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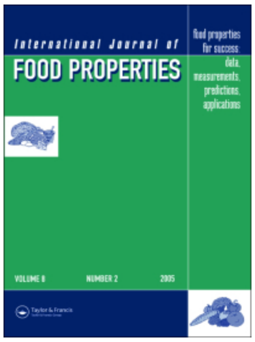

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Nutritional and toxicological characteristics of *Saccharina latissima*, *Ulva fenestrata*, *Ulva intestinalis*, and *Ulva rigida*: a review

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ABSTRACT
Nutrient and toxicant levels as well as their bioavailability in *S. latissima* and *Ulva* species (*fenestrata, intestinalis, rigida*) were reviewed. Nutritional quality was assessed by nutrient contribution to daily reference intake (DRI) per portion (5 g dry weight), nutrient density score NRF21.3, and comparisons to reference foods. Toxicological assessments comprised tolerable daily intake (TDI)-levels. Based on mean %DRI per portion, *S. latissima* and *Ulva* species were good sources (%DRI >15) of calcium, magnesium, iron, selenium, and vitamin B12. Mean %DRI was < 10% for fiber, sodium, and protein. Toxicological concerns were mainly due to iodine (mean %TDI per portion: 3160% for *S. latissima* and 41–91% for *Ulva* species). Mean %TDIs for inorganic arsenic, cadmium, and lead were <20% for *S. latissima* and 9–97%, 6–15%, and 21–46%, for the selected *Ulva* species, respectively. Bioavailability data were scarce and is, together with nutritional impact of processing, an important aspect to address in future studies.

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Seaweed; macroalgae; bioavailability; nutrient content; elemental composition

Introduction

The market of seaweed – marine macroalgae – for human consumption is growing rapidly in Europe and globally, driven by the search for novel tasty and nutritious foods with low environmental impact.[1,2] Production of seaweed supplied from aquaculture or wild stocks is suggested to have great potential as a resource-efficient source of nutrients, including protein[3] with lower environmental impact compared to most animal-based foods and without competing for arable land.[4,5] Mapping the variability in nutritional composition of different seaweed species is suggested as an important prerequisite to guide producers and consumers toward healthier choices.[6]

Seaweed provides essential macro- and micronutrients.[7] The high content of minerals[8] as well as the presence of vitamin B12 and long-chain *n*-3 fatty acids distinguish seaweed from conventional plant-based foods. However, improved knowledge of bioavailability and risk-benefit analyses of seaweed are identified as main research priorities to support sustainability in future European seaweed-based product development.[2] A concern when considering seaweed as food is the risk for toxic levels of heavy metals and high concentrations of iodine in some species.[9,19]

Saccharina latissima (*S. latissima*) and *Ulva* spp. are seaweeds of increasing interest in a European production and consumption perspective.[12] Previous studies have reviewed the nutritional

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composition of seaweed biomass in general;[6,13] of red seaweed species;[14] or have focused on selected nutrients.[8,15–17] However, the complete nutritional quality and levels of potentially toxic elements of *S. latissima* and *Ulva* spp. remain to be thoroughly compiled and investigated.

Therefore, this study aimed to assess the nutritional and toxicological characteristics of *S. latissima* and three species of *Ulva; Ulva rigida*, *Ulva fenestrata* and *Ulva intestinalis*, based on data from the scientific literature. Furthermore, to provide new insights on the potential role of seaweed in future sustainable diets, the nutritional profiles of *S. latissima* and *Ulva* species were compared with reference foods which seaweeds could serve as alternatives to in the human diet.

Materials and methods

Literature search

Scientific original articles providing information on the content and/or bioavailability of nutrients and heavy metals in *Saccharina latissima*, *Ulva fenestrata, Ulva intestinalis* and *Ulva rigida* were identified by literature search using the databases Scopus, SciFinder and PubMed (details on the search strategies are specified in the Supplementary material Table S1a,b) and were further cross-checked with references from the Harvard Aquatic Food Composition Database[18] (assessed October–November 2021). Articles included in this review are those published in peer-reviewed scientific journals between 2011 and October 2021, written in English. Articles were included if they reported content of one or more nutrient(s) or one or more heavy metal(s), based on chemical analyses of whole and full-grown biomass, of one or more of the selected seaweed specie(s). In case studies comprised dried biomass, they were included regardless of the drying-technique, e.g., freeze-drying, air-drying, sun-drying, or oven-drying. Studies were also included if they investigated bioavailability of one or more nutrient(s) in any of the selected seaweed species, either in studies on humans, monogastric mammals, or in *in-vitro* models. The following exclusion criteria were defined: (i) papers on cosmetic, pharmaceutical, or agricultural applications of seaweed; (ii) seaweed harvested in locations with reported or determined contamination (as areas with contamination were assumed not to be representative for an average production site); (iii) papers only reporting data on seedlings, parts of the thallus or on extracts of the selected seaweed species; (iv) papers presenting data in a format that could not be harmonized to content per 100 g dry weight (DW) of seaweed; (v) papers investigating bioavailability of nutrient(s) in ruminants or non-mammals. All articles identified (after removal of duplicates) were screened based on information in titles and abstracts and those that were judged to meet the inclusion criteria were reviewed in full text.

Data source, harmonization and reporting

In this review, content of energy, macronutrients, minerals and heavy metals, and information on bioavailability of nutrients, were retrieved from the original scientific studies identified through the literature search. Harvest location and harvest season were screened for in all articles included. Data on *Ulva* spp. were extracted whenever it was identified in the retrieved original articles. In this review, three kinds of data for *Ulva* are revealed; (1) data for the individual targeted species (*U. fenestrata, U. rigida and U. intestinalis*); (2) data for *Ulva* spp., meaning data reported for unknown *Ulva* species, and (3) data for "*Ulva* all," meaning merged data reported for all the three selected *Ulva* species and *Ulva spp*. The term "*Ulva* species" is used whenever referring to *Ulva* genus. Literature regarding vitamin content in the investigated seaweed species was found to be scarce.[10] Therefore, data on vitamins for *S. latissima* and *Ulva* spp. were retrieved from a publicly accessible food composition database published by Centre for the Study and Valorization of Algae (CEVA)[11,19] (accessed October 2021 and March 2022). Content of nutrients and heavy metals was harmonized to the unit "content per 100 g DW." A portion size of 5 g DW was used as reference for seaweed consumption as suggested by the European Food Safety Authority (EFSA)[9] and used in the CEVA database.[20] Data is reported as mean and median (min-max).

Regarding protein, fat, carbohydrates and fiber, data was included as reported, regardless of method of determination used by the original study. For example, we have used the term "fat" regardless of whether data were reported as total fatty acids or as gravimetrically determined total lipids/total fat. For protein, data on crude protein content were included independently of the nitrogen-to-protein conversion factor used. Only when nitrogen content was reported, a conversion factor of 5.0 was used to convert it to crude protein, as suggested by Angell et al..[21]

Nutritional quality assessments

Nutritional quality was assessed as the percentage contribution of one portion (5 g DW) of seaweed to Dietary Reference Intakes (DRI) of selected nutrients, as defined by the Nordic Nutrition Recommendations[22] (Supplementary material, Table S2). In addition, the nutrient density of seaweeds and reference foods was assessed by using the index Nutrient Rich Foods (NRF), conceptualized by Drewnowski[23] (Equation 1).

$$\text{Nutrient Rich Foods} = \sum_{i=1}^{x} \frac{Nutrient\ i}{DRI\ i} - \sum_{j=1}^{y} \frac{Nutrient\ j}{MRI\ j}, \quad (1)$$

where x indicates the number of nutrients to encourage and y the number of nutrients to limit, nutrient i/j describes the content of nutrient i or nutrient j per reference unit, and MRI is the Maximum Recommended Intake for the non-desirable nutrient (Supplementary material, Table S2).

In this review, the nutrient density was calculated according to NRF21.3 which has been applied to seafood elsewhere.[24,25] This NRF index includes 21 nutrients to encourage (protein, dietary fiber, *n*-3 fatty acids, calcium, iron, iodine, magnesium, phosphorus, potassium, selenium, zinc, vitamin A, vitamin B6, folate, thiamine, riboflavin, niacin, vitamin B12, vitamin C, vitamin D, vitamin E) and three nutrients to limit (sodium, saturated fat, added sugars). Content of *n*-3 fatty acids was assessed as the sum of available data for alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), even when one or two of them were missing.

