Trends in Food Science & Technology 141 (2023) 104204

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Comparative assessment of food safety regulations and standards for arsenic, cadmium, lead, mercury and iodine in macroalgae used as food and feed in China and Europe

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A R T I C L E I N F O

Handling Editor: Dr. J O'Brien

Keywords:
Seaweed
Food safety
Inorganic contaminants
Iodine
Regulation
Standard

A B S T R A C T

Background: Seaweed, or macroalgae has traditionally been part of Asian cuisine for decades and is also becoming increasingly popular as a food source in Europe and other Western countries. However, seaweed can accumulate elements from the environment and consequently may be a source of exposure to toxic elements, or potentially harmful levels of micronutrients. Food safety issues related to the use of seaweed as food and animal feed are very important given the increased use of such products.

Scope and approach: Current standards, regulations and recommendations regarding heavy metals (cadmium, lead and mercury), arsenic and iodine in seaweed food and feed products in China and Europe are included in this review. Furthermore, the levels of these elements in different seaweed products, dietary exposure, and risk management measures for seaweed products are also discussed.

Key findings and conclusions: The chemical hazards of particular concern in seaweeds are iodine, inorganic arsenic and cadmium depending on seaweed species, consumption and processing or preparation methods. In the absence of harmonized international standards or guidelines that specifically address food safety of seaweed production, processing and utilization, there are considerable differences in the regulations and standards concerning inorganic contaminants and iodine among different countries. This comprehensive review identifies knowledge gaps and provides a scientific basis for further work regarding developing unified food safety legislation, standards or guidelines related to seaweed products.

1. Introduction

Seaweed, or macroalgae, has received increased attention in recent years as a sustainable food source, and seaweed farming can promote sustainable development, and contribute to the demand for food for the world's growing population (Forster & Radulovich, 2015, pp. 289–313). Cultivation of macroalgae is practiced in about 50 countries, with the largest quantities produced in Eastern and Southeastern Asia. Approximately 60% of the global macroalgae comes from China, which has become the largest producer globally (FAO, 2020). The quantity of the world cultivated macroalgae has increased to 35.8 million tons in 2019, of which about 28.5 million tons have been used for direct consumption or further processed into food, food additives and supplements (Cai et al., 2021; FAO, 2020; FAO and WHO, 2022).

Macroalgae is a phylogenetically diverse group, consisting of several different species within the brown algae (Phaeophyceae), red algae

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https://doi.org/10.1016/j.tifs.2023.104204
Received 21 July 2023; Received in revised form 7 October 2023; Accepted 11 October 2023
Available online 12 October 2023

(Rhodophyta) and green algae (Chlorophyta). A variety of macroalgal species are used as foods with different degrees of processing, such as whole foods, ingredients, and dietary supplements (Aakre et al., 2021; Bouga & Combet, 2015). For decades, macroalgae has been regarded as healthy food in many countries and regions especially in Asian cultures, where it is consumed as fresh, dried or salted products, or as ingredients in soups, sushi, salads, snacks and other dishes (Zava & Zava, 2011; Cai et al., 2021). Recently, macroalgae has become increasingly popular among consumers in Western countries (Aakre et al., 2021; Bouga & Combet, 2015; Ficheux et al., 2022). In addition, macroalgae can be used as animal feed, pharmaceuticals and biofertilizer (Araújo et al., 2021; FAO, 2018; Øverland et al., 2019).

Macroalgae is a potential source of bioactive ingredients for functional foods and nutritional supplements (Domínguez, 2013). Several studies have shown that certain types of seaweeds can be a source of dietary fiber, polysaccharides, amino acids and minerals (Wells et al., 2017; Peñalver et al., 2020; Raja et al., 2022). However, due to the accumulation of elements from the environment, seaweeds may be a source of excessive iodine (I) as well as inorganic elements including lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As) (Anbazhagan et al., 2021; Banach et al., 2020; Blikra et al., 2022). These elements may pose potential risks to human and animal health (Almela et al., 2006; Chen et al., 2018; Todorov et al., 2022). Based on relevant literature and information available in the European Rapid Alert System for Food and Feed (RASFF) (RASFF portal, 2021; RASFF portal, 2022), inorganic arsenic, cadmium and iodine were identified as the major food safety hazards in seaweeds, while lead and mercury were regarded as moderate hazards (Anbazhagan et al., 2021; Banach et al., 2020).

High contents of heavy metals (PC, Cd and Hg), arsenic and iodine in macroalgae and their products, highlight the need to assess the dietary contribution of these elements from macroalgae in order to scientifically evaluate the food safety of such products. At present, there is neither international Codex Alimentarius Commission standards nor control technical guidelines that specifically address the food safety issues related to seaweed (FAO and WHO, 2022). However, some major seaweed-producing and consuming countries are particularly concerned with the control of heavy metals, arsenic and iodine in seaweed products, and have formulated and implemented regulations or standards to protect consumer health. There is limited specific legislation covering seaweed in the food regulations in the European Union (EU) and the European Economic Area (EEA). Thus, dissimilarities exist in the evaluation of the safety of products made from seaweed in different countries within the EU/EEA (Lähteenmäki-Uutela et al., 2021). China has implemented some food safety standards in terms of maximum levels (MLs) for inorganic contaminants in seaweed and seaweed-based products which exclude iodine. Furthermore, it is difficult to define the acceptable levels of inorganic contaminants and iodine in seaweeds as food or food ingredient. The concerns and uncertainties regarding the safety of seaweed products pose challenges to food safety authorities in many parts of the world.

This paper compiles and compares the current standards, regulations and recommendations regarding heavy metals (Cd, Pb and Hg), arsenic and iodine in seaweed food and feed products in China and Europe. This may be used for identifying knowledge gaps in different countries and may form the basis for the further work related to developing unified food safety legislation, standards or control guidelines related to macroalgae.

2. Methods

The focus of this paper is arsenic, lead, cadmium, mercury and iodine in edible macroalgae for human consumption and animal feed. The regulations within the EU, including France and Germany, and China, including Hong Kong and Taiwan are compiled and evaluated in the present study. Specific threshold values for some heavy metals, arsenic and iodine in seaweed-based food from countries within the EU (e.g. France and Germany), are included because national limits exist. Furthermore, scientific reports and standards from international organizations such as the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO) and Codex Alimentarius Commission (CAC), are included. The MLs for inorganic contaminants in seaweeds as food formulated by other countries have also been collected and compared. In addition, Springer Link database, Science Direct database and Google Scholar were used to retrieve literature on major hazards that may occur in seaweeds. The current data on concentrations and bioavailability of these elements in seaweed products, dietary exposure assessment of these elements from seaweeds consumption and other hazards in the seaweed food chain are discussed in this paper.

3. Results

3.1. Current regulations and standards on inorganic contaminants and iodine in macroalgae used as food and feed in China and Europe

In the EU, the Commission Regulation (EC) 2023/915 (repealing Regulation (EC) No 1881/2006) establishes MLs for certain contaminants in foodstuffs (EU, 2023). However, currently no specific standards for seaweed as a foodstuff have been developed, apart from the regulations for arsenic, lead and cadmium in food supplements completely or mainly derived from seaweed (EU, 2018). Regulation (EC) No 396/2005 sets a default level for mercury in algae (EU, 2005a). Iodine is a nutrient and is consequently not covered by the Commission's Regulation for contaminants. In Europe, France was the first country to conduct a safety evaluation of seaweeds as a food source for the French population (ANSES, 2020; Ficheux et al., 2022). France has established national MLs for inorganic arsenic, lead, cadmium, mercury and iodine in edible seaweeds used as a vegetable or condiment (CEVA, & Centre d.Etude et de Valorisation des Algues, 2014; ANSES, 2018; ANSES, 2020). The Federal Institute for Risk Assessment (BfR) of Germany has evaluated the health risk of iodine from dried marine algae and Germany has strict restrictions on the iodine content in dried seaweeds placed on the market (Berlin Federal Institute for Risk Assessment BfR, 2004). The EU has issued a recommendation (EU) 2018/464 on monitoring metals and iodine in seaweeds used as food and feed (EU, 2018). This recommendation demonstrates the necessity of generating occurrence data on contaminants in seaweed and evaluating the contribution of seaweed to the exposure to inorganic contaminants and iodine. These data will be used to evaluate the necessities of establishing MLs for lead, cadmium and arsenic in seaweed products and modifying the ML for mercury in algae, and whether it is necessary to take risk management actions for iodine exposure of these products.

The contaminant content of certain seaweed species also needs to be investigated because they may be used as feed, considering both animal health and the possible transfer to food products of animal origin. MLs for undesirable substances including total arsenic and inorganic arsenic, lead, cadmium and mercury in feed materials and animal feed have been established in Directive 2002/32/EC of the European Parliament and of the Council, and its amendments (EU, 2002; EU, 2013). The MLs for lead, cadmium and mercury are set for feed materials in general, whereas the ML for arsenic is specified for feed materials derived from seaweeds.

In China, the MLs for contaminants in food are set to protect consumers' health, and take into consideration relevant food safety assessments and international regulations. The national food safety standard on maximum levels of contaminants in foodstuff (GB 2762-2022) has established MLs for inorganic arsenic and lead in seaweed and seaweed-based products (NHCPRC & SAMR, 2022). The national feed hygiene standard (GB 13078-2017) has also specified the limits and test methods for toxic substances and microorganisms in feed materials and animal feeds, including MLs for total arsenic, lead, cadmium and mercury in feed materials containing seaweed and its products (SAC &

GAQSIQ, 2017). The Ministry of Health and Welfare in Taiwan has amended the sanitation standard for contaminants and toxins in food, which included MLs for inorganic arsenic, lead, cadmium and mercury in seaweed (MHWTC, 2018). The Food, Environment and Hygiene Department of Hong Kong has also established MLs for toxic metals in various foods including a ML for inorganic arsenic in seaweed in the Food Adulteration (Metallic Contamination) Regulation 2018; FEHD, HKC, 2018).

