. 2007).
**Reported as Hijikia fusiformis (Yan et al. 1999).

main edible seaweeds, of which 20 are brown seaweeds, 10 are red seaweeds, and 3 are green seaweeds (Pereira 2016).

Edible seaweeds have high nutritional value as a source of polyunsaturated fatty acids, proteins, carbohydrates, vitamins, and minerals (Cuesta et al. 2017; Roohinejad et al. 2017). Furthermore, they have been widely utilized in nutritional supplements and health foods (Cuesta et al. 2017; Wells et al. 2017). Human consumption of seaweeds varies by nation. In Japan, the annual per capita consumption was 9.6 g of seaweed per day as of 2014. The global use of seaweeds for human consumption is increasing due to their contribution to health and their wider use as food additives (Wells et al. 2017). Seaweeds contain 10 to 20 times the amount minerals when compared to land plants. The minerals are gathered from seawater, which makes seaweed rich in macro-elements and trace elements (Holdt and Kraan 2011; Pereira 2011; Piñeiro 2012; Rubio et al. 2017).

Compared to land vegetables, the ash content in seaweeds (macro-minerals and trace elements) is high at 20-50% dry weight (Holdt and Kraan 2011; Pereira 2016). The mineral composition of seaweeds may be influenced by environmental conditions (Holdt and Kraan 2011; Rubio et al. 2017; Siahaan, Pangestuti, and Kim 2018), their age, and their capability to absorb inorganic substances from the environment due to the polysaccharides in their cell walls. Different groups of seaweeds have different capability to uptake minerals (Siahaan, Pangestuti, and Kim 2018). However, seaweeds accumulate not only desirable minerals but also undesirable metals from the surrounding environment, which can affect their safety for human consumption (Holdt and Kraan 2011; Rubio et al. 2017; Siahaan, Pangestuti, and Kim 2018). The USA, France, Australia, and New Zealand have established specific regulations for toxic elements in edible seaweeds (Almela et al. 2006).

Minerals are chemical elements that are essential for normal metabolic functioning. The human body requires a certain amount of some minerals to function properly, and can affect different aspects of human health, including obesity (Karatela, Paterson, and Ward 2017). The following minerals are considered essential for humans: Ca, Cu, Fe, Mg, Zn (Pehrsson et al. 2000; Campbell 2001; Mann and Truswell 2017), K, Na, P (Pehrsson et al. 2000; Campbell 2001), Se, Mn, Cr (Campbell 2001; Mann and Truswell 2017), and I (Piñeiro 2012; Mann and Truswell 2017). Toxic minerals do not have beneficial effects in humans and have adverse effects on the body by impairing or overstimulating an important chemical process (Karatela, Paterson, and Ward 2017). These include Hg, Pb, Cd, As (Campbell 2001; Lajçi et al. 2017), and Al (Campbell 2001).

This review discusses the composition of essential and toxic minerals in three genera and eleven species of main edible seaweeds used for human consumption around the world (Table 1). We also consider their availability in relation to their production volumes from aquaculture and harvesting wild stock (FAO 2018). The results could be used to support the proper use of seaweeds in relation to their mineral content, as well as the development of functional foods, dietary supplements, and nutraceuticals.

Edible green seaweed

Characteristics and worldwide production

The color of green seaweeds (Figure 1) is mainly due to the presence of chlorophyll a, which is contained in chloroplasts,

Figure 1. Green seaweed *Ulva* spp.

Table 2. Aquaculture and harvesting wild stock production volumes (metric tons) of main edible green seaweed (FAO 2018).

Scientific name	Aquaculture world production metric tons	Capture world production metric tons
Caulerpa spp.	955	0
Codium fragile	3,980	171
Ulva clathrata (formerly *Enteromorpha clathrata*)	3,400	0
Monostroma nitidium	6,159	675
Total	14,494	846

and chlorophyll b. These pigments have the same proportion as in higher plants. Most of the green seaweeds occur in littoral zones. The sea lettuces (*Ulva* spp.) are the most common green seaweeds observed in various habitats (Piñeiro 2012). The green seaweeds *Ulva* spp. (formerly *Enteromorpha* spp.), *Monostroma* spp., *Caulerpa* spp., and *Codium* spp. are commonly known as sources of food (Kılınç, Koru, and Turan 2013).

The global aquaculture production of main edible green seaweeds reached 14,494 tons in 2017 (Table 2) out of the total of 31'810,863 tons of seaweeds produced that year. Green seaweeds have the third highest aquaculture production among edible seaweeds include the species *Monostroma nitidium*, *Codium fragile*, *Caulerpa* spp., and *Ulva clathrata* (formerly *Enteromorpha clathrata*). The macro-mineral and trace element content (% dry wt.) in green seaweed species from Northwest Europe is 11–55%, depending on the seasonal and environmental variations (Holdt and Kraan 2011).

Mineral composition of green seaweed

The mineral composition of green seaweeds has been reported for 23 edible Chlorophyta species: *Caulerpa lentillifera, Caulerpa racemosa, Caulerpa sertularioides, Caulerpa taxifolia, Cladophora albida, Cladophoropsis vaucheriaeformis, Codium bursa, Codium fragile, Codium indicum* (formerly *Codium iyangarii*)*, Codium reediae, Codium yezoense, Dasycladus vermicularis, Ulva flexuosa* (formerly *Enteromorpha flexuosa*), *Ulva intestinalis* (formerly *Enteromorpha intestinalis*), *Ulva prolifera* (formerly *Enteromorpha prolifera*), *Monostroma hariotti, Gayralia oxysperma* (formerly *Monostroma oxyspermum*), *Ulva lactuca* (formerly *Ulva fasciata*), *Ulva fenestrata, Ulva australis* (formerly *Ulva pertusa*), *Ulva reticulata, Ulva rigida,* and *Ulvaria splendens* (Piñeiro 2012; Pereira 2016). "Ultra-trace elements" include Al, As, Au, Ba, Br, Cd, Co, Cr, Cu, Fe, Hg, and I. The contents of these elements has been reported for 25 species in the genera *Bryopsis, Caulerpa, Cladophora, Cladophoropsis, Codium, Ulva* (formerly *Enteromorpha*), *Monostroma*, and *Ulvaria* (Piñeiro 2012). The ultra-trace elements present in most species were Cd, Co, Cr, Cu, and Fe.

This review focuses on the concentration of essential and toxic minerals in one gram of dry mater in edible seaweed. Tables 3 and 4 show the results for edible green seaweeds. K (3.1–27 mg/g d.w.), Ca (6.9–25.3 mg/g d.w.), Mg, and Fe are present in all green seaweed. The highest K value occurred in *Ulva clathrata,* and the highest Ca value occurred for *C. fragile*. Na had a wide range of concentrations (4.0–92.3 mg/g d.w.), with the highest value in *C. fragile* and the lowest value in *Ulva clathrata.* P also had a wide range (0.29–30 mg/g d.w.), with no P found for *C. fragile* and the highest value found for *Ulva clathrata.*

Data for Cu were found for only two seaweeds: *Caulerpa* spp. (8 µg/g d.w.) and *Ulva clathrata* (7.5 µg/g d.w.). The range of Fe in green seaweeds was 0.025–9.43 mg/g d.w., with the highest value in *C. fragile*. Data for Se were only found for *Ulva clathrata* with a value of 0.41 µg/g d.w. Mn

Table 3. Essential minerals composition of edible green seaweed.