Here, NRF21.3 was calculated using portion size as reference amount to reflect differences in the dietary role between compared foods. Capping was applied when nutrients exceeded DRI per portion size (for details on capped nutrients, please refer to Supplementary material Figure S1). Briefly, capping is used to avoid over-crediting nutrient contents that exceed their DRIs by rounding off their nutrient content per reference unit to 100% of DRI. Although earlier research suggests that capping might not be necessary when comparing the nutritional quality of foods across food groups,-[26] the use of capping may be justified in cases where one or few nutrients are largely exceeding the DRI, as is the case for e.g., iodine in *S. latissima* and the targeted *Ulva* species. However, both capping and the number as well as choice of nutrients may affect the nutrient density, therefore we conducted a sensitivity analysis including NRF21.3 without capping and a second variant of the index (NRF11.3 based on 11 nutrients to encourage) (Supplementary material Table S2). The NRF11.3 index has been suggested as useful, in particular, when comparing foods across different food groups.[26]

Assessment of toxicological risk

The potential toxicological risks of heavy metals, vitamins, and minerals were assessed as percentage contribution of the content in one portion (5 g DW) relative to the tolerable daily intake (%TDI). Tolerable daily intake for heavy metals was defined as either one-seventh of the tolerable weekly intake (TWI) or, when TWI was not available, as the benchmark dose lower confidence limits (BMDL), as defined by EFSA.[27–30] TWI estimates the amount per unit body weight of a potentially harmful substance that can be ingested weekly over a lifetime without risk of adverse health effects. BMDL is presented whenever a tolerable intake cannot be determined and represents the minimum dose that gives a clear, low-level health risk, usually in the range of 1–10% of a particular adverse health effect. If different BMDLs were available for a specific substance, e.g., one for adults and one for children, the lowest level was used. The contents of minerals and vitamins per portion (5 g DW) of seaweed were assessed against the daily upper limits (UL) as defined by NNR[22] when such a limit is defined. The TWI, BMDL, and UL for heavy metals and nutrients are specified in the Supplementary material (Table S3).

Reference foods

Depending on species, seaweed could be seen as a carbohydrate, a protein, salad, or spice alternative on the plate. Until the dietary role of different seaweed species is more clearly defined, it is useful to compare their nutritional performance to different food categories. The %DRI and nutrient density of one portion (5 g DW) of seaweeds were compared to selected reference foods within four different food groups: herbs (basil, dill, parsley, and chives), salad components (lettuce, kale, broccoli, spinach), legumes (chickpeas, peas, red beans, and soybeans) and fish/shellfish (herring, salmon, cod, and oysters). Nutrient content of the reference foods was obtained from the Swedish Food Composition database[31](Supplementary material, Table S4a-c). Portion sizes were retrieved from the software Dietist NetPro (version 20,230,111). Comparisons of %DRI per portion of seaweed and reference foods were reported for nutrients that contributed to at least 15% of DRI per 5 g DW (mean or median) of *S. latissima* and/or *Ulva* all.

Results

Search results

In total, 245 articles were assessed in full text, whereof 114 articles were included in this review (Figure 1, Table 1).[9,32–142] Of these 114 articles, 45 contained data for *S. latissima* and 82 contained data for *Ulva* species (*U. fenestrata* $n = 35$; *U. intestinalis* $n = 23$, *U. rigida* $n = 30$ and/or *Ulva* spp. $n = 6$) (i.e., some articles contained data for more than one species). The majority ($n = 105$) of the included studies contained information on nutrient content of one or several of the selected seaweed species, while fewer studies ($n = 37$) contained information on heavy metals and only two studies provided information on bioavailability aspects (Table 1). For *S. latissima*, almost all data reported were for samples harvested in Europe ($n = 44$), except for two studies in North America. Studies on *Ulva* species reported data from harvest sites in Europe ($n = 34$), Asia ($n = 20$), Africa ($n = 7$), and South America ($n = 3$). Included studies represent samples harvested from January to December. Excluded studies and reasons for exclusion are listed in the Supplementary material (Table S5).

Nutrient content and nutritional performance of S. latissima and Ulva species

Nutrient content: Content of energy, macronutrients, minerals, and trace elements per 100 g DW of *S. latissima* and *Ulva* species is presented in Table 2. Comparing the mean macronutrient content of *S. latissima* and *Ulva* all showed that *S. latissima* was higher in EPA and DHA while it was lower in protein, saturated fatty acids and ALA. The mean content of total carbohydrate, fiber, and fat were within similar ranges for *S. latissima* and *Ulva* all. Eight studies reported soluble fibers separately, indicating that soluble fiber varies between 30% and 70% of the total fiber content in *S. latissima*[70,92,115] and between 20% and 60% of total fiber in *Ulva* species[41,70,92,100,115,134] (data not shown).

Regarding minerals and trace elements, the mean content of calcium, iodine, phosphorus, and potassium was higher in *S. latissima*, while this species was lower in iron, magnesium, and selenium, compared to *Ulva* all (Table 2). For some minerals and trace elements, the content varied substantially

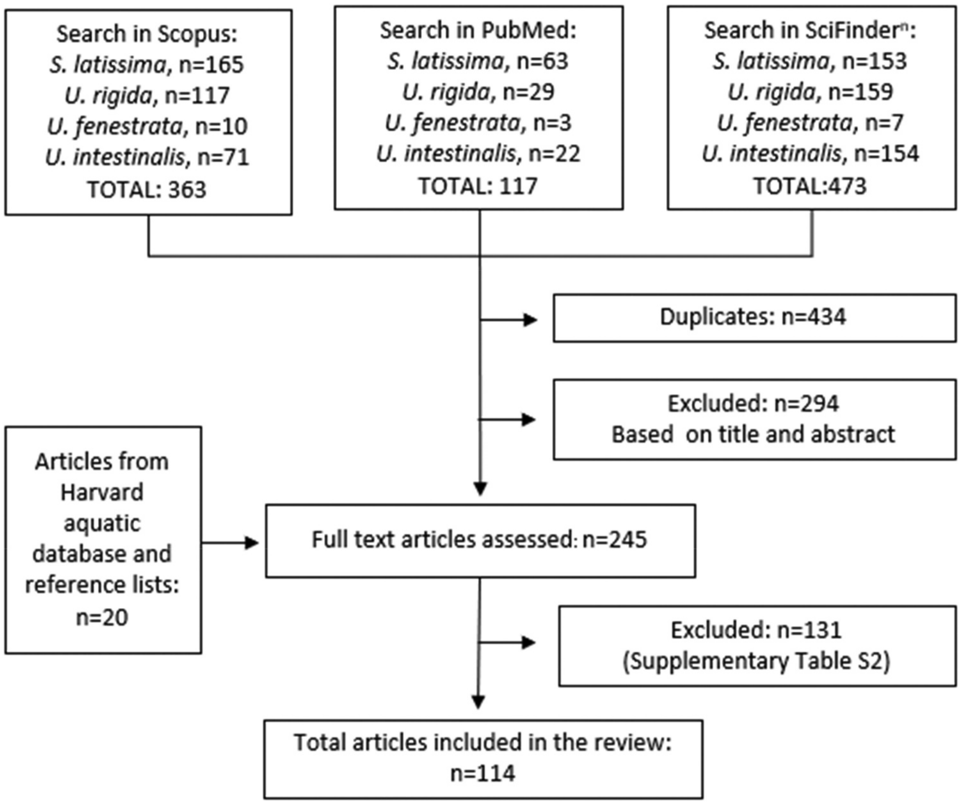

Figure 1. Flow chart for the literature search and selection of articles.

between different *Ulva* species. For example, *U. intestinalis* had a higher mean content of iodine, iron, and potassium, while *U. rigida* had a higher mean content of selenium, compared to the other *Ulva* species. Discrepancies between mean and median values were found for some nutrients; e.g., median content of iron was lower compared to mean content in *S. latissima*, *U. intestinalis*, and *U. fenestrata* while median content of selenium and zinc was substantially higher compared to mean content in *U. intestinalis*.

Based on data from the CEVA food composition database[11,19] *S. latissima* was lower in vitamin A, riboflavin, niacin, vitamin B6, B12, and C, compared to *Ulva* spp., the difference being most pronounced for vitamin B12 (Table 3). Only vitamin E and folate were higher in *S. latissima* compared to *Ulva* spp. The content of vitamin D and thiamine was similar in *S. latissima* and *Ulva* spp.

Nutrition quality in relation to recommended intake: Percentage contribution to DRI for energy, macronutrients, minerals, and trace elements per portion (5 g DW) of *S. latissima* and *Ulva* species is presented in Table 4. For most macronutrients, the mean %DRI per portion was lower than 1%, for *S. latissima* and the targeted *Ulva* species (Table 4). Only for fiber, the mean %DRI reached higher levels, varying between 3% and 6% per portion. Among minerals and trace elements, iodine stands out with the highest mean %DRI per portion (12600% for *S. latissima and* 279% for *Ulva* all), followed by iron (23% for *S. latissima* and 67% for *Ulva* all). In addition, calcium, magnesium, and selenium exceeded 15% of DRI, for at least one seaweed species (mean or median) (Table 4). Among the vitamins, only vitamin B12 exceeded 15% of DRI, in at least one of the seaweeds (7% in *S. latissima* and 34% in *Ulva* spp) (Table 3).

Nutrition quality in relation to reference foods: Comparison of the %DRI of those nutrients exceeding 15% (mean or median) per portion of *S. latissima* and/or *Ulva* all to content in reference foods is illustrated in Figure 2. Mean %DRI contribution from the seaweeds was commonly higher compared to reference foods. However, legumes showed a higher contribution of calcium compared to

Table 1. Overview of included articles ($n = 114$).