An overview of EU and Chinese standards on MLs for inorganic contaminants and iodine in seaweed and seaweed-based products is given in Table 1 and it will be described further in the following section.

3.2. Arsenic (As)

3.2.1. Tolerable intake of arsenic and risk characterization

Arsenic (As) is a metalloid of various inorganic and organic forms (EFSA, 2009b). The toxicity of arsenic is closely related to its speciation. Research shows that inorganic arsenic is more toxic than organic compounds, and its toxicity generally decreases with increased methylation (Sharma & Sohn, 2009). In 2009 and 2011, both the European Food Safety Authority (EFSA) and the FAO/WHO Joint Expert Committee on Food Additives (JECFA) withdrew the former Provisional Tolerable Weekly Intake (PTWI) for arsenic because it was no longer considered to have health protection effects (EFSA, 2009b; JECFA, 2011a). The EFSA Panel on Contaminants in the Food Chain developed a series of benchmark dose lower confidence limits ($BMDL_{01}$), ranging from 0.3 to 8 μg/kg bodyweight (b.w.) per day for increased incidence of lung cancer, skin cancer, bladder cancer and skin lesions (EFSA, 2009b), and the BMDLs established by JECFA range from 2 to 7 μg/kg b.w. per day for increased incidence of lung cancer, bladder cancer and skin damage (JECFA, 2011a).

3.2.2. Maximum levels for arsenic in macroalgae foods, supplements and feed

As seaweed has gained increased popularity as food, regulation of arsenic content has become increasingly important due to the potential health risks associated with seaweed consumption. In China, the national food safety standard for the maximum levels of contaminants in food (GB2762-2022) has set a ML of 0.3 mg/kg for inorganic arsenic in supplementary food with seaweed additives for infants, and 0.5 mg/kg

Table 1
The maximum levels for arsenic (total and inorganic), cadmium, lead, mercury and iodine in seaweed and seaweed-based products for human consumption and animal feeds in China and EU, as well as France, Germany, Taiwan and Hong Kong.

Elements	EU			France	Germany	China		Taiwan	Hong Kong
	Seaweed food products[c]	Food supplements[d]	Feed containing seaweed[e]	Seaweed food products[f]	Dried seaweed products[g]	Seaweed and its food products[h]	Feed materials containing seaweed[i]	Seaweed and its products[j]	Seaweed and its products[k]
	mg/kg	mg/kg	mg/kg	mg/kg dw[a]	mg/kg	mg/kg	mg/kg	mg/kg ww[b]	mg/kg ww[b]
Total arsenic	–	–	40	–	–	–	40	–	–
Inorganic arsenic (iAs)	–	–	2	3	–	0.3 (supplementary food with seaweed additives for infants) 0.5 (aquatic seasoning containing seaweed)	–	1.0	1.0
Cadmium (Cd)	–	3.0	1	0.5	–	–	2	1.0	–
Lead (Pb)	–	3.0	10	5	–	0.5 (fresh seaweed, wet weight[b]) 1.0 (seaweed-based products)	10	1.0	–
Mercury (Hg)	0.01	0.10	0.1	0.1	–	–	0.5	0.5	–
Iodine (I)	–	–	–	2000	20	–	–	–	–

Note:"—"no standard available.

[a] Dry weight.

[b] Wet weight, values are given per weight relative to food with a moisture content of 85%.

[c] Regulation (EC) 396/2005 on maximum residue levels of pesticides in or on food and feed of plant and animal origin. The maximum residue level for algae and prokaryotes organisms is 0.01 mg/kg.

[d] European Commission. (2023). Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. *Off. J. Eur. Union*, *119*, 103–157. A ML of 3.0 mg/kg Cd has been set specifically for food supplements consisting at least of 80% from dried seaweed and from products derived from seaweed.

[e] Directive 2002/32/EC and its amending regulation (EU) No 1275/2013 specify undesirable substances in animal feed. MLs are relative to feed with a moisture content of 12%.

[f] ANSES (2020).Opinion of the French Agency for Food, Environmental and Occupational Health & Safety on maximum cadmium levels for seaweed intended for human consumption. Request No 2017-SA-0070. https://www.anses.fr/en/system/files/ERCA2017SA0070EN.pdf. MLs for trace elements and iodine in seaweed used as a vegetable or condiment are in mg/kg dry matter.

[g] Berlin Federal Institute for Risk Assessment BfR, 2004. Health risks linked to high iodine levels in dried algae. BfR Opinion No.026/2007. mobil.bfr.bund.de/cm/349/health_risks_linked_to_high_iodine_levels_in_dried_algae.pdf.

[h] National Health Commission of PRC & State Administration for Market Regulation (NHCPRC & SAMR). (2022). GB 2762-2022. The national food safety standard for maximum levels of contaminants in food.

[i] Standardization Administration of China & General Administration of Quality Supervision, Inspection and Quarantine (SAC &GAQSIQ). (2017).GB13078-2017. The national hygienic standard for feeds. MLs are relative to feed with a moisture content of 12%.

[j] Ministry of Health and Welfare Taiwan of China (MHWTC). (2018). Sanitation Standard for Contaminants and Toxins in Food: Appendix1. Maximum levels (ML) of metals in foods. https://db.lawbank.com.tw/Eng/FLAW/FLAWDAT01.aspx? Lsid = FL088408. MLs are given per weight relative to seaweed with a moisture content of 85% (wet weight).

[k] Food and Environmental Hygiene Department, Hong Kong special administrative region of China (FEHD, HKC).(2018).Food Adulteration Regulation-Metallic Contamination (Amendment), Food and Environmental Hygiene Department of Hong Kong. https://www.cfs.gov.hk/english/whatsnew/whatsnew_fstr/whatsnew_fstr_PA _Food_Adulteration_ Metallic_Contamination.html. MLs are given per weight relative to seaweed with a moisture content of 85%(wet weight).

for aquatic seasoning that mainly consists of products derived from seaweed, Table 1 (NHCPRC & SAMR, 2022). The Food and Environmental Hygiene Department (FEHD) of Hong Kong special administration region and the Ministry of Health and Welfare of Taiwan have both set a ML for inorganic arsenic in seaweeds of 1.0 mg/kg wet weight (ww), which is set for seaweed with a moisture content of 85% (FEHD, HKC, 2018; MHWTC, 2018). The EU Commission Regulation (EU) 2023/915 on contaminants in food has set MLs for inorganic arsenic in certain foods such as rice, but not seaweed or seaweed-based food (EU, 2023). In France, a ML of 3 mg/kg dry weight (dw) has been established for inorganic arsenic in edible seaweeds used as a vegetable or condiment (AFSSA, 2009; ANSES, 2020; CEVA, & Centre d.Etude et de Valorisation des Algues, 2014) (Table 1).

Animal feed produced from seaweed has been widely used in animal husbandry and aquaculture, therefore, the potential risks of arsenic pollution in the food chain, and consequently to human health should be considered (Monagail et al., 2018). The feed hygiene national standard (GB 13078-2017) has established a ML of 40 mg/kg for total arsenic in feed materials containing seaweeds, which is calculated with a dry matter content of 88% (SAC & GAQSIQ, 2017), Table 1. Similarly, the ML for total arsenic in feed materials completely or mainly derived from seaweed is 40 mg/kg (calculated based on feed with a moisture content of 12%) in the EU (EU, 2002). However, the content of total arsenic in feed materials does not accurately reflect the potential health risks associated with seaweed. As the ratios of different forms of arsenic vary among different seaweed species, the ML for inorganic arsenic rather than total arsenic should be regulated in feed materials (Almela et al., 2006). Therefore, complying with requests of the competent authorities, the responsible operator has to prove that the content of inorganic arsenic is less than 2 mg/kg in seaweed products, which is particularly important for the seaweed species *Hizikia fusiforme*, also known as *Sargassum fusiforme* (EU, 2002).

3.3. Cadmium (Cd)

3.3.1. Tolerable intake of cadmium and risk characterization

Cadmium is a contaminant of potential health concerns primarily related to its toxicity to the kidneys (EFSA, 2009a). EFSA established a tolerable weekly intake (TWI) of 2.5 μg/kg b.w. for cadmium based on dietary cadmium exposure, urinary cadmium and urinary beta-2-microglobulin the latter being a biomarker related to tubular effects in the kidneys (EFSA, 2009a; EFSA, 2011). The half-life of cadmium in human kidneys was as long as 15 years. Therefore, the JECFA withdrew the PTWI of 7 μg/kg b.w. and instead established a Provisional Tolerable Monthly Intake (PTMI) of 25 μg/kg b.w. (JECFA, 2011b).

3.3.2. Maximum levels of cadmium in macroalgae foods, supplements and feed

Seaweed naturally accumulates cadmium from the surrounding environment, consequently the cadmium content of seaweed products is generally higher than in other products. A ML of 3.0 mg/kg Cd has been established for food supplements consisting of at least 80% dried seaweed and from products derived from seaweed in Commission Regulation (EU) 2023/915, Table 1. But MLs for cadmium in edible seaweeds intended for direct human consumption have not yet been established in the EU (EU, 2023). ANSES has recommended to lower the ML for cadmium in seaweed products, and the French High Council for Public Health (CSHPF) has recommended that the ML for cadmium in edible seaweeds should be less than 0.5 mg/kg dw (ANSES, 2020). The Ministry of Health and Welfare of Taiwan, China has stipulated that the cadmium content in seaweed for food should not exceed 1.0 mg/kg ww (MHWTC, 2018). With respect to feed, Directive 2002/32/EC has established a ML for cadmium in feed materials derived from seaweed of 1 mg/kg (calculated based on feed with a moisture content of 12%) (EU, 2002; EU, 2013). The feed hygiene national standard of China (GB 13078-2017) has set the ML for cadmium in feed materials containing seaweed at 2 mg/kg, which is calculated with a dry matter content of 88% (SAC & GAQSIQ, 2017), Table 1.

