New Zealand Food Safety
Haumaru Kai Aotearoa

Evaluation of food safety risks associated with seaweed and seaweed products

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Scientific Interpretative Summary

This SIS is prepared by New Zealand Food Safety (NZFS) risk assessors to provide context to the following report for MPI risk managers and external readers.

NZFSSRC406656/FW22013 Evaluation of food safety risks associated with seaweed and seaweed products.

There is a wide and growing range of seaweed products commercially available in New Zealand (NZ). Most of these products are imported, predominantly from the People's Republic of China, the Republic of Korea and Japan.

New Zealand Food Safety (NZFS) commissioned the New Zealand Food Safety Science and Research Centre (NZFSSRC) to undertake a review of known food safety hazards relating to commercial harvesting of seaweed for human consumption to improve NZFS's understanding of the potential food safety risks associated with seaweed food products. This report summarises the types of edible seaweed products commercially available in NZ and internationally, and the characteristics and occurrence of selected chemical and microbiological hazards associated with these products.

Outbreaks, and indeed cases of sporadic illness, reported with seaweed as the suspected or confirmed vehicle are few. Reported outbreaks have been associated with the contamination of red, green, or brown seaweed in dried, frozen, or fresh form. Contamination has occurred before reaching the consumer, i.e., at the growing area or during processing.

The report updates existing NZFS knowledge on the occurrence of iodine and the elemental contaminants arsenic, cadmium, lead, mercury in seaweed. High concentrations of iodine and inorganic arsenic are related to particular types of seaweed; specifically, iodine in brown seaweed and inorganic arsenic in hijiki (a type of brown seaweed). High concentrations of contaminant elements appear to be related to contamination levels in the growing environment. Cases of thyrotoxicosis in Australia and NZ have been attributed to the use of kelp as an ingredient in soymilk products, due to the high concentration of iodine in kelp.

The report shows that there is limited meaningful information that can be gathered from the few published surveys of microbiological hazards in seaweed and seaweed products. The microbiological hazards identified were assessed as more likely to be sporadic issues linked to pollution levels at harvest, or poor hygiene during harvest or manufacture. *Aeromonas* spp., *Salmonella* spp., *Vibrio* spp., and norovirus were the microbiological hazards highlighted because they have been detected in seaweed and would survive some seaweed processing conditions. *Escherichia coli* O157 was detected, although it is unclear if the *E. coli* detected in seaweed actually carried Shiga toxin (*stx)* genes.

The report also highlights the paucity of information on marine biotoxins in seaweed, and the occurrence of chemical and microbiological hazards in processed seaweed products, such as dried and preserved seaweed.

The major data gaps identified by the study include:

- up-to-date information on consumption of seaweed products in NZ
- information on seaweed processing methods and their effects on different microbiological and chemical hazards
- data on the typical physico-chemical properties (e.g., pH, moisture content or water activity) of various commercially available seaweed products
- data on the occurrence of marine biotoxins in seaweed.

The report describes recommendations, including targets for a potential survey of hazards in imported seaweed and seaweed products.

EVALUATION OF FOOD SAFETY RISKS ASSOCIATED WITH SEAWEED AND SEAWEED PRODUCTS

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SUMMARY

Introduction

This report has been prepared by the Institute of Environmental Science and Research (ESR) and the Cawthron Institute for the New Zealand Food Safety (NZFS), Ministry for Primary Industries (MPI). NZFS risk assessors and risk managers are currently reviewing the risk management of food safety risks associated with seaweed and seaweed products intended for human consumption that are commercially available in New Zealand.

This report was commissioned to provide a review of data which will; inform the risk management questions and identify data gaps in current knowledge.

Potential hazards considered in the study included microbiological (including marine biotoxins and mould/mycotoxins), and chemical hazards (iodine and heavy metals) but excluded pesticide residues, food additives and other environmental contaminants such as dioxins, polychlorinated biphenyls and polybrominated diphenyl ethers.

Seaweed gathered recreationally for personal or whānau consumption or use (that is not for sale) is outside the scope of this report.

Data sources

The data summarised in the review, were obtained from:

- A search of the literature written in English conducted using the PubMed and Web of Science search engines. References lists from the papers recovered were also checked for relevant papers.
- A search of the grey literature using Google search engine.
- A search of New Zealand and international government/organisation websites for information on; hazard regulatory limits, dietary consumption, product recalls, notifications, and border refusals/rejections.
- Dietary information from the 1997 National Nutrition Survey, the 2002 National Children's Nutrition Survey and the 2008/09 Adult Nutrition Survey.
- New Zealand seaweed product import and retail survey data provided by NZFS.

Findings

There is a wide range of seaweed and seaweed products that are commercially available in New Zealand. The most common are dried nori sheets (either as snacks or as a sushi ingredient), other types of dried seaweeds for use in cooking or salads, frozen wakame salad, seaweed-based snacks and various foods containing seaweed as a minor ingredient or flavouring.

These products are derived from various species of seaweed, including:

- Green seaweeds - sea grapes (*Caulaerpa* spp.) and sea lettuce (*Ulva* spp.).
- Brown seaweeds - mozuku (*Cladosiphon okamuranus)*, sea spaghetti (*Himanthalia elongate*), sea grapes (*Hormosira banksii*), giant kelp (*Macrocystis pyrifera*), kombu

(*Saccharina japonica*, and other species of the genus *Laminaria*), hijiki (*Sargassum fusiforme)* and wakame (*Undaria pinnatifida)*.

- Red seaweeds - sea chicory (*Chondracanthus chamisso*), Irish moss (*Chondrus crispus),* dulse (*Palmaria palmata)*, laver (*Porphyra*/*Pyropia* spp.) and ogonori *(Gracilaria spp*.).

Most seaweed or seaweed products commercially available in New Zealand are imported, predominantly from China, the Republic of Korea and Japan. In New Zealand, there is limited commercial harvesting of seaweed for human consumption. One processor harvests giant kelp for dried flake and powder products, and there is small scale harvesting of wakame and kombu for salads and dried products.

Seaweed and seaweed-containing foods are a small part of the New Zealand diet. The amount of annually imported seaweed and seaweed products intended for human consumption was approximately 1000 tonnes in 2021, which corresponds to 0.2 kg/capita/year. Seaweed consumption patterns of New Zealanders are mostly unknown and were not specifically captured in past national nutritional surveys.

The available evidence suggests that there are three pathways by which hazards can contaminate or accumulate in seaweed and seaweed products:

1. The hazard may be a naturally occurring component of seaweed (e.g. iodine). The concentration of iodine is generally higher in brown seaweeds (*Ochrophyta*).
2. Seaweed can bioaccumulate chemical hazards (inorganic arsenic, lead, cadmium, mercury) present in the marine environment. Bioaccumulation of chemical hazards can be seaweed species dependent, such as the accumulation of inorganic arsenic in hijiki.
3. Bacteria or viruses can contaminate seaweed if present in the marine environment (e.g. *Aeromonas* spp*, Clostridium perfringens* and *Vibrio* spp.) or can be introduced during processing from contaminated equipment, water supplies or infected food handlers. These factors are unlikely to be seaweed-specific but will be process-specific or be dependent on harvesting waters contaminated with human or animal faecal matter. Mycotoxins and marine biotoxins can also potentially contaminate seaweed products, but the evidence for this occurring is scarce.

Products that contain seaweed as a primary ingredient imported into New Zealand can be classified into five main product types: dried seaweed (other than nori), nori, frozen seaweed salads, shelf-stable seaweed products and seaweed-based snacks. The processing of these products can differ considerably between and within product categories, with different process steps applied, and a variety of ingredients added, to produce a wide range of seaweed products.