	Saccharina latissima		*Ulva*			Type of data retrieved for the review		
Author (Year)	Harvest site	Harvest time	Specie	Harvest site	Harvest time	Nutrient content	Heavy metal content	Bioavailability aspects
Abdollahi et al.[32]	Sweden	May 2016	-	-	-	x	-	-
Afonso et al.[33]	-	–	*intestinalis fenestrata*	Portugal	July	x	x	-
Afonso et al.[34]	Norway	Mar 2017	-	-	-	x	x	-
Akalya et al.[35]	-	–	*intestinalis*	India	Dec 2019	-	x	-
Akköz et al.[36]	-	–	*intestinalis*	Turkey	n.d.	x	x	-
Bak et al.[37]	Faraoe Island	Jun, Jul, Aug, Oct 2015; Jan, Mar, Apr 2016	-	-	-	x	-	-
Barbosa et al.[38]	Portugal	May 2012; Apr, July, Sep, Oct, Dec 2013	-	-	-	x	-	-
Batista et al.[39]	-	–	*rigida*	Portugal	n.d.	x	-	-
Beacham et al.[40]	Great Britain	May 2017	*fenestrata*	Great Britain	May 2017	x	-	-
Benjama and Masniyom[41]	-	–	*intestinalis*	Thailand	Dec 2007, Apr 2008	x	-	-
Berik and Çankiriligil[42]	-	–	*fenestrata*	Turkey	Feb 2011-Feb 2012	x	-	-
Biancarosa et al.[43]	Norway	Oct 2014	*intestinalis fenestrata*	Norway	Oct 2014	x	-	-
Bikker et al.[44]	France, Scotland	Aug, Sep 2013	*fenestrata*	Ireland, France, Scotland	May 2013	x	-	-
Blikra et al.[45]	Norway	Jun 2020	-	-	-	x	x	-
Bogolitsyn et al.[46]	Russia	Jun-Jul 2012	-	-	-	x	-	-
Cabrita et al.[47]	Portugal	2013	*spp.1*	Portugal	Jul 2005	x	x	-
Cañedo-Castro et al.[48]	-	–	*rigida*	Mexico	n.d.	x	-	-
Chirapart et al.[4]9]	-	–	*intestinalis*	Thailand	n.d.	x	-	-
Correia et al.[49]	Norway	n.d.	-	-	-	x	x	-
Costa et al.[50]	-	–	*intestinalis fenestrata*	Portugal	Jan, Feb 2019	x	-	-
Dammak Walha et al.[51]	-	–	*rigida*	Tunisia	Mar 2015-Feb 2016	x	x	-
Díaz et al.[52]	-	–	*rigida*	Chile	2003–2004	-	x	-
Diop et al.[53]	-	–	*fenestrata*	Senegal	Jan, Aug 2013	x	x	-
El-Said[54]	-	–	*fenestrata*	Egypt	March 2011	x	x	-
Escobido et al.[55]	-	–	*intestinalis*	n.d.	Jan-Apr 2016	x	-	-

(*Continued*)

Table 1. (Continued).

	Saccharina latissima		*Ulva*			Type of data retrieved for the review		
Author (Year)	Harvest site	Harvest time	Specie	Harvest site	Harvest time	Nutrient content	Heavy metal content	Bioavailability aspects
Ferreira et al.[56]	-	–	*rigida*	Portugal	n.d.	x	-	-
Flores et al.[57]	-	–	*fenestrata*	n.d.	n.d.	-	-	x
Frikha et al.[58]	-	–	*rigida*	Tunisia	May (year not reported)	x	-	-
Gaillard et al.[59]	Norway	Autumn 2014–2015; Spring 2015	-	-	-	x	-	-
Gao et al.[60]	-	–	*rigida*	UK	Aug 2013	x	-	-
García-Sartal et al.[61]	-	–	*rigida*	Spain	n.d.	-	x	-
García-Sartal et al.[62]	-	–	*rigida*	n.d.	n.d.	x	x	-
Ghanemi et al.[63]	-	–	*intestinalis*	Persian Gulf	n.d.	x	-	-
Harrysson et al.[64]	-	–	*fenestrata*	Sweden	n.d.	x	-	-
Hossain et al.[65]	-	–	*intestinalis*	Bangladesh	March 2018	x	-	-
Ismail et al.[66]	-	–	*fenestrata*	Egypt	Oct 2016	x	x	-
Jannat-Alipour et al.[67]	-	–	*intestinalis*	Iran	n.d.	x	x	-
Jara-Marini et al.[68]	-	–	*intestinalis* *fenestrata*	Mexico	Aug 2011, Feb, May, Oct 2012	x	x	-
Jard et al.[69]	France	Jul 2010	-	–	-	x	-	-
Jard et al.[70]	France	Jul 2010	*fenestrata*	France	Jul 2010	x	-	-
Jayasinghe et al.[71]	-	–	*fenestrata*	Sri Lanka	Jul-Dec 2016	x	x	-
Kisten et al.[72]			*rigida*	South Africa	Jun, Jul 2014	x	x	-
Kreissig et al.[73]	Greenland	Jun-Sep 2017 and 2018	-	–	-	x	x	-
Krogdahl et al.[74]	Norway	n.d.	-	–	-	x	-	-
Kumar et al.[75]	-	–	*rigida*	India	Jan-Apr, 2009	x	-	-
Kumar et al.[76]	-	–	*rigida*	India	Sep 2018	x	-	-
Leri et al.[77]	Scotland	n.d.	-	–	-	x	-	-
Machado et al.[78]	-	–	*rigida*	Portugal	n.d.	x	-	-
Maehre et al.[79]	-	–	*intestinalis* *fenestrata*	Norway	May-Jun 2010 May-Jun 2012	x	x	-
Maia et al.[80]	Portugal	2013	*spp. 1*	Portugal	2013	x	-	-
Maia et al.[81]	Portugal	n.d.	-	–	-	x	-	-
Manns et al.[82]	Denmark	Feb, Jul 2013	-	–	-	x	-	-

(*Continued*)

Table 1. (Continued).

	Saccharina latissima		*Ulva*			Type of data retrieved for the review		
Author (Year)	Harvest site	Harvest time	Specie	Harvest site	Harvest time	Nutrient content	Heavy metal content	Bioavailability aspects
Milinovic et al.[83]	-	-	*rigida*	Portugal	Aug-Sep 2019	x	-	-
Monteiro et al.[84]	Norway, UK, France	Apr, May 2017	-	–	-	x	-	-
Monteiro et al.[85]	Norway	Apr, May, June 2018	-	–	-	x	-	-
Moreda-Piñeiro et al.[86]	-	–	*rigida*	Spain	n.d.	x	x	-
Moreda-Piñeiro et al.[87]	-	–	*rigida*	Spain	n.d.	x	-	-
Moreira et al.[88]	-	–	*spp.* *rigida*	France Portugal	May 2017 May 2017	x	-	-
Moutinho et al.[89]	-	–	*rigida*	n.d.	n.d.	x	-	-
Mwalugha et al.[90]	-	–	*fenestrata*	Kenya	Jun-Oct 2013	x	-	-
Negreanu-Pîrjol et al.[91]	-	–	*spp. 1*	Romania	Jan-Apr 2010	x	-	-
Neto et al.[92]	France	Apr 2015	*rigida*	Portugal	Jan 2016	x	-	-
Nielsen et al.[93]	Denmark	Aug 2012	-	–	-	x	-	-
Nielsen et al.[94]	Norway	Apr 2018	-	-	-	x	-	-
Nitschke and Stengel[95]	-	–	*intestinalis*	Ireland	Aug 2014	x	-	-
Nunes et al.[96]	-	–	*fenestrata*	Portugal	n.d.	x	-	-
Olsson et al.[97]	Sweden	Aug 2014	*intestinalis* *fenestrata*	Sweden	July 2014	x	x	-
Oucif et al.[98]	-	–	*fenestrata*	Algeria	May 2016	x	x	-
Paiva et al.[99]	-	–	*rigida*	Portugal	Apr 2013	x	-	-
Paiva et al.[100]			*rigida*	Portugal	Apr 2013	x	-	-
Paul and Sheeba[101]	-	–	*rigida*	India	Jan 2014	x	-	-
Peasura et al.[102]	-	–	*intestinalis*	Thailand	July 2010	x	-	-
Pétursdóttir and Gunnlaugsdóttir[103]	Iceland	*2012*	-	-	-	-	x	-
Pirian et al.[104]	-	–	*fenestrata*	Iran	Feb-Mar 2015	x	-	-
Queirós et al.[105]	-	–	*rigida*	Portugal	Aug 2016 – June 2017	x	-	-
Raab et al.[106]	UK	n.d.	-	-	-	-	x	-
Ramin et al.[107]	Norway	n.d.	-	-	-	x	-	-
Rasyid[108]	-	–	*fenestrata*	Indonesia	n.d.	x	x	-

(*Continued*)

Table 1. (Continued).