Scientific Name	Essential minerals mg/g d.w. Cu, Se, Cr and I µg/g d.w.												Reference
	K	Ca	Na	P	Cu	Fe	Se	Mn	Zn	Mg	Cr	I	
Caulerpa spp.*	3.18	18.5	25.74	0.29	8	0.813		0.04	0.06	3.8	3.1		Ca, Cu, Fe, & Mg (Misurcová 2012); K, Na, P & Mn (Pereira 2011); Cr (Robledo and Freile Pelegrin 1997); Zn (Mišurcová, Machů, and Orsavová 2011)
Codium fragile	14.2	25.3	92.3			9.43				15.2	16.8	154	K, Ca, Na, Mg, I & Fe and Cr (Piñeiro 2012)
Ulva clathrata (formerly *Enteromorpha clathrata*)	27.0	8.0	4.0	30.0	7.5	1.712	0.41	0.051	0.18	35.0	1.05	7530	K, Ca, Na, Cu, Fe, Mg & I (MacArtain et al. 2007); P (Aguilera-Morales et al. 2005); Cr & Mn (Pérez et al. 2007); Se (Burton et al. 1980); Zn (Mišurcová, Machů, and Orsavová 2011)
*Monostroma nitidium***	8.1	6.9	18.0	2.0		0.025						63	K, Ca, Na, P & Fe (Nisizawa 1987); I (Hou et al. 1997)

*Data of *Caulerpa racemosa*.
**Data of *Monostroma* spp.

is present in *Caulerpa* spp. (0.04 mg/g d.w.) and *Ulva clathrata* (0.051 mg/g d.w.). Zn values were found for only *Caulerpa* spp. (0.06 mg/g d.w.) and *Ulva clathrata* (0.18 mg/g d.w.). The range of Mg content was 3.8–35 mg/g d.w., with the highest value in *Ulva clathrata* and no values found for *M. nitidium.* The Cr content was 1.0–16.9 µg/g d.w, with the highest value in *C. fragile*. Green seaweeds had low values for I (0.063–0.154 mg/g d.w.) with the exception of *Ulva clathrata* (7.53 mg/g d.w.).

Compared with brown and red seaweeds, the selected types of edible Chlorophyta have low content of the essential minerals K (3.18–14.2 mg/g d.w.), Zn (0.06–18 mg/g d.w.), and Cu (7.5–18 µg/g d.w.) with the exception of *Ulva clathrata,* which had a high content of K (27.0 mg/g d.w.). Green seaweeds have high content of Ca and Na with the exception of *Ulva clathrata,* which has a low content of Na (4.0 mg/g d.w.). The Na content was highest in *C. fragile*. *Ulva clathrata* has a high content of I (7530 µg/g d.w) and Mg (35 mg/g d.w.), and *C. fragile* has a high content of Fe of 9.43 mg/g d.w. Among green seaweeds, *Ulva clathrata* had the most complete profile of minerals but had low levels of sodium content compared to the potassium content.

Regarding toxic minerals (Table 4) in green edible seaweeds, the Al content is reported only for the species *C. fragile* (95.7 µg/g d.w.), while Pb was observed in *Caulerpa* spp. (0.030 µg/g d.w) and *Ulva clathrata* (0.205 µg/g d.w.). In the case of Cd, there is a wide range between genera and species, with *Caulerpa* spp. showing 2.2 µg/g d.w. and *Ulva clathrata* showing 0.205 µg/g d.w. Arsenic was found in only two species: *C. fragile* (15.9 µg/g d.w.) and *Ulva clathrata* (2.15 µg/g d.w.), which had less than *C. fragile.* Inorganic As was not found in *C. fragile*, but low levels of inorganic As were found in *Ulva clathrata* (0.346 µg/g d.w.). It is assumed that there is a higher content of organic arsenic in this species. Mercury was found in only *Ulva clathrata* (0.020 µg/g d.w.). No toxic minerals were found in *M. nitidium.*

Edible red seaweed

Characteristics and worldwide production

Red seaweeds (Figure 2) are the most diverse and dominant group of seaweeds present in the ocean. Besides containing carotenes and xanthophylls, they contain the photosynthetic pigment phycobilin (phycoerythrin and phycocyanin), which is what gives them their color (Salamanca, Peñaranda, and Alvarez 2005). They are found in the intertidal and sub-tidal zones to depths of up to 40–250 m and mostly grow on dark ocean beds (Piñeiro 2012).

Red seaweeds had the highest aquaculture production worldwide in 2017 with a total of 17'241,088 tons. Of this amount, 6'874,676 tons correspond to main edible seaweed (Table 5). The main edible seaweed in this category production is nori (*Gracilaria* spp.). The content of macro-minerals and trace elements (% dry wt.) in red seaweed species from Northwest Europe is 7–29% depending of the seasonal and environmental variations. For the genus *Palmaria*, the levels differ between seaweeds from aquaculture (27%) and

Table 4. Toxic minerals composition of main edible green seaweed.

Scientific Name	Toxic minerals µg/g d.w. Al	Pb	Cd	As	Inorganic As	Hg	Reference
Caulerpa spp.*		0.030	2.2				Pb (Robledo and Freile Pelegrin 1997); Cd (Piñeiro 2012)
Codium fragile	95.7			15.9			Al & As (Piñeiro 2012)
Ulva clathrata (formerly *Enteromorpha clathrata***)		0.205	0.020	2.15	0.346	0.020	Pb, As, Inorganic As & Cd (Almela et al. 2006); Hg (Holdt and Kraan 2011)
*Monostroma nitidium****							

*Data of *Caulerpa racemosa*.
**Data of *Enteromorpha* spp.
***Data of *Monostroma* spp.

Figure 2. Red seaweed *Gracilaria chilensis*.

Table 5. Aquaculture and harvesting wild stock production volumes (metric tons) of main edible red seaweed (FAO 2018).

Scientific name	Aquaculture world production metric tons	Capture world production metric tons
Gracilaria spp.	4'311, 039	47,653
Gracilaria verrucosa	589	NR
Palmaria palmata	NR	NR
Porphyra tenera	829,998	50
Porphyra/Pyropia spp.	1'733, 050	0
Total	6'874, 676	47,703

NR = not reported.

seaweeds harvested from wild stocks (15%) (Holdt and Kraan 2011).

Red seaweeds are considered as the most important source of many biologically active metabolites in comparison to the other seaweeds classes. Their walls are made of cellulose, agar, and carrageenans. The level of sulfatation of carrageenan molecules and the presence of carboxyl and hydroxyl groups give metal-binding properties to red seaweeds (Siahaan, Pangestuti, and Kim 2018).

Mineral composition of red seaweed

The content of the essential minerals K, Na, Ca, Mg, and P in edible red seaweed has been reported for 29 species or genera: *Chondrus crispus*, *Gracilaria* spp., *Palmaria palmata*, *Pyropia tenera (*formerly *Porphyra tenera)*, *P. umblicalis*, *P. yezoensis*, *Gymnogongrus durvillei* (formerly *Ahnfeltiopsis concinna*), *Ceramium boydenii*, *Ceramium kondoi*, *Chondrus ocellatus*, *Corallina pilulifera*, *Eucheuma denticulatum*, *Gelidium amansii*, *Gloiosiphonia capillaris*, *Gracilariopsis longissimia* (formerly *Gracilaria confervoides*), *G. coronopifolia*, *G. parvispora*, *G. salicornia*, *Halymenia formosa*, *Hyalosiphonia caespitosa*, *Kappaphycus alvarezii*, *Laurencia okamurae*, *Leathesia marina* (formerly *Leathesia difformes*), *Myelophycus simplex*, *Palmaria* spp., *Polysiphonia stricta* (formerly *Polysiphonia urceolate*), *Porphyra/Pyropia* spp., *P.*

vietnamensis, and *Rohodomela confervoides* (Piñeiro 2012; Pereira 2016). The contents of ultra-trace elements Al, As, Au, Ba, Br, Cd, Co, Cr, Cu, Fe, Hg, and I have been reported for 25 edible red seaweeds species and the two genera *Palmaria* and *Porphyra/Pyropia* (Piñeiro 2012).

Tables 6 and 7 show the essential and toxic mineral compositions for red seaweeds. In the case of the content of essential minerals (Table 6), the potassium content was in the range of 27.2–81.0 mg/g d.w., with the highest values for *Palmaria palmata* and the lowest for the genus *Porphyra/Pyropia* spp. For calcium, there were similar values among the whole group of red seaweeds with a range of 3.39–4.02 mg/g d.w. For phosphorus, the range was 2.0 to 18.2 mg/g d.w., with the lowest value for *P. tenera* and the highest in the genus *Gracilaria.* Compared to the other groups, the red seaweeds had low contents of the essential minerals Ca and P with the exception of *Gracilaria* spp. (18.2 mg/g d.w.). Na values had a wide range (5.87-54.65 mg/g d.w.), with the highest content occurring in *Gracilaria* spp. and the lowest occurring in *P. Palmate.* This red seaweed also had the highest content of K (81 mg/g d.w.).