3.4. Lead (Pb)

3.4.1. Tolerable intake of lead and risk characterization

Lead is an environmental and industrial contaminant, which may accumulate in organisms due to its non-biodegradable nature (Boskabady et al., 2018). Lead pollution poses a significant threat to food safety and human health particularly for high-risk subgroups of the population such as children (1–7 years old), pregnant women and infants, due to the critical effects of lead on neurodevelopment (Hwang et al., 2019). In 2010 and 2011, the EFSA and JECFA both withdrew the former PTWI for lead (EFSA, 2010; JECFA, 2011b). The EFSA panel on contaminants in the food chain derived a $BMDL_{01}$ of 0.5 μg Pb/kg b.w. per day for developmental toxicity, and $BMDL_{01}$ of 0.63 and 1.50 μg Pb/kg b.w. per day for kidney and cardiovascular effects, respectively (EFSA, 2010).

3.4.2. Maximum levels of lead in macroalgae foods, supplements and feed

The EU has established a ML for lead in food supplements of 3.0 mg/kg, but no ML exists in the EU for seaweed or seaweed-based products (EU, 2023). In France, the ML for lead in edible seaweed is 5 mg/kg dw (CEVA, & Centre d.Etude et de Valorisation des Algues, 2014; ANSES, 2020). In China, the ML for lead in fresh seaweed is 0.5 mg/kg ww, and the ML for lead in seaweed-based food products is 1.0 mg/kg, which refers to the commercially available products (NHCPRC & SAMR, 2022). However, due to changes in moisture content during the drying process, the maximum limits for heavy metals in dried products are to be converted and they apply on a fresh weight basis (NHCPRC & SAMR, 2022). The ML set by the Ministry of Health and Welfare of Taiwan for lead in seaweed consumed directly or used in seaweed-based products is 1.0 mg/kg ww (MHWTC, 2018). The EU has set a ML for lead in feed materials of 10 mg/kg (calculated based on feed with a dry matter content of 88%) (EU, 2002). The feed hygiene national standard (GB 13078-2017) of China has set the same ML for lead in feed materials containing seaweed (SAC & GAQSIQ, 2017), Table 1.

3.5. Mercury (Hg)

3.5.1. Tolerable intake of mercury and risk characterization

Mercury (Hg) is a highly toxic element which can bioaccumulate and biomagnify in the marine environment (EFSA, 2004). The toxicity of mercury is related to the chemical form and route of uptake (EFSA, 2012b). Methylmercury (MeHg) is a highly toxic form of organic mercury, which mainly accumulates in predatory marine fish (JECFA, 2019a; JECFA, 2019b). The JECFA established a PTWI of 4 μg/kg b.w. for inorganic mercury and a PTWI of 1.6 μg/kg b.w. for methylmercury (JECFA, 2011a). The EFSA evaluated the PTWIs set by JECFA for inorganic mercury and methylmercury in 2012 and established a TWI for methylmercury of 1.3 μg/kg b.w. (EFSA, 2012b).

3.5.2. Maximum levels of mercury in macroalgae foods, supplements and feed

Mercury levels in seaweed tend to be considerably lower than that of other non-essential metals. In Europe, no ML has been specifically established for mercury in seaweed, except for the ML established for food supplements in general of 0.10 mg/kg (EU, 2023). However, there is a ML for mercury in algae at the default level of 0.01 mg Hg/kg in the regulation (EC) 396/2005 on pesticides (EU, 2005a). In France, the ML for mercury in edible seaweed is set at 0.1 mg/kg dw (ANSES, 2020; CEVA, & Centre d.Etude et de Valorisation des Algues, 2014). Due to the relatively low concentrations of mercury in seaweed, MLs for mercury in seaweed and seaweed-derived foods have not been stipulated in the mandatory national food safety standard maximum levels of contaminants in foods (GB 2762-2022) in China (NHCPRC & SAMR, 2022). However, the Ministry of Health and Welfare of Taiwan, China has established a ML for mercury in seaweed of 0.5 mg/kg ww (MHWTC, 2018). The ML for mercury in feed materials in the EU is set at 0.10 mg/kg (which is relative to feed with a dry matter content of 88%) (EU, 2002). Whereas in China, the ML for mercury in feed materials containing aquatic organisms (including seaweed) is 0.5 mg/kg, which is also calculated with a dry matter content of 88% (SAC & GAQSIQ, 2017). Table 1.

3.6. Iodine (I)

3.6.1. Recommended intake levels and tolerable upper intake levels of iodine

Iodine is an essential trace element required for the synthesis of thyroid hormones triiodothyronine (T3) and thyroxine (T4), which play critical roles in metabolism, and normal growth and development during fetal life. Thus, small amounts of iodine are needed regularly, and marine food is the main dietary source of iodine. The recommended intake established by EFSA and WHO is 150 μg/day for adults (WHO, & UNICEFICCIDD, 2007; EFSA, 2017; JECFA, 2019c).

Although iodine is essential for the growth and development of humans and animals, excessive consumption of iodine may cause adverse health consequences and may be associated with hyperthyroidism or hypothyroidism (Müssig, 2009; Katagiri et al., 2017). For humans, the different tolerable upper intake levels (ULs) and recommended intake levels for iodine have been established by international organizations, in the US, EU and China (Table 2 & Table 3). China specified ULs and Reference Nutrition Intakes (RNIs) for iodine based on iodine balance, thyroid iodine accumulation and conversion rate, thyroid iodine content of newborns, and iodine supplementation for pregnant women and adults (NHFPCPRC, 2017). In Europe, the former

Table 2
Tolerable upper intake levels (ULs) for iodine set by different institutions(μg/day).

Population	ULs for iodine(μg/day)		
	NAM of US (2006) [a]	EFSA (2006) [b,c]	NHFPCPRC, China (2017) [d]
Adults	1100 (Adults excluding pregnant and lactating women); 1000 (pregnant and lactating women)	600	600
Children and teenagers	200 (1–3 years)	200 (1–3 years)	— (1–3 years)
	300 (4–8 years)	250 (4–6 years)	200 (4–6 years)
	600 (9–13 years)	300 (7–10 years)	300 (7–10 years)
	900 (14–18 years)	450 (11–14 years)	400 (11–13 years)
		500 (15–17 years)	500 (14–17 years)

Note:"—"indicates that it has not been formulated.
*IOM has changed name to National Academy of Medicine (NAM).
[a] Institute of Medicine (2006). Dietary Reference Intakes: The Essential Guide to Nutrient Requirements. Washington, DC: The National Academies Press. https://nap.nationalacademies.org/catalog/11537/dietary-reference-intakes-the-essential-guide-to-nutrient-requirements.
[b] Scientific Committee on Food (SCF). (2002). Opinion of the Scientific Committee on Food on the tolerable upper intake level of iodine. Brussels, Belgium: SCF. http://europa.eu.int/comm/food/fs/sc/scf/index_en.html.
[c] EFSA. (2006b).Tolerable upper intake levels for vitamins and minerals. https://www.efsa. europa.eu/sites/default/files/efsa_rep/blobserver_assets/ndatolerableuil.pdf.
[d] National Health and Family Planning Commission of PRC (NHFPCPRC). (2017).WS/T 578.3–2017. Chinese dietary reference intakes-Part 3: Trace element. http://down.foodmate.net/standard/yulan.php?itemid=51366.

Table 3
Population Reference Intakes (PRIs) or Reference Nutrition Intakes (RNIs) for total iodine (μg/day).

Population	PRIs or RNIs for iodine(μg/day)		
	WHO/UNICEF/ICCIDD (2007) [a]	EFSA (2014, 2017) [b,c]	NHFPCPRC, China (2017) [d]
Adults	150 (for adults excluding pregnant and lactating women); 250 (for pregnant and lactating women)	150 (for adults excluding pregnant and lactating women); 200 (for pregnant and lactating women)	120 (for adults excluding lactating women); 230 (for pregnant); 240 (for lactating women)
Children and teenagers	90 (0–6 years)	90 (1–10 years)	85 (0–6 months)
	120 (7–12 years)	120 (11–14 years)	115 (6–12 months)
	150 (13–18 years)	130 (15–17 years)	90 (1–10 years)
			110 (11–13 years)
			120 (14–17 years)

[a] WHO, UNICEF & ICCIDD (2007). Assessment of Iodine Deficiency Disorders and Monitoring Their Elimination. A Guide for Programme Managers—3rd edition. World Health Organization, Geneva, 2007.
[b] EFSA. (2014). Scientific opinion on dietary reference values for iodine. Panel on Dietetic Products, Nutrition and Allergies (NDA) EFSA Journal, 12(5), 3660. https://doi.org/10.2903/j.efsa.2014.3660.
[c] EFSA. (2017). Technical report of European Food Safety Authority: Dietary reference values for nutrients. EFSA Supporting publication 2017:e15121. https://doi.org/10.2903/sp.efsa.2017. e15121.
[d] National Health and Family Planning Commission of PRC(NHFPCPRC). (2017). WS/T 578.3–2017. Chinese dietary reference intakes-Part 3: Trace element.