	Saccharina latissima		*Ulva*			Type of data retrieved for the review		
Author (Year)	Harvest site	Harvest time	Specie	Harvest site	Harvest time	Nutrient content	Heavy metal content	Bioavailability aspects
Reka et al.[109]	-	–	*fenestrata*	India	Oct-Jan	x	-	-
Ripol et al.[110]	-	–	*intestinalis fenestrata*	Portugal	July	x	-	-
Rohani-Ghadikolaei et al.[111]	-	–	*intestinalis fenestrata*	Iran	n.d.	x	-	-
Roleda et al.[112]	France, Norway	2015–2016	-	-	-	x	-	-
Roleda et al.[113]	France, Norway	2015–2016	-	-	-	x	x	-
Samarasinghe et al.[114]	Denmark	May 2018	*fenestrata;*	Denmark	2018	x	-	-
Samarasinghe et al.[115]	Denmark	May 2018	*spp. 1*	Denmark	Jun 2018	x	x	-
Sá Monteiro et al.[9]	Denmark	n.d.	*fenestrata*	Denmark	n.d.	x	x	-
Sappati et al.[116]	USA	May, Jun 2017	-	-	-	x	-	-
Schiener et al.[117]	Scotland	Aug, Oct 2010; Feb, Mar, May, July, Sep, Oct 2011	-	-	-	x	x	-
Schiener et al.[118]	Great Britain	Nov 2014	-	-	-	x	x	-
Sharma et al.[119]	Norway	Jul 2015; May, Jun, Aug 2015	-	-	-	x	x	-
Shuuluka et al.[120]	-	-	*rigida; fenestrata*	South Africa	Jan 2008-May 2009	x	-	-
Stévant et al.[121]	France	May 2016	-	-	-	x	-	-
Stévant et al.[122]	France	May, Jun 2015	-	-	-	x	-	-
Stévant et al.[123]	Norway	May 2016	-	-	-	x	x	-
Susanto et al.[124]	-	-	*intestinalis*	Japan	Jun 2017	x	-	-
Tabarsa et al.[125]	-	–	*fenestrata*	Iran	Apr 2008	x	-	-
Taboada et al.[126]	-	–	*rigida*	Spain	n.d.	x	-	-
Taylor and Jackson[127]	-	–	*intestinalis*	Lithuania	Autumn 2020		x	-
Thodhal Yoganandham et al.[128]	-	–	*fenestrata*	India	n.d.	x	-	-
Tibbetts et al.[129]	Canada	Apr 2010	-	-	-	x	-	-
Tolpeznikaite et al.[130]	-	–	*intestinalis*	Lithuania	Autumn 2020	x	x	-
Trigo et al.[131]	-	–	*fenestrata*	n.d.	n.d.	-	-	x

(*Continued*)

Table 1. (Continued).

	Saccharina latissima		*Ulva*			Type of data retrieved for the review		
Author (Year)	Harvest site	Harvest time	Specie	Harvest site	Harvest time	Nutrient content	Heavy metal content	Bioavailability aspects
Turan and Tekogul[132]	-	–	*rigida*	Turkey	Aug 2010	x	-	-
Turan et al.[133]	-	-	*fenestrata*	Turkey	Apr-Jun 2013	x	-	-
Uribe et al.[134]	-	-	*spp. 1*	Chile	Apr 2017	x	-	-
Verma et al.[135]	-	–	*fenestrata*	India	n.d.	x	-	-
Viera et al.[136]	-	–	*rigida*	Gran Canaria	n.d.	x	-	-
Viera et al.[137]			*fenestrata*	UK	n.d.	x	-	-
Vilg et al.[138]	Sweden	Jun, Aug, Oct 2012	-	-	-	x	-	-
Wan et al.[139]			*rigida*	Ireland	Aug 2010	x	-	-
Yıldız and Dere[140]			*rigida*	Turkey	Jun 2009	x	-	-
Zeroual et al.[141]	-	–	*rigida intestinalis*	Morocco	n.d.	x	x	-

n.d = no data
[1]Data reported for unknown *Ulva* species.

Table 2. Content of energy, macronutrients, minerals and trace elements for dried unprocessed *S. latissima and Ulva* species per 100 g dry weight. Data presented as mean//median (min-max).[1]

	S. latissima	n	*U. rigida*	n	*U. intestinalis*	n	*U. fenestrata*	n	*Ulva spp.*	n	*Ulva* all[3]	n
Energy (kcal)	290 // 307 (198–365)	5	237 // 221 (167–350)	5	263	1	n.d	n.d.	250	1	242 // 250 (167–350)	7
Macronutrients												
Protein (g)[4]	7.85 // 7.60 (1.10–21.4)	103	15.2 // 15.8 (4.60–27.1)	17	14.4 // 12.6 (5.57–34.4)	13	14.3 // 16.6 (5.45–31.6)	27	14.3 // 15.9 (2.47–20.2)	9	14.5 // 14.2 (2.47–34.4)	66
Carbohydrate (g)[4]	50.8 // 52.6 (20.0–76.0)	56	44.2 // 46.0 (16.7–58.1)	10	45.1 // 44.8 (35.5–57.0)	8	55.0 // 57.4 (34.7–71.8)	9	61.8 // 61.8 (55.0–68.6)	2	49.0 // 49.4 (16.7–71.8)	29
Fiber (g)[4]	24.8 // 30.5 (6.20–40.9)	6	27.0 // 34.7 (2.65–47.3)	11	34.1 // 34.2 (5.87–62.2)	4	19.0 // 13.3 (5.60–54.0)	9	36.7 // 43.4 (17.9–47.2)	6	27.5 // 25.0 (2.65–62.2)	30
Fat (g)[4]	1.65 // 1.70 (0.40–5.50)	34	1.85 // 1.20 (0.80–5.39)	13	3.25 // 2.81 (0.43–8.70)	10	1.77 // 1.57 (0.19–3.60)	22	2.35 // 2.67 (0.69–3.84)	8	2.16 // 1.63 (0.19–8.70)	53
Saturated fatty acids (g)	0.16 // 0.10 (0.06–0.55)	12	1.29 // 1.53 (0.076–1.92)	6	0.10	1	0.28 // 0.32 (0.12–0.37)	4	3.42 // .23 (0.18–9.84)	3	1.37 // 0.35 (0.08–9.84)	14
ALA (mg)	14.3 // 7.91 (0.9–49.0)	16	19.1 // 20.8 (12.2–26.2)	5	97.0	1	211 // 240 (78.0–287)	4	46.1 // 46.1 (20.9–71.3)	2	94.2 // 48.8 (12.2–287)	12
EPA (mg)	17.7 // 13.3 (2.81–69.4)	24	3.74 // 3.35 (2.40–5.88)	4	5.00	1	21.5 // 24.0 (10.0–28.0)	4	6.75 // 6.75 (6.60–9.91)	2	10.9 // 6.60 (2.40–28.0)	11
DHA (mg)	5.45 // 1.60 (1.04–23.8)	12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.51 // 1.51 (1.32–1.70)	2	1.51 // 1.51 (1.32–1.70)	2

(*Continued*)

Table 2. (Continued).

	S. latissima	n	*U. rigida*	n	*U. intestinalis*	n	*U. fenestrata*	n	*Ulva spp.*	n	*Ulva* all[3]	n
Minerals and trace elements												
Calcium (g)	2.86 // 1.74 (0.790–10.9)	16	1.21 // 0.55 (0.01–4.93)	10	1.11 // 0.84 (0.00–2.90)	9	1.22 // 1.27 (0.16–2.78)	13	.75 // 1.18 (0.66–2.15)	3	1.19 // 1.00 (0.00–4.93)	35
Copper (mg)	0.46 // 0.23 (0.110–3.86)	24	1.79 // 2.00 (0.14–3.97)	16	1.17 // 0.82 (0.02–5.81)	16	1.53 // 0.31 (0.05–14.7)	25	1.17 // .78 (0.34–2.41)	3	1.48 // 0.67 (0.02–14.7)	60
Iodine (mg)	379 // 360 (3.90–906)	36	n.d.	n.d.	12.4 // 10.9 (4.51–13.0)	6	3.20 // 4.92 (1.90–11.4)	4	7.98 // 4.71 (2.33–16.9)	3	8.37 // 9.90 (1.90–16.9)	13
Iron (mg)	54.7 // 14.2 (1.60–344)	24	75.9 // 73.8 (30.0–187)	16	455 // 108 (8.90–2800)	10	47.3 // 21.0 (4.04–199)	21	441 // 508 (13.9–802)	3	162 // 54.7 (4.04–2800)	50
Magnesium (g)	0.67 // 0.70 (0.46–0.97)	15	2.73 // 3.35 (0.00–8.69)	10	1.48 // 1.50 (0.03–4.12)	9	1.04 // 1.44 (0.08–3.05)	12	1.85 // 1.95 (1.48–2.11)	3	1.87 // 1.68 (0.00–8.69)	34
Phosphorus (mg)	277 // 245 (144–490)	26	101 (44.0–158)	2	163 // 203 (100–456)	6	66.7 // 75.1 (0.00–220)	6	239 // 230 (128–360)	3	152 // 128 (0.00–456)	17
Potassium (g)	6.29 // 6.24 (1.50–10.3)	23	1.70 // 1.35 (0.027–4.71)	8	1.60 // 1.47 (0.03–3.90)	9	1.38 // 0.72 (0.03–4.26)	15	1.85 // 1.85 (1.79–1.91)	2	1.54 // 1.17 (0.03–4.71)	34
Selenium (µg)	228 // 125 (6.00–1150)	12	318 // 300 (80.0–553)	10	26.0 // 531 (0.20–2550)	5	13.6 // 14.0 (4.90–19.0)	5	935 // 1110 (195–1500)	3	379 // 230 (0.20–2550)	23
Sodium (g)	4.00 // 4.08 (0.97–6.47)	22	1.80 // 1.60 (0.43–4.10)	7	1.44 // 0.77 (0.01–7.30)	8	1.05 // 0.61 (0.00–5.20)	14	4.10 // 4.10 (3.24–4.95)	2	1.52 // 0.70 (0.00–7.30)	31
Zinc (mg)	3.44 // 3.09 (0.80–7.37)	25	1.72 // 2.32 (0.00–7.00)	23	2.12 // 10.5 (0.60–82.2)	14	1.49 // 2.05 (0.44–8.20)	23	3.22 // 2.32 (1.62–5.73)	3	4.05 // 1.77 (0.00–82.2)	63

n.d. = no data

[1]Data retrieved from scientific literature. *n* = number of datapoints (some original articles provided more than one datapoint).