Specific information on the impact of seaweed processing on pathogenic microorganisms, marine biotoxins and mycotoxins is generally lacking and assessments of potential risks are based on the general characteristics of the organisms and substance, rather than on seaweed-specific studies.

All seaweeds are washed following harvest, and this can remove surface-adhering hazards, such as microorganisms and biotoxin-producing dinoflagellates. Soaking of seaweed in water, with or without heat, has been shown to decrease the inorganic arsenic and iodine levels of seaweed by up to 60 and 90%, respectively.

Chilled seaweed products that have not undergone a heat treatment step represent a potential food safety risk, as *Listeria monocytogenes, Aeromonas* spp., and some *Vibrio* spp. strains can grow at chilling temperatures. However, it is not clear if the shelf life of fresh seaweed is short enough to preclude this risk and whether these organisms will grow on the seaweed matrix. Pathogenic *Escherichia coli*, *Shigella* spp., *Salmonella* spp., *V. parahaemolyticus*, *V. vulnificus* and norovirus in chilled seaweed products all pose a possible risk depending on the initial contamination concentrations. However, it is unclear whether any chilled, non-heat-treated products are imported into New Zealand.

Seaweed products are often salted and salting will inhibit the growth of microorganisms. However, while studies have reported the impact of salting on the microbial load of seaweed, there is a paucity of information on the effects of salting on pathogenic microorganisms in seaweed.

It is likely that most seaweed products receive some level of heat treatment, ranging from short duration blanching to boiling for several hours. These heat treatments should inactivate most microorganisms, although blanching may be insufficient to inactivate bacterial spores.

The majority of imported seaweed products are dried, which should prevent growth of microorganisms and contribute to their inactivation. The single study that examined the behaviour of microbial pathogens (*E. coli, A. hydrophila* and *V. parahaemolyticus*) on seaweed (sea lettuce (*Ulva reticulata*)) during drying demonstrated an initial increase in bacterial numbers, followed by a steady decline.

High concentrations of iodine and inorganic arsenic are related to particular types of seaweed, while high concentrations of the other contaminant elements considered in this report (cadmium, lead, mercury) appear to be related to contamination levels in the growing environment. Only iodine has been associated with adverse health effects in humans due to its presence in seaweed. This is probably not surprising as effects of excessive iodine on thyroid function can occur after a relatively short period of exposure (days to weeks), while adverse effects due to the other chemical hazards occur after chronic exposure to high levels of the hazard.

Of the biological hazards included in this report only *Salmonella* has been both detected in surveys of seaweed and confirmed as the causative organism for a seaweed associated outbreak. Additionally, *Aeromonas* spp., *Bacillus cereus,* Shiga toxin-producing *Escherichia coli* (STEC) and *Vibrio* spp. have been detected in seaweed or seaweed products. However, there are only a few published microbiological surveys of seaweed and seaweed products. While the potential for seaweed to be contaminated by marine biotoxins has been identified, no reports of known disease-causing marine biotoxins in seaweed were found.

Norovirus, *L. monocytogenes, Salmonella* spp. and *V. parahaemolyticus* have shown ability to survive some of the typical steps used in seaweed processing (drying, heat treatment, chilling/freezing).

Recommendations for a potential survey of hazards in imported seaweed and seaweed products and identification of majority data gaps was also included in the current report.

1 INTRODUCTION

1.1 BACKGROUND

This report has been prepared by the Institute of Environmental Science and Research (ESR) and the Cawthron Institute in response to a request from New Zealand Food Safety (NZFS), Ministry for Primary Industries (MPI) to the New Zealand Food Safety Science & Research Centre (NZFSSRC) to deliver project 406656: Food Safety Risks Associated with Seaweed Products.

NZFS risk assessors and risk managers are currently considering the following risk management questions relating to food safety risks associated with seaweed and seaweed products intended for human consumption that are commercially available in New Zealand:

- Which seaweed product/hazard combinations currently present a significant food safety risk or regulatory concern to New Zealand? What are the key contributing risk factors?
- Do the identified risks need to be managed to protect public health? How should the identified food safety issues be prioritised for risk management action?
- What are the options for hazard control and risk management (both regulatory and non-regulatory)? At which point of the food chain (for imports, this includes pre-border, border and post-border) can control measures effectively be applied?
- Are additional import and/or domestic controls (including monitoring) necessary to manage the risks? If needed, how do we define what products should be included/excluded from the scope of any regulatory requirements?
- For imported food, should products from certain countries be targeted for control and monitoring?
- What do other countries do to manage these risks?
- Are there any potential emerging issues associated with seaweed products that NZFS should be aware of?

This report was commissioned to provide a review of data which will; inform the risk management questions, identify data gaps in current knowledge and make recommendations for possible surveys to help address data gaps.

1.2 SCOPE

This review considers seaweed and seaweed products for human consumption. In this report “seaweed” is defined as fresh seaweed that has not undergone any processing, except for post-harvest steps such as washing, sorting, chilling or freezing. “Seaweed product” is defined as seaweed that has undergone further processing such as drying, salting, heating or marinading.

In New Zealand, karengo, also called parengo, laver or nori (*Porphyra/Pyropia* spp.) is a traditional food of Māori and wild-harvested karengo is consumed alongside other seaweed species. Seaweed gathered recreationally for personal or whānau consumption or use (that is not for sale) is outside the scope of this study. Foods that are not for sale, as defined in the Food Act 2014, are not regulated under the Act. The risk management questions this study supports relate only to regulated food, whether domestically produced or imported.

Table 1 provides a summary of the scope of seaweed and seaweed products and potential food safety hazards considered in this review.

Table 1. Scope of the review

Scope	Included in scope	Excluded from scope
General	Red, green, and brown seaweed (macroalgae) and products derived from, or containing these seaweeds that are for human consumption, and which may be farmed or wild-harvested.	• Microalgae (e.g. spirulina, Chlorella) • Products not for human consumption
Seaweed products	Domestically produced and imported seaweed products that are commercially available in New Zealand, including various forms of the following product types: • Fresh seaweed (chilled or frozen) • Dried seaweed • Other preserved seaweed (e.g. salted, acidified, marinated, fermented) • Food containing seaweed (e.g. beverages, snacks, soup bases, confectionary) • Flavouring extracts and dietary supplements	• Seaweed collected for personal use or consumption (non-commercial) • Seaweed-derived food additives (e.g. carrageenan, alginate) • Seaweed derivatives for pharmaceutical or medicinal applications
Microbial hazards	• Pathogenic bacteria • Viruses • Parasites • Toxigenic moulds (in dried products) • Marine biotoxins	
Chemical hazards	• Heavy metals • Micronutrients	• Pesticide residues • Food additives • Other environmental contaminants (e.g. dioxin, polychlorinated biphenyls)

1.3 DATA SOURCES

The data summarised in the review were obtained from the following sources:

- A search of the literature written in English conducted using the PubMed and Web of Science search engines. References lists from the papers recovered were also checked for relevant papers.
- A search of the grey literature using Google search engine.
- A search of New Zealand and international government/organisation websites for; information on hazard regulatory limits, dietary consumption, product recalls, notifications, and border refusals/rejections.
- Dietary information from the 1997 National Nutrition Survey, the 2002 National Children's Nutrition Survey and the 2008/09 Adult Nutrition Survey.
- New Zealand seaweed product import and retail survey data provided by NZFS.

Further information is detailed in Appendix A.