Scientific Committee on Food (SCF) proposed a tolerable upper intake level (UL) of 600 μg per day for adults, which was endorsed by EFSA, and this is also the maximum amount of iodine recognized as unlikely to cause adverse effects during long-term intake (EFSA, 2002; EFSA, 2006b; SCF, 2002). At the national level, France has set a maximum daily intake (MDI) of 150 μg for iodine in food supplements (ANSES, 2018). The National Academy of Medicine (NAM) in the United States, formerly the Institute of Medicine, has set an UL of 1100 μg per day for adults (Institute of Medicine, 2006).

3.6.2. Maximum levels of iodine in macroalgae foods, supplements and feed

Generally, seaweed is considered as an iodine-rich material. The consumption of seaweed may increase the risk of excessive iodine intake, but this depends on the amounts of seaweed consumed (Aakre et al., 2020; EFSA, 2006a; SCF, 2002). To date, maximum levels for iodine in seaweed or seaweed-based products for human consumption have not been established in the EU or China. Due to changes in people's consumption habits (from condiments to vegetable form), EFSA and ANSES have assessed the potential risks of excessive iodine intake from the consumption of seaweed-based products. In France, the maximum level of iodine was revised to 2000 mg/kg dw for all species of edible seaweed in 2009 (AFSSA, 2009; ANSES, 2018). In contrast, the German legislation has set a maximum of 20 mg/kg iodine for dried macroalgae products and has recommended the establishment of uniform maximum levels for iodine in seaweed in the EU (Berlin Federal Institute for Risk Assessment BfR, 2004). Table 1.

The European Commission has authorized potassium iodide and calcium iodate as sources of iodine in farm animals. The maximum levels for total iodine in complete feed in the EU are as follows: 3 mg/kg for horses, 4 mg/kg for dogs, 5 mg/kg for cats, 2 mg/kg for dairy cattle and minor ruminants, and 3 mg/kg for layers (EFSA, 2013).

3.7. Current regulations on seaweed as food in other countries

In addition to the regulations and standards presented from Europe and China, other countries, such as South Korea, Singapore, Australia and New Zealand have also developed relevant regulations for MLs of selected contaminants in food to protect consumers' health (Table 4).

In South Korea, nori or laver (*Porphyra* spp.) and sea mustard or wakame (*Undaria* spp.) are very popular foods. The maximum limits for contaminants in food including seaweed products are covered in Article 5 of Chapter II of the South Korean Food Code (SKMFDS, 2019). It has set a ML for lead in sea mustard (*Undaria pinnatifida*) (including sporophyll of sea mustard) of 0.5 mg/kg. The ML for cadmium in laver (including seasoned laver) or sea mustard (including sporophyll of sea mustard) is 0.3 mg/kg, and the limits for heavy metals in dried seaweed products shall be converted to fresh weight basis according to the dehydration rate (SKMFDS, 2019).

The Agri-Food and Veterinary Authority (AVA) of Singapore has set MLs for heavy metals and arsenic in various foodstuffs including MLs for cadmium and inorganic arsenic in seaweeds in the Sale of Food Act (Chapter 283, Section 56(1)) G.N.No.S 372/1988-Food Regulations and its revised edition. It specifies that seaweed containing cadmium and inorganic arsenic in excess of 2 mg/kg shall not be allowed to be imported, sold, advertised, manufactured, consigned or delivered (AVA, Singapore, 2005).

Food Standards Australia New Zealand (FSANZ), which develops food standards for Australia and New Zealand, conducted a survey to investigate inorganic arsenic level in dried seaweed and seaweed-based products available in Australia (FSANZ, 2013). Given that seaweed such as *Undaria pinnatifida* is regularly consumed by humans, the Australian New Zealand Food Standards Code-Standard 1.4.1-Contaminants and Natural Toxicants has set a ML of 1.0 mg/kg for inorganic arsenic in seaweed and seaweed products, which is calculated with respect to the mass of seaweeds at 85% hydration (Food Standards Australia New Zealand FSANZ, 2016).

Codex standards are based on a sound scientific basis provided by independent international risk assessment bodies such as the JECFA and the Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA). Generally, they serve as a basis for international legislation. The provisions on the maximum limits for heavy metals in food and feed are mainly stipulated in the General standard for Contaminants and Toxins in Food and Feed (CODEX STAN 193–1995) established by Codex Committee on Contaminants in Foods (CCCF). Regardless of whether a ML exists or not, the levels of contaminants in all foods should comply with the basic principle of "As Low As Reasonably Achievable" (ALARA). MLs have been established for foods which contribute substantially to the total dietary exposure (CAC, 2019). Currently, the Coordinating Committee for Asia (CCASIA) has developed only one regional standard related to dried laver, roasted laver and seasoned laver products of the genus *Porphyra* (CXS 323R-2017). The regional standard requires that "laver products shall comply with the MRLs for contaminants listed in the *General Standard for Contaminants and Toxins in Food and Feed* established by the CAC (CAC, 2017). However, international legislation on guidance levels and specific codes of practice for seaweed have not yet been established.

Japanese food hygiene legislation states that the Ministry of Health, Labor and Welfare of Japan shall set MLs for Cd, Hg and other major contaminants in food. Although seaweed is a highly popular and widely consumed food in Japan, there are no specific MLs for contaminants or UL for iodine in seaweed products (JETO, 2010). However, a variety of advisories have been issued on how to reduce the safety hazards of seaweed consumption (JMAFF, 2015).

Table 4
The MLs for inorganic contaminants and iodine in seaweeds for human consumption in South Korea, Singapore, Australia and New Zealand.

Elements	South Korea[a]	Singapore[b]	Australia and New Zealand[c]
	Seaweed food products	Seaweed food products	Seaweed food products
	mg/kg	mg/kg	mg/kg ww [a]
Inorganic arsenic (iAs)	–	2	1.0
Cadmium (Cd)	0.3 applicable only to laver (including seasoned laver), sea mustard (including sporophyll of sea mustard)	2	–
Lead (Pb)	0.5 applicable only to sea mustard (including *sporophyll* of sea mustard)	–	–
Iodine (I)	–	–	–

Note: "—"no standard available; [a] wet weight, values are given per weight relative to seaweeds with a moisture content of 85%.

[a] South Korea's Ministry of Food and Drug Safety (MFDS). (2019). Food Code, Chapter 2. Common Standards and Specifications for General Foods.No.2019-57. Ministry of Food and Drug Safety, July 3, 2019. http://www.mfds.go.kr. MLs for dried products shall be converted and applied on a fresh weight basis considering such changes in water content, where water content changes due to drying process.

[b] Agri-Food and Veterinary Authority (AVA,Singapore).(2005).G.N.No.S 264/88.Sale of Food Act (Chapter 283,Section 56(1)) Food regulations Part III General provisions. http://statutes.agc.gov.sg. MLs are calculated with respect to the weight of seaweed products as sold.

[c] Food Standards Australia New Zealand (FSANZ) (2016). Australia New Zealand Food Standards Code–Standard 1.4.1–Contaminants and natural toxicants. Federal Register of Legislative Instruments F2013C00140 and F2016C00167. https://www.legislation.gov.au/Series/F2015L00408. The level for seaweed whether dried, dehydrated, concentrated or not is to be calculated with respect to the mass of the seaweed at 85% hydration.

4. Discussion

There are several different standards and regulations governing the MLs of heavy metals, arsenic and iodine in seaweed and seaweed products, but there are currently no harmonized international standards or legislation for contaminants and iodine in seaweed. Seaweed has different properties and grows in different environments than terrestrial agricultural plants, consequently they are associated with other food safety issues. The elemental composition of seaweed is highly variable and influenced by species, growing conditions, harvesting time and processing methods (Chen et al., 2018). This variability poses a challenge to the establishment of MLs for inorganic contaminants and iodine in seaweeds. Furthermore, the consumption patterns of seaweed differ among countries and population groups. In the following we will discuss the variability in the levels of arsenic, cadmium, lead, mercury and iodine in different seaweed products, bioavailability, dietary exposure, risk management measures and other hazards in the seaweed food chain in order to identify the needs for further development of international standards and regulations.

4.1. Variability in heavy metals, arsenic and iodine levels in seaweed products

4.1.1. Arsenic levels in seaweed

Some studies have demonstrated that seaweed can contain high levels of arsenic, and that the speciation of arsenic is predominantly dependent on the species of seaweed rather than the environment it originated from (Huang et al., 2022; Wolle et al., 2021). It has been reported that Phaeophyceae (brown algae) generally contains higher concentrations of total arsenic (between 0.80 and 250 mg/kg dw) than Rhodophyta (red algae) and Chlorophyta (green algae) (between 0.13 and 50 mg/kg dw and 0.10–30 mg/kg dw, respectively) (Almela et al., 2006; Huang et al., 2022; Hwang et al., 2010; Ma et al., 2018). Occurrence data compiled by EFSA showed that total arsenic levels varied in different seaweed species, and the highest mean levels of total arsenic (54 mg/kg dw) and inorganic arsenic (2.8 mg/kg dw) were found in kombu (*Saccharina japonica* syn. *Laminaria japonica*), however the species hijiki (*Sargassum fusiforme*), which is known to have a high content of inorganic arsenic, was not included in the data set (EFSA, 2023). The content of inorganic arsenic, to which most detrimental health effects have been associated, was lower than 1 mg/kg dw in most of the species of edible seaweed analyzed (Huang et al., 2022). The toxicity of organic arsenic appears to be lower, and with the exception of the *Sargassum* species and *Laminaria digitata* (Hogstad et al., 2023), inorganic arsenic constitutes less than 15% of total arsenic in seaweed (JECFA, 2011a). It is necessary to further study the toxicity of the main arsenic species present in seaweed in order to scientifically evaluate their risks (EFSA, 2023).