[2]Data for *Ulva* spp. represents data reported for unknown *Ulva* species.

[3]Data for "*Ulva* all" represents merged data reported for *U. rigida*, *U. fenestrata*, *U. intestinalis* and *Ulva* spp.

[4]Data as reported in original studies, regardless of method of determination. Data on crude protein content was included regardless of the nitrogen-to-protein conversion factor used. Only when nitrogen content was reported, a conversion factor of 5.0 was used to convert it to crude protein, as suggested by Angell et al.[21] Carbohydrates may or may not include indigestible carbohydrates (fiber).

Table 3. Content per 100 g DW and percentage contribution to daily reference intake (%DRI) per portion (5 g DW) of vitamins for dried unprocessed *S. latissima* and *Ulva* spp. Data presented as mean (min-max).[1]

	Content per 100 g DW				%DRI per portion (5 g DW)	
	S. latissima	n	*Ulva* spp.[2]	n	*S. latissima*	*Ulva* spp.[2]
Vitamin A (µg)	50	1	180 (160–190)	2	0.31	1.13 (1.00–1.19)
Vitamin D3 (µg)	1.3	1	1.29 (0.62–1.90)	6	0.65 (0.55–0.65)	0.65 (0.31–0.95)
Vitamin E (mg)	4.3 (0.5–11)	9	2.46 (0.30–10.4)	14	2.39 (0.28–6.28)	1.37 (0.17–5.77)
Thiamine (mg)	0.1 (0.0–0.4)	8	0.1 (0.0–0.4)	16	0.40 (0.00–1.60)	0.40 (0.00–1.60)
Riboflavin (mg)	0.1 (0.0–0.3)	8	0.2 (0.0–0.5)	11	0.37 (0.00–1.11)	0.74 (0.00–1.85)
Niacin (mg)	2.1 (1.2–3.2)	7	5.8 (1.1–11)	10	0.66 (0.38–1.00)	1.81 (0.34–3.31)
Vitamin B6 (mg)	0.2 (0.1–0.2)	6	0.3 (0.2–0.4)	4	0.74 (0.37–0.74)	1.11 (0.74–1.48)
Folate (µg)	164 (32.6–277)	7	102 (8.8–280)	9	2.34 (0.47–3.96)	1.46 (0.13–4.00)
Vitamin B12 (µg)	2.6 (0.0–6.9)	7	13.6 (1.1–74.6)	7	6.50 (0.00–17.3)	34.0 (2.75–187)
Vitamin C (mg)	31.6 (0.0–128)	19	68.9 (0.0–264)	35	2.11 (0.00–8.51)	4.59 (0.00–17.8)

[1]Data retrieved from food composition database published by Centre for the Study and Valorization of Algae (CEVA).[11,19]
[2]Data for *Ulva* spp. represents data reported for unknown *Ulva* species.

Ulva all, as well as higher contribution of magnesium and iron compared to *S. latissima*. In addition, fish/shellfish showed higher contribution of selenium and vitamin B12 per portion, compared to both *S. latissima* and *Ulva* all.

Nutrient density, assessed as NRF21.3 per portion with capping, was higher for *Ulva* all compared to *S. latissima* (Figure 3). Both *S. latissima* and *Ulva* all had a higher nutrient density than herbs and salad components and a lower nutrient density compared to fish/shellfish and legumes. More detailed information on the contribution of different nutrients to NRF21.3 per portion with capping (Table S6) and the relative ranking of the seaweeds and individual reference food items, when applying different versions of the NRF index (capped *vs* uncapped, NRF21.3 *vs* NRF11.3) (Figure S1), are provided in the Supplementary material. When uncapped values were used instead of capped values, *S. latissima* ranked substantially higher than *Ulva* all and all reference foods, explained by the very high iodine content of *S. latissima*. Applying NRF11.3 per portion with capping (instead of NRF21.3) did not change the overall pattern, compared to Figure 3.

Content of heavy metals and toxicological risk assessment

Content of heavy metals per 100 g DW of *S. latissima* and *Ulva* species is presented in Table 5. *S. latissima* had a higher mean content of total arsenic than *Ulva* all, while the opposite was found for inorganic arsenic. However, only few data points were identified for inorganic arsenic in the targeted *Ulva* species, with large variation. *Ulva* all was also higher in lead and mercury. None of the included studies reported inorganic mercury (iHg) or methylmercury (MeHg), the two forms of mercury that can lead to adverse health effects.[30] For cadmium, the mean content was slightly higher in *S. latissima* than in *Ulva* all. Comparing mean and median content of heavy metals showed large discrepancies for cadmium and lead in all species except *Ulva* spp, and for mercury in *U. fenestrata*.

Table 4. Percentage contribution to daily reference intake (%DRI) for energy, macronutrients, minerals, and trace elements from dried unprocessed *S. latissima*, and *Ulva* species, per portion (5 g dry weight). Data is presented as mean//median (min-max).[1.]

	S. latissima	*U. rigida*	*U. intestinalis*	*U. fenestrata*	*Ulva* spp.[2]	*Ulva* all[3]
Energy	0.64 // 0.68 (0.44–0.81)	0.53 // 0.49 (0.37–0.78)	0.58	n.d.	.55	0.51 // 0.53 (0.35–0.74)
Macronutrients						
Protein	0.45 // 0.44 (0.06–1.22)	0.87 // 0.90 (0.26–1.55)	0.82 // /0.72 (0.32–1.97)	0.82 // 0.78 (0.31–1.81)	(0.14–1.16)	0.83 // 0.81 (0.14–1.97)
Carbohydrate[4]	0.83 // 0.86 (0.33–1.24)	0.72 // 0.75 (0.27–0.95)	0.74 // 0.73 (0.58–0.93)	0.90 // 0.94 (0.57–1.17)	1.01 // 1.01 (0.90–1.12)	0.80 // 0.81 (0.27–1.17)
Fibre[5]	4.13 // 5.07 (1.03–6.82)	4.49 // 5.78 (0.44–7.98)	5.69 // 5.70 (0.98–10.4)	3.16 // 2.21 (0.93–9.01)	6.11 // 7.24 (2.98–7.86)	4.58 // 4.16 (0.44–10.4)
Fat	0.08 // 0.08 (0.02–0.27)	0.09 // 0.06 (0.04–0.27)	0.16 // 0.14 (0.02–0.43)	0.08 // 0.09 (0.01–0.18)	0.12 // 0.13 (0.03–0.19)	0.11 // 0.08 (0.01–0.43)
Saturated fatty acids	0.03 // 0.02 (0.01–0.110	0.24 // 0.29 (0.01–0.36)	0.02	0.05 // 0.06 (0.02–0.07)	.64 // .04 (0.03–1.84)	0.26 // 0.06 (0.01–1.84)
Omega-3 fatty acids[6]	0.08 // 0.06 (0.01–0.20)	0.04 // 0.04 (0.03–0.05)	0.19 // 0.19 (0.18–0.19)	0.44 // 0.50 (0.16–0.58)	.10 // .10 (0.05–0.15)	0.19 // 0.15 (0.03–0.58)

(*Continued*)

Table 4. (Continued).

