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# New marine low trophic resources as food: nutritional and food safety aspects

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Food agencies recommend increasing the consumption of aquatic food to promote healthy living and sustainability, and, particularly, to prevent Western lifestyle-related diseases and secure sustainable food systems. This requires growth in global seafood production, and the utilization of low trophic species (LTS) is suggested. LTS are already considered nutritious and important in Asian and Pacific diets. As the use of LTS is expanding in Western diets, producers and consumers need information on the food safety practices associated with them and their nutritional content. LTS are mainly immobile or slow-moving extractive species or organisms that feed on such, and their nutrient and contaminant content varies by species and location. Species-specific knowledge on nutritional contents and safe consumption limits is often missing, making the monitoring and analysis of contaminants, nutrients, and consumption data crucial to guiding the utilization and consumption of LTS. Using global and regional standards regarding nutrients, food hazards, and labeling, this review highlights the appropriate guidelines and regulations for guiding the utilization of selected novel species and also identifies knowledge gaps.

## KEYWORDS

seafood, low trophic, aquatic, nutrients, contaminants, heavy metals

## 1 Introduction

The United Nations (UN) emphasizes the need for sustainable food security and improved nutrition for all (UN, 2015). Food production and consumption (oral exposure) are responsible for significant global environmental and human health challenges (Gordon et al., 2017; Poore and Nemecek, 2018a), and rapid population growth has exacerbated these. As land-based resources are limited, and this production is reaching its carrying capacity, the procurement of food (and feed) from well-managed oceans is essential for nutritional security, economies, livelihoods, and cultures (SAPEA, 2017; Costello et al., 2020; Gephart et al., 2021; Golden et al., 2021; Crona et al., 2023; Zamborain-Mason et al., 2023). Increased production at lower trophic levels by capture and culture may lead to more sustainable and

responsible utilization of marine food resources. (SAPEA, 2017; Costello et al., 2020; Krause et al., 2022). Ocean foods may present an opportunity for better performance regarding nutrition, greenhouse gas emissions, freshwater use, nitrogen and phosphorus emissions, or more sustainable diets (Poore and Nemecek, 2018b; Hallström et al., 2019; Gephart et al., 2021). This strategy, namely of shifting human diets from high-greenhouse gas-emitting land-based sources of protein (e.g., red meat) to lower-greenhouse gas-emitting ocean-based protein sources, and of improving both individuals' health and the global economy through food (and feed) from marine low trophic species (LTS), has been put forward by multiple actors such as the UN, the Ocean Panel (Costello et al., 2020), and SAPEA (SAPEA, 2017).

The term LTS is used for a range of species, including non-fed or extractive species and species that feed on such, and also deposit or suspension feeders. Several LTS may contribute to improved food security (Krause et al., 2022), including seaweed (macroalgae), abalone (snails), bivalve mollusks, and sea urchins (roe), which are used as examples of LTS in this review and may be a source of essential nutrients such as protein, vitamins, minerals, and omega-3-rich lipids. Higher levels of undesirable contaminants due to the biomagnification in the food chain support the view that a shift toward food sources from LTS is advisable. Mariculture, fresh water, and land-based aquaculture production are perceived as options that can further reduce the content of contaminants, as they allow better control of feed ingredients and outgrowing environments than the harvesting of wild populations.

Increased seafood consumption may also benefit human health globally. An unhealthy diet is a significant risk factor for developing chronic diseases such as cardiovascular heart disease (CVD), stroke, obesity, metabolic syndrome, and diabetes (Murray et al., 2020). It is well documented that increased fish and seafood consumption may reduce the incidence of lifestyle diseases (FAO/WHO, 2011a; EFSA, 2015). The latest thorough risk-benefit assessment by the Norwegian Scientific Committee for Food and Environment (VKM) concluded that the benefits of fish consumption far outweighed the food safety risks in the Norwegian context (VKM, 2022). However, food culture varies around the world, and the Western diet has evolved to include new and novel food resources (e.g., algae, sea cucumbers, and sea urchins). When raw materials, processes, and cuisines change, new challenges to food safety and nutrient availability arise. Food hazards, heavy metals, contaminants, and marine biotoxins are associated with marine food and LTS (Venugopal and Gopakumar, 2017; Eilertsen et al., 2022; Elvevoll et al., 2022; FAO/WHO, 2022; FAO, 2022). The European and global legislation and guidance documents intended to ensure food safety associated with producing and utilizing specific LTS, giving important information such as limits for maximum (MLs) daily or weekly intake, are often lacking. Our aim in this review has been to aggregate the available guidance, as similar standards, laws, and regulations apply to food in general, and to provide a guide on how to assess food safety risks when a regulatory framework is not in place. Altogether, this review paper identifies and highlights appropriate guidelines and regulations and identifies gaps and specific needs for knowledge, to guide the utilization of the selected novel marine LTS.

The objective of this review is to provide a clear and concise overview of the most relevant guidelines and codes of practice adopted by the United Nations [World Health Organization (WHO)/Food and Agriculture Organization (FAO)] Codex Alimentarius Commission (CAC), in addition to the regional regulations from the European Commission (EC) and the United States (USA).

## 2 Seafood and nutritional contribution

Seafood is an important part of balanced diets. It contains several essential nutrients (Jensen et al., 2016; Durazzo et al., 2022; VKM, 2022; Zamborain-Mason et al., 2023), is generally regarded as nutritious, and its benefits to human health are related to many physiological functions. In seafood, lean animal proteins are combined with healthy long-chain polyunsaturated fatty acids of the omega-3 class (marine *n*-3 LC-PUFA) and highly bioavailable micronutrients. With a few exceptions, seafood protein compares favorably with other protein sources (Jayasekara et al., 2020; Zamborain-Mason et al., 2023).