4.1.2. Cadmium levels in seaweed

Many studies have reported cadmium concentrations in seaweed and seaweed-based products. EFSA reported that the average content of cadmium found in algae-based formulations was 1.5 mg/kg ($n = 314$) and in seaweed 1.1 mg/kg ($n = 202$) (EFSA, 2012a). The levels of cadmium were highly variable among seaweed species. In the report by EFSA, the red algae, particular laver (*Porphyra* spp.) contained the highest mean levels of cadmium, but relatively high levels were also found in the brown algae wakame (*Undaria pinnatifida*), and the average cadmium content in green algae species was the lowest (EFSA, 2023). According to the results of the analyses of 343 edible seaweed samples reported by the Centre for Study and Promotion of Algae of France (CEVA), there were 108 samples (31.5%) with cadmium levels which exceeded 0.5 mg/kg dw (CEVA, & Centre d.Etude et de Valorisation des Algues, 2014; ANSES, 2018). Todorov et al. (2022) analyzed 46 edible seaweed samples purchased in the United States, and higher cadmium levels were found in brown and red macroalgae: the range in brown algae was 0.3–1.9 mg/kg dw ($n = 28$), in red algae 0.3–2.7 mg/kg dw ($n = 16$), and in green algae 0.2–0.3 mg/kg dw ($n = 2$). Cadmium levels were also analyzed in more than 1000 samples of edible seaweeds in China, and the highest mean concentration of cadmium was found in *Porphyra* spp. (2.7 mg/kg dw), which was higher than that in *Saccharina* spp. (syn. *Laminaria* spp.) (0.7 mg/kg dw) and *Undaria* spp. (1.95 mg/kg dw) (Zhao et al., 2015).

4.1.3. Lead levels in seaweeds

Several studies have reported the lead levels in seaweed. Almela et al. (2006) reported lead concentrations which ranged from below the Limit of Detection (LOD) (<0.05 mg/kg dw) to 2.4 mg/kg dw in 112 seaweed samples sold in Spain, with the highest levels in *Undaria pinnatifida*. Hwang et al. (2010) found an average lead level of 0.7 mg/kg dw ($n = 426$) in seaweeds sold in Korean markets, with concentrations ranging from <LOD (0.002 μg/mL) to 2.7 mg/kg dw. Large variations were reported within *Sargassum* spp. (0.4–2.6 mg/kg dw) and *Laminaria* spp. (0.1–2.9 mg/kg dw), likely due to differences in geographic origin of the seaweed, or processing conditions (Todorov et al., 2022). EFSA (2023) also reported variations in lead concentrations from compiled occurrence data, but lead levels were all relatively low (EFSA, 2023). In general, the available data suggest that the lead contribution from seaweed consumption to the total dietary exposure is relatively low, but it cannot be ruled out that exposure to lead may potentially become a safety issue due to the increasing seaweed intake (Food Safety Authority of Ireland FSAI, 2020).

4.1.4. Mercury levels in seaweeds

The mercury content in seaweed is generally reported as the total mercury content. The mercury levels detected in red and green algae are frequently below the limit of detection (Chen et al., 2018; Filippini et al., 2021; Todorov et al., 2022). The concentrations were only above the Limit of Quantification (LOQ) of 0.02 mg Hg/kg in brown algae, with the highest mercury levels found in *Sargassum fusiforme*, 0.04 ± 0.02 mg/kg dw (Todorov et al., 2022). Chen et al. (2018) reported that brown algae had significantly higher mean mercury content (0.06 mg/kg, $n = 153$) than red algae (0.01 mg/kg, $n = 142$). EFSA (2023) reported that the total mercury levels in seaweed were relatively low.

4.1.5. Iodine levels in seaweeds

There are significant differences in iodine content among different seaweed species. Some brown algae, especially *Saccharina* spp. have extremely high levels of iodine, in some cases exceeding 10,000 mg/kg dw (ANSES, 2018). In comparison, iodine levels were generally reported to be below 1000 mg/kg dw in red algae and below 100 mg/kg dw in green algae (Jelena et al., 2021). This is in line with the occurrence data compiled by EFSA (2023), where the lowest mean level of iodine was seen in green algae, and the highest mean level in brown algae. Kombu was the species with the highest reported mean iodine concentration of 3529 mg/kg (EFSA, 2023).

4.1.6. Effects of seaweed processing

The content of elements in seaweed products may be affected by processing methods. It has been found that some preparation practices or processing methods (such as washing, blanching, boiling, soaking and cooking) could reduce the levels of certain chemical hazards (Duinker et al., 2020). Considering that dried or salted seaweed products are often not ready-to-eat food, the contents of contaminants and iodine should be monitored in samples which are representative of the condition or state of the consumed product. It was reported that the process of washing and soaking could reduce the total arsenic content in hijiki by about 60 percent (Hanaoka et al., 2001). Different processing techniques have been shown to cause significant reductions in iodine levels in seaweed products: 10% for washing, 34–44% for soaking, and 58% for steaming and boiling (Nitschke & Stengel, 2016). However, the effects of different processing techniques on heavy metals, arsenic and iodine contents in different species are variable and further research is warranted (Blikra et al., 2022).

4.2. Bioavailability of heavy metals, arsenic and iodine in seaweed

When evaluating the intake and toxicity of heavy metals, arsenic and iodine, the bioavailability in seaweed products is often overlooked. Assessment of bioavailability is necessary to understand how readily elements in seaweed are absorbed during digestion (Blikra et al., 2022). However, the bioavailability is generally not taken into consideration when setting MLs in food. For setting health bases guidance values, the EFSA states that bioavailability depends on the chemical form of the element and should be considered when deriving an UL, if appropriate (EFSA, 2021). Furthermore, it is emphasized that processing may have an impact on the levels of contaminants and iodine, and there is currently a knowledge gap on the effect of processing on the bioavailability of elements in seaweed (EFSA, 2023).

The bioavailability of elements in seaweed depends on several factors, such as species, methodology (*in vivo* or *in vitro* bioavailability), chemical forms of the elements (organic or inorganic) and degree of processing (Blikra et al., 2022; Romarís-Hortas et al., 2011). However, *in vivo* studies in humans on the bioavailability of arsenic, cadmium, lead, mercury and iodine from seaweed remain relatively scarce. Furthermore, the bioavailability and toxicity vary greatly for different chemical forms particularly of mercury and arsenic, consequently chemical speciation data are required. Further research is needed on the bioavailability of potentially toxic elements such as arsenic and iodine for food safety evaluations of seaweed and seaweed-containing foods.

4.3. Dietary exposure to heavy metals, arsenic and iodine from seaweed consumption

4.3.1. Seaweed as a foodstuff

Eating and utilizing seaweed has a long history of use in Asia, but the consumption rates vary among different countries. The average consumption of seaweed has been estimated to be 5.2 g/adult per day for Chinese, 10.4 g per day for Japanese and 8.5 g per day for South Koreans (Chen et al., 2018; Anbazhagan et al., 2021; Zava & Zava, 2011). Huang et al. (2022) reported that the daily intake of inorganic arsenic from consuming red algae or green algae (assuming 1 kg/year consumption) was generally below 0.02 μg/kg body weight (bw) per day, whereas the estimated exposure to inorganic arsenic was higher for brown algae (0.8–3.8 μg/kg bw per day). This study concluded that consumption of *Sargassum* spp. may pose a risk to human health due to the excessive intake of inorganic arsenic, and this risk required continuous monitoring (Huang et al., 2022). A study on the dietary iodine intake among 63,323 inhabitants from various parts of China showed that kelp (*Saccharina* spp. syn. *Laminaria* spp.) and laver (*Porphyra* spp.) were consumed both in lower frequency and quantity than iodized salt and ground-water in some areas (Sui et al., 2011). In this study, the findings indicated that the dietary iodine intake of the Chinese population was generally safe at present (Sui et al., 2011). However, the estimated exposure of iodine, lead, arsenic and cadmium from seaweed consumption has not been conducted thoroughly in China due to the limited statistical data on the frequency and amount of seaweed consumed by different sub-populations and age groups.

Use of seaweed as a food or food ingredients has also been practiced in European cultures. The consumption of commercially available seaweed products, seaweed-containing foods and supplements has been reported in Norway, the UK and other European countries (Aakre et al., 2020; Bouga & Combet, 2015). An exposure assessment of lead, cadmium, inorganic arsenic, mercury and iodine from seaweed consumption was performed assuming a single weekly serving size of 5 g through the European Food Risk Assessment Fellowship Programme (EU-FORA) 2018/2019 (Monteiro et al., 2019). The study concluded that seaweed consumption by the general population would pose a low health risk for mercury, cadmium, and lead intake. For most of the population, there was no risk of excessive iodine and inorganic arsenic exposure if seaweed was consumed rarely. However, a more detailed consumption assessment was required for high-risk sub-groups, such as pregnant women, children and individuals with thyroid dysfunction (Monteiro et al., 2019). EFSA (2023) concluded that consumption of certain seaweeds can contribute to the overall dietary exposure to cadmium, lead, inorganic arsenic and iodine intake. However, further work was recommended to explore the relationship between seaweed consumption and the dietary exposure to inorganic contaminants and iodine intake, including collection of occurrence data, the impact of processing techniques and more detailed consumption data (EFSA, 2023).

4.3.2. *Seaweed as a food ingredient*

Commission Regulation (EU) 2023/915 and GB 2762-2022, do not include seaweed incorporated processed foods, such as seaweed-added chocolates, sushi sheets, and seaweed tea. However, seaweed as a food ingredient is increasingly popular among consumers. More attention should be paid to the MLs of contaminants and food safety issues of such processed products. According to the General standard for Contaminants and Toxins in Food and Feed (CODEX STAN 193–1995), MLs for contaminants are generally to be established for primary products and may be applied to processed, derived and multi-ingredient foods using appropriate conversion factors (CAC, 2019).When the levels are consistently different in processed products from which they are derived, and there is sufficient information on pollution pattern, it may be appropriate to establish separate MLs for these processed products (CAC, 2019).