	S. latissima	*U. rigida*	*U. intestinalis*	*U. fenestrata*	*Ulva* spp.[2]	*Ulva* all[3]
Minerals and trace elements						
Calcium	17.9 // 10.9 (4.94–68.3)	7.56 // 3.45 (0.03–30.8)	6.97 // 5.25 (0.01–18.1)	7.61 // 7.96 (0.98–17.4)	7.40 // 4.66\ (4.10–13.4)	7.42 // 6.26 (0.01–30.8)
Copper	2.64 // 1.25 (0.61–21.4)	9.94 // 11.1 (0.75–20.1)	6.48 // 4.53 (0.11–32.3)	8.48 // 1.74 (0.29–81.6)	6.52 // 4.31 (1.86–13.4)	8.24 // 3.73 (0.11–81.6)
Iodine	12600 // 12000 (130–30190)	n.d.	361 // 412 (150–433)	164 // 107 (63.2–380)	266 // 157 (77.0–563)	279 // 330 (63.2–563)
Iron	22.8 // 5.92 (0.67–143)	31.6 // 30.7 (12.4–77.8)	190 // 45.1 (3.71–117)	19.7 // 8.75 (1.69–83.1)	184 // 212 (5.79–334)	67.4 // 22.1 (1.69–1164)
Magnesium	10.7 // 11.1 (7.30–15.4)	37.4 // 43.4 (0.05–138)	23.5 // 23.8 (0.41–65.3)	22.9 // 16.5 (1.26–48.4)	29.3 // 31.0 (23.5–33.5)	29.7 // 26.6 (0.05–138)
Phosphorus	2.31 // 2.04 (1.20–4.08)	0.84 // 0.84 (0.37–1.32)	1.69 // 1.36 (0.83–3.80)	0.63 // 0.56 (0.00–1.83)	1.99 // 1.92 (1.07–3.00)	1.27 // 1.07 (0.00–3.80)
Potassium	9.53 // 9.45 (2.27–16.7)	2.58 // 2.04 (0.04–7.14)	2.42 // 2.23 (0.05–5.91)	2.09 // 1.09 (0.04–6.45)	2.80 // 2.80 (2.71–2.89)	2.33 // 1.77 (0.04–7.14)
Selenium	20.7 // 11.4 (0.55–104)	28.9 // 27.2 (7.27–50.3)	48.3 // 2.36 (0.02–231)	1.23 // 1.27 (0.45–1.73)	85.0 // 101 (17.7–136)	34.4 // 20.9 (0.02–232)
Sodium	8.33 // 8.49 (2.02–13.5)	3.75 // 3.32 (0.83–8.54)	3.00 // 1.61 (0.03–15.2)	2.19 // 1.26 (0.00–10.8)	8.53 // 8.53 (6.75–10.3)	3.16 // 1.46 (0.00–15.2)
Zinc	2.15 // 1.93 (0.50–4.61)	1.39 // 1.08 (0.00–4.38)	6.56 // 1.33 (0.38–51.4)	1.28 // 0.93 (0.27–5.13)	2.01 // 1.45 (1.01–3.58)	2.53 // 1.11 (0.00–51.4)

n.d. = no data

[1]Refence values for daily intake presented in Supplementary material (Table S2). Number of datapoints similar as in Table 2.

[2]Data for *Ulva* spp. represents data reported for unknown *Ulva* species.

[3]Data for "*Ulva* all" represents merged data reported for *U. rigida*, *U. fenestrata*, *U. intestinalis*, and *Ulva* spp.

[4]%DRI for carbohydrates may be overestimated as carbohydrate content data may include indigestible carbohydrates (fiber), while DRI refers only to digestible carbohydrates.

[5]%DRI for fiber may be underestimated as some fiber content data only includes crude fiber.

[5]Calculated based on available data for alpha-linolenic acid (ALA, 18:3 *n*-3), eicosapentaenoic acid (EPA, 20:5 *n*-3) and docosahexaenoic acid (DHA,22:6 *n*-3). Data on DHA was missing for *U. rigida*, *U. intestinalis*, and *U. fenestrata*. For *U. rigida* one datapoints include only ALA, and one is reported as total omega 3-fatty acids without information on what fatty acids are included.

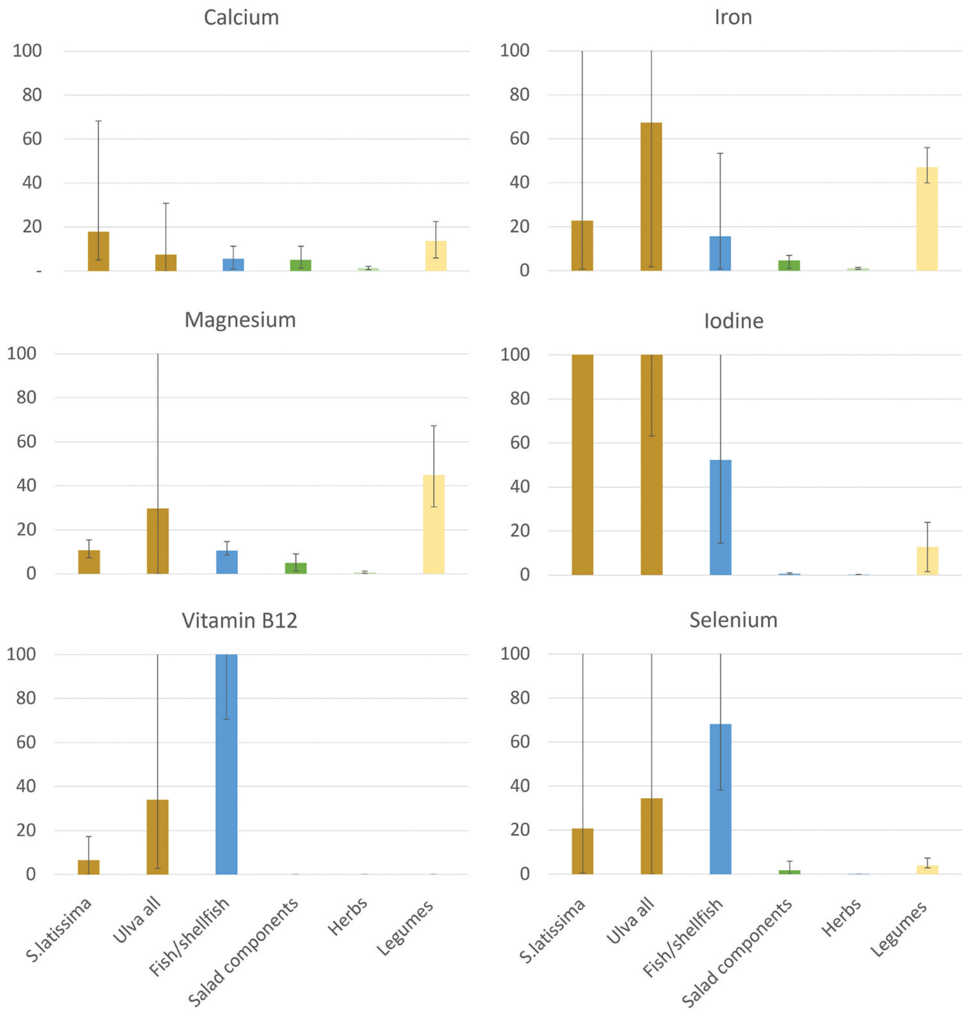

Figure 2. Percentage contribution to daily reference intakes (%DRI) (y-axis) of selected nutrients from one portion of seaweed and selected reference food groups. Portion size for seaweed is 5 g DW. Fish/shellfish includes raw salmon (125 g), herring (125 g), cod (125 g) and oysters (70 g). Salad components includes fresh broccoli (75 g), kale (70 g), lettuce (40 g) and spinach (30 g). Herbs includes fresh basil, chives, dill, parsley (all 5 g). Legumes includes dry red beans, chickpeas, peas and soya beans (all 80 g). Bars illustrates mean, the minimum and maximum values are illustrated by the black line for each bar.

The percentage contribution to daily tolerable intake (%TDI) of heavy metals and iodine from one portion (5 g DW) of seaweed is presented in Table 6. For heavy metals, the mean %TDI per portion generally varied between appr. 10–30%, except for lead in *U. intestinalis* reaching appr. 50% and inorganic arsenic in *Ulva* spp. reaching almost 100%. For iodine, the content in one portion of *S. latissima* exceeded the TDI more than 30 times (mean), while *Ulva* all contributed to appr. 70% of TDI, per portion.

Bioavailability

Only two studies investigating the bioavailability of nutrients or heavy metals in the targeted seaweed species were identified and included in this review. Flores et al.[57] used the Caco-2 cell model to assess iron bioavailability in *U. fenestrata* after *in vitro* gastrointestinal digestion. The relative fractional uptakes of iron were similar from *U. fenestrata* and spinach and was suggested to be lower than 7% for both.

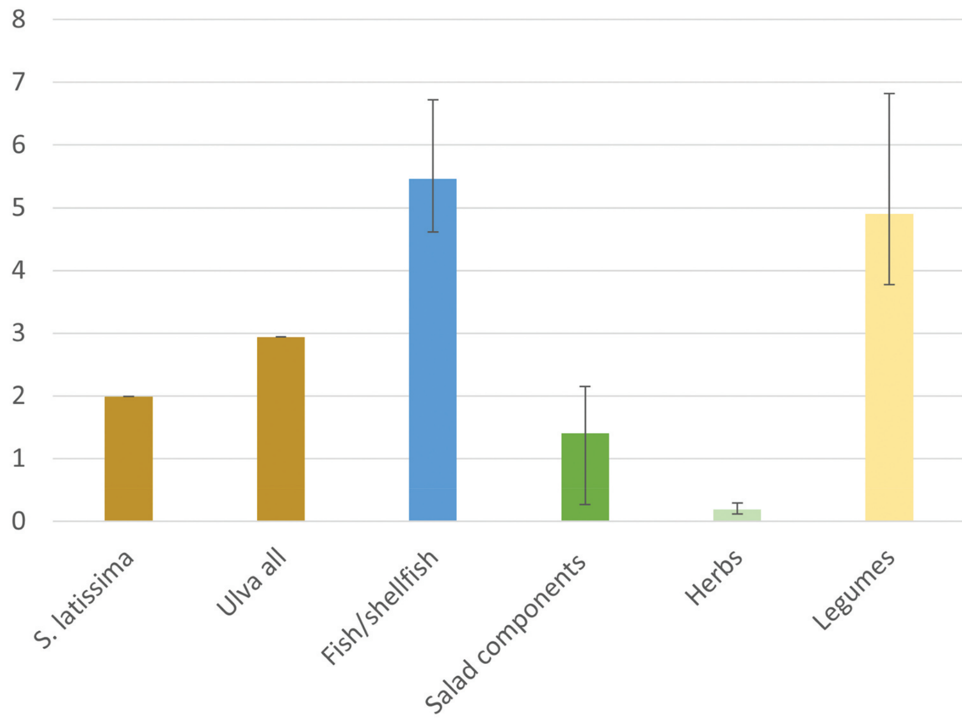

Figure 3. NRF21.3 per portion with capping for *S. latissima*, *Ulva* all and selected reference food groups. Portion sizes for seaweeds are 5 g DW. Fish/shellfish includes raw salmon (125 g), herring (125 g), cod (125 g) and oysters (70 g). Salad components includes fresh broccoli (75 g), kale (70 g), lettuce (40 g) and spinach (30 g). Herbs includes fresh basil, chives, dill, parsley (all 5 g). Bars illustrates mean, the minimum and maximum values are illustrated by the black line for each bar.