1.4 REPORT FORMAT

Section two of the report introduces edible seaweed species, global and domestic production, the types of seaweed and seaweed products commercially available in New Zealand and their originating country.

The international and domestic regulatory and non-regulatory chemical and microbiological hazard limits in seaweed or seaweed products are summarised in Section three. Seaweed-related recalls, notifications or border rejections are summarised in Section four. Seaweed related outbreaks recorded in the literature are summarised in Section five.

Sections six and seven provide profiles of the microbiological and chemical hazards that may be associated with seaweed or seaweed products, including possible health effects and evidence of their presence on seaweeds.

Section eight summarises the information found on processing of selected seaweed products and the effect of various processing treatments (for example, washing or soaking, drying, roasting) on the presence and levels of the hazards in the products.

Data on consumption of seaweed and seaweed products in New Zealand and overseas are provided in Section nine.

Overall conclusions and commentary on key food safety issues, risks and data gaps from a New Zealand perspective are provided in section ten, followed by recommendations for the scope of potential future surveys of seaweed and seaweed products in section eleven.

2 EDIBLE SEAWEED

2.1 INTRODUCING SEAWEED

Seaweeds are multicellular algae, known as macroalgae, making them distinct from the unicellular algae (known as microalgae or in the case of marine microalgae, phytoplankton). Like terrestrial plants, seaweeds use photosynthesis to produce energy, but otherwise differ from land-based plants in their biology and biochemistry (Dhargalkar and Pereira, 2005; Mabeau and Fleurence, 1993; Rajapakse and Kim, 2011).

There are three major seaweed groups (Nelson, 2020):

- Green algae (Chlorophyta), typically grow in freshwater or terrestrial habitats, including inter-tidal zones.
- Brown algae (Ochrophyta), typically grow in marine environments.
- Red algae (Rhodophyta) can grow anywhere from the high inter-tidal zone to deep marine water. Despite the name, red algae may not be red in colour. Some red algae may be purple, khaki green or brown.

2.2 NOMENCLATURE AND DISTRIBUTION

Table 2 lists the seaweed species that are associated with seaweed or seaweed products available for purchase in New Zealand.

Note, some products do not specify the species of seaweed on the product packaging. Seaweed species other than those listed in Table 2 may be present in seaweed food products available for purchase in New Zealand.

A range of different species of green, brown and red seaweeds are eaten around the world. These seaweeds have acquired common names according to the society in which they are consumed, often leading to the same species of seaweed acquiring multiple common names, or more than one species of seaweed having the same common name. Examples of common names, common food uses, and growing areas are also provided in Table 2.

In the remaining sections of this report, where a common name is used in the reference material, the same common name is used in this report. If the reference provides the scientific name for the seaweed species, the scientific name is also given. Scientific names for seaweeds are written in full to avoid confusion between genera and/or species.

Table 2. Selected seaweed species associated with seaweed or seaweed products available for purchase in New Zealand

Scientific classification	Common names	Common food uses	Grows in New Zealand waters	Growing areas
Green Algae				**Fresh water or marine environments depending on species**
Caulerpa spp.	Sea grapes/umibudo/latok/arosep	Fresh vegetable	Yes	Tropical/sub-tropical waters
Ulva spp.	Sea lettuce/green nori	Salad, soup, cooked dish	Yes	Worldwide
Brown Algae				**Marine environments (some species not listed below can be freshwater)**
Cladosiphon okamuranus	Mozuku	Salad, soup, appetizer	No	East Asia
Himanthalia elongata	Sea spaghetti/sea thong	Salad, soup, stir fry, pasta dish, baking	No	Northern north hemisphere
Hormosira banksii	Neptune's necklace/ sea grapes	Served fresh in salad or topping	Yes	New Zealand and temperate Australia
Macrocystis pyrifera	Giant or bladder kelp	Dried garnish	Yes	Temperate waters of northern and southern hemispheres
Species from Laminariaceae family, for example: *Saccharina japonica* *Ecklonia radiata*	Kombu/dasima/haidai/kelp	Soup base, stock, tea, salad	 No Yes	 East Asia North New Zealand, Australia, east and west Africa, Oman, Japan and Korea
Sargassum fusiforme	Hijiki/tot	Seasoning, cooked dish, stir-fry	No	East Asia
Undaria pinnatifida	Wakame (Asian kelp)	Seaweed salad, miso soup	Yes	Worldwide

Scientific classification	Common names	Common food uses	Grows in NZ waters	Growing areas
Red Algae				**Marine environments (some species not listed below can be freshwater)**
Chondracanthus chamissoi	Sea chicory	Salads, soups, garnish	No	Peru/Chile
Chondrus crispus	Irish moss/ carrageenan moss/rehia	Boiled to produce a gel, tonic, ingredient in cooked dishes	No	North Atlantic
Gracilaria spp.[1]	Sea moss/ogonori	Seaweed salad, component of ahi poke (raw fish salad)	Yes	Worldwide, sea temperature above 10°C
Palmaria palmata	Dulse/dillisk	Seaweed salad, dry snack, cooked dish	No	North Atlantic
Porphyra/*Pyropia* spp.	Nori/zicai/gim/laver/karengo/parengo	Dried sushi sheets, dry snack, cooked dish	Yes	Worldwide

Sources

Selection of seaweed species based on information from New Zealand online retailers including (https://wakamefresh.com/, https://pacificharvest.co.nz/, https://www.nzkelp.co.nz/ and http://enzalg.co.nz/ Accessed 16 May 2022) and unpublished data supplied by C. Esguerra, Food Regulation, New Zealand Food Safety (11 May 2022).

Distribution of growing areas provided by Cawthron Institute (pers. comm. 23 June 2022) and from Nelson (2020)

Notes

1 *Gracilaria* spp. have not been specifically identified in retail products but have been observed on food service menus.

2.3 GLOBAL PRODUCTION OF SEAWEED

2.3.1 Seaweed uses

Around the world, seaweed is used for a wide range of purposes. For human dietary purposes, seaweeds are consumed in its fresh form or further processed into various food products or into food additives, such as carrageenan. For horticultural or agricultural purposes, seaweeds are harvested for animal feed or biofertiliser/biostimulants. Other uses of seaweed include pharmaceuticals, nutraceuticals, health supplements, cosmetics, bio-packaging and biofuel (Cai *et al*., 2021).

2.3.2 Global seaweed production 2000 to 2020

The Food and Agriculture Organisation of the United Nations (FAO) has identified 221 species of seaweed with commercial value (Ferdouse *et al.*, 2018). In 2019, the world seaweed production was primarily from farmed cultivation (34.7 million tonnes) compared to wild-harvested (1.1 million tonnes) (Cai *et al*., 2021).

The species of seaweed with the largest global cultivated harvest in 2015 were *Eucheuma* seaweeds (*Eucheuma* spp.), followed by Japanese kelp (*Saccharina japonica*), *Gracilaria* seaweeds (*Gracilaria* spp.), wakame (*Undaria pinnatifida*), Elkhorn sea moss (*Kappaphycus alvarezii*), and nori (*Porphyra/Pyropia* spp.) (Annex 3 of Ferdouse *et al.*, 2018).

Eucheuma spp. and *Kappaphycus* spp. are mainly harvested for carrageenan extraction for cosmetic and food uses, as well as small amounts being consumed as a food by the coastal communities where they are harvested (Cai *et al.*, 2021). These species are not considered further in this report as food additives are not within the project scope.

FAO maintains a database of global estimates of aquaculture production which contains live weight production estimates for a selection of 27 seaweed species groups (FAO, 2022). The FishStatJ interface to the database does not give the option to distinguish between seaweed harvested for human consumption and for other uses at the seaweed species level. Some countries report seaweed production by groups of species, so global production of individual species is frequently underestimated (FAO, 2022).