When assessing the nutritional benefits of seafood, the focus has been on two marine *n*-3 LC-PUFAs, eicosapentaenoic acid (EPA, 20:5*n*-3) and docosahexaenoic acid (DHA, 22:6*n*-3). This is due to strong scientific evidence of the positive health impact of *n*-3 LC-PUFAs, their contribution to the attenuation of lifestyle diseases, and the lack of availability from other dietary sources (VKM, 2022). Other key nutrients in seafood include minerals and trace elements such as iodine, selenium, and vitamins D and B<sub>12</sub> (Golden et al., 2021). Seafood can provide essential vitamins and minerals such as vitamin D, selenium, iodine, zinc, magnesium, and calcium (Zamborain-Mason et al., 2023). These vitamins and minerals are often more abundant in seafood than in the meat of land animals, making the consumption of seafood a great means of increasing one's intake of them (Wright et al., 2018).

The nutritional contribution from LTS is less systematically studied, but the field is rapidly evolving. A recent paper has assessed the nutritional contribution and food safety aspects of specific seaweed (Jacobsen et al., 2023). *Saccharina latissima* and *Ulva* species are good sources of calcium, magnesium, iron, selenium, and the vitamin B<sub>12</sub>, as they contribute to > 15% of the daily reference intake (DRI) per 5-g portion of dry weight. The contribution to DRI for fiber, sodium, and protein was lower. Food safety was compromised by very high iodine levels for *S. latissima*. In sea cucumber, *Cucumaria frondosa*, the content of micronutrients and minerals is generally high compared with that in other seafood, particularly of the vitamins B<sub>12</sub> and E, and selenium (as high as 40% of DRI) (Langdal et al., 2023; Muhsin et al., 2023). The content of *n*-3 fatty acids in sea cucumbers was similar to that in lean seafood, such as cod and shrimp, and food safety was compromised by the content of inorganic arsenic in sea cucumbers from Norwegian waters.

The recent work of the European Food Safety Authority (EFSA) on nutritional profiling states that fish and shellfish, in addition to their by-products, can significantly increase the intake of *n*-3 LC-PUFAs, iodine, and vitamin D (EFSA, 2022). The contribution

of seafood as a source of animal protein, vitamins and minerals, and carbohydrates was assessed as less significant to the European diet.

## 2.1 Marine *n*-3 LC-PUFAs

Seafood consumption is known to reduce the risk of developing cardiometabolic diseases (Rimm et al., 2018; Chandra et al., 2020). These results are based on epidemiological evidence and meta-analyses (Afshin et al., 2019; VKM, 2022) and on preclinical and clinical studies (Maehre et al., 2015b; Innes and Calder, 2020). The recommendations for seafood consumption are often based on the contents of EPA and DHA, and seafood consumption entailing a daily intake of 200 mg–500 mg of EPA and DHA is recommended by the UN Food and Agricultural Organization (FAO) and World Health Organization (WHO) (FAO/WHO, 2011a). Other recommendations and possible mechanisms for the dietary prevention of cardiometabolic diseases have been reviewed elsewhere (Maehre et al., 2015a; VKM, 2022).

## 2.2 Iodine

The trace element iodine (I) is important for the regulation of metabolic rate, embryology, and physical, mental, and cognitive development (WHO, 2007). In Europe, salt iodization has reduced iodine deficiency. It is, however, still a public health concern (WHO, 2007; EFSA, 2022), and a high prevalence of I deficiency is still evident in subpopulations in several European countries (Ittermann et al., 2020). It is essential that individuals who are pregnant or planning to become pregnant have an adequate I intake to avoid any long-term adverse impact on the child (Hay et al., 2019). However, it is also important to note that excessive I can cause thyroid gland dysfunction. It is worth noting that brown seaweed has an exceptionally high content of I. The high I content makes brown seaweed an excellent source of I, but regular intake of only a few grams would cause excessive intake of I (Aakre et al., 2020; Aakre et al., 2021; Jacobsen et al., 2023). The EFSA's Scientific Committee on Food (SCF) suggests a maximum upper-level (UL) intake of 600 µg I per day for adults, adjusted for different age groups based on differences in body weight (EFSA, 2014a).

## 2.3 Selenium

An adequate intake of selenium (Se) is crucial for good health. Se helps activate the thyroid hormone, and selenoenzymes have important antioxidant properties (Winther et al., 2020). Unfortunately, many adult Europeans do not meet the daily recommended, or adequate, intake (AI) of Se, which is 70 µg per day (EFSA, 2014b). A low intake of Se has been linked to reduced immune function, cognitive decline, and an increased risk of goiter, autoimmune thyroiditis (Hashimoto's disease), hyperthyroidism (Graves' disease), and mortality (EFSA, 2014b). In addition, Se intake is associated with antiviral mechanisms and infection

protection and is regarded as essential for reproduction (Winther et al., 2020).

Interestingly, the intake of LTS may protect against mercury (Hg) toxicity due to the high content of Se in LTS and other seafood (Yamashita et al., 2013; Mellingen et al., 2022; Jacobsen et al., 2023; Langdal et al., 2023). The ideal ratio of Se to mercury is 1 to 1, or greater than 1; this reduces the bioavailability of mercury in the body (Jinadasa et al., 2021). However, it is important to note that while Se is essential for good health, consuming too much Se can have adverse health effects. The UL for all adults, including pregnant and lactating women, for Se intake is 300 µg per day in the European Union (EU; EFSA, 2018a) and 400 µg per day in the USA (NAP, 2019).

## 2.4 Proteins

Proteins are essential for growth and development, and both quantity and quality are important when evaluating proteins in raw materials and products. A protein intake of 0.83 g per kg body weight per day has been recommended (FAO/WHO/UNU, 2007). Protein absorption, digestion, and assimilation capacity are important factors when considering protein quality, hence, protein source quality is evaluated using different means (Adhikari et al., 2022). Marine proteins contain all the essential amino acids (EAAs) (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine) and are, in general, good sources of these.

The chemical score (CS) is a tool for assessing the quality of dietary proteins. The CS reflects the potential of the protein to supply the necessary amount of essential amino acids, and this is determined by comparing each EAA in the food protein with the corresponding EAA in the reference protein, as set by FAO/WHO (FAO/WHO/UNU, 2007). Animal proteins typically have a CS of 1.0 and contain sufficient levels of all EAAs, while the CSs of cereal or staple proteins often range from 0.4 to 0.6. Legumes and nuts usually fall somewhere in between. Conversely, seafood has a high protein quality, with levels of all EAAs above or equal to the reference levels (FAO/WHO/UNU, 2007; Jensen et al., 2023). This makes seafood superior to terrestrial plants and comparable to the protein sourced from terrestrial animals.