Addition of physiological levels of vitamin C increased the iron bioavailability of *U. fenestrata* more than three-fold, while addition of vitamin C did not enhance iron bioavailability of other seaweed species.[57]

The effect of vitamin C on iron bioavailability from spinach was not assessed by Flores et al.,[57] but a 2-fold enhancement has previously been reported.[143]

Trigo et al.[131] assessed protein digestibility and amino acid bioavailability of *U. fenestrata* and *S. latissima*, also using the Caco-2 cell model following *in vitro* gastrointestinal digestion. The protein digestibility of crude *U. fenestrata* was similar as for control casein, while the protein digestibility of *S. latissima* was statistically significantly lower compared to casein (17% *vs* 33%) and to *U. fenestrata* (28%). The amino acid bioavailability was similar between crude *S. latissima* (8.5%), crude *U. fenestrata* (7.3%) and casein (7.6%) with no statistical differences detected.

Discussion

Based on information retrieved from 114 scientific articles and the CEVA database, this review summarizes the content and bioavailability of nutrients and heavy metals in *S. latissima, U. fenestrata*, *U. intestinalis*, *U. rigida*, and *Ulva* spp. Overall, our findings show that one portion of *S. latissima* or *Ulva* species can provide nutritionally relevant contributions (>15% of DRI) to the intake of iron, selenium, calcium (*S. latissima*) and magnesium (*Ulva* species). *Ulva* species may also be a source of vitamin B12, even though it remains unknown if this vitamin in *Ulva* is biologically active in humans.[144] Further, it was observed that none of the seaweeds included in this study provide nutritionally meaningful amounts per portion of most other nutrients, including protein, fat, and fiber. An exception is iodine, for which the content raises toxicological concerns, especially for *S. latissima*, which can contribute to more than 30 times the UL of iodine, per portion. The content of inorganic arsenic, lead, and cadmium may also

Table 5. Content of heavy metals for dried unprocessed *S. latissima and Ulva* species per 100 g dry weight. Data is presented as mean//median (min-max).[1]

	S. latissima	n	*U. rigida*	n	*U. intestinalis*	n	*U. fenestrata*	n	*Ulva spp*[2]	n	*Ulva* all.[3]	n
Arsenic (µg)	5820 // 5710 (300–9250)	40	491 // 542 (310–568)	4	45 // 565 (44.0–660)	4	400 // 355 (9.00–790)	8	946 // 1080 (595–1160)	3	512 // 554 (9.00–1160)	19
Inorganic arsenic (µg)	34.5 // 30.3 (16.0–74.0)	13	40	1	n.d.	0	n.d.	0	448 // 448 (65.0–830)	2	312 // 65 (40.0–830)	3
Cadmium (µg)	106 // 86.0 (22.0–296)	19	81.8 // 40.1 (28.1–219)	4	77.2 // 34.0 (1.80–360)	11	109 // 34.0 (3.80–1360)	18	34.6 // 23.0 (16.0–64.7)	3	89.9 // 33.5 (1.80–1360)	36
Lead (µg)	86.6 // 34.3 (5.20–450)	26	181 // 90.0 (53.0–400)	3	353 // 91.0 (0.10–1890)	11	163 // 94.5 (7.80–1120)	12	229 // 269 (88.7–328)	3	244 // 93.0 (0.1–1890)	29
Mercury (µg)	3.80 // 2.65 (1.00–11.7)	8	n.d.	0	0.70 // 0.50 (0.20–1.40)	3	10.7 // 0.50 (0.00–52.0)	5	6.7	1	6.95 // 0.50 (0.00–52.0)	9

n.d. = no data
[1]Data from original articles. *n* = number of datapoints (some original articles provided more than one datapoint).
[2]Data for *Ulva* spp. represents data reported for unknown *Ulva* species.
[3]Data for "*Ulva* all" represents merged data reported for *U. rigida*, *U. fenestrata*, *U. intestinalis*, and unknown *Ulva* spp.

Table 6. Percentage contribution to tolerable daily intake (%TDI) of heavy metals and iodine for dried unprocessed *S. latissima and Ulva* species per portion (5 g dry weight). Data is presented as mean//median (min-max).[1]

	S. latissima	*U. rigida*	*U. intestinalis*	*U. fenestrata*	*Ulva* spp.[2]	*Ulva* all[3]
Inorganic arsenic	7.51 // 6.59 (3.48–16.1)	8.70	n.d.	n.d.	97.3 // 97.3 (14.3–180)	67.8 (8.70–180)
Cadmium	19.4 // 15.7 (4.00–54.1)	15.0 // 7.32 (5.13–40.0)	14.1 // 6.20 (0.33–65.7)	19.8 // 6.20 (0.69–248)	6.31 // 4.20 (2.92–11.8)	16.4 // 6.12 (0.33–249)
Lead	11.3 // 4.48 (0.68–58.8)	23.6 // 11.8 (6.92–52.2)	46.1 // 11.9 (0.01–246)	21.3 // 12.3 (1.02–146)	3.0 // 35.1 (11.6–42.8)	31.8 // 12.1 (0.01–246)
Iodine	3160 // 3000 (32.5–7550)	n.d.	90.5 // 103 (37.6–108)	41.0 // 26.7 (15.8–95.0)	66.5 // 39.3 (19.4–141)	69.7 // 82.5 (15.8–141)

n.d. = no data
[1]Refence values for daily tolerable intake presented in Supplementary material (Table S5). Number of datapoints similar as in Table 4.
[2]Data for *Ulva* spp. represents data reported for unknown *Ulva* species.
[3]Data for "*Ulva* all" represents merged data reported for *U. rigida*, *U. fenestrata*, *U. intestinalis*, and unknown *Ulva* spp.

constitute a risk for health if seaweeds, especially *Ulva* species, would be consumed frequently. The review showed that research on vitamin content and bioavailability of nutrients and toxic substances in *S. latissima* and the targeted *Ulva* species are very limited and thus represent important knowledge gaps.

Nutritional performance compared to reference foods

A crucial point in the assessment of the nutritional value of seaweed for human consumption is their role in the diet. However, little is known on how consumers in the European and Nordic countries will include seaweed in the diet, which complicates the selection of reference foods for nutritional comparisons. In this review, a selection of different reference food categories was included, to elucidate how the selected seaweed species, perform nutritionally, compared to foods that seaweed may replace or complement. Furthermore, comparisons were made using realistic portion sizes, since these varies between the selected reference foods. For seaweed, the suggested portion size by EFSA is 5 g DW,[9] corresponding to 30–40 g fresh weight, assuming an average DW percentage of 12.5 and 14.5 for *S. latissima* and *Ulva* species, respectively.[145] The suggested portion size for seaweed is lower compared to normal portions of protein-rich foods, such as fish/shellfish (70–125 g fresh weight) and legumes (80 g DW, corresponding to appr. 190 g fresh weight), and more comparable to salad components such as iceberg lettuce and spinach (35 g fresh weight). On the contrary, one portion of seaweed may be larger compared to one portion of herbs (5 g fresh weight).

In relation to the reference foods, *S. latissima* and the targeted *Ulva* species appear to have both nutritional strengths and limitations. For example, per portion, *S. latissima* may be a better source of calcium and the selected *Ulva* species may be a better source of iron, compared to all reference food groups. In addition, the *Ulva* species may be a better source of magnesium, compared to fish/shellfish, salad components, and herbs, and both *S. latissima* and *Ulva* species may be better sources of selenium and vitamin B12 compared to salad components, herbs, and legumes. However, the contribution of vitamin B12 and selenium from one portion of *S. latissima* and the selected *Ulva* species is <10% and ≤50%, respectively, of the contribution from one portion of fish/shellfish. For vitamin D, folate, and fiber, the included seaweeds are less interesting sources than fish/shellfish, salad components, and legumes, respectively, per portion. When applying a broader nutritional assessment, based on the nutrient density (assessed as NRF 21.3, capped) per portion, this study showed that the targeted seaweeds were ranked higher than herbs and salad components, but lower than legumes and fish/shellfish.

Toxicological concerns and legal regulations

This study shows that toxicological concerns related to the use of seaweed as food may be raised due to the content of iodine, inorganic arsenic, lead, and cadmium, although it is highly species dependent. Data for iHg and MeHg were missing, so %TDI for these substances can only be estimated theoretically. If total mercury would be either 100% iHg or MeHg, the mean %TDI per portion would be below 5% for both, in both *S. latissima* and *Ulva* all (data not shown).