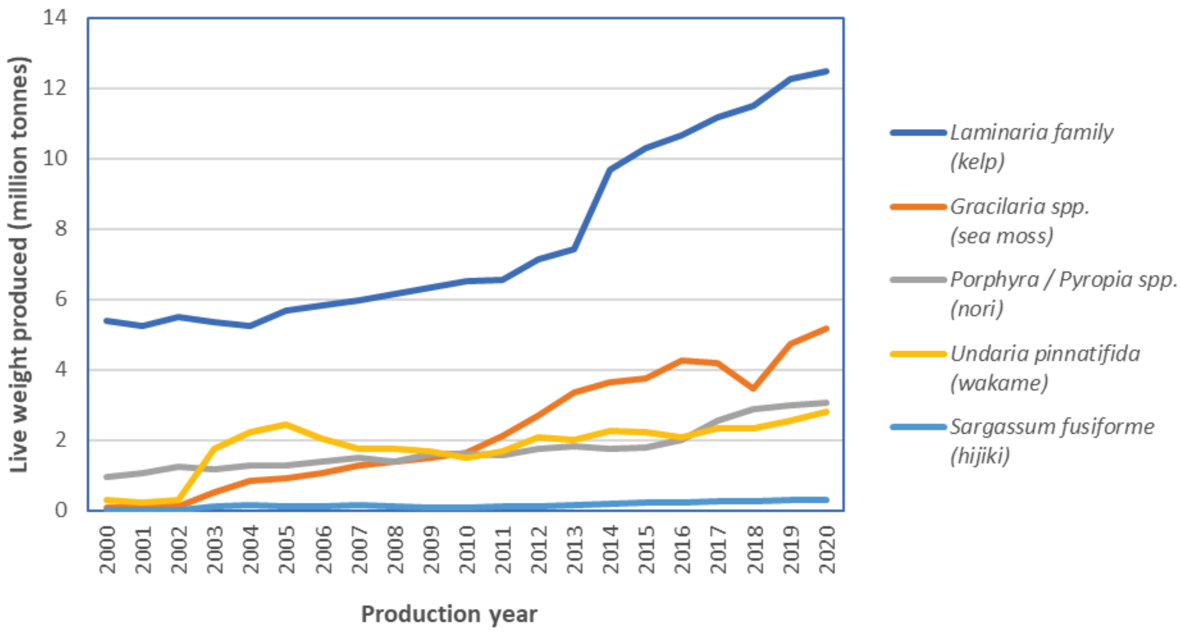
The estimated annual production of all seaweeds captured by the FAO database increased from 10.5 million tonnes in 2000 to 35 million tonnes in 2020.

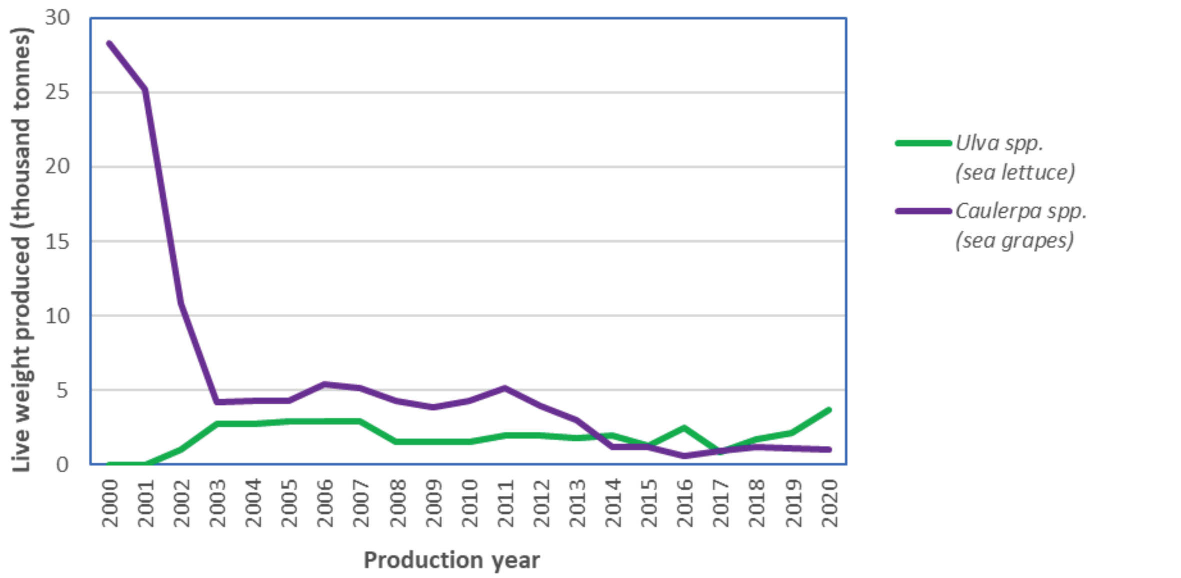
Seaweed live weight production data for all uses was extracted from the database for the species identified in Table 2 that were also identified at species level in the database. The global annual production estimates between 2000 and 2020 for the seaweeds are shown in Figure 1.

Nori seaweed production has gradually increased over the last twenty years, but at a slower rate than kelp (*Laminaria* family) and G*racilaria* spp. Production of wakame seaweed (*Undaria pinnatifida*) has been similar to nori (*Porphyra/Pyropia* spp.) since 2010. Production of sea lettuce (*Ulva* spp.) and sea grapes (*Caulerpa* spp.) is measured in thousands of tonnes live weight which is much lower than approximately 300,000 tonnes of hijiki (*Sargassum fusiforme*) seaweed and approximately 3 million tonnes for wakame or nori produced in 2020.

The increase in production of *Gracilaria* spp. seaweeds can in part be associated with production of agar for food and non-food industries and for use as abalone feed (Cai *et al*., 2021).

Figure 1. FAO annual global estimates of production of selected seaweed species





Source FAO Global Fishery and Aquaculture Production Statistics Version 2022.1.0 (FAO, 2022)
Notes Estimates for kelp include data from *Saccharina japonica* (Japanese kelp) and *Macrocystis pyrifera* (Giant kelp)

2.3.3 Production by country

Data from the FAO aquaculture database (FAO, 2022) show that in 2020 there were seven countries that produced more than 10,000 tonnes of at least one of the edible seaweed types identified in Table 2. The production given by live weight tonnes is summarised in Table 3. As in the previous section, it is not known how much of this production is used for human consumption. Note that neither New Zealand nor Australia has records relating to aquatic plants in the FAO Global Fishery and Aquaculture Production database.

Table 3. Production of selected edible seaweed species by countries that produced more than 10 tonnes of at least one of the selected seaweed species, 2020

Species group as specified in FAO database	Production (1,000 tonnes live weight)						
	China	Indonesia	Republic of Korea	Democratic People' s Republic of Korea	Japan	Chile	Viet Nam
Sargassum spp.	-	81	< 1	-	-	-	-
Sargassum fusiforme (Hijiki)	265	-	28	-	-	-	-
Saccharina japonica (Japanese kelp)	11,165	-	675	600	30	-	-
Undaria pinnatifida (Wakame)	2,256	-	501	-	53	-	-
Porphyra/Pyropia spp. (Nori)	2,220	-	544	3	289	-	-
Gracilaria spp.	3,690	1,457	4	-	-	18	12

Source FAO Global Fishery and Aquaculture Production Statistics Version 2022.1.0 (FAO, 2022)
Symbol - No data in database

Asia is a major seaweed production region with 97% of the world's farmed and wild-harvested seaweed produced in Asia in 2019 (Cai *et al.*, 2021). Table 3 shows that China produces the largest volume of the seaweed species listed compared to other countries in the database.