4.4. *Risk management*

Some seaweed-producing and seaweed-consuming countries have established regulations for food safety hazards in seaweed products. As seen in section 3, the MLs for some major hazards in seaweed differ among elements and countries. The management of food safety issues associated with seaweed is generally lacking at an international level. The MLs for cadmium in seaweed as a foodstuff vary from none in the EU and China, to 1 mg/kg ww in Taiwan of China and 2 mg/kg in Singapore. Similarly for inorganic arsenic, the maximum limits vary from none in the EU, to 0.3–0.5 mg/kg in supplementary food for infants and aquatic seasoning containing seaweed in China. As for iodine, neither the EU nor China has maximum levels in food, and since iodine is a nutrient, it is not covered by Commission's Regulation for contaminants, but some national limits have been implemented. However, these limits vary extensively, from 20 mg I/kg dw in Germany, to 2000 mg I/kg dw in France. Harmonized international legislation could alleviate the need for national food safety evaluations of seaweed and seaweed-based products, as well as benefit the import and export trade of such foods and its products.

4.5. *Other hazards in the seaweed food chain*

Although iodine, arsenic and cadmium have been identified as major hazards related to seaweed consumption, several other hazards have been identified in seaweed such as persistent organic pollutants (e.g. dioxins and polychlorinated biphenyls), radionuclides and pesticide residues (EFSA, 2023; FAO and WHO, 2022). Furthermore, there are several potential microbial hazards associated with seaweed during growth, cultivation, harvest and handling. In the European seaweed chain, microbiological hazards such as *Salmonella* spp., *Bacillus* spp. and norovirus have been identified (EFSA, 2023). Because seaweed may be consumed raw, there is the opportunity for pathogens to survive (Banach et al., 2020). The consolidated version of Regulation (EC) No.2073/2005 concerns microbiological criteria for foodstuffs. Chapter 1 thereof lists the food safety criteria for several food categories, but there is no food category devoted to seaweed (EU, 2005b). In China, seaweed is generally consumed after being cooked, but the microbiological safety issues associated with ready-to-eat seaweed-based products (such as sushi) have been the focus of attention. The national food safety standard for algae and its products (GB 19643-2016) has set MLs for total aerobic count (1×10^5 CFU/g), coliform bacteria (30 CFU/g) and molds (3×10^2 CFU/g) in ready-to-eat seaweed products (NHCPRC & SAMR, 2016). The national food safety standard for pathogenic bacteria in prepackaged food (GB 29921-2021) stipulates that *Salmonella* must not be detected in ready-to-eat seaweed products (NHCPRC & SAMR, 2021). When processing seaweed, cross-contamination may occur. So it is important to carry out risk monitoring of the entire process of cold chain production, storage, and transportation of ready-to-eat seaweed products.

5. Conclusion and future perspectives

In recent years, increased awareness regarding sustainable and alternative plant-based food sources, and focus on healthy diets, have promoted the position of seaweed in the global cuisine. However, seaweed may be a source of exposure to potentially toxic elements, such as inorganic arsenic, cadmium and lead, or potentially harmful levels of micronutrients, particularly iodine. The impact of an increased seaweed consumption on the dietary exposure to heavy metals, inorganic arsenic and on iodine intake will depend on the seaweed species, quantity consumed and processing/preparation methods.

There are significant gaps in global regulations and standards concerning food safety of seaweed that require more attention. Although some regulations and guidance documents are available for certain marine resources, seaweeds remain insufficiently acknowledged. In the absence of Codex standards or guidelines that specifically address food safety aspects of seaweed production, processing and utilization, MLs for inorganic contaminants (arsenic, lead, cadmium, mercury) and limits for iodine in seaweed have been established in some national regulations and standards. Some consumption advisories have been provided on moderate intake and/or the appropriate handling and food preparation practices to address potential food safety issues related to seaweed. The EU has only developed some regulations regarding feed and dietary supplements made from seaweed. However, some countries within the EU have developed national regulations for seaweed used as food. In China, there are regulations only for certain elements in seaweed for human consumption and feed mainly made from seaweeds.

Notwithstanding, there are considerable differences in the regulations and standards on heavy metals, arsenic and iodine in seaweed products among countries. Different countries or regions have formulated different MLs mainly based on the health protection level of their domestic consumers, seaweed production and consumption volume, and trade situation. However, the scarce data on intake (quantities, frequencies, mode of use), occurrence and bioavailability of heavy metals, arsenic and iodine in seaweeds and its products, has hampered the risk assessment and management of the major hazards. Consequently, harmonized regulations or standards related to the safety of seaweed used as food and feed are still lacking. The present review on the food safety regulations and standards for inorganic contaminants and iodine in seaweeds for human consumption and animal fodder provides an overview of current risk management, and contributes to future work to establish appropriate international standards and food safety regulations for seaweed products. It is envisaged that such standards and legislation would in turn safeguard the production, processing and utilization of seaweed for food and feed.

Author contributions

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Declaration of competing interest

There are no conflicts of interest to declare.

Data availability

No new data was used for the research described in the article.

Acknowledgments

This work was supported by the National Natural Science Foundation of China International (Regional) Cooperation and Exchange Programs (NSFC-RCN, 32061133008); China Agriculture Research System (CARS 50); Central Public-interest Scientific Institution Basal Research Fund, Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences (20603022023011) and the Research Council of Norway (Project No. 320687; SafeKelp).

References

Aakre, I., Evensen, L. T., Kjellevold, M., Dahl, L., & Markhus, M. W. (2020). Iodine status and thyroid function in a group of seaweed consumers in Norway. *Nutrients, 12*(11), 3483. https://doi.org/10.3390/nu12113483

Aakre, I., Solli, D. D., Markhus, M. W., Hanne, K. M., Dahl, L., Henjum, S., Alexander, J., Korneliussen, P. A., Madsen, L., & Kjellevold, M. (2021). Commercially available kelp and seaweed products–valuable iodine source or risk of excess intake? *Food & Nutrition Research, 65*, 7584. https://doi.org/10.29219/fnr.v65.7584

AFSSA. (2009). *Opinion of the French Food Safety Agency on the recommended maximum inorganic arsenic content of laminaria and consumption of these seaweeds in light of their high iodine content*. Maisons-Alfort, France: AFSSA.

Agri-food and veterinary authority (AVA,Singapore). *G.N.No.S 264/88.Sale of Food Act (Chapter 283,Section 56(1)) Food regulations Part III General provisions：Incidental Constituents in Food.1-234*, (2005). http://statutes.agc.gov.sg.

Almela, C., Clemente, M. J., Vélez, D., & Montoro, R. (2006). Total arsenic, inorganic arsenic, lead and cadmium contents in edible seaweed sold in Spain. *Food and Chemical Toxicology, 44*(11), 1901–1908. https://doi.org/10.1016/j.fct.2006.06.011

Anbazhagan, V., Partheeban, E. C., Arumugam, G., Arumugam, A., Rajendran, R., Paray, B. A., Al-Sadoon, M. K., & Al-Mfarij, A. R. (2021). Health risk assessment and bioaccumulation of metals in brown and red seaweeds collected from a tropical marine biosphere reserve. *Marine Pollution Bulletin, 164*(4), Article 112029. https://doi.org/10.1016/j.marpolbul.2021.112029

ANSES. (2018). Opinion of the French Agency for Food, Environmental and Occupational Health & Safety on the risk of excess iodine intake from the consumption of seaweed in foodstuffs. Request No 2017-SA-0086 https://www.anses.fr/en/system/files/NUT2017SA0086EN.pdf.

ANSES. (2020). Opinion of the French Agency for Food, Environmental and Occupational Health & Safety on maximum cadmium levels for seaweed intended for human consumption. Request No 2017-SA-0070 https://www.anses.fr/en/system/files/ERCA2017SA0070EN.pdf.

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I. C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., & Ullmann, J. (2021). Current status of the algae production industry in Europe: An emerging sector of the blue bioeconomy. *Frontiers in Marine Science, 7*, Article 626389. https://doi.org/10.3389/fmars.2020.626389

Banach, J. L., Hoek-van den Hil, E. F., & Van der Fels-Klerx, H. J. (2020). Food safety hazards in the European seaweed chain. *Comprehensive Reviews in Food Science and Food Safety, 19*(2), 332–364.

Blikra, M. J., Henjum, S., & Aakre, I. (2022). Iodine from brown algae in human nutrition, with an emphasis on bioaccessibility, bioavailability, chemistry, and effects of processing: A systematic review. *Comprehensive Reviews in Food Science and Food Safety, 21*, 1517–1536. https://doi.org/10.1111/1541-4337.12918

Boskabady, M., Marefati, N., Farkhondeh, T., Shakeri, F., Farshbaf, A., & Boskabady, M. H. (2018). The effect of environmental lead exposure on human health and the contribution of inflammatory mechanisms, a review. *Environment International, 120*, 404–420. https://doi.org/10.1016/j.envint.2018.08.013

Bouga, M., & Combet, E. (2015). Emergence of seaweed and seaweed-containing foods in the UK: Focus on labeling, iodine content, toxicity and nutrition. *Foods, 4*(2), 240–253.

Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A., Lucente, D., Mair, G., Miao, W., Potin, P., Przybyla, C., Reantaso, M., Roubach, R., Tauati, M., & Yuan, X. (2021). *Seaweeds and microalgae: An overview for unlocking their potential in global aquaculture development*. Rome: FAO Fisheries and Aquaculture Circular.