The ranges of the essential minerals Cu, Fe, Se, Mn, Zn, Mg, Cr, and I were similar between the selected species with the exception of the high content of Zn in *Porphyra/Pyropia* spp. (0.383 mg/g d.w.), the high I content in *Gracilaria* spp. (4260 µg/g d.w.), and the high Mn content in *P. tenera* (0.360 mg/g d.w.). Se was only found in *Porphyra/Pyropia* spp. (0.16 µg/g d.w.). Cu values (3.7–15.8 µg/g d.w.) were higher in *P. tenera* and lowest in *P. palmata.* There were high values of Fe (0.383–0.5 mg/g d.w.) in the whole group of red seaweeds with the exception of *Gracilaria* spp. (0.036 mg/g d.w.).

Regarding toxic minerals (Table 7), Al was only found in one genus, in which the amount varied widely. The high value was 1555 µg/g d.w. for *Porphyra/Pyropia* spp., and the lowest was 4 µg/g d.w. for *P. tenera.* The Pb content had a wide range (0.123–1.52 µg/g d.w.) with the highest value for *P. palmata* and the lowest for *P. tenera*. Similar values for Cd were found for the whole group (0.319–0.877 µg/g d.w.) with the exception of the genus *Gracilaria* with a value of 3.0 µg/g d.w. The total As content was 5.7–32.7 µg/g d.w. with a marked presence in the genus *Porphyra/Pyropia* (24.1–32.7 µg/g d.w.). However, for inorganic arsenic, the highest values were in the genus *Gracilaria* (0.93 µg/g d.w.). A wide range of mercury values was found for only the genus *Porphyra/Pyropia* (0.01–0.44 µg/g d.w.).

Edible brown seaweed

Characteristics and worldwide production

The color of brown seaweeds (Figure 3) results from the dominance of xanthophyll pigments and fucoxanthin, which mask chlorophyll a and c, *β*-carotenes, and other xanthophyll pigments. Their cells are made of cellulose and alginic acid. Brown seaweeds contain reserves of complex polysaccharides and higher alcohols, and their natural habitat is mostly the coastal areas in cold water bodies. The body of brown seaweeds is very flexible, which allows them to bend

Table 6. Essential minerals composition of main edible red seaweed.

Scientific Name	Essential minerals mg/g d.w. Cu, Se, Cr and I µg/g d.w.												Reference
	K	Ca	Na	P	Cu	Fe	Se	Mn	Zn	Mg	Cr	I	
Gracilaria spp.*	34.17	4.02	54.65	18.2	8.0	0.036			0.043	5.65		4260	K, Ca, Na, Fe, Zn & Mg (Pereira 2011); P (Toledo, M. et al. 2009); I (Holdt and Kraan 2011); Cu(Norziah and Ching 2000)
Palmaria palmata	81.0	3.8	10	5.0	3.7	0.717		0.011	0.037	1.6	0.98	72	K, Na, Ca & Mg (Piñeiro 2012); I (Teas et al. 2004); P (Misurcová 2012); Cu, and Mn (Pereira 2011); Zn & Fe (Siahaan, Pangestuti, and Kim 2018); Cr (Mišurcová et al. 2009)
Porphyra tenera	35.0	3.9	36.2	2.0	15.8	1.832		0.360	0.020	5.65	2	185	K, Na, Ca, Mg, Cr and I (Piñeiro 2012); Cu, Mn & P (Misurcová 2012); Zn & Fe (Siahaan, Pangestuti, and Kim 2018)
Porphyra/Pyropia spp.	27.2	3.39	5.87	5.1	9.5	0.383	0.16	0.012	0.383	3.50	1.64	35.8	K, Na, Ca, Mg, P, Cr & I (Piñeiro 2012); Cu (Misurcová 2012); Mn & Se (Smith et al. 2010); Zn & Fe (Siahaan, Pangestuti, and Kim 2018)

*As and P data as *Gracilaria chilensis*; Cu and Cd as *Gracilaria changgi*.

Table 7. Toxic minerals composition of edible red seaweed.

Scientific Name	Toxic minerals μg/g d.w.						Reference
	Al	Pb	Cd	As	Inorganic As	Hg	
Gracilaria spp.*			3.0	7.5	0.93		As & inorganic As (Díaz et al. 2012); Cd (Norziah and Ching, 2000)
Palmaria palmata		1.52	0.877	5.7	0.595		As (Piñeiro 2012); Pb, Cd & inorganic As(Almela et al. 2006)
Porphyra tenera	2.6	0.123	0.83	24.1	0.280	0.44	Al, Cd & Hg (Piñeiro 2012); Pb, As & inorganic As(Almela et al. 2006)
Porphyra spp.	1555	0.2	0.319	32.7	0.189	0.01	Al (Piñeiro 2012); Hg & Pb(Smith et al. 2010); Cd, As & inorganic As(Almela et al. 2006)

*Cd data of Gracilaria changgi.

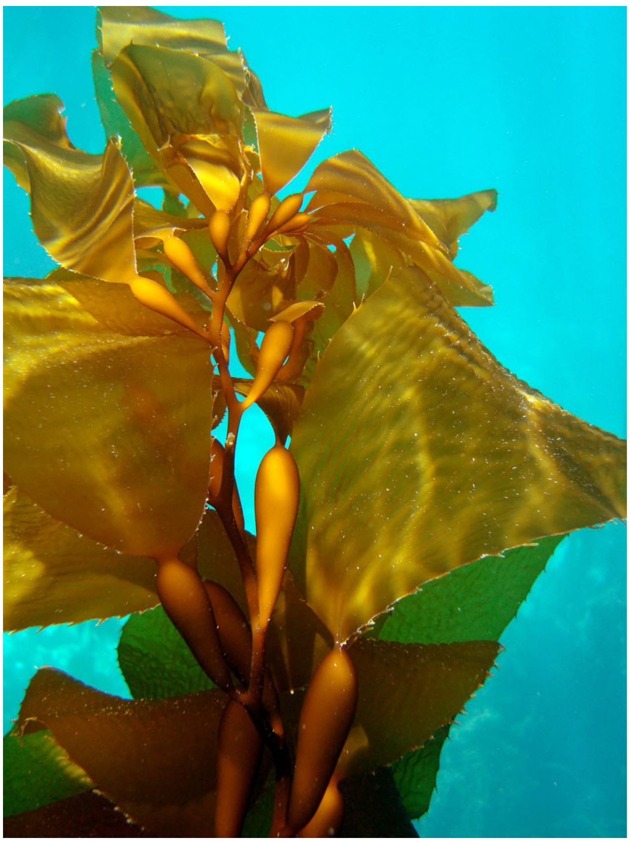

Figure 3. Brown seaweed *Macrocystis pyrifera*.

Table 8. Aquaculture and harvesting wild stock production volumes (metric tons) of main edible brown seaweed (FAO 2018).

Scientific name	Aquaculture world production metric tons	Capture world production metric tons
Laminaria digitata	0	32,573
Saccharina japonica (formerly *Laminaria japonica*)	11’174,505	45,520
Saccharina latissima (formerly *Laminaria saccharina*)	140	0
Macrocystis spp.	1	35,092
Sargassum fusiforme	254,594	0
Undaria pinnatifida	2’341,463	0
Total	13’770,703	113,185

NR = not reported.

or orient with the wave action. They are the largest seaweeds and can be up to 35 m in length (Piñeiro 2012).

The capability of seaweeds to absorb inorganic substances from the environment is directly related to the presence of polysaccharides in their cell walls. This is the reason why different groups of seaweeds have different ability to retain minerals. Brown seaweeds have higher absorption rates than green and red seaweeds due to the presence of alginic acid, alginate, and alginic acid salt. These polysaccharides have an affinity with calcium, magnesium, sodium, and potassium salts. Brown seaweeds are also a significant source of iodine, especially the genus *Laminaria*, which has a great capacity to accumulate iodine at more than 30,000 times the iodine concentration in seawater (Siahaan, Pangestuti, and Kim 2018).

Brown seaweeds have high production for edible seaweed with 13’770,703 tons produced in 2017 (Table 8). The highest amount is produced for “kombu” seaweeds (*Saccharina japonica* formerly *Laminaria japonica*) with a total of 11’174,505 tons, followed by “wakame” with 2’341,463 tons. The macro-mineral and trace element content in brown seaweeds species from Northwest Europe is 14–45% d.w. depending of the seasonal and environmental variations. For the genera *Laminaria* and *Saccharina,* there are higher values of ash in the fronds (16–45%) with respect to total values (15–39%) (Holdt and Kraan 2011). The concentration of salts of Ca and K and the element F has been found to be more than double during spring and summer months in the brown seaweeds *Laminaria digitata* and *Saccharina latissima,* but the concentrations of other metals did not show a seasonal pattern (Wells et al. 2017).