According to FAO Global Fishery and Aquaculture Production data:

- Hijiki (*Sargassum fusiforme*) is produced by China and the Republic of Korea and possibly by Indonesia (*Sargassum* spp.).
- China produces 90% of global production of Japanese kelp or kombu (*Saccharina japonica*), with approximately 5% of global production occurring in each of the Republic of Korea and the Democratic People's Republic of Korea. Japan produces < 1% of global production of kombu a year.
- Wakame is produced mainly in China (80% of global production) with smaller amounts in the Republic of Korea (18%) and Japan (2%).
- Nori (*Porphyra*/*Pyropia* spp.) is mainly produced in China (72%), Republic of Korea (18%) and Japan (9%).
- China and Indonesia are the main producers of *Gracilaria* seaweeds.

The global international trade in seaweed was estimated to be worth US$4 billion in 2016. Of this, the global amount of edible seaweed importations are 250,000 tonnes with a value of US$648 million in 2016 (Ferdouse *et al.*, 2018). China (140,000 tonnes), the European

Union (15,000 tonnes), Japan (33,000 tonnes) and the United States (8,500 tonnes) imported the most edible seaweed.

2.4 THE NEW ZEALAND SEAWEED INDUSTRY

A report on the New Zealand seaweed sector has been published by the Sustainable Seas National Science Challenge Group (Bradly *et al.*, 2021).

The report states that, in New Zealand, commercial farming of seaweed as a stand-alone activity does not exist. Seaweed is harvested from mussel lines on existing shellfish farms, wild-harvested or collected as beach-cast seaweed. New Zealand does not have commercial hatcheries or farming on a large scale.

In 2020, there were 59 permit holders with 170 associated marine farms who are eligible to farm seaweed, mainly located in the Marlborough Sounds, the Coromandel Peninsula and Wellington Harbour. These are all multi-species farms (for example mussel farms) and not all of these permit holders will be actively harvesting seaweed. Seaweeds commercially harvested in New Zealand are mainly used for agriculture or horticulture purposes (for example feed supplements, biostimulants and fertiliser), with smaller amounts used in producing products for the beauty, health and wellness, and food markets.

Bradly *et al.* (2021) lists small-scale New Zealand commercial activities such as harvesting, processing and sale of seaweed products for human consumption. Review of the list identified three companies associated with seaweed as a food or food ingredient that were still operating in August 2022:

- NZ Kelp – harvests and processes New Zealand giant kelp (*Macrocystis pyrifera*) from Akaroa Harbour to produce various dried food products, such as kelp flakes and powder.[1]
- Pacific Harvest - supplies a range of local and imported air-dried edible seaweed products, including wakame and kombu (also known as konbu) harvested from New Zealand waters.[2] They source, test and repackage wakame, Irish moss, nori, sea chicory, sea lettuce and sea spaghetti from overseas suppliers.
- Wakame Fresh - harvests and processes wakame from mussel farms in the Coromandel area for retail and food service.[3]

Review of NZ Kelp's products indicated seaweed harvested in New Zealand is being used as a flavour in New Zealand manufactured gins. NZ Kelp supply kelp products to Dr Beak and Roots gin distillers. Two other seaweed flavoured gins were also found from a Google search. Mt Fyffe distillery use an unspecified seaweed harvested from the Kaikōura coast and Imagination Gin distillery use wakame foraged by a licensed harvester from the Wellington and Wairarapa coasts.

Up to 6 tonnes per annum of *Pyropia*/*Porphyra* spp. were harvested for domestic consumption under an historic commercial licence by an independent operator until this was stopped after the 2016 Kaikōura earthquake to let the seabed recover (Bradly *et al.*, 2021).

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[1] https://www.nzkelp.co.nz/valere-1 (Accessed 16 May 2022)
[2] https://pacificharvest.co.nz/ (Accessed 16 May 2022)
[3] https://wakamefresh.co.nz/ and https://www.facebook.com/wakamefresh/ (Accessed 16 May 2022)

2.5 SEAWEED PRODUCTS IMPORTED INTO NEW ZEALAND

Most seaweed products commercially available in New Zealand are imported. Table 4 provides estimates of imports of edible seaweed products into New Zealand during the period 2019–2021 based on unpublished data supplied by NZFS (C. Esguerra, Food Regulation, New Zealand Food Safety, 8 April 2022). The table does not include imports of products outside the scope of this study, such as, microalgae (e.g. spirulina, Chlorella), carrageenan and alginates.

These data are based on import entries under four Harmonised System (HS) Codes that specifically cover seaweed products for human consumption, and entries under other HS Codes not specific to seaweed but that had product descriptions containing the word "seaweed". The information summarised in Table 4 should be considered as indicative only, since they are dependent on how the import entries were lodged by importers (for example the HS Code and product descriptors used).

Table 4 shows that the combined amount of all types of edible seaweed and seaweed products imported into New Zealand was a little over 1,000 tonnes in 2021, which is just over 100 tonnes greater than imported in 2019.

The largest import volume was for dried laver seaweed product (nori sheets, *Porphyra*/*Pyropia* spp.), with 560 tonnes of product imported into New Zealand in 2021. This nori group captured products with descriptors that included the terms: dried, roasted, toasted, or seaweed wrap, but excluded products described as snacks. This product is primarily imported from the Republic of Korea (59%) with other major suppliers being China (30%) and Japan (10%).

The second largest import category was other dried seaweed products, with 190 tonnes being imported into New Zealand in 2021. These products were also predominantly imported from China (40%), the Republic of Korea (33%) and Japan (22%). The amount of dried hijiki (*Sargassum fusiforme*) imported was small in comparison to the total of other dried seaweeds

Frozen seaweed salad (wakame, *Undaria pinnatifida*) was predominantly (99%) imported from China (141 tonnes). Undefined frozen or dried seaweed (102 tonnes) came from China (41%), the Republic of Korea (41%), Canada (7%) and the United Kingdom (6%).

Seaweed products imported into New Zealand from Thailand are mainly processed foods that contain seaweed as an ingredient. 74% of products classed as "food containing or derived from seaweed" and 39% of products classed as "seaweed snacks or snacks containing seaweed" were imported from Thailand.

Table 4. Imports into New Zealand of seaweed products for human consumption (excluding supplements), 2019 to 2021

Product category	Quantity (kg)			Country of origin (average percentage of annual imports)[1] [1]
	2019	2020	2021	
Dried laver (nori sheets) [2]	274,442	310,370	558,920	Republic of Korea (59%) China (30%) Japan (10%)
Dried seaweed (various species other than hijiki) [3]	264,070	192,705	190,154	China (40%) Republic of Korea (31%) Japan (22%)
Dried hijiki [4]	6	24	157	Japan (46%) China (33%) Australia (19%)
Frozen seaweed preparations [5]	162,875	108,603	140,757	China (99%)
Other frozen or dried seaweed [6]	72,269	126,735	102,075	China (41%) Republic of Korea (41%) Canada (7%) United Kingdom (6%)
Seaweed-based snacks and snacks containing seaweed [7]	109,601	67,534	31,994	Republic of Korea (55%) Thailand (39%)
Food containing or derived from seaweed [8]	4,632	42,572	23,784	Thailand (74%) Spain (19%)
Preserved seaweed (other than dried seaweed and frozen seaweed salad) [9]	4,023	25,418	5,598	China (36%) Republic of Korea (32%) Japan (17%) Lithuania (11%)
Seasoning and flavouring products [10]	5,161	3,955	3,660	China (47%) Chinese Taipei (23%) Japan (17%)
Chilled seaweed	10	3	2	[11]
Total	**897,089**	**877,919**	**1,057,101**	

Source Unpublished data supplied by NZFS (C. Esguerra, Food Regulation, New Zealand Food Safety, 8 April 2022)

Notes

1 Exporting countries listed in the table are those where annual imports into New Zealand of the product category are greater than 5%.