## 2.5 Dietary fiber

Although seafood is generally low in carbohydrates, seaweeds, the LTS industries of which are booming, may be considered a new source of dietary fiber (Peñalver et al., 2020). The consumption of dietary fiber is associated with many health benefits, such as improved lipid and carbohydrate metabolism and bowel function. Other fiber characteristics that are believed to mediate beneficial health effects include reduced nutrient absorption, ability to bind water and form gels, increased viscosity in the intestinal tract, and the fermentability and production of short-chain fatty acids in the colon (EFSA, 2022). In mixed diets, dietary fiber consumption has

been inversely associated with the risk of cardiovascular disease (CVD) and type II diabetes (T2DM). However, the mechanisms facilitating this are unclear and may depend on the fiber type (EFSA, 2022).

In Europe, the dietary fiber intake is generally below the recommendations (25 g per day). Fiber consumption above the recommendations for maintaining normal bowel function will likely reduce the risk of developing chronic diseases. The EFSA panel considers that increasing dietary fiber consumption is a matter of public health importance (EFSA, 2022).

## 3 General nutrient recommendations, labeling, and claims

### 3.1 Nutrient profiling

Following the Farm to Fork strategy, the EFSA is also working on a policy revision for nutrient profiling. Nutrient profiling means classifying or ranking foods in accordance with their nutrient content, which in turn is based on the association of the nutrient's ability to prevent disease or promote health (EFSA, 2022). In line with this, the EC plans to propose a revision of the existing legislation on providing food information to consumers in 2023. The revision aims to establish “nutrient profiles”, that is, thresholds beyond which nutrition and health claims are restricted or not allowed.

Dietary fiber and potassium intake are assessed as inadequate in many European adult populations. Consequently, an increase in consumption is encouraged for the amelioration of adverse health effects.

It is important to note that the intakes of EPA and DHA may be inadequate for primary CVD risk prevention in populations where the consumption of fish, seafood, and fish products is low (EFSA, 2022). In addition, certain subgroups may have inadequate intakes of vitamin D, calcium, iodine, and iron, and diet modification alone may not be enough to ensure adequate intakes.

However, the EFSA scientific panel has pointed out that average protein intakes are mostly above their population reference intake (PRI) in Europe. PRI is defined as “the level of (nutrient) intake that is adequate for almost all individuals (97.5%) in a population group” (EFSA, 2022).

Even though some processed fish products have a sodium content that is well above the recommended sodium intake, regular fish consumption is generally advised, with recommendations ranging from one to four servings per week, and the recommended serving size ranging from 30 g to 200 g, but mainly from 100 g to 150 g. Some countries recommend the consumption of fatty fish, one country recommends low-to-medium fat fish, and many countries emphasize the importance of eating assorted species, both regarding type of fish and the fishing locations from which they are sourced (EFSA, 2022). This demonstrates the variation in recommendations for fish products that is likely to be translated to other seafood, such as products containing LTS, for which data are often still scarce.

A future shift in human diets from less sustainable terrestrial sources to marine resources has to focus on the utilization of LTS and how they may contribute to health (SAPEA, 2017; Costello et al., 2020). Nevertheless, in this transition it will be necessary to ensure that data collection on LTS and its associated products is carried out, and to initiate clinical and epidemiological studies, to provide the best-possible recommendations to the consumers across the world.

### 3.2 Nutrient reference values

The FAO/WHO Codex Committee on Nutrition and Foods for Special Dietary Uses (CCNFSDU) revised the 1993 nutrient reference value (NRV) for the essential nutrients, protein, vitamins, and minerals over several years. It presented a report titled “General Principles for Establishing Nutrient Reference Values for the General Population” to make labeling easier for processors and inform consumers globally (Lewis, 2019). The CCNFSDU has agreed on the term NRVs-R (nutrient reference value requirement) for the essential nutrients, protein, vitamins, and minerals (Table 1), which are values to be used as references in nutrition labeling. These values are derived from authoritative recommendations (from actors such as the FAO/WHO, EFSA, and IOM) on the reference nutrient intake values (RDIs) for optimal daily nutrient intake and are based on the best-available scientific knowledge of the daily amount of energy or nutrients needed for optimal health.

While the actual NRV is not shown on the nutrition label, labels normally give the percentage of the daily requirement for essential nutrients, to indicate how much each nutrient in a portion of food contributes to healthy nutrient intake. NRVs may be used to guide consumer food choices, compare different food items, and to calculate the intake of the nutrients. The processes used to derive a given NRV for a nutrient, and the actual NRV, are described in detail in the “Codex nutrient reference values” report (Lewis, 2019).

In addition to the CCNFSDU NRVs, the EU (EC, 2011a) and the USA (daily value and reference daily intake; DV and RDI, respectively) (NAP, 2019) have established reference values. These consider region-specific factors such as nutrient absorption or bioaccessibility from regional food products and specific nutrient requirements of their population. In addition to these general reference values, which apply to all foods, the NRV for the essential nutrients (Table 1) and the daily tolerable upper levels of intake (ULs) have been established (Table 2) for the EU and the USA; however, there may be national or other regional recommendations or regulations.

#### 3.2.1 Seaweed labeling to prevent excess iodine in the diet

The development of a seaweed industry, increased seaweed production, and the utilization of seaweed in the Western world have recently attracted particular interest. A panel of experts from the FAO/WHO has reviewed all food safety aspects of seaweed globally (FAO/WHO, 2022). One of the aspects of concern was the high content of I.

TABLE 1 Nutrient reference values (NRVs) for the requirement of essential nutrients, that is, protein, vitamins, and minerals, as reviewed by the Codex Committee on Nutrition and Foods for Special Dietary Uses (CCNFSDU) (Lewis, 2019), the European Union (daily reference intakes, DRI) (EC, 2011a), and the USA (daily value and reference daily intake; DV and RDI, respectively) (NAP, 2019).