Mineral composition of brown seaweed

The composition of the essential minerals K, Na, Ca, Mg, and P in edible brown seaweeds has been reported for 24 species: *Fucus vesiculosus*, *Himantalia elongata*, *Laminaria digitata*, *Saccharina japonica* (formerly *Laminaria japonica*), *S. latissima*, *Sargassum fusiforme* (formerly *Hizikia fusiformis*), *Undaria pinnatifida*, *Colpomenia sinuosa*, *Desmarestia viridis*, *Dictyota acutiloba*, *Dictyota sandivicensis*, *Laminaria ochroleuca*, *Padina australis*, *Punctaria plantaginea*, *Sargassum carpophyllum*, *Sargassum aquifolium* (formerly *Sargassum echinocarpum*), *Sargassum henslowianum*, *Sargassum miyabei* (formerly *Sargassum kjellmanianum*) *Sargassum obtusifolium*, *Sargassum parvifolium*, *Sargassum polycystum*, *Sargassum thunbergii*, *Sargassum vachellianum*, and *Turbinaria conoides* (Piñeiro 2012; Pereira 2016). The content of ultra-trace elements Al, As, Au, Ba, Br, Cd, Co, Cr, Cu, and Fe has been reported for 24 species of edible brown seaweeds (Piñeiro 2012).

The essential and toxic mineral content for edible brown seaweeds is presented in Tables 9 and 10. Regarding essential

Table 9. Essential minerals composition of main edible brown seaweed.

Scientific Name	Essential minerals mg/g d.w. Cu, Se, Cr and I μg/g d.w.												Reference
	K	Ca	Na	P	Cu	Fe	Se	Mn	Zn	Mg	Cr	I	
Laminaria digitata	115.7	10.05	38.1	3.0	2.9	0.047	0.026	0.002	0.017	6.5	1.3	2000	K, Ca, Na, Mg, Cu, Fe & Cr (Piñeiro 2012); P, Mn, & I (Misurcová 2012); Se (Burton et al. 1980); Zn (Pereira 2011)
Saccharina japonica[1]	96.3	12.7	29.2	4.8	<0.5	0.080	8.0	0.004	0.018	6.4	1.0	2100	K, Ca, Na, Mg, Cu, Fe, Cr & I(Piñeiro 2012); Mn, & P (Misurcová 2012); Se (CHO et al. 1995); Zn (Siahaan, Pangestuti, and Kim 2018)
Saccharina latissima[2]					<0.5	0.040					<0.5	230	Cu, Fe, Cr & I (Piñeiro 2012)
Macrocystis pyrifera	118	37.9	41.2	7.8	0.92	0.267	31.7	0.007	0.700	10.6	0.7	2100	Cr, Mn, Fe, Ca, P, Na, K, Cu, I (Smith et al. 2010); Mg, Zn & Se (Ross et al. 2008); As & inorganic As (Díaz et al. 2012)
Sargassum fusiforme[3]	52.63	18.6	32.9	1.16	1.0	0.886	10.0	0.001	0.013	13.46	0.55	430	Ca, Fe & Zn (Pereira 2011); P (Nisizawa, 1987); I (Holdt and Kraan 2011); K, Na, Cu, Se, Mn & Mg (CHO et al. 1995); Cr (Mišurcová et al. 2009)
Undaria pinnatifida	4.8	8.9	98.4	3.6	4.3	0.184	8.0	0.0075	0.032	8.68	55	139	K, Na, Ca, Mg, P, Cu & I (Piñeiro 2012); Fe & Mn (Misurcová 2012); Se and Cr (CHO et al. 1995); Zn (Siahaan, Pangestuti, and Kim 2018)

[1] *Saccharina japonica* (formerly *Laminaria japonica*), Se: Kijang, July data.
[2] *Saccharina latissima* (formerly *Laminaria saccharina*).
[3] *Sargasum fusiforme* (formerly *Hizikia fusiformis*).

minerals (Table 9), the range of K was 4.80–118 mg/g d.w., with the highest value occurring for *Macrocystis pyrifera*, followed by the genus *Laminaria* with values of 115.7 mg/g d.w. for *L. digitata* and 96.3 mg/g d.w. for *Saccharina japonica*. The same behavior was observed for calcium (8.99–37.9 mg/g d.w.), where *M. pyrifera* also had the highest content, followed by *S. fusiforme* (18.6 mg/g d.w.).

For Na, the brown seaweeds had similar values (29.2–41.2 mg/g d.w.) with the exception of *Undaria pinnatifida*, which had a high Na value (98.4 mg/g d.w.). The phosphorus content was also similar (1.16–4.8 mg/g d.w.) with the exception of *M. pyrifera*, which had a higher value (7.8 mg/g d.w.). Fe had similar values for the genus *Laminaria* (0.040-0.080 μg/g d.w) and higher value for *Sargasum fusiforme* (0.886 μg/g d.w), followed by *M. pyrifera* (0.267 μg/g d.w) and *U. pinnatifida* (0.184 μg/g d.w).

There was high variability in the content of Cu in brown seaweeds (<0.5–4.3 μg/g d.w), with a higher value in *U. pinnatifida* (4.3 μg/g d.w), followed by *L. digitata* (2.9 μg/g d.w), and with low presence in *Saccharina japonica* and *Saccharina latissima*. Se was high in brown seaweeds compared to the other groups with the exception of *Laminaria digitata*. The highest value for Se was in *M. pyrifera* (31.7 μg/g d.w.). The brown seaweeds presented a wide range of Cr content (<0.5–55 μg/g d.w) with a very high value for *U. pinnatifida* (55 μg/g d.w) for this mineral. Iodine had a high presence in this group, with the lowest values occurring for U. pinnatifida (13,955 μg/g d.w) and highest values occurring for the genus *Laminaria* and *M. pyrifera*, where it reached up to 2100 μg/g d.w. For magnesium and manganese, there were similar values in the whole group. Brown seaweeds have low manganese content and high magnesium content in comparison to red and green seaweed. The Mg content was highest in *S. fusiforme*.

Regarding toxic minerals, *Saccharina japonica* had the highest content of Al (8.9 μg/g d.w.), followed by *Saccharina latissima* (7 μg/g). Al was not found in *S. fusiforme* and *U. pinnatifida* (Table 10). The amount of aluminum in brown seaweeds is much lower than in red and green seaweeds (Table 13). Low values of Hg are present in brown seaweeds group with the exception of *Saccharina japonica* (0.4 μg/g d.w.). Inorganic As and Cd are present in the whole group of brown seaweeds, with very high values for *S. fusiforme* (74.4 μg/g d.w). High values of Cd occurred in *M. pyrifera*.

Health benefits and recommended dietary mineral intakes

Poor health and behavioral conditions are related to a deficiency of minerals or an excess of toxic ones (Campbell 2001; Siahaan, Pangestuti, and Kim 2018). Seaweeds have 10–100 times higher mineral content than traditional vegetables, with mineral content reaching 36% of its dry weight. Thus, they could make an important contribution to the daily intake of minerals. It has been reported that seaweeds have a balanced content of Na and K with a low Na/K ratio in the range of 0.14–0.16 (Mohamed, Hashim, and Rahman 2012). Diets with a Na/K ratio of 0.84 have been considered

Table 10. Toxic minerals composition of main edible brown seaweed.

Scientific Name	Toxic minerals μg/g d.w. Al	Pb	Cd	As	Inorganic As	Hg	Reference
Laminaria digitata	0.18	0.106	0.4	65.7	0.251		Cd (Piñeiro 2012); Pb, As & inorganic As (Almela et al. 2006); Al (Ross et al. 2008)
Saccharina japonica[1]	8.9	<LOD	0.02	116	1.44	0.4	Al, Cd, and Hg (Piñeiro 2012); Pb, As & inorganic As(Almela et al. 2006)
Laminara saccharina	7		2.8	76.2		<0.05	Cd, As, Hg & Al (Piñeiro 2012)
Macrocystis pyrifera	<50	0.3	6.5	68	1.7	0.05	Al(Piñeiro 2012); Cd (Ross et al. 2008); As & inorganic As (Díaz et al. 2012); Hg and Pb (Smith et al. 2010); Cd (Ross et al. 2008); As & inorganic As(Díaz et al. 2012)
Sargassum fusiforme[2]		0.88	0.62	111	75.4	0.0259	Pb, As, inorganic As & Cd (Almela et al. 2006); Hg (Holdt and Kraan 2011)
Undaria pinnatifida		0.113	1.55	41.4	<LD	0.014	As(Piñeiro 2012); Pb, inorganic As & Cd (Almela et al. 2006); Hg (Holdt and Kraan 2011)

[1]*Saccharina japonica* (formerly *Laminaria japonica*).
[2]*Sargasum fusiforme* (formerly *Hizikia fusiformis*), I data as *Hizikia fusiformis* (Hijiki).
LOD = limit of detection.