2 Dried laver (*Porphyra* spp.) is commonly known in New Zealand as dried nori. This imported product category mainly consists of nori sheets used as a wrapper for sushi, and seasoned nori snacks.

3 Dried seaweed includes various species and forms of dried seaweed, other than hijiki seaweed.

4 Hijiki seaweed has its own HS Code, and therefore, can be differentiated from other types of dried seaweed.

5 Frozen seaweed preparations are predominantly seaweed salad made of wakame (*Undaria pinnatifida*).

6 The product category "other frozen or dried" includes import entries under the HS Code for "for frozen or dried (not hijiki)" that do not have product descriptors that allow for their specific product type to be determined.

7 "Seaweed-based snacks" typically contain seaweed as a primary ingredient (e.g. fried seaweed, seaweed chips, seaweed tempura). "Snacks containing seaweed" contain minor amounts of seaweed (typically < 5%) (e.g. mixed nuts and seeds with seaweed, biscuits and crackers).

8 Examples of food containing seaweed are seaweed soup, kelp noodle, tofu with seaweed and seaweed roll.

9 Preserved seaweed includes salted, seasoned or pickled seaweed, which have not been entered under the HS Codes for dried or frozen seaweed.

10 Examples of seasoning/flavouring products are seaweed powder, miso soup powder or paste containing seaweed, and seaweed flavouring extracts.

11 In 2019 -2020 chilled seaweed imported from US, Chinese Taipei and Hong Kong, in 2021 chilled seaweed imported from Japan.

2.6 SEAWEED AND SEAWEED PRODUCTS AVAILABLE AT RETAIL OUTLETS IN NEW ZEALAND

2.6.1 Product Range

In 2022, NZFS commissioned a seaweed product collection study to understand the range of retail products commercially available to the New Zealand public (Drysdale, 2022). The study recorded the label information from:

- 244 products included in the GS1 On Pack database[4], which mainly contains data for products available from New Zealand's major supermarket chains; and
- 140 products purchased from ten specialty/ethnic/health retail stores in the Auckland region and three online stores.

The list of 384 products collected reflects the wide variety of seaweed products available for purchase by the public from various types of retail outlets. Label information collected included the product description, ingredient list, percentage amount of seaweed (when provided), use and preparation instructions, shelf-life and the country of origin.

The products were classified by NZFS into product types based on their product characteristics. These product types and their typical characteristics and uses are summarised in Table 5.

Evaluation of the ingredient information showed that most products could be grouped into two groups based on the proportion of seaweed contained in the products. The first group consist of products that contain seaweed as a primary ingredient, for example when seaweed appears as the first ingredient in the ingredient list. This group includes dried seaweed, dried nori, frozen seaweed salad, shelf-stable seaweed preparations and seaweed-based snacks. These products generally contain more than 45% seaweed.

The second group consists mostly of food that have seaweed as a minor ingredient, typically ≤5%. There were very few products found from retail outlets that contained seaweed in the intermediate range (for example 30% content), despite these products being specifically targeted in the survey.

Most of the products collected were processed products, some of which are presented as ready-to-eat (RTE) products, which are unlikely to go through further preparation steps by the consumer.

Of the seaweed species listed on product packaging, kelp (Laminariaceae family), wakame (*Undaria pinnatifida*) and laver (*Pyropia/Porphyra* spp.) were the most common across product types. Hijiki (*Sargassum fusiforme) and* sea lettuce (*Ulva linnaeus*) were also available as a dried seaweed product. Some products did not specify the seaweed species on the packaging.

The seaweed products are likely eaten as RTE snacks, salads, or garnishes, or used as ingredients for sushi, snack mixes, drinks, health supplements, or flavouring for soups.

[4] The GS1 On Pack Database is a database of label information for packaged food available for sale in New Zealand. It largely contains information on products sold in supermarket chains owned by Foodstuffs and Woolworths New Zealand, representing the majority of food sales in New Zealand.

Table 5. Seaweed products commercially available from selected New Zealand retail shops and online stores (May 2022)

Product type	% Seaweed content	Species [1] (as indicated on packaging)	Forms	Storage	Typical uses	Country of origin [3]
Products with seaweed as the primary ingredient [2]						
Dried seaweed (excluding dried nori)	99 to 100	Kelp (*Laminaria* family.) Wakame (*Undaria pinnatifida*) Laver (*Porphyra* spp.) Hijiki (*Sargassum fusiforme)* Sea lettuce (*Ulva linnaeus*)	Cuts, slices, flakes Salted or unsalted Some are dried and roasted	Shelf-stable	Ingredient in soups and stews Rehydrated and used like a vegetable (e.g. salad or side dish) Fried and seasoned to make chips (snack)	China Japan Republic of Korea Chinese Taipei European Union (unspecified country)
Dried laver (nori sheets and snacks)	50 to 70	Laver (*Porphyra* spp.)	Sheets, snack-sized cuts, strips May be roasted/toasted Seasoned or unseasoned	Shelf-stable	Ready-to-eat (RTE) or may be toasted before consumption Sushi or rice wrapping Snack Cut into strips and used as a topping or garnish	China Japan Republic of Korea
Frozen seaweed salad	60 to 85	Wakame (*Undaria pinnatifida*)	Seasoned strips or cuts	Frozen	RTE salad, side dish, component of sushi	China
Shelf-stable seaweed preparations (non-dried)	60 to 85	Wakame (*Undaria pinnatifida*) Kelp (*Laminaria* spp.)	Seasoned, pickled, or salted seaweed Retorted products, e.g. seaweed soup	Shelf-stable	RTE salad or side dish Snacks	China Japan Republic of Korea
Seaweed-based snacks	45 to 60	Laver (*Porphyra* spp.)	Baked, roasted, fried Tempura, seaweed snacks, chips and rolls	Shelf-stable	Toppings Snacks	China Japan Republic of Korea Thailand

Product type	% Seaweed content	Species [1] (as indicated on packaging)	Forms	Storage	Typical uses	Country of origin [3]
Products containing seaweed as a minor ingredient						
Seasoning/ flavouring products	Most are < 5%, a few seasoning pastes contain ~ 17%	Wakame (*Undaria* spp.) Kelp (as extract or powdered kelp)	Liquid seasoning Flavouring paste Dry mix powder	Shelf-stable	Soup/stew base Instant miso soup Flavouring	China Japan Korea
Snacks and snack mixes	≤ 5	Laver (*Porphyra* spp.)	Mixes of crackers, nuts, seeds with nori strips Confectionery made with seaweed	Shelf-stable	Snacks	Unknown
Crackers or baked items	< 2	No species recorded	Rice crackers Biscuits	Shelf-stable	Snacks	Unknown
Beverage	Unknown	Kelp (*Laminaria* spp.)	Soy drink, rice drink	Shelf-stable	Drink	Unknown
Supplemented food	≤ 5	Kelp (*Laminaria* spp.) Red seaweed	e.g. supplemented food blends and powders	Shelf-stable	Nutritional drinks	Unknown
Other foods containing seaweed	≤ 5	No species recorded	e.g. fish-based products, tofu, prepared soups, seaweed rolls	Frozen	Various	Unknown
			e.g. sushi	Chilled	RTE food	New Zealand
			e.g. instant noodles, risotto mix	Shelf-stable	Instant meals	Unknown

Source
Table prepared by NZFS

Notes
1 Seaweed species as described on the product packaging. Not all product has species displayed, so other seaweed species may be associated with these product types.
2 Primary ingredient means that seaweed is the first ingredient in the ingredient list and constitutes the biggest proportion of the food.
3 Unknown indicates the country of origin was not indicated on the product packaging.