CEVA, Centre d.Etude et de Valorisation des Algues. (2014). *Edible seaweed and French regulation - synthesis made by CEVA (31/03/2014)*. Pleubian, France: CEVA.

Chen, Q., Pan, X. D., Huang, B. F., & Han, J.-L. (2018). Distribution of metals and metalloids in dried seaweeds and health risk to population in southeastern China. *Scientific Reports, 8*, 3578.

Codex Alimentarius Commission (CAC). (2017). Regional standard for laver products (CXS 323r-2017). In *Codex Alimentarius*. Rome. Cited December 2022 https://fao.org/fao-who-codexalimentarius/codex-texts/list-standards/en/.

Codex Alimentarius Commission (CAC). (2019). *General standard for contaminants and toxins in food and feed, CXS 193-1995, rev.4-2017, ame.9-2019*. Rome, Italy: World Health Organization, Food and Agriculture Organization of the United Nations.

Domínguez, H. (2013). Algae as a source of biologically active ingredients for the formulation of functional foods and nutraceuticals. *Functional Ingredients from Algae for Foods and Nutraceuticals*, 1–19. https://doi.org/10.1533/9780857098689.1

Duinker, A., Kleppe, M., Fjære, E., Biancarosa, I., Heldal, H. E., Dahl, L., & Lunestad, B. T. (2020). Knowledge update on macroalgae food and feed safety-based on data generated in the period 2014–2019 by the Institute of Marine Research, Norway. Cited 30 October 202. In *Havforskningsinstituttet*. Bergen, Norway.hi.no/hi/nettrapporter/rapport-fra-havforskningen-en-2020-44.

European Food Safety Authority (EFSA). (2002). *Opinion of the scientific committee on food on the tolerable upper intake level of iodine*. European Commission, Health & Consumer Protection Directorate-General.

European Food Safety Authority (EFSA). (2004). Opinion of the scientific panel on contaminants in the food chain on a request from the Commission related to mercury and methylmercury in food. *EFSA Journal, 34*, 1–14. https://doi.org/10.2903/j.efsa.2004.34

European Food Safety Authority (EFSA). (2006a). Statement on a request from the Commission related to iodine in seaweed. *EFSA Journal, 4*(10), 2. https://doi.org/10.2903/j.efsa.2006.1046

European Food Safety Authority (EFSA). (2006b). *Tolerable upper intake levels for vitamins and minerals*. Parma, Italy: EFSA.
European Food Safety Authority (EFSA). (2009b). Scientific opinion on arsenic in food. *EFSA Journal, 7*(10), 199. https://doi.org/10.2903/j.efsa.2009.1351
European Food Safety Authority (EFSA). (2010). EFSA panel on contaminants in the food chain (CONTAM). Scientific opinion on lead in food. *EFSA Journal, 8*, 1570. https://doi.org/10.2903/j.efsa.2010.1570
European Food Safety Authority (EFSA). (2011). EFSA panel on contaminants in the food chain (CONTAM), scientific opinion on tolerable weekly intake for cadmium. *EFSA Journal 2011, 9*(2), 1975. https://doi:10.2903/j.efsa.2011.1975.
European Food Safety Authority (EFSA). (2012a). Cadmium dietary exposure in the European population. *EFSA Journal 2012, 10*(1), 2551. https://doi.org/10.2903/j.efsa.2012.2551
European Food Safety Authority (EFSA). (2012b). Scientific opinion on the risk for public health related to the presence of mercury and methylmercury in food. *EFSA Journal, 10*(12), 2985. https://doi.org/10.2903/j.efsa.2012.2985
European Food Safety Authority (EFSA). (2013). Scientific opinion on the safety and efficacy of iodine compounds (E2) as feed additives for all species: Calcium iodate anhydrous and potassium iodide, based on a dossier submitted by HELMAG. Parma, Italy efsa.onlinelibrary.wiley.com/doi/pdf/10.2903/j.efsa.2013.3101.
European Food Safety Authority (EFSA). (2017). *Technical report of European food safety authority: Dietary reference values for nutrients*. EFSA Supporting publication, Article e15121. https://doi.org/10.2903/sp.efsa.2017.e15121
European Food Safety Authority (EFSA). (2021). Statement on the derivation of Health-Based Guidance Values (HBGVs) for regulated products that are also nutrients. *EFSA Journal, 19*(3), 39, 6479 https://efsa.onlinelibrary.wiley.com/doi/epdf/10.2903/j.efsa.2021.6479.
European Food Safety Authority (EFSA). (2023). Scientific report on the dietary exposure to heavy metals and iodine intake via consumption of seaweeds and halophytes in the European population. *EFSA Journal 2023, 21*(1), 7798. https://doi.org/10.2903/j.efsa.2023.7798
European Food Safety Authority(EFSA). (2009a). Scientific opinion of the panel on contaminants in the food chain on a request from the European commission on cadmium in food. *EFSA Journal, 980*, 1–139.
European Union (EU). (2002). Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on undesirable substances in animal feed. *Official Journal of the European Communities, 45*(L 140), 10–21.
European Union (EU). (2005a). Commission Regulation (EC) No 396/2005 of the European Parliament and the Council of 23 February 2005 on maximum residue levels of pesticides in or on food and feed of plant and animal origin and amending Council Directive 91/414/EEC. *Official Journal of the European Union, L70*, 1–16.
European Union (EU). (2005b). Commission Regulation (EC) No 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs. *Official Journal of the European Union, L338*, 1–26.
European Union (EU). (2013). Commission Regulation (EU) No 1275/2013 of 6 December 2013 amending Annex I to Directive 2002/32/EC of the European Parliament and of the Council as regards maximum levels for arsenic, cadmium, lead, nitrites, volatile mustard oil and harmful botanical impurities. *Official Journal of the European Union, 56*(L 328), 86–92.
European Union (EU). (2018). Recommendation (EU) 2018/464 of 19 March 2018 on the monitoring of metals and iodine in seaweed, halophytes and products based on seaweed. *Official Journal of the European Union, 61*(L 78), 16–18.
European Union (EU). (2023). Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. *Official Journal of the European Union, L119*, 103–157.
FAO. (2018). *The global status of seaweed production, trade and utilization*. Rome: FAO. Globefish Research Programme.
FAO. (2020). *The state of world Fisheries and aquaculture 2020. Sustainability in action*. Rome: Food and Agriculture Organization of the United Nations.
FAO and WHO. (2022). Report of the expert meeting on food safety for seaweed – current status and future perspectives. Rome, 28–29, October 2021. In *Food safety and quality series No. 13*. Rome.
Ficheux, A. S., Pierre, O., Garrec, R. L., & Roudot, A. C. (2022). Seaweed consumption in France: Key data for exposure and risk assessment. *Food and Chemical Toxicology, 159*, Article 112757. https://doi.org/10.1016/j.fct.2021.112757
Filippini, M., Baldisserotto, A., Menotta, S., Fedrizzi, G., Rubini, S., Gigliotti, D., Valpiani, G., Buzzi, R., Manfredini, S., & Vertuani, S. (2021). Heavy metals and potential risks in edible seaweed on the market in Italy. *Chemosphere, 263*, Article 127983. https://doi.org/10.1016/j.chemosphere.2020.127983
Food Standards Australia New Zealand (FSANZ). (2013). *Food Standards Australia New Zealand. Survey of inorganic arsenic in seaweed and seaweed-containing products available in Australia*. Canberra.
Food and Environmental Hygiene Department, Hong Kong special administrative region of China (FEHD, HKC). (2018). Food adulteration regulation-metallic contamination (amendment). *Food and Environmental Hygiene Department of Hong Kong*, 1–24. https://www.cfs.gov.hk/english/whatsnew/whatsnew_fstr/whatsnew_fstr_PA_Food_Adulteration_Metallic_Contamination.html.
Forster, J., & Radulovich, R. (2015). *Chapter 11-seaweed and food security, seaweed sustainability* (pp. 289–313). Academic Press. https://doi.org/10.1016/B978-0-12-418697-2.00011-8
Hanaoka, K., Yosida, K., Tamaño, M., Kuroiwa, T., Kaise, T., & Maeda, S. (2001). Arsenic in the prepared edible brown algae hijiki, Hizikia fusiforme. *Applied Organometallic Chemistry, 15*(6), 561–565. https://doi.org/10.1002/Aoc.195
Hogstad, S., Cederberg, L. D., Eriksen, H., Kollander, B., Ólafsson, G., & Mikkelsen, B. (2023). *A Nordic approach to food safety risk management of seaweed for use as food. Current status and basis for future work*. Copenhagen, Denmark: Nordic Council of Ministers. https://doi.org/10.6027/temanord2022-564
Huang, Z. X., Bi, R., Musil, S., Pétursdóttir, Á. H., Luo, B. C. e, Zhao, P. H., Tan, X., & Jia, Y. F. (2022). Arsenic species and their health risks in edible seaweeds collected along the Chinese coastline. *Science of the Total Environment, 847*, Article 157429.
Hwang, Y. H., Hsiao, C. K., & Lin, P. W. (2019). Globally temporal transitions of blood lead levels of preschool children across countries of different categories of Human Development Index. *Science of The Total Environment, 659*, 1395–1402. https://doi.org/10.1016/j.scitotenv.2018.12.436
Hwang, Y. O., Park, S. G., Park, G. Y., Choi, S. M., & Kim, M. Y. (2010). Total arsenic, mercury, lead, and cadmium contents in edible dried seaweed in Korea. *Food Additives & Contaminants Part B-Surveillance, 3*(1), 7–13. https://doi.org/10.1080/19440040903532079
Institute of Medicine. (2006). *Dietary reference intakes: The essential guide to nutrient requirements*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11537
Japan External Trade Organization (JETO). (2010). *Handbook for agricultural and Fishery products import regulations 2009*. Japan External Trade Organization. February 2010.
Japanese Ministry of Agriculture, Forestry and Fisheries (JMAFF). (2015). How to cook hijiki at home for safer eating. http://www.maff.go.jp/j/syouan/tikusui/gyokai/g_kenko/busitu/pdf/hijiki02.pdf.
JECFA. (2011a). Safety evaluation of certain contaminants in food: Seventy-second report of the Joint FAO/WHO expert committee on food additives (JECFA). *World Health Organization (WHO)*. Food Additives Series 63.
JECFA. (2011b). *Evaluation of certain contaminants in food: Seventy-third report of the Joint FAO/WHO Expert committee on food additives (JECFA)*. Geneva, Switzerland: World Health Organization (WHO) Technical Report Series 960.
JECFA. (2019a). Mercury. Retrieved from http://apps.who.int/foodadditives-contaminants-jecfa-atabase/chemical.aspx?chemID=1806.
JECFA. (2019b). Methylmercury. Retrieved from http://apps.who.int/food-additives-contaminants-jecfa-database/chemical.aspx?chemID=3083.
JECFA. (2019c). Iodine. Retrieved from http://apps.who.int/foodadditives-contaminants-jecfa-database/chemical.aspx?chemID=2048.
Jelena, M., Carla, R., Mário, D., & João, P. N. (2021). Determination of total iodine content in edible seaweeds: Application of inductively coupled plasma-atomic emission spectroscopy. *Algal Research, 53*, Article 102149. https://doi.org/10.1016/j.algal.2020.102149
Katagiri, R., Yuan, X., Kobayashi, S., & Sasaki, S. (2017). Effect of excess iodine intake on thyroid diseases in different populations: A systematic review and meta-analyses including observational studies. *PLoS One, 12*(3), Article e0173722. https://doi.org/10.1371/journal.pone.0173722
Lähteenmäki-Uutela, A., Rahikainen, M., Camarena-Gómez, M. T., Piiparinen, J., Spilling, Y., & Yang, B. (2021). European Union legislation on macroalgae products. *Aquaculture International, 29*, 487–509. https://doi.org/10.1007/s10499-020-00633-x
Ma, Z. L., Lin, L. D., Wu, M. J., Yu, H. G., Shang, T. G., Zhang, T. T., & Zhao, M. (2018). Total and inorganic arsenic contents in seaweeds: Absorption, accumulation, transformation and toxicity. *Aquaculture, 497*, 49–55.
Ministry of Health and Welfare Taiwan of China (MHWTC). (2018). Sanitation standard for contaminants and toxins in food: Appendix1. Maximum levels (ML) of metals in foods. https://db.lawbank.com.tw/Eng/FLAW/FLAWDAT01.aspx?Lsid=FL088408.
Monagail, M. M., Cummins, E., Bermejo, R., Daly, E., Costello, D., & Morrison, L. (2018). Quantification and feed to food transfer of total and inorganic arsenic from a commercial seaweed feed. *Environment International, 118*, 314–324. https://doi.org/10.1016/j.envint.2018.05.032
Monteiro, M. S., Sloth, J., Holdt, S., & Hansen, M. (2019). Analysis and risk assessment of seaweed. *EFSA Journal, 17*, Article e170915. https://doi.org/10.2903/j.efsa.2019.e170915
Müssig, K. (2009). *Iodine-induced toxic effects due to seaweed consumption. Comprehensive handbook of iodine* (pp. 897–908).
National Health Commission of PRC & State Administration for Market Regulation (NHCPRC & SAMR). (2016). *GB 19643-2016.The national food safety standard for algae and its products*.
National Health Commission of PRC & State Administration for Market Regulation (NHCPRC & SAMR). (2021). *GB 29921-2021.The national food safety standard for MLs of pathogenic bacteria in prepackaged food*.
National Health Commission of PRC & State Administration for Market Regulation (NHCPRC & SAMR). (2022). *GB 2762-2022. The national food safety standard for Maximum levels of contaminants in food*.
National Health and Family Planning Commission of PRC(NHFPCPRC). (2017). *WS/T 578.3-2017.Chinese dietary reference intakes-Part 3: Trace element*.
Nitschke, U., & Stengel, D. B. (2016). Quantification of iodine loss in edible Irish seaweeds during processing. *Journal of Applied Phycology, 28*(6), 3527–3533. https://doi.org/10.1007/s10811-016-0868-6
Øverland, M., Mydland, L. T., & Skrede, A. (2019). Marine macroalgae as a source of protein and bioactive compounds in feed for monogastric animals. *Journal of the Science of Food and Agriculture, 99*(1), 13–24. https://doi.org/10.1002/jsfa.9143
Peñalver, R., Lorenzo, J. M., Ros, G., Amarowicz, R., Pateiro, M., & Nieto, G. (2020). Seaweeds as a functional ingredient for a healthy diet. *Marine Drugs, 18*, 301. https://doi.org/10.3390/md18060301
Raja, K., Kadirvel, V., & Subramaniyan, T. (2022). Seaweeds, an aquatic plant-based protein for sustainable nutrition - a review. *Future Foods, 5*, Article 100142.
RASFF portal. (2021). High level of Cadmium in seaweed meal. Available at: https://webgate.ec.europa.eu/rasff-window/screen/notification/501501. (Accessed 7 March 2023).