Table 11. Na/k ratio in main edible seaweed.

	Na/K ratio	Division
Caulerpa spp	8.09	Chlorphyta
Codium fragile	6.5	Chlorophyta
Ulva clathrata[1]	0.14	Chlorophyta
Monostroma nitidium	2.22	Chlorophyta
Gracilaria spp.	1.59	Rhodophyta
Palmaria palmata	0.12	Rhodophyta
Porphyra tenera	1.03	Rhodophyta
Porphyra/Pyropia spp.	0.21	Rhodophyta
Laminaria digitata	0.39	Phaeophyceae
Saccharina japonica[2]	0.30	Phaeophyceae
Laminaria saccharina[3]	ND	Phaeophyceae
Macrocystis pyrifera	0.34	Phaeophyceae
Sargassum fusiforme[4]	0.62	Phaeophyceae
Undaria pinnatifida	20.5	Phaeophyceae

[1]*Ulva clathrata* (formerly *Enteromorpha clathrata*).
[2]*Saccharina japonica* (formerly *Laminaria japonica*).
[3]*Saccharina latissima* (formerly *Laminaria saccharina*).
[4]*Sargassum fusiforme* (formerly *Hizikia fusiformis*), ND = No data avalilable.

low in sodium and high in potassium (Perez and Chang 2014). This is nutritionally important because diets with a high Na/K ratio are linked to hypertension. One exception was the green seaweed *Ulva clathrata,* which had a high sodium content that raises the Na/K ratio, which was also the case for *Caulerpa* spp., *C. fragile,* and *M. nitidium* as shown in Table 11.

Red and brown seaweeds have lower Na/K ratios with the exception of *U. pinnatifida,* which is commonly known as wakame. However, antihypertensive properties have been reported for this seaweed. This could be related to the presence of some peptides that inhibit angiotensin-1-converting enzyme, which regulates blood pressure (Mohamed, Hashim, and Rahman 2012). Green seaweeds have the highest Na/K ratios with the exception of *Ulva clathrata.* The red seaweed *P. palmata* (0.12) has the lowest Na/K ratio among the group of main edible seaweeds.

The most deficient minerals in humans are Cr, Mg, Zn, and Ca (Campbell 2001). All seaweeds contain high amounts of Ca, Mg, Na, P, Zn, and I and are one of the most important sources of calcium and phosphorus (Mohamed, Hashim, and Rahman 2012). Compared with other mineral-rich foods, seaweeds have greater content of Ca, Cr, I, Fe, Mg, P, Se, Zn, K, and Na, but not copper and manganese. Seaweeds have very low values of Cu compared to other foods, such as raw meats and dried shiitake mushrooms (Table 14).

Iron is an essential element that participates in a wide variety of metabolic process, including respiration, energy production, deoxyribonucleic acid (DNA) synthesis (Abbaspour, Hurrell, and Kelishadi 2014; Camaschella 2015), and cell proliferation. In excessive amounts, iron can be toxic (Camaschella 2015) and lead to tissue damage (Abbaspour, Hurrell, and Kelishadi 2014). Iron absorption is limited to 1 to 2 mg daily, and most of the iron needed daily (about 25 mg per day) is provided through recycling by macrophages that phagocytose senescent erythrocytes. Iron-deficiency and the resulting anemia are global health problems. Iron-deficiency continues to be the top-ranking cause of anemia worldwide and has a substantial effect on the lives of young children and premenopausal women. The most common causes of iron deficiency are insufficient dietary intake, loss of blood, and malabsorption (Camaschella 2015).

Among the three groups of seaweeds, green seaweeds have the highest iron content (up to 9.4 mg/g d.w.). Green seaweeds contain at least 90% more iron than other foods that are known for their high iron content, such as dried spearmint (1.23 mg/g) and whole meat (0.72 mg/g) (USDA 2019). The green seaweed *C. fragile* and the red seaweed *P. tenera* could be potential sources of iron for populations that are susceptible to deficiency, even for vegan or vegetarian populations.

Zinc is an essential micronutrient that is required for the activity of more than 300 enzymes and 1,000 transcription factors (Roohani et al. 2013) and plays a vital role in the host defense against pathogens (Sapkota and Knoell 2018). However, prolonged excessive dietary intake of Zn can lead to deficiencies in copper and iron, as well as nausea, headache, fever, and abdominal pain. Zn is also a human skin irritant (Saha et al. 2016). Zinc deficiency results in affected epidermal, gastrointestinal, skeletal, and reproductive systems (Roohani et al. 2013), and the various pathological conditions include impaired immunity (Roohani et al. 2013; Yasuda and Tsutsui 2016; Sapkota and Knoell 2018), neural development disorders, degenerative diseases (Yasuda and

Table 12. Dietary reference intake (DRIs): Recommended Dietary Allowances (RDAs) and Adequate Intakes (AIs) of essential mineral and the contribution of these from main edible seaweed.

	Ca	Cr	Cu	I	Fe	Mg	Mn	P	Se	Zn	K	Na
*RDAs, AIs[a]	**1000**	35	**900**	**150**	**8**	**420**	2.3	**700**	**55**	**11**	4700	1500
*RDAs, AIs[b]	**1000**	25	**900**	**150**	**18**	**320**	1.8	**700**	**55**	**8**	4700	1500
*RDAs, AIs[c]	**1000**	30	**900**	**150**	**8**	**420**	2.3	**700**	**55**	**11**	4700	1300
*RDAs, AIs[d]	**1200**	20	**900**	**150**	**8**	**320**	1.8	**700**	**55**	**8**	4700	1200
*RDAs, AIs[e]	**1200**	30	**900**	**150**	**8**	**420**	2.3	**700**	**55**	**11**	4700	1200
*RDAs, AIs[f]	**1200**	20	**900**	**150**	**8**	**320**	1.8	**700**	**55**	**8**	4700	1200
*RDAs, AIs[g]	**1000**	15	**440**	**90**	**10**	**130**	1.5	**500**	**30**	**5**	3800	1200
**Chlorophyta	6.9-25.3	1.05-16.8	7.5-8	63-7530	0.025-9.43	3.8-35	0.040-0.051	0.29-30	0.41	0.06-0.18	3.18-27	4-92.3
**Rodophyta	3.39-4.02	0.98-2	3.7-15.8	35.8-4280	0.036-1.845	1.6-5.65	0.011-0.36	2.0-18.2	0.16	0.020-0.383	27.2-81	5.87-54.65
**Phaeophyceae	8.99-37.9	<0.5-55	<0.5-4.3	139-2110	0.04-0.886	6.4-13.46	0.001-0.0075	1.16-7.86	0.026-31.7	0.013-0.700	4.80-118	29.2-98.4

*Food and Nutrition Board, Institute of Medicine,National Academies (2011); Recommended Dietary allowances (RDAs) in **bold type** and Adequate Intakes (AIs) in ordinary type; Ca, Fe, Mg, Mn, P, Zn, K and Na mg/day; Cr, Cu, I and Se μ/day. [a]Males 31-50, [b]Females 31-50, [c]Males 51-70, [d]Females 51-70, [e]Males >70 and [f]Females >70, [g]Children 4-8.
**Ca, Fe, Mg, Mn, P, Zn, K and Na mg/g d.w., Cu, Cr, I and Se μ/g d.w.

Table 13. Maximum levels (MLs) of toxic minerals and I established in different countries for several food commodities and the presence of these in different groups of seaweeds.