Nutrient	European Union	United States	FAO/Codex
	(DRI/NRV) (EC, 2011a)	(DV/RDI) (NAP, 2019)	(NRV-R) (Lewis, 2019)
<b>Vitamins</b>			
Vitamin A (µg)	800	900	800
Vitamin D (µg)	5	20	5
Vitamin E (mg)	12	15	–
Vitamin K (µg)	75	120	60
Vitamin C (mg)	80	90	100
Thiamin (vitamin B <sub>1</sub> ) (mg)	1.1	1.2	1.2
Riboflavin (vitamin B <sub>2</sub> ) (mg)	1.4	1.3	1.2
Niacin (vitamin B <sub>3</sub> ) (mg)	16	16	15
Vitamin B <sub>6</sub> (mg)	1.4	1.7	1.3
Folic acid/folate (vitamin B <sub>9</sub> ) (µg)	200	400	400
Cobalamin (vitamin B <sub>12</sub> ) (µg)	2.5	2.4	2.4
Pantothenic acid (vitamin B <sub>5</sub> ) (mg)	6	5	5
Biotin (vitamin B <sub>7</sub> ) (µg)	50	30	30
<b>Minerals</b>			
Potassium (mg)	2,000	–	–
Chloride (mg)	800	2,300	–
Calcium (mg)	800	1,300	1,000
Phosphorus (mg)	700	1,250	700
Magnesium (mg)	375	420	310
Iron (mg)	14	18	14–22
Zinc (mg)	10	11	11–14
Copper (µg)	1,000	900	900
Manganese (mg)	2	2.3	3
Fluoride (mg)	3.5	–	–
Selenium (µg)	55	55	60
Chromium (µg)	40	35	–
Molybdenum (µg)	50	45	45
Iodine (µg)	150	150	150
Protein (g) (0.83 g per kg BW)			50*

\*Equals 50 g for a person with a BW of 60 kg. BW, body weight.

The intake of I is too low to gain all its health benefits in many European populations (Brantsæter et al., 2018). The content of I in food items is regulated by laws pertaining to ULs both in the USA and the EU (Table 2). Thus, guiding producers and consumers on new food resources is challenging.

It is important to be aware that certain types of seaweed, particularly some brown seaweeds (*Laminaria* sp. and *Saccharina*

sp.), are high in I (Aakre et al., 2021). Consuming too much I can be harmful, especially for vulnerable groups. The VKM advises that consumers practice moderation when consuming seaweeds to avoid excessive I intake (Aakre et al., 2021; Hogstad et al., 2023).

To assist consumers in making informed choices, Norwegian seaweed producers have created an industrial guideline that

**TABLE 2** Daily tolerable upper intake levels (ULs) of essential nutrients, that is, vitamins and minerals, as reviewed by the European Food Safety Authorities (EFSA) (EFSA, 2018a) and Food and Nutrition Board, National Academies (NAP, US) (NAP, 2019).

	Tolerable upper intake levels	Tolerable upper intake levels
	(UL) Adult, EU (EFSA, 2018a)	(UL) Adult (17- to 70-year-olds), USA (NAP, 2019)
<b>Nutrient</b>		
<b>Minerals</b>		
Boron (mg)	10	20
Calcium (mg) (in 19- to 50-year-olds)	2,500	2,500
Chloride (g)	–	3.6
Copper (mg)	5	10
Chromium	–	–
Fluorides (mg)	7	10
Phosphorus (g)	–	4
Iron (mg)	–	45
Magnesium (mg) (added salts)	250	350
Manganese (mg)	–	11
Molybdenum (mg)	0.6	2
Potassium	–	–
Selenium (µg)	300	400
Silicon	–	–
Sodium (g)	–	–
Iodine (µg)	600	1,100
Zinc (mg)	25	40
Nickel (mg)	–	1
Vanadium (mg)	–	1.8
<b>Vitamins</b>		
Folic acid/folate (µg)	1,000	1,000
Pantothenic acid	–	–
Biotin	–	–
Niacin (mg)	910	35
Nicotinamide (mg)	900	–
Nicotinic acid (mg)	10	–
Vitamin A (µg RE)	3,000	3,000
Retinol and retinol esters, post menopause	1,500	–
Vitamin B <sub>1</sub>	–	–
Vitamin B <sub>2</sub>	–	–

(Continued)

**TABLE 2** Continued

	Tolerable upper intake levels	Tolerable upper intake levels
	(UL) Adult, EU (EFSA, 2018a)	(UL) Adult (17- to 70-year-olds), USA (NAP, 2019)
Vitamin B <sub>6</sub> (mg)	25	100
Vitamin B <sub>12</sub>	–	–
Vitamin C	–	2,000
Vitamin D (µg)	100	100
Vitamin E (mg)	300	1,000
Vitamin K	–	–
Choline (g)	–	3.5

includes labeling recommendations for products with a high I content (ALGET2, 2022). When labeling pre-packaged products of pure seaweed, the recommendation is that the overview of nutrient levels must include I content per 100 g. When the I value is high, the label should include the recommended daily intake of I and state that excessive iodine intake over time can affect the thyroid gland. When labeling prepackaged products containing seaweed as an ingredient, only the amount of I in mg per 100 g of the whole product must be on the label.

The content and bioaccessibility of I can be significantly reduced by processing and through common culinary techniques such as blanching, boiling, drying, and frying food (Peñalver et al., 2020; Blikra et al., 2021).

### 3.3 Nutrition and health claims

Two FAO/WHO Codex nutrition labeling guidelines (FAO/WHO, 2001; FAO/WHO, 2013) give a global standard approach to presenting nutrition information on food labels and describe the conditions for making nutritional and health claims.

Certain foods or ingredients can have specific beneficial nutrients or nutritional properties. These can be marked on food labels as a “nutrition claim” when they satisfy the given regulations. Examples of such nutrition claims are “source of protein”, “source of fiber”, “fat-free”, or “with no added sugars”. In addition, “health claims” suggest a connection between a food item, or one of its constituents, and health. These regulations apply to all foods (EC, 2006c; EC, 2012).

The EC has also instituted regulations related to the labeling and presentation of nutrition and health claims on foods (Gilsenan, 2011). The EC has listed the conditions for using product claims to prohibit false claims, such as that the food is safe or nutritionally adequate and that the claims do not encourage excess consumption (EC, 2012). These nutritional and health claims are regulated and can only be used in the labeling and advertising of foodstuffs if they appear on the lists of authorized claims.