The large variations in content of heavy metals within seaweed species complicate the comparison between data sources. However, for heavy metals, the present study reported higher lead content in *S. latissima* compared to data compiled from food composition databases (mean/median: under detection limit; max: 47 µg per 100 g)[146] and a recent Nordic report (mean: 32 µg per 100 g).[147] Furthermore, food composition databases indicate much lower level of total mercury in *S. latissima* (mean/median: under detection limit; max: 0.9 µg per 100 g)[146]compared to our findings. For *U. fenestrata*, data compiled in this review were 1.5- and 5-times higher mean content of lead and cadmium, respectively, compared to food composition databases[146] and 3-, 4- and 5-times higher mean content of lead, cadmium, and total mercury, respectively, compared to a recent Nordic report (Hogstad et al. 2022). Neither Hornborg et al.[146] nor the Nordic report[147] reported data for other *Ulva* species.

So far there are no specific regulations in EU or internationally on maximum levels for food hazards in seaweed foods (not including food supplements). However, general legislation on foods applies also for seaweed. For example, for mercury the legislation on maximum residue levels of pesticides in food and feed (EC Regulation No 296/2005) set a maximum level of 0.01 mg per kg wet seaweed. Assuming 12.5% and 14.5% DW for *S. latissima* and *Ulva* species, this corresponds to an upper limit of 8.0 and 6.9 µg total mercury per 100 g DW, for *S. latissima* and *Ulva* all, respectively. Even though this study did not identify mercury as a major toxicological concern considering the small portion addressed (5 g DW), it shows that the content of total mercury in samples of both *S. latissima* and *Ulva* species may exceed the allowed upper level, per 100 g DW. Certain seaweed species may also require approval according to the regulation on novel food (Regulation EC 2015/2283) before they can be used as food. Whole non-fractionated *S. latissima* and *U. fenestrata* are not classified as novel food, while novel food status has not yet been decided for the other *Ulva* species included here.

Protein, fiber, and fat

Based on our results, seaweeds are unlikely to become a major source of protein, fiber, or fat in the diet. The portion sizes that would be required to provide a nutritionally relevant contribution of these nutrients may be a concern from a toxicological perspective. Up-concentrating proteins, fibers, or fat through extraction protocols could however be a promising strategy to produce new food ingredients while reducing the content of specific heavy metals such as cadmium.[148]

As a source of protein, the *Ulva* species are more interesting than *S. latissima*, due to higher protein content, that may reach similar levels as legumes.[149] Similar ratios of essential amino acids to non-essential amino acids as for soybean flour have been reported for both *Ulva* spp. and *S. latissima*.[115] According to this review, *S. latissima* and *Ulva* species appear to have similar potential as provider of total fiber and fat. However, *S. latissima* has a greater proportion of soluble fiber (30–70% *vs* 20–60% of total fiber) and long-chain *n*-3 fatty acids (50–90% *vs* 10–30% of the total *n*-3 fatty acids), compared to the *Ulva* species.

Bioavailability

Health impact of foods depends not only on the content but also on the bioavailability and biological activity of nutrients and other substances. This can vary greatly between different food items, depending on e.g., its ingredients and its specific matrix structure. As far as we know, the bioavailability of nutrients and heavy metals in *S. latissima* and the selected *Ulva* species has yet to be addressed through human clinical trials. However, two *in vitro* studies on this matter were identified.[57,131] Flores et al.[57] concluded that Caco-2 cell uptake of iron from *U. fenestrata* is similar to that of spinach and can be further enhanced by addition of vitamin C. The second study concluded that amino acid bioavailability of *S. latissima* and *U. fenestrata* was equal to that of casein.[131] Interestingly, Trigo et al.[131] reported a higher *in vitro* protein digestibility in *U. fenestrata* compared to *S. latissima*. Factors such as the amount of cell wall-bound protein and fiber content can influence the access of digestive proteases to seaweed proteins, thus explaining the different digestibility values between species.[150,151] Also, levels of anti-nutrients, such as polyphenols, play an important role. A recent review article concluded that iodine bioavailability for *Saccharina* species varies between 57% and 71%.[152–158] Regarding vitamin B12, both biologically active and inactive forms may be present in foods. Whether vitamin B12 in *S. latissima* and *Ulva* species contains biologically active vitamin B12 or not, remains to be elucidated.[144]

Strengths, limitations, method considerations

This study collected nutritional data for *S. latissima*, *U. rigida*, *U. intestinalis*, and *U. fenestrata*, with complementary data on *Ulva* spp., allowing to assess the nutritional composition, the nutritional quality, content of potentially toxic elements and bioavailability aspects. Nutritional assessments were performed with multiple methods (%DRI and nutrient density index NRF, in comparison to reference foods), thus strengthening the conclusions of the nutritional performance of the seaweeds. However, our review only provided information for four seaweed species whose properties may differ from other edible species. Additionally, the impact of harvest season and geographical location on content of nutrients and heavy metals was not the focus of this review, but would be useful additional information to guide toward optimal future seaweed production systems.

Another limitation was that nutritional and toxicological assessments were made without taking into account possible impact of post-harvest processing techniques, such as blanching. Despite blanching being an effective technique at reducing iodine, it significantly changes total amino acid content and total monosaccharide content,[148] thus likely changing the nutritional quality of the original biomass. Finally, as stated in the methods section, we have included data as reported in the included original studies, without adjusting for any differences in analysis methods. Depending on method, the content of some nutrients may however be under- or overestimated. For example, some studies reported crude fiber, which represents only fractions of insoluble fiber and no soluble fibers, meaning that fiber content, and thereby %DRI of fiber, may be underestimated. For carbohydrate, there is the opposite risk, since many studies report total carbohydrate, including indigestible carbohydrates, while DRI for carbohydrates refers to digestible carbohydrates only. Furthermore, the fat content can be overestimated if determined via solvent extraction and gravimetric determination, but slightly underestimated if done via fatty acid analysis. For protein, the choice of nitrogen-to-protein conversion factor may lead to slight under- or overestimations. However, the main conclusions of this review remain, independently of the possible misestimations of macronutrient content.

Future perspectives

To support the development of nutritious and healthy foods from *S. latissima* and the selected *Ulva* species, it would be useful with more studies on the content of aqueous and lipophilic vitamins and on how different harvest season and harvesting location impact the content of nutrients and heavy metals. Further investigations on how different post-harvest processing techniques influence nutritional and toxicological characteristics of the included seaweeds would also be useful. This is because it would help identifying processing parameters for maximal reduction of heavy metals and iodine, in parallel with maintenance or improved nutritional content and quality, including bioavailability. Besides blanching, such processing could comprise rinsing, ensilaging, fermentation, brining, freeze-thawing, together with upcoming and established methods to concentrate e.g., protein, specific polysaccharides, and phenolic compounds. Furthermore, better understanding of the dietary role of *S. latissima* and *Ulva* species, e.g., portion sizes and which food items these species can replace or complement on the plate, is crucial to better assess their nutritional contribution and toxicological risks as food. Randomized controlled clinical trials are also necessary to clarify the bioavailability of nutrients and heavy metals in foods based on *Ulva* and *S. latissima* or with these species as ingredients. Other aspects to explore are the presence of allergens and microbiological hazards. Finally, based on our findings, we call for a shift from considering "seaweed" as a single food commodity to address it by the individual species; similarly, to fruits (e.g., apple and orange) or vegetables (e.g., cabbage and spinach). Future studies, on the above-mentioned perspectives, will be useful for seaweed producers and seaweed food manufacturers, and not the least as guidance to the EU Commission, soon expected to evaluate the need for risk management actions targeted to different seaweed species as foods in EU.[147]

Conclusion

Data compiled in this review show that one portion of whole dried *S. latissima* and selected *Ulva* species (*U. rigida, U. fenestrata, and U. intestinalis)* may be nutritionally meaningful sources of some micronutrients, while their nutritional contribution of macronutrients is small. For iron, magnesium, selenium, calcium (*S. latissima*) and vitamin B12 (*Ulva* species) one portion of seaweed may contribute to ≥15% of recommended daily intake. The content of iodine was identified as the main toxicological concern, especially for *S. latissima*. The content of inorganic arsenic, lead, and cadmium may also constitute a health risk, especially for *Ulva* species, if consumed frequently. The considered seaweed species were shown to have both nutritional strengths and limitations compared to selected reference foods. Based on a nutrient density index score taking 24 nutrients into account, the two species ranked higher than herbs and salad components, and lower than legumes and fish/shellfish. Bioavailability data were scarce and is an important future research aspect to clarify the nutritional quality of different seaweeds. Further work is also warranted regarding the biological activity of vitamin B12 and impact of post-harvest processing on nutrients and heavy metals. In conclusion, the results from this review indicate that *S. latissima* and *Ulva* species may provide a meaningful contribution of some micronutrients often limited in plant-based foods; however, toxicological concerns especially related to high iodine content may restrict the intake levels that can be considered safe. Ultimately, the nutritional potential of the addressed seaweeds will depend on their role in future diets and this review provides new insights on what their nutritional impacts could become, depending on intake levels and foods replaced.

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Author contributions

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