	I	Pb	Cd	Inorganic As	Hg
Singapore-any other seaweed (ppm)[1]			2.0		0.05
EC-dried seaweed-Food supplements (mg/kg net weight)[2]			3.0		
EC- food supplements (mg/kg net weight)[2]		3.0	1.0		0.1
French regulation (mg/kg dry weight)[3]	2000	5	0.5	3	0.1
FDA- maximum level in selected food (ppm)[4]		0.1	2.0	0.5	1.0
Australia New Zealand (mg/kg)[5]		2.0	2.0	1.0	0.5
Codex Alimentarius (mg/kg)[6]		0.3	2.0	0.2	0.5
Chlorophyta (μg/g d.w.)	1540-7530	0.03-0.2	0.02	0.346	0.02
Rhodophyta (μg/g d.w.)	30-4260	0.2-1.52	0.31-3	0.18-0.59	0.01-0.44
Phaeophyceae (μg/g d.w.)	100-2110	0.10-0.8	0.02-6.5	0.25-75.54	0.01-0.4

[1]Agri-Food & Veterinary Authority of Singapore legislation (http://statutes.agc.gov.sg).
[2]Commission regulation (EC) No 1881/2006 of December 2006 setting maximum levels for certain contaminants in foodstuffs; Amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs. Food supplements consisting exclusively or mainly of dried seaweed or of products derived from seaweed. The maximum level applies to the food supplements as sold.
[3]Edible seaweed and French regulation- Synthesis made by Center d'Etude et de Valorization des Algues (CEVA), 2014.
[4]US Food and Drug Administration (FDA). Inorganic As in eggs and uncooked edible tissue of chickens and turkeys; As shellfish and shellfish products; Cd for fish, crabmeat, prawns and shrimps; Pb in dried fruits including raisins (FDA 2013, 2015) and Hg in all fish (Food and Drug Administration 2019)
[5]Australian New Zealand Food Standards Code- Standard 1.4.1-Contaminants and Natural Toxicants. Inorganic As for seaweed; Cd for mollusks (excluding dredge/bluff oysters and queen scallops); Hg mean level in mollusks and fish.
[6]Codex Alimentarius-International Food Standards. General Standard for Contaminants and Toxins in Food and Feed (CODEX STAN 193-1995) Amended in 2015. Inorganic As for rice polished; Cd for marine bivalve mollusk; Pb and Hg for fish.

Tsutsui 2016), and delayed recovery following infection (Sapkota and Knoell 2018).

Globally, up to 50% of wheat-cultivated soil is considered poor in bioavailable Zn, and about a third of the worlds population is estimated to be at risk of Zn deficiency, especially children under 5 years did because of their large demand for Zn to support growth. Half a million children under 5 years old die from causes related to Zn deficiency (Cakmak and Kutman 2018). Zinc supplementation in at-risk populations has been shown to restore host defense and reduce pathogen-related mortality (Sapkota and Knoell 2018). Seaweeds are high in Zn content, particularly brown and red seaweeds. The Zn content can reach up to 0.70 mg/g, depending on the species and geographical area. Besides seaweeds, the main food sources of Zn are mollusks and wheat germ, which have Zn contents of 0.9 and 0.12 mg/g, respectively (Table 14).

Manganese is an essential mineral that is involved in the metabolism of proteins, lipids and carbohydrates. It is needed for normal immune function, regulation of blood sugar, and cellular energy (Mišurcová, Machů, and Orsavová 2011; Jenkitkasemwong et al. 2018). Manganese deficiency might lead to severe skeletal and reproductive abnormalities (Mišurcová, Machů, and Orsavová 2011; Saha et al. 2016), although dietary deficiency is unlikely to occur in people eating a normal, varied diet. Large dietary intakes of manganese are not harmful to humans with normal renal function, and hypermanganesemia is impossible to achieve from food sources alone (Mann and Truswell 2017). The red seaweed *P. tenera* has similar values to other sources that are rich in this mineral, such as ground ginger, and it has a higher content than turmeric (Table 14). Nevertheless, manganese toxicity has been associated with neuropsychiatric symptoms and Parkinsons disease, and high Mn content in the liver has been reported in alcoholic liver disease (Mišurcová, Machů, and Orsavová 2011; Jenkitkasemwong et al. 2018).

Cr is required to produce energy from blood sugar and is actively involved in insulin function and lipid metabolism (Saha et al. 2016). There are few data on the content of this essential mineral in food. There is great variability in the content of this mineral in the different groups of seaweeds, with greater presence in green and brown seaweeds. There are very high values in only one gram of the brown seaweed *U. pinnatifida* with respect to the recommended dietary allowances for this essential mineral. The recommended amounts of Cr in milligrams per day for children aged 4-8 years old can be achieved with the consumption of only

Table 14. Composition of essential minerals in some edible seaweeds comparing to other mineral-rich food sources.

Essential mineral	Food source*		Seaweed (d.w.)	
Ca mg/g	Tofu	21.34	*Macrocystis pyrifera*	37.9
	Kale	2.54	*Codium fragile*	25.3
Cr µg/g	Chicken meat***	0.25	*Undaria pinnatifida*	55
	Black tea***	0.26 ± 0.08	*Codium fragile*	16.8
Cu µg/g	Meats raw	110	*Porphyra tenera*	15.8
	Mushrooms shitake dried ****dridridridriedddired dried	50	*Porphyra/Pyropia* spp.	9.5
I µg/g	Eggs**	1.6	*Ulva clathrata*[1]	7530
	Fish**	1.2	*Gracilaria* spp.	4260
Fe mg/g	Spearmint dried	1.23	*Codium fragile*	9.43
	Whole meat	0.72	*Porphyra tenera*	1.84
Mg mg/g	Rice bran	7.81	*Ulva clathrata*[1]	35
	Basil dried	7.11	*Codium fragile*	15.2
Mn mg/g	Ginger ground	0.33	*Porphyra tenera*	0.36
	Turmeric ground	0.19	*Ulva clathrata*[1]	0.051
P mg/g	Rice bran crude	16.77	*Ulva clathrata*[1]	30
	Pumpkin seeds dried	9.85	*Gracilaria* spp.	18
Se µg/g	Nuts (brazil nuts dried)	19.17	*Macrocystis pyrifera*	31.7
	Mustard seed round	2.08	*Laminaria japonica*	8.0
Zn mg/g	Mollusks	0.90	*Macrocystis pyrifera*	0.70
	Wheat germ crude	0.12	*Porphyra tenera*	0.383
K mg/g	Parsley freeze-dried	63	*Macrocystis pyrifera*	118
	Tomatoes sun-dried	34.27	*Laminaria digitata*	115.7
Na mg/g	Salt table	38.75	*Undaria pinnatifida*	98.4
	Cheese parmesan	18.04	*Codium fragile*	92.3

*(USDA 2019).
**(Haldimann et al. 2005).
*** (Gonzalez-Weller et al. 2015).
**** (Ahmed et al. 2017).
[1]*Ulva clathrata* (formerly *Enteromorpha clarthrata*).
[2]*Laminaria japonica* (formerly *Saccharina japonica*).

one gram of *C. fragile*, although attention to its aluminum content is required.

Mg and Ca have key roles in bone and teeth health. In addition, Mg is also involved in cellular metabolism and as many as 300 enzyme systems, while Ca is involved in the regulation of the heartbeat, nerve transmission, muscle contraction, blood coagulation, and the activation of insulin and the thyroid hormone calcitonin (Mann and Truswell 2017). Some references for brown and green seaweeds indicate higher Ca levels than in tofu (21.34 mg/g) and kale (2.54 mg/g) (USDA 2019). Green seaweeds *Ulva clathrata* and *C. fragile* have the lowest magnesium content, but it is at least similar to that provided by pumpkin seeds (5.92 mg/g) (USDA 2019).

Cu is required for strong, flexible connective tissue, the oxidation of vitamin C (Saha et al. 2016), and hemoglobin synthesis (Saha et al. 2016; Mann and Truswell 2017). A lack of copper could lead to an enlarged heart, elevated cholesterol, and week blood vessels. However, high levels of copper can cause toxicity, and human deaths have been known to occur from deliberate ingestion of large quantities of copper sulfate (Saha et al. 2016). Cu has similar levels in green and red dry seaweeds. The highest value occurs in the red seaweed *P. tenera* (0.57 µ/g), and there is little presence in the brown seaweeds in the genus *Laminaria,* with values less than <0.5 µg/g dry weight.

Phosphorus is an essential part of bones and teeth and is necessary for important enzymes that store and release energy for body functions. Excess phosphorus combines with other minerals to form insoluble salts in the intestines and urinary tract (Campbell 2001) and contributes to degenerative diseases such as kidney damage and osteoporosis (Campbell 2001; Siquier-Coll et al. 2019). The maximum phosphorus content reported for green and red dry seaweeds (Table 12) are higher than those in foods rich in phosphorus, such as pumpkin seeds. P has similar levels in all three groups of seaweeds.