No specific health claim has been developed for any LTS or extracts of these. Thus, to achieve this, well-designed, controlled trials are necessary to confirm any putative nutraceutical benefits of such novel marine raw materials.

On the other side, there are already approved nutritional claims, related to the recommendations for the intake of dietary fiber and also of the marine n-3 LC PUFAs, EPAs, and DHAs. These may be attributed to LTS depending on the nutritional content of the product. The approved health claim for dietary fiber may also be attributed to seaweed products containing enough fiber. Other already approved nutrition and health claims may be attributed to products containing a minimum of 40 mg dietary fiber per 100 g edible weight.

This is an example of the formulation of a nutritional claim:

“a claim that a food is a source of omega-3 fatty acids, and any claim likely to have the same meaning for the consumer, may only be made where the product contains at least 0,3 g alpha-linolenic acid per 100 g and per 100kcal, or at least 40 mg of the sum of EPA and DHA per 100 g and per 100kcal” (EC, 2012).

The associated health claim, “EPA and DHA contribute to the normal function of the heart” may be used only for food that is at least a source of EPA and DHA (EC, 2006c). “To bear the claim, information shall be given to the consumer that the beneficial effect is obtained only with a daily intake of 250 mg of EPA and DHA”. A nutritional.

“claim that a food is high in omega-3 fatty acids, and any claim likely to have the same meaning for the consumer, may only be made where the product contains at least 0.6 g alpha-linolenic acid per 100 g and per 100 kcal, or at least 80 mg of the sum of eicosapentaenoic acid and docosahexaenoic acid per 100 g and per 100 kcal” (EC, 2010).

Other approved health claims for EPA and DHA (EC, 2006c; EC, 2010; EC, 2012) are that:

- “DHA and EPA contribute to the normal function of the heart” (at an intake of 0.25 g per day)
- “DHA and EPA contribute to the maintenance of normal blood pressure” (at an intake of 3 g per day)
- “DHA and EPA contribute to the maintenance of normal blood triglyceride levels” (at an intake of 2 g per day)
- “DHA contributes to maintenance of normal brain function” (at an intake of 0.25 g per day)
- “DHA contributes to the maintenance of normal vision” (at an intake of 0.25 g per day)
- “DHA maternal intake contributes to the normal brain development of the fetus and breastfed infants” [at an intake of 0.2 g DHA plus the daily recommended intake of omega-3 fatty acids (EPA + DHA) for adults, which is 0.25 g per day]
- “DHA maternal intake contributes to the normal development of the eyes of the foetus and breastfed infants” [at an intake of 0.2 g DHA plus the daily recommended intake of omega-3 fatty acids (EPA + DHA) for adults which is 0.25 g per day].

## 4 Chemical hazards

Specific CAC (FAO/WHO, 1995) and EC (EC, 2006b) maximum limits (MLs) of heavy metals and contaminants remain undetermined for low trophic species such as abalone, sea snails, sea cucumbers, and sea urchins (or any Echinodermata). Thus, the use of MLs for comparable seafood items, such as bivalve mollusks, is extensive when assessing the food or product safety of such species, organisms, or products (EC, 2006b; EC, 2011c; EC, 2015a; Blikra et al., 2021).

In the case of novel resources, even if frequently consumed in Asian cuisines, there is a lack of data on the content in products and the quantities and frequencies of consumption. This lack of data adds to the challenge of assessing food safety. Calculating the tolerable consumption based on the available general limits of consumption may be an alternative strategy to assess these risks. It is important to remember that these general limits are given for the exposure of a specific hazard from all foods in the diet, and thus not only the exposure from the product but that from the whole diet must be assessed. These limits ensure safe consumption without an enhanced lifetime risk of diseases and may be used to guide consumers. Such limits are given as a tolerable weekly intake (TWI), provisional TWI (PTWI), reference dose (RfD), or the BMDL (Table 3). In addition, it is important to consider factors such as body weight and age (in terms of fertility and pregnancy), when assessing these limits to protect vulnerable groups.

### 4.1 Heavy metals

#### 4.1.1 Mercury

The inorganic heavy metal mercury (Hg), or more precisely, its organic form methylmercury (MeHg), is known to accumulate in predators and organisms at higher trophic levels. This heavy-metal toxin can cross important barriers in the body, such as the placenta, the blood–brain barrier, and the blood–cerebrospinal fluid barriers (Chiocchetti et al., 2017). MeHg, which may make up more than 90% of the total Hg in seafood, is particularly concerning due to its cytotoxic capacity, which is higher than that of inorganic Hg (Hong et al., 2012; Barone et al., 2021). MeHg is lipid soluble and is easily absorbed by and transported throughout the body (Martinez-Finley and Aschner, 2014). It is important to note that food sources from lower trophic levels generally have a lower Hg content due to the absence of biomagnification (Córdoba-Tovar et al., 2022).

There are TWI for Hg and MeHg to avoid prenatal neurodevelopment toxicity. The TWI for MeHg is 1.6 µg per kg body weight (BW) according to the CAC and 1.3 µg per kg BW according to the EC. The TWI for inorganic Hg is 4 µg per kg BW according to the EC (See Table 3) (FAO/WHO, 1995; EFSA, 2015).

The MLs of Hg for unspecified fish muscle and fishery products, including mollusks and crustaceans, is 0.5 mg per kg wet weight (WW) of edible tissue. Higher limits exist for predatory or long-lived, bottom-dwelling fish (1.0 mg per kg WW) (FAO/WHO, 1995, EC, 2006b). A higher ML may reflect either that their consumption

TABLE 3 General tolerable weekly intakes (TWIs) and lower-end benchmark doses (BMDLs) for dietary consumption issued by the European Commission (EC) (EC, 2006b) and the FAO/WHO Codex Committee on Nutrients (CAC) (FAO/WHO, 1995) for the intake of heavy metals (inorganic arsenic, cadmium, lead, and mercury) from food.