2.6.2 Sushi

Sushi is a food containing seaweed commonly eaten in New Zealand. As of 1 January 2022, there were 1,926 businesses (operating through 3,512 outlets or sites) with a registered Food Control Plan or National Programme that included the sale of sushi within the scope of their operation[5]. These businesses are mainly from the retail and food service sectors, such as supermarkets, restaurants and cafes, takeaways, and caterers.

The typical use of seaweed in sushi is as dried nori sheets (*Pyropia*/*Porphyra* spp.) which forms the wrapper of sushi, plus wakame (*Undaria pinntifida*) which is used in some varieties of sushi as a filler or garnish.

[5] Information supplied by C. Esguerra, Food Regulation, New Zealand Food Safety (18 March 2022).

3 REGULATORY RISK MANAGEMENT

Regulations governing the safety of food that consumers eat have generally been developed to apply to traditional or commonly encountered foods that consumers are exposed to within their country or region. The increase in international trade and consumption of seaweed as well as the emergence of new types of seaweed as food, have stimulated studies reviewing the applicability and suitability of food safety regulations, as well as the food safety attributes, of seaweeds (Banach *et al.*, 2020).

3.1 MAXIMUM LIMITS FOR CHEMICAL HAZARDS IN SEAWEED PRODUCTS

Table 6 shows the established maximum regulatory or recommended limits for elemental contaminants in seaweeds, some of which are briefly discussed in the following sections.

The recommended German maximum limit for iodine in dried algae (20 mg/kg) is substantially lower than limits in Australia or France. A subsequent report by the French Agency for Food, Environmental and Occupational Health and Safety (ANSES) suggests that the German limit is expressed on a fresh weight basis and would correspond to approximately 400 mg/kg of iodine on a dry weight (dw) basis (ANSES, 2018).

It has been reported that the US Food Chemical Codex recommends a limit of 5000 mg/kg dw for the iodine content of kelp as a food ingredient (FSANZ, 2016b).

Table 6. Maximum limits for seaweed chemical contaminants

Jurisdiction	Contaminant	Commodity description	Limit type	Limit (mg/kg dw unless otherwise stated)	Reference
Codex	No relevant limits				1
New Zealand and Australia	Arsenic (inorganic)	Seaweed	Regional regulatory limit	1 (at 85% hydration)	2
Australia	Iodine	Imported brown seaweed (Phaeophyceae)	Import limit	1000	3
	Arsenic (inorganic)	Imported hijiki seaweed *(Sargassum fusiforme)* only	Import limit	1 (at 85% hydration)	4
EU	Cadmium	Food supplements consisting exclusively or mainly of dried seaweed or of products derived from seaweed	Regional regulatory limit	3 (as sold)	5
France	Arsenic (inorganic)	21 specified macroalgae and 3 microalgae	National regulatory limit	3	6
	Cadmium			0.5	
	Lead			5	
	Mercury			0.1	
	Tin			5	
	Iodine			2000	
Germany	Iodine	Dried algae	Recommendation	20	7
Hong Kong	Arsenic (inorganic)	Seaweed	National regulatory limit	1 (fresh weight basis)	8
United States	No relevant limits				9

Abbreviation
dw: dry weight

References

1 https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXS%2B193-1995%252FCXS_193e.pdf

2 Australia New Zealand Food Standards Code – Schedule 19 – Maximum levels of contaminants and natural toxicants (legislation.gov.au)

3 Brown seaweed and Iodine.pdf (foodstandards.gov.au)

4 https://www.awe.gov.au/biosecurity-trade/import/goods/food/type/brown-seaweed#classes-of-seaweed_2

5 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R0629&from=ES

6 ANNEXES (cybercolloids.net)

7 https://mobil.bfr.bund.de/cm/349/health_risks_linked_to_high_iodine_levels_in_dried_algae.pdf

8 https://www.gld.gov.hk/egazette/pdf/20182223/es220182223113.pdf

9 https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-action-levels-poisonous-or-deleterious-substances-human-food-and-animal-feed

3.1.1 New Zealand/Australia

In New Zealand and Australia, the maximum levels of contaminants are set out in Schedule 19 of the Australia New Zealand Food Standards Code.

Arsenic

Risk mitigation strategies have been established to reduce the risk of exposure of the New Zealand and Australian public to arsenic through the diet. These include:

1. The introduction and maintenance of a maximum limit (ML) for inorganic arsenic in seaweed since 1991. This limit is 1 mg/kg and is found in Standard 1.4.1 Contaminants and Natural Toxicants.
2. The introduction and maintenance of MLs for inorganic arsenic for other commodities, such as crustacea (2 mg/kg), fish (2 mg/kg) and molluscs (1 mg/kg).

3.1.2 Australia only

Food Standards Australia New Zealand (FSANZ) has prepared two seaweed-related imported food risk statements (FSANZ, 2016a; b).

Inorganic arsenic

Specific types of seaweed (particularly Sargassaceae family species) contain higher levels of inorganic arsenic than other seaweeds. These levels are often higher than that allowed by the Australia New Zealand Food Standards Code. FSANZ concluded that inorganic arsenic in hijiki seaweed is a medium or high risk to public health, due to the carcinogenicity of inorganic arsenic (FSANZ, 2016a).

Iodine

FSANZ concluded that iodine in brown seaweed (class Phaeophyceae) is a medium or high risk to public health as:

- exposure to excess iodine can disturb thyroid gland function by stimulating thyroid hormone production, resulting in thyrotoxicosis. The severity of the adverse effects depends on the iodine status of the individuals and any pre-existing thyroid dysfunction,
- cases of excess iodine-induced illness from consumption of brown seaweed have been reported in Australia, and
- there have been three food recalls in Australia of brown seaweed of the Phaeophyceae class due to the presence of excessive iodine levels (FSANZ, 2016b).

Brown seaweeds of the Phaeophyceae class are classified as risk foods under the Imported Food Control Order 2019.[6] Consignments of brown seaweed are referred by the Department of Agriculture, Fisheries and Forestry (DAFF) for analytical testing under the Imported Food Inspection Scheme (IFIS).[7] Brown seaweeds are tested for iodine, with hijiki seaweed additionally tested for inorganic arsenic (see Table 6 for maximum limit).

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[6] https://www.legislation.gov.au/Details/F2022C00024 Accessed 2 August 2022
[7] https://www.agriculture.gov.au/biosecurity-trade/import/goods/food/type/brown-seaweed Accessed 2 August 2022

3.1.3 International, regional and other national standards

Codex

There are no specific Codex texts related to food safety aspects of seaweed. A regional standard for laver products (genus *Pyropia/Porphyra*) exists but it does not specifically address food safety aspects of the product (Codex, 2017). In 2021, it was pointed out at the 44th Codex Alimentarius Commission[8] that "*there is currently no Codex Guideline addressing food safety in this area*" and "*an attempt to develop Codex standards or guidance could be premature given the lack of data to support science-based standards and could result in non-tariff barriers to trade and inhibit productive innovation*".