Selenium is incorporated into selenium proteins that have antioxidant and anti-inflammatory effects on the production of active thyroid hormone. Low selenium has been associated with poor immune function and cognitive decline (Rayman 2012; Mann and Truswell 2017). Higher selenium status has antiviral effects. It is essential for successful male and female reproduction, and it reduces the risk of autoimmune thyroid disease (Rayman 2012). In excess, Se might increase the risk of type-2 diabetes (Rayman 2012) and can cause garlic breath, hair and nail loss, poor dental health, and disorders of the skin and nervous system (Rayman 2012; Saha et al. 2016; Mann and Truswell 2017).

Fish are the richest sources of selenium, followed by meats, grains, dairy products, and cereals (Mann and Truswell 2017). Brown seaweeds can be a potential source of selenium, with only one gram of some types covering 100% of the recommended dietary allowances (RDAs) for children aged 4 to 8 years. Therefore, caution should be exercised so as not to exceed the recommended limits in this age group (Table 12). Similarly, *L. digitata* and *M. pyrifera* also exceed the recommended dietary allowances for this mineral.

Iodine is indispensable for the synthesis of the thyroid hormones thyroxin (T4) and tri-iodothyronine (T3), which are required for growth, organ development, and utilization of nutrients by the body. Iodine deficiency increases the risk of mental retardation, hypothyroidism, lower cognitive function, decreased work productivity, and thyroid dysfunction

(Lee et al. 2016). Furthermore, it is also the world's greatest cause of brain damage and mental retardation. The World Health Organization (WHO) estimates that 1.6 billion people are at risk of iodine deficiency, with at least 20 million suffering from mental defects that are preventable by correction of iodine deficiency.

The major cause of iodine deficiency disorders is inadequate dietary intake of iodine from foods grown in soils from which iodine has been leached by glaciation, high rainfall, or flooding. Iodine deficiency is a major international public health problem, and there are large populations at risk due to their iodine-deficient environments, which are characterized by iodine-deficient soil. Foods of marine origin like fish, shellfish, and seaweeds are rich in iodine because of the greater iodine concentration in sea water compared to fresh water (Mann and Truswell 2017). In sensitive people, too much Iodine can trigger a hyperactive thyroid gland, and excessive seaweed consumption was found to be frequently associated with hyperthyroidism and Hashimotós thyroiditis (Holdt and Kraan 2011; Mann and Truswell 2017) in countries where seaweeds are traditionally used as food (Holdt and Kraan 2011).

Iodine is present in greater quantity in the group Phaeophyceae, followed by Rhodophyta, and in smaller amount in the group Chlorophyta. Brown seaweeds are characterized by high iodine content, but the green seaweed *Ulva clathrata* and red seaweed *Gracilaria* spp. have high iodine content. The maximum levels reported for iodine for 1 g d.w. in some seaweeds can reach up to 20 times the recommended daily levels (Table 12).

The recommended daily intake for essential minerals for humans varies between countries. The Dietary Reference Intakes (DRIs) are nutrient reference values developed by the Institute of The National Academies of Sciences as a guide for good nutrition. These values provide a scientific basis for the development of food guidelines in the United States and Canada. The RDA is the average daily dietary intake level that is sufficient to meet the nutrient requirements of nearly all healthy individuals in a group (97-98 percent). It is calculated from an Estimated Average Requirement (EAR) if sufficient scientific evidence is available. Thus, the RDA is calculated, and an AI is usually developed.

The RDAs and AIs for essential minerals vary based on age, sex, pregnancy, and lactation (Table 12). One gram of seaweed can provide 55-183% of the AIs for Cr, with the highest level occurring for the brown seaweeds *U. pinnatifida* and *C. fragile*. Both seaweeds contain higher chromium content that other foods that are rich in this mineral, such as chicken and black tea (Table 14). Seaweeds are a rich source of iodine and can provide 20-500% of the RDAs for this mineral. They are also a good source of Fe, with one gram of the green seaweed *C. fragile* contributing up to 117% of the RDAs, followed by the red seaweed *Porphyra tenera*, which has greater iron content than whole meat. One gram of seaweed can cover up to 57.6% of the RDAs for Se, with the highest content occurring in the brown seaweeds *M. pyrifera* and *Saccharina japonica*. Seaweeds are also a good source of Mg, P, Ca, Se, and K, with higher content than other types of food (Table 14).

The five elements that are most common in most species of the three groups of seaweeds are K, Na, Ca, Mg, and Fe. Compared to the other two groups, Chlorophyta has a lower level of K and Ca. The highest level of F is in *C. fragile* (Table 14). The three groups have similar levels of zinc and manganese, while chromium is found in greater amounts in Phaeophyceae.

The essential mineral content of K, Ca, Se, and I was highest in brown seaweed, followed by red seaweed for K and by green seaweed for Ca, Se, and I. An exception was the red seaweed *Gacilaria* spp. and the green seaweed *Ulva clathrata*, which both have high iodine content. The highest Zn, Cu, and Mn levels were present in red seaweeds, followed by brown for Zn and Cu and by green for Mn. The highest levels of Zn were present in the red seaweed *Gracilaria* spp., followed by the brown seaweed *U. pinnatifida*. The highest Na, P, Fe, and Cr content was present in green seaweeds, followed by red. Brown seaweeds presented the lowest level with the exception of *U. Pinnatifida*, which is high in Na and Cr. The highest Mg levels were in green seaweeds, followed by brown seaweed. The green seaweed *C. fragile* has the highest amounts of iron and high cadmium levels after *U. pinnatifida*.

Food safety

Food consumption is the main pathway for human exposure to toxic metals (Saha et al. 2016). Some seaweeds exhibit affinity for toxic minerals, and the concentrations are strongly dependent on the environmental parameters (salinity, temperature, pH, light, nutrient concentrations, and oxygen) (Besada et al. 2009; Wells et al. 2017). The concentrations also tend to differ among phylogenetic groups, with brown algae typically having higher levels of most metals in comparison with red or green algal species (Wells et al. 2017).

Under certain conditions, toxic minerals can bioaccumulate in seaweeds to hazardous levels and migrate to the human body through the diet, resulting in negative health effects such as allergies, hyperpigmentation, and cancer caused by As and Cd. After their absorption in the gastrointestinal system, they target the liver, placenta, kidneys, lungs, brain, and bones (Wongsasuluk et al. 2014). Some toxic minerals can reach harmful concentrations in edible seaweeds, but there is no information on how bioaccessible or bioactive the metals in most seaweeds are in human digestion (Wells et al. 2017).

The toxic effects of As lead to a higher incidence of several cancers (Wells et al. 2017). Inorganic arsenic is very toxic (Holdt and Kraan 2011; Mann and Truswell 2017) and has a negative effect on the human nervous system (Holdt and Kraan 2011). Seafood is a major food source of arsenic in a nontoxic organic form, which is absorbed and excreted (Mann and Truswell 2017; Wells et al. 2017). Seaweeds contain high levels of total arsenic (mainly organic arsenic), and in most species, the major arsenic compounds are

Table 15. Potential hazards related to mineral composition of edible seaweeds based on the consumption of one gram of dry seaweed per day and considering the lowest value of MLs within the different countries.