Hazard	TWI		BMDL	
	EC	CAC	EC	CAC
	$\mu\text{g per kg BW}$	$\mu\text{g per kg BW}$	BMDL <sub>01</sub> $\mu\text{g per kg BW}$	BMDL <sub>05</sub> $\mu\text{g per kg BW}$
Arsenic (inorganic)	–	–	0.3	3.0
Cadmium	2.5	25 (PTMI)		
Lead* (EFSA, 2010)	–	–	–	–
Mercury	1.3	1.6		

\*No threshold, European Commission (EC) Codex Committee on Nutrients (CAC). BW, body weight.

is assessed as low or that some species have an inherently higher content.

#### 4.1.2 Cadmium

Exposure to cadmium (Cd) can have adverse effects on the growth, neurodevelopment, and cognitive function of children (Kippler et al., 2016; Chatzi et al., 2019). In light of this, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) set a provisional tolerable monthly intake (PTMI) of 25  $\mu\text{g per kg BW}$  for Cd in 2011, recognizing the long half-life of Cd in humans (FAO/WHO, 2011b). The EC has established a TWI of 2.5  $\mu\text{g per kg BW}$ . For fish muscle (unspecified), the ML for Cd has been set at 0.05 mg per kg WW, while it is as high as 1.0 mg per kg WW for the edible part of bivalve mollusks (EC, 2006b; EC, 2021).

#### 4.1.3 Arsenic

There are more than 100 arsenic (As) compounds in the environment, and their toxicity varies. Inorganic arsenic (iAs) is classified as a class 1 carcinogen, while organic forms have lower toxicity levels (IARC, 2012). Although there are no EC MLs for total As content in seafood intended for human consumption, some countries have issued regional regulations. For example, China has set a ML of 0.5 mg per kg WW iAs in “aquatic animals and products (excluding fish and fish products)” (CFDA, 2017). France has also a specific regulation or ML of 3.0 mg per kg DW on seaweed food and condiments (ANSES, 2020) (Table 4). It is worth noting that a revision of PTWI of iAs in 2009 established a range from the benchmark dose (BMD). Lower confidence limit BMDL<sub>01</sub> values of between 0.3  $\mu\text{g}$  and 8  $\mu\text{g per kg BW per day}$  were associated with a 1% increase in the probability of getting lung, skin, or bladder cancer, and also skin lesions. Thus, the maximum daily dietary intake of iAs should be below 0.3  $\mu\text{g per kg BW}$ . This means that an adult weighing 60 kg should have a maximum of 18  $\mu\text{g iAs per day}$  (EFSA, 2009b). JECFA also performed a risk assessment in 2010 based on lung cancer rates and proposed a BMDL<sub>05</sub> value of 3.0  $\mu\text{g per kg BW}$  (FAO/WHO, 2011b; Afonso et al., 2020). Organic As is assumed to be far less toxic (FAO/WHO, 2011b; Coelho, 2019; Afonso et al., 2020), and is the main form present in foods of marine origin. However, some organisms, such as certain seaweed species, may contain high levels of iAs (Duinker et al., 2020). Because

analyses or data on levels of total As and the numerous species of As are generally not available, especially for new LTS food resources, this is considered a knowledge gap.

#### 4.1.4 Lead

Lead (Pb) is a heavy metal that is particularly harmful to children and the fetus when transferred via the placenta. Its harmful effects may affect many organs and systems, such as the brain, liver, kidney, and bones. The Panel on Contaminants in the Food Chain (CONTAM panel) assessed the harmful effects of Pb in food in 2010 (EFSA, 2010). It could not identify a lower threshold for Pb-induced effects and deemed the prevailing PTWI to be inappropriate. Thus, it is crucial to keep exposure from all Pb sources as low as possible (EFSA, 2010). The European ML of Pb is 0.3 mg per kg WW fish muscle for most fish species but much higher, 1.5 mg per kg WW, for mollusks (EC, 2006b).

## 4.2 Persistent organic pollutants

It is important to be aware of the presence of persistent organic pollutants (POPs) in seafood, as they can have harmful effects on human health. POPs include halogenated synthetic compounds, which can be chlorinated [such as polychlorinated biphenyls (PCBs), polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzo-*p*-furans (PCDDFs)] or be organochlorine pesticides [such as DDT, toxaphene, and chlordane, in addition to the polybrominated diphenyl ethers (PBDEs)]. Some of these are byproducts of industrial synthesis or combustion (PCDD/Fs), while others are designed for specific industrial uses (e.g., PCBs and PBDEs) or as pesticides (e.g., DDT, lindane, and chlordane). The presence of other POPs such as polycyclic aromatic hydrocarbons (PAHs) has also attracted attention. POPs are toxic compounds that accumulate (during the lifespan of the organism) and magnify successively at higher levels in the food chain, with higher concentrations found in fatty fish/seafood due to their lipid toxicity (EC, 2017). Fortunately, the levels of POPs are generally lower in LTS (Landrigan et al., 2020). Legislative measures have led to a decline in the levels of POPs in the environment (van den Berg et al., 2017; Guo et al., 2019), but they still persist due to their long half-lives.

TABLE 4 Maximum limits (MLs) for the content of heavy metals (arsenic, inorganic arsenic, cadmium, lead, and mercury) in seaweed, seaweed products, abalone, sea urchin roe, and oyster.

Hazard	Seaweed				Abalone (EC, 2006a)	Sea urchin roe (EC, 2006a)	Oyster (EC, 2006a)
	FAO/WHO (2022); Banach et al. (2020) and CEVA (2019)						
	Feed (ANSES, 2020)	Food (Gilsenan, 2011; ANSES, 2020)	Food supplements (EFSA, 2009b)	Algae (vegetables and condiments) (CEVA, 2019; ANSES, 2020)			
	mg per kg DW	mg per kg DW	mg per kg WW	mg per kg DW	mg per kg WW Edible flesh	mg per kg WW Edible flesh	mg per kg WW Edible flesh
<b>Arsenic (total)</b>	40	No ML	No ML		No ML	No ML	No ML
<b>Arsenic (inorganic)</b>	2	No ML 3.0***	No ML	3.0 ***	No ML	No ML	No ML
<b>Cadmium</b>	1	No ML 0.5***	3.0	0.5***	No ML	No ML	1.0
<b>Lead</b>	10	No ML 5 ***	3.0	5.0***	No ML	No ML	1.5
<b>Mercury</b>	0.1	No ML 0.1***	0.10	0.1***	No ML	No ML	0.5
<b>Iodine</b>	2–5 [52] **	France 2,000 [53]* Germany 20 mg per kg WW [54]		2,000***			

\*With the caution that seaweed and derived products should not be consumed by (i) people with thyroid dysfunction, heart disease, or kidney failure; (ii) those taking medication containing iodine or lithium; and (iii) pregnant or breastfeeding women.