RASFF portal. (2022). Excessive iodine content in dried seaweed from China. Available at: https://webgate.ec.europa.eu/rasff-window/screen/notification/575103. (Accessed 7 March 2023).

Romarís-Hortas, V., García-Sartal, C., del Carmen Barciela-Alonso, M., Domínguez-González, R., Moreda-Piñeiro, A., & Bermejo-Barrera, P. (2011). Bioavailability study using an in-vitro method of iodine and bromine in edible seaweed. *Food Chemistry, 124*(4), 1747–1752. https://doi.org/10.1016/j.foodchem.2010.07.117

Scientific Committee on Food (SCF). (2002). *Opinion of the Scientific Committee on Food on the tolerable upper intake level of iodine*. Brussels, Belgium: SCF.

Sharma, V. K., & Sohn, M. (2009). Aquatic arsenic: Toxicity, speciation, transformations and remediation. *Environment International, 35*, 743–759.

South Korea's Ministry of Food and Drug Safety (SKMFDS). (2019). Food code. In *Chapter 2. Common standards and Specifications for general foods.No.2019-57. Ministry of food and Drug safety*. July 3 2019 http://www.mfds.go.kr.

Standardization Administration of China, General Administration of Quality Supervision, Inspection and Quarantine (SAC & GAQSIQ). (2017). *GB13078-2017.The national hygienic standard for feeds*.

Sui, H. X., Li, J. W., Mao, W. F., Zhu, J. H., He, Y. N., Song, X. Y., Ma, N., Zhang, L., Liu, S. N., Liu, Z. P., & Li, F. Q. (2011). Dietary iodine intake in the Chinese population. *Biomedical and Environmental Sciences, 24*(6), 617–623. https://doi.org/10.3967/0895-3988.2011.06.005

Todorov, T. I., Wolle, M. M., & Conklin, S. D. (2022). Distribution of 26 major and trace elements in edible seaweeds from the US market. *Chemosphere, 294*, Article 133651. https://doi.org/10.1016/j.chemosphere.2022.133651

Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., Smith, A. G., Camire, M. E., & Brawley, S. H. (2017). Algae as nutritional and functional food sources: Revisiting our understanding. *Journal of Applied Phycology, 29*, 949–982.

WHO, UNICEF, ICCIDD. (2007). Assessment of iodine deficiency disorders and monitoring their elimination. In *A Guide for Programme Managers* (3rd ed.). Geneva: World Health Organization.

Wolle, M. M., Todorov, T. I., & Conklin, S. D. (2021). Arsenic species in seaweeds commercially available in the United States. *ACS Food Science & Technology, 1*(4), 511–523.

Zava, T. T., & Zava, D. T. (2011). Assessment of Japanese iodine intake based on seaweed consumption in Japan: A literature-based analysis. *Thyroid Research, 2011, 4*(1), 14. https://doi.org/10.1186/1756-6614-4-14

Zhao, Y. F., Wu, J. F., Shang, D. R., Ning, J. S., Zhai, Y. X., Sheng, X. F., & Ding, H. Y. (2015). Subcellular distribution and chemical forms of cadmium in the edible seaweed, porphyra yezoensis. *Food Chemistry, 168*, 48–54. https://doi.org/10.1016/j.foodchem.2014.07.054

Food Standards Australia New Zealand (FSANZ). (2016). Australia New Zealand food standards code–standard 1.4.1–contaminants and natural toxicants. Federal Register of Legislative Instruments F2013C00140
. and, F2016C00167., 1–8. https://www.legislation.gov.au/Series/F2015L00408.

Food Safety Authority of Ireland (FSAI). (2020). Safety considerations of seaweed and seaweed-derived foods available on the Irish Market. Report of the Scientific Committee of the Food Safety Authority of Ireland (FSAI).1-83.https://www.fsai.ie/getmedia/ab05b59a-786a-400c-9ed2-2e3ebbc04c72/safety-considerations-of-seaweed-and-seaweed-derived-foods-available-on-the-irish-market-(1).pdf?ext=.pdf.

Berlin Federal Institute for Risk Assessment (BfR). (2004). Health risks linked to high iodine levels in dried algae. Updated BfR Opinion No.026/2007. Updated on 12 June 2007.1-1. mobil.bfr.bund.de/cm/349/health_risks_linked_to_high_iodine_levels_in_dried_algae.pdf.