European Union

European Union (EU) legislation pertaining to heavy metals in seaweed exists for animal feed and some food supplements, but not for seaweed-containing foods (Banach *et al.*, 2020).

France

In France, certain seaweed species were authorised for consumption as vegetables and condiments in 1990, the first European country to do so (Mabeau and Fleurence, 1993). It appears that, outside this authorisation, seaweeds are treated as novel foods, requiring specific approvals. MLs were established for cadmium, lead, mercury, tin and iodine as set out in Table 6.

United Kingdom

In the United Kingdom, limits in the range 0.1-5.0 mg/kg of total arsenic in food are specified under The Arsenic in Food Regulations 1959,[9] however these regulations specifically exclude fish or edible seaweed (Rose *et al.*, 2007).

United States

In the United States, both brown and red algae have received 'generally recognised as safe' (GRAS) status "if their use is confined to ingredients of spices, seasonings, and flavourings as is now stated in the Code of Federal Regulations".[10] The Code of Federal Regulations further specifies the maximum daily intake of iodine for foods in which kelp is an ingredient.[11]

3.2 MICROBIOLOGICAL LIMITS FOR SEAWEED PRODUCTS

3.2.1 New Zealand/Australia

No microbiological limits are set specifically for seaweed in Schedule 27 of the Australia New Zealand Food Standards Code.[12] However, the microbiological limits for *Listeria monocytogenes* in RTE foods will be relevant to RTE seaweed products (snacks, salads, etc.). For RTE foods in which growth of *L. monocytogenes* can occur, the organism should not be detected in any of five 25 g samples. For RTE foods in which growth of *L. monocytogenes* will

[8] CAC44 / what foods may Codex be dealing with in the future? | CODEXALIMENTARIUS (fao.org)
[9] https://www.legislation.gov.uk/uksi/1959/831/pdfs/uksi_19590831_en.pdf Accessed 2 August 2022
[10] http://wayback.archive-it.org/7993/20171031063512/https://www.fda.gov/Food/IngredientsPackagingLabeling/GRAS/SCOGS/ucm260873.htm Accessed 15 August 2022
[11] https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=172.365 Accessed 15 August 2022
[12] Australia New Zealand Food Standards Code – Schedule 27 – Microbiological limits in food (legislation.gov.au) Accessed 4 May 2022

not occur, the organism should not be detected at a concentration above 100 CFU/g in any of five 25 g samples. There are no other ‘generic’ microbiological limits in Schedule 27 that could potentially be applicable to seaweed and seaweed products.

FSANZ has provided guidance on whether foods should be covered by the *L. monocytogenes* microbiological limits (FSANZ, 2016c). Seaweed products will vary in this respect, with shelf-stable products not considered to be RTE foods.

3.2.2 Other countries

France, the Republic of Korea and China have set microbiological limits for seaweeds, as shown in Table 7. For France, the guidelines pertain to dry seaweed products. The Korean Food Code[13] section 23-2 provides a product standard for RTE foods/convenience foods and specifically identifies gimbap (Korean dried seaweed rolls) as an RTE food. The Chinese guidelines apply to both marine algae, algal products and dried laver. Note, dried laver is the raw material used to produce seasoned/roasted laver (nori).

Microbiological limits specific for seaweed were not found for any other countries.

Table 7. Microbiological limits for seaweed and seaweed products in France, the Republic of Korea and China

Microorganism/hygiene indicator	Limit (CFU/g unless otherwise stated)			
	France [a]	Republic of Korea [b]	China	China
Applicable to	**Dried algae**	**All ready-to-eat foods**	**Dried laver [c]**	**Pre-packaged algae products [d]**
Aerobic mesophiles	≤ 10^5	NA	NA	NA
Aerobic plate counts	NA	NA	< 3×10^4	NA
Coliforms (faecal)	≤ 10	NA	<30 per 100g	NA
Mould	NA	NA	<300	NA
Anaerobe sulphite reducers	≤ 10^2	NA	NA	NA
Bacillus cereus	NA	<10^3	NA	NA
Clostridium perfringens	≤ 1	<10^2	NA	NA
Salmonella spp.	Not present per 25 g	Not present per 25 g	Not present per 25 g	Not present per 25 g
Shigella spp.	NA	NA	Not present per 25 g	NA
Staphylococcus aureus	≤ 10^2	<10^2	Not present per 25 g	NA
Vibrio parahaemolyticus	NA	<10^2	Not present per 25 g	NA

Abbreviation NA Not applicable, no limit has been documented

References
a CEVA (2019)
b Korean Food Code (https://www.mfds.go.kr/eng/brd/m_15/view.do?seq=72437)
c Chinese GB/T 23597-2009 Dried Laver standard as listed in Choi *et al.* (2014). An update to 2009 standard will be implemented May 2023 (https://codeofchina.com/standard/GBT23597-2022.html)
d USDA (2020)

[13] https://www.mfds.go.kr/eng/brd/m_15/view.do?seq=72437 Accessed 23 June 2022

3.3 LIMITS FOR MARINE BIOTOXINS

Maximum limits for marine biotoxins in seaweed were not found for any countries.

3.4 OTHER RISK MANAGEMENT MEASURES

Food regulatory bodies from some countries have issued advisory statements informing consumers to avoid hijiki seaweeds, due to high inorganic arsenic concentrations. New Zealand Food Safety has identified hijiki seaweed as a food containing high levels of inorganic arsenic.[14]

In July 2004 the United Kingdom Food Standard Agency advised people against hijiki consumption due to the high levels of inorganic arsenic (FSA, 2020). Food safety agencies in Canada[15], Hong Kong[16] and Ireland[17] also have public notices on their websites.

While Codex has not set any relevant standards specifically addressing hazards in seaweed, a regional standard was adopted in 2017 for laver products (CXS 323R-2017)[18]. This standard applies to dried laver, roasted laver and seasoned laver products from the genus *Pyropia/Porphyra*. Included in this standard are moisture content limits for the food. All products covered in this standard must comply with the maximum levels of the *General Standard for Contaminants and Toxins in Food and Feed* (CXS 193-1995)[19], which sets out contaminant levels for arsenic, cadmium and lead in a range of different food types/commodities, but not seaweed.

[14] https://www.mpi.govt.nz/food-safety-home/safe-levels-of-chemicals-in-food/arsenic/ Accessed 23 June 2022
[15] https://inspection.canada.ca/food-safety-for-consumers/fact-sheets/specific-products-and-risks/chemical-hazards/inorganic-arsenic/eng/1332268146718/1332268231124 Accessed 23 June 2022
All sites accessed on 16 May 2022
[16] https://www.cfs.gov.hk/english/programme/programme_rafs/programme_rafs_fc_02_08.html
[17] https://www.fsai.ie/faq/hijiki_seaweed.html
[18] https://www.fao.org/fao-who-codexalimentarius/sh-proxy/es/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXS%2B323R-2017%252FCXS_323Re.pdf
[19] https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXS%2B193-1995%252FCXS_193e.pdf

4 RECALLS AND BORDER REJECTIONS OF SEAWEED AND SEAWEED PRODUCTS DUE TO CHEMICAL AND MICROBIOLOGICAL HAZARDS

4.1 INTRODUCTION

This section of the report provides information on recalls, border rejections and food safety notifications related to seaweed and seaweed products which are recorded at a national or regional level.

The details of specific events including dates and actions taken are listed in Appendix B. Where multiple batches of the same product type from the same company are recorded with the same fault within the timeframe of a fortnight, the records have been combined to a single record. A fortnight was chosen, as this timeframe covered