\*\*The EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP) recommends that the maximum iodine contents in complete feed should be reduced as follows: dairy cows and minor dairy ruminants, 2 mg I per kg; laying hens, 3 mg I per kg; horses, 3 mg I per kg; dogs, 4 mg I per kg; and cats, 5 mg I per kg (EFSA, 2013).

\*\*\* In the latest publication by the French High Council for Public Health (CSHPF) reviewed a list of seaweed that could be authorized for human consumption, together with recommendations on maximum levels (ANSES, 2020).

### 4.2.1 Dioxins and PCBs

Seventeen of the 210 known dioxins and 12 of the 209 PCBs (the dl-PCBs), are considered food hazards (EFSA, 2018b). These dioxins and dl-PCBs have similar structural and toxicological properties and exert their toxicological effects via binding to the aryl hydrocarbon receptor (AhR). When it comes to fish fillets and fishery products, the European ML for dioxins and dl-PCBs is set at 6.5 pg TE per g WW (EC, 2011c). The TWI for dioxins and dl-PCBs was lowered from 14 pg to 2 pg toxic equivalents (TEQ) per kilogram of body weight due to their documented adverse effects on semen quality and possibly also on male fertility (EFSA, 2018b).

### 4.2.2 Polycyclic aromatic hydrocarbons

The presence of polycyclic aromatic hydrocarbons (PAHs) in seawater and sediments arises from the incomplete combustion of organic matter, coal, or oil sources. PAH deposits in the marine environment are a result of industrial and transport activity that deposits PAHs directly into the ocean, or inputs from rivers stemming from inland activities. Marine sediments may contain high levels of PAHs and pose a risk through bioaccumulation. The capacity to metabolize PAHs is less developed in some filter feeding organisms than it is in fish and crustaceans, and PAHs may thus accumulate due to low elimination rates (Sampaio et al., 2021). The

PAH's lipophilicity, absorption, persistency, and toxicity increase with its molecular weight. PAH metabolites such as benzo[a]pyrene (BaP), may bind to DNA and cause heritable mutations. There are no MLs for fresh, chilled, or frozen seafood, except for bivalve mollusks, which have a ML of 5 µg per kg WW for BaP and 30 µg per kg WW for PAH4 (the sum of BaP, benzo(a)anthracene, chrysene, and benzo(b)fluoranthene) (EC, 2011b). However, as PAHs arise from the incomplete combustion of organic matter, it is important to note that grilled or smoked fatty seafood may contain high levels of PAHs (EFSA, 2008).

### 4.2.3 Poly- and perfluorinated compounds

Thousands of poly- and perfluorinated compounds (PFAS) can accumulate in humans and the environment. These compounds are commonly used in non-stick cookware, stain- and water-repellent textiles, carpets, and furniture, and firefighting foams, and have leached into the oceans (Landrigan et al., 2020). Recently, the EC set a TWI of 4.4 ng per kg BW of the sum for selected PFAS compounds, including perfluorooxane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS), to protect human health (EFSA, 2020). The EFSA has assessed various associations between serum levels of PFAS and several outcomes. The most

critical effect of the sum of PFASs was evaluated to be on the immune system, particularly in children who, after prenatal and postnatal exposure to PFAS, may experience a decreased vaccination response (EFSA, 2020; VKM, 2022).

#### 4.2.4 Pesticide residues

The pesticide contamination of marine organisms is generally the result of leach from pesticide use in terrestrial agriculture. The EU legislation covers more than 1,000 pesticides currently or previously used in agriculture, but for pesticides not covered by the legislation, the EU has set a general maximum residue limit (MRL) of 0.01 mg per kg. It is important to note that farmed seaweeds may contain pesticide residues if pesticides are used in the outgrowth phase, and the EC has established MRLs for some seaweeds (EC, 2005b; FAO/WHO, 2022). However, limited information is available on the content of pesticides in other LTS species, and species-specific MRLs are largely not available.

### 4.3 Radionucleotides

The allowed content of radionucleotides in food is regulated by very general guidelines. Foods are divided into “infant foods” and “foods other than infant foods”. Most of the marine LTS fall in the second category (FAO/WHO, 1995). The EU has set maximum levels of food after nuclear accidents/disasters (EC, 2016). This includes a broad category, “other food except minor food”, which may apply to seaweed, abalone, sea urchin, and oyster. However, seaweed, which is able to extract minerals and trace elements from its environment, remains somewhat unexplored (Duinker et al., 2020), except when it is used as a bioindicator for <sup>129</sup>I and for nuclear leaches in the marine environment (Duinker et al., 2020; FAO/WHO, 2022).

### 4.4 Biotoxins

Marine biotoxins are chemicals produced by specific types of toxin-producing algae. Seafood, particularly filter feeders, feed on such algae, and exposure may thus occur by eating seafood. The symptoms of poisoning vary with the type and level of toxin consumed (EFSA, 2009a; Jong, 2017).

Ciguatera fish poisoning (CFP) is the most frequent illness associated with the consumption of fish with ciguatoxins (CTXs) from microalgae (*Gambierdiscus* spp. and *Fukuyoa* spp.) (Chain, 2010). Neurotoxic shellfish poisoning (NSP) and paralytic shellfish poisoning (PSP), generally caused by shellfish consumption, usually cause gastroenteritis in addition to neurologic symptoms (Watkins et al., 2008; Etheridge, 2010). Amnesic shellfish poisoning (ASP), a result of excessive domoic acid consumption, causes neurologic but not gastrointestinal symptoms (Jeffery et al., 2004). Diarrhetic shellfish poisoning (DSP), caused by excessive okadaic acid and dinophys toxin consumption, on the other hand, present with gastrointestinal but not with neurologic symptoms (Jong, 2017). Azaspiracid shellfish

poisoning (AZP), triggered by azaspiracid toxins, may cause severe gastroenteritis (Jong, 2017).