			Essential minerals above RDIs				Toxic minerals		
Scientific name	Common names	High Na/k	Cr	I	Fe	Se	Pb	Cd	As-in As
Caulerpa spp.	Sea grapes or Green caviar	Medium	High (Children) low (adults)	Nd		Nd		Medium	Nd
Codium fragile	Dichotomous sponge tang or Shui-sung	Medium		Low		Nd	Nd	Nd	Nd
Ulva clathrata[1]	Green nori			High			Medium		Low
Monostroma nitidium	Hitoegusa, Green laver	Low	Nd			Nd	Nd	Nd	Nd
Gracilaria spp.	Ogo, Ogonori or Sea Moss, Pelillo		Nd	High		Nd	Nd	Medium	High
Palmaria palmata	Dulse					Nd	High	Low	Medium
Pyropia tenera[2]	Nori			Low		Nd	Low	Low	Low
Porphyra/Pyropia spp. pp.	Nori or purple laver, Luche						Medium		
Laminaria digitata	Kombu/Konbu			High				Medium	Low
Saccharina japonica[3]	Japanese kombu			High					High
Saccharina latissima[4]	Royal or sweet Kombu			High		Nd			Nd
Macrocystis pyrifera	Huiro, Giant kelp, Giant bladder kelp, kelp pepper			High		High (children)	Medium	High	Medium
Sargassum fusiforme[5]	Hoshi hiziki, Hijiki			High			High	Low	High
Undaria pinnatifida	Wakame, Mekabu, Quandai-CAI	High	High				Low	Medium	

[1]*Ulva clathrata* (formerly *Enteromorpha clathrata*).
[2]*Pyropia tenera* (formerly *Porphyra tenera*).
[3]*Saccharina japonica* (formerly *Laminaria japonica*).
[4]*Saccharina latissima* (formerly *Laminaria saccharina*).
[5]*Sargassum fusiforme* (formerly *Hizikia fusiformis*), Nd = no data.

arsenosugars (Holdt and Kraan 2011; Wells et al. 2017). However, the seaweed species *S. fusiforme* has large amounts of the inorganic form (Holdt and Kraan 2011).

Pb (Zhang et al. 2012) and Al (Kawahara et al. 2007) are not essential elements for the human body, and excessive intake can damage the nervous, skeletal, circulatory, enzymatic, endocrine, and immune systems. Children, pregnant women, and elderly people are particularly sensitive to lead exposure, and lead also has significant effects on intelligence quotients and physical development in children (Zhang et al. 2012). Al is toxic to most life because of its peculiar chemical properties. It binds to the phosphate groups of DNA or RNA, influences DNA topology, and affects gene transcription. In humans, Al inhibits more than 200 biologically important functions and has a relationship with neurodegenerative diseases (Kawahara et al. 2007).

Mercury has been found to be a causative agent of various disorders, including neurological, immunological, cardiac, reproductive, and genetic disorders. Toxic minerals have been linked to diseases such as Alzheimer's and Parkinson's disease, among others (Zahir et al. 2005). The lead levels in edible Chlorophyta, Rhodophyta, and Phaeophyceae comply with the maximum allowed levels of this toxic mineral from the EC, French, Australia, and New Zealand regulations, but not the standards established by the Codex Alimentarius and Food and Drug Administration (FDA) for other food commodities (Table 13). The highest levels of this toxic mineral occur in *P. palmata* and *S. fusiforme* (Table 15).

The maximum levels for heavy metals in regulatory frameworks for foods differ from nation to nation. EU Commission Regulation 18881/2006 legislation sets maximum levels for chemical contaminants in foodstuffs and was as amended by regulation 69/2008 (European Commission 2013). The USA has established levels for certain types of foods through different regulations issued by the FDA, while Australia and New Zealand establish maximum levels of heavy metals in a common regulation for both countries: Food Standards Australia New Zealand (FSANZ)-1.4.1. Contaminants and Natural Toxicants, which laid down maximum levels of five heavy metals in specified foods. The Codex Alimentarius General Standard for Contaminants and Toxins in Food and Feed (CODEX STAN 193-1995 amended in 2015) lists the maximum levels for metals in food that are recommended by the Codex Alimentarius Commission (CAC) to be applied to commodities moving in international trade (Table 13).

The three divisions of selected edible seaweeds present high levels of I and inorganic As, which exceed the established maximum levels for I in certain species for French regulations for seaweed and the maximum level for inorganic As for the USA regulations in other food commodities. Mercury levels in Chlorophyta, Rhodophyta, and Phaeophyceae comply with the FDA, Australia/New Zealand regulations, and Codex Food Standards. Chlorophyta also meets the Singapore, EC, and French regulations for this toxic mineral. The exceptions are the Rhodophyte *P. tenera* and the Phaeophyceae *Saccharina japonica*, which have higher Hg levels than the maximum levels established by the regulations of France, EC, and Singapore.

The only data found for Chlorophyta meet the permissible limits for Cd. The maximum levels of Cd in Rhodophyta and Phaeophyceae exceed the maximum acceptable limits of most regulations, and more Cd is present in Phaeophyceae. All three groups exceed acceptable limits for inorganic As established by the FDA and Codex Alimentarius (Table 13).

Aluminum is not an essential mineral for humans, and high toxicity has been reported (Kawahara et al. 2007). Regulations do not establish maximum levels for the presence of Al in foods, but the WHO recommends weekly Al intake of less than 7 mg/kg. This means an adult of 60 kg can consume up to

60 mg/day (Kawahara et al. 2007). Only a few values have been reported for Al and l in edible seaweed. The data indicate that it is present in low levels (mg/g d.w.) and do not exceed the WHO recommendations (Chlorophyta: 0.095; Rhodophyta: 0.004–1.55; Phaeophyceae: 0.0001–<0.050).

Edible seaweeds in the US are covered by the US FDA's *Current Good Manufacturing Practice, Hazard Analysis, and Risk-based Preventive Controls for Human Food regulation.* This regulation is intended to ensure safe manufacturing, processing, packing, and holding of food products for human consumption in the United States. Facilities covered by the preventive controls requirements in 21 CFR 117 are those that manufacture, process, pack, or hold human food, which applies to both domestic and foreign food processors exporting food covered by 21 CFR 117 to the US (FSPCA 2016). Preventive controls programs are structured to work in conjunction with and be supported by other relevant programs, such as Good Manufacturing Practices (GMPs), good agricultural practices, and good transportation practices as a basis for food safety management. Preventive controls programs incorporate not only process-related controls in the HACCP framework, but also controls related to food allergens, sanitation, suppliers, and other areas requiring preventive control. Exemptions for preventive controls are foods subject to HACCP regulations (seafood part 123 and juice part 120); foods subject to low-acid canned food regulations (microbiological hazards regulated under part 113); dietary supplements (part 111); and alcoholic beverages. The HACCP regulation for seafood applies only to aquatic animals and not aquatic plants (FSPCA 2016).

Risk factors related to the consumption of seaweeds can include the seaweed varieties and the unpredictable influence of environmental factors on the degree of uptake of toxic mineral content, such as temperature and season. Other factors are physical similarities between seaweed species and potential difficulty in differentiating between those with high levels of toxic minerals and those with lower levels, as well as the use of generic terms such as kelp or seaweed in product ingredient lists instead of the scientific name. The generic name gives no indication about the type of seaweed in the product.

Food chemical risks associated with seaweed consumption includes the intake of essential and toxic minerals above safe levels (Table 15). These hazards must be considered when developing a food safety plan based on preventive controls for seaweeds for human consumption. It is possible that an unsafe level of essential or toxic minerals is not eliminated or reduced when processing the seaweeds for consumption. As control strategies for this type of hazard, the growing region should be considered prior to use with a supply-chain program as preventive control. Furthermore, approved chemical methods should be used for the detection of minerals in food to confirm the presence of safe levels. Proper food labeling of seaweeds and seaweed-containing products that include the scientific name is required, as well as strict monitoring of labels to avoid a certain level of minerals with impact on public health in certain populations.

Conclusions

Seaweeds could be used as sustainable functional foods or a source of food supplements for essential minerals (Ca, Cr, I, Fe, Mg, P, Se, Zn, Mn, K, and Na). They could even be a solution to worldwide deficiency in minerals among humans (Fe, Zn, and I). A single gram of dry seaweed contains higher levels of these minerals than other sources of mineral-rich foods and can provide a significant amount of the RDAs or AIs of essential minerals. However, it is important to mention the high amounts of iodine, selenium, and chromium in some seaweeds exceed the recommended levels and are linked to negative effects on human health.

The toxic minerals in seaweeds are also important to consider and evaluate for the presence of inorganic arsenic, lead, and cadmium in some seaweeds species. Little information is available on the toxic mineral composition of edible seaweeds with significant volumes of consumption, and there is a wide variety of seaweeds that have not been studied for their mineral composition or their potential use for human consumption. From the viewpoint of food safety, it is important for countries with edible seaweed production to investigate the presence of essential and toxic minerals in relation to particular conditions of geography and environment. The development and establishment of maximum levels for some toxic minerals in seaweeds for human consumption are needed worldwide. The use of the seaweeds' scientific names and label declarations of the presence of certain minerals with effects on public health should be required.

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Author contributions

Both authors collected literature and wrote and designed the paper. All authors approved this review for publication.

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