The EU recognizes that the biotoxin poisoning risk is associated predominantly with bivalve mollusk consumption. Both producers and authorities are subject to regulation to manage food safety in these food chains (Table 5) (EC, 2004). An important component is the continuous monitoring of algal and toxin levels in the water bodies used for the production of, and those in, produced mollusks, to inform and give the ability to close production areas and prohibit harvest when unacceptable biotoxin levels are exceeded. O'Mahony has reviewed regulations and assessed their contribution to the risk management approach (O'Mahony, 2018).

### 4.5 Microbiological hazards

Pathogenic microorganisms from the growth environment, harvest, processing, or handling may pose a challenge to food safety. The sanitary conditions in the whole food chain and when food is consumed are vital. Naturally occurring viruses (hepatitis A and norovirus) and bacteria (*Salmonella*) that are associated with fecal contamination and pathogens, such as *Vibrio* species, may be present at harvest and outgrowing sites (Wright et al., 2018). In EC regulation no. 2073/2005 the only microbiological criterion is a ML for *Listeria monocytogenes* (EC, 2005a). The FAO and WHO have developed and recently revised technical guidelines on growing area aspects of bivalve mollusk (FAO/WHO, 2021), using the monitoring of *E. coli* as a proxy for fecal contamination (Table 6), and some aspects of this has been further adapted for sea urchins. There will be a change in EC legislation in terms of the classification of sea urchins as echinoderms, which in turn will change the legislation regarding the harvesting, processing, and retailing of sea urchins. At the time of submitting the final manuscript, this legislation has yet to be ratified.

The producers network in the North Atlantic region (ALGET2) has developed rigorous guidelines that cover the entire value chain on sustainable production or products from macroalga (ALGET2, 2022). These guidelines are derived from Norwegian, Icelandic, and Faroese legislation. France (CEVA) has also put some regulations in place for dried seaweed (CEVA, 2019) (Table 7).

TABLE 5 Biotoxin health standards in EC regulation 853/2004 (EC, 2004) for live bivalve mollusks, measured in the whole body or any part eaten separately. Table legend: Adapted from (O'Mahony, 2018).

Biotoxin group	Abbreviation	Maximum permissible quantity (edible tissue)
Paralytic shellfish poison	PSP	800 µg per kg
Amnesic shellfish poison	ASP	20 mg per kg of domoic acid
Okadaic acid, dinophys toxins, and pectenotoxins together	DSP	160 µg per kg of okadaic acid equivalents per kg
Yessotoxins	YTX	3.75 mg per kg
Azaspiracid	AZP	160 µg per kg

TABLE 6 Shellfish classification based on *Escherichia coli* monitoring (EC, 2004; EC, 2015b).

Category	Microbiological standard	Treatment required
Class A	$\leq 230$ <i>E. coli</i> /100 g	No treatment required may go direct for human consumption
Class B	$\leq 4,600$ <i>E. coli</i> /100 g <i>E. coli</i> (90% compliance)	Must be depurated, heat treated, or relayed to meet class A requirements
Class C	$\leq 46,000$ <i>E. coli</i> /100 g	Must be relayed for 2 months to meet class A or class B requirements, or may also be heat treated

## 5 Conclusion

Food agencies recommend the consumption of higher levels of aquatic food in the diet for improved health and sustainability. To achieve sustainable production, future gains in the global production of seafood are expected to come from the capture and culture of LTS. As such new raw materials, processes, and cuisines are developed, there will inevitably be new challenges pertaining to food safety and nutritional content. To address this, standards, laws, and regulations to be used when assessing the nutritional value and food safety of LTS have been identified. The global FAO Codex, in addition to the regional EC and US regulations, have been used as main sources, even though some national regulations also exist.

As LTS are mainly extractive species, or feed on such species, the nutritional composition and level of food hazards vary with the species, geographical location, and post-harvest handling. As mentioned, levels of contaminants may originate from a variety of sources, including geochemical processes, leaching soils, sewage, or industrial activities. Due to the variation of species, locations, and the novelty of a proportion of LTS on the markets, more species-specific data on nutritional contents and associated limits of safe consumption are warranted.

A widely used method when assessing food safety when specific MLs are missing for food hazards associated with the species, organism, or product is to use the MLs for comparable seafood items. For example, sea cucumbers, which are widely consumed in Asia, have not been assigned detailed MLs for the content of heavy metals by the CAC (FAO/WHO, 1995), the EC, or the National Standard of China. Risk assessments of such organisms may therefore be performed through comparison with MLs given by

TABLE 7 Microbiological criteria for dried seaweed (macroalgae).

Mesophilic aerobic germs	$\leq 10^5$ per g
Fecal coliforms	$\leq 10$ per g
Anaerobic sulfite-reducing bacteria	$\leq 10^2$ per g
<i>Staphylococcus aureus</i>	$\leq 10^2$ per g
<i>Clostridium perfringens</i>	$\leq 1$ per g
<i>Salmonella</i>	Absence in 25 g

Adapted from the French hygiene standard by CEVA (CEVA, 2019).

the EC (EC, 2006b) for similar organisms, such as “bivalves”, or the ML by the National Standard of China (NSC) for “aquatic animals and their products”(CFDA, 2017; Elvevoll et al., 2022).

In addition, the lack of consumption data (on quantities, frequencies, products, or species) challenges more general food safety and nutritional assessments. When such vital data are missing, a possible approach may be to perform an assessment of daily or weekly consumption specific limits of intake of the nutrients (NRV or UL), and hazards (TWI or BMD) may also be used.

It is important to closely monitor and analyze the nutrients and contaminants present in LTS to make informed decisions about the risks associated with consuming such species. Doing so can ensure that the food supply remains safe and healthy for all. In addition, more rigorous monitoring and analysis of consumption data is needed to enable more valid risk assessments and guide the utilization of LTS.

## Author contributions

EE: Conceptualization, Funding acquisition, Investigation, Project administration, Writing – original draft, Writing – review & editing. K-EE: Writing – review & editing. MA: Funding acquisition, Project administration, Writing – review & editing. NB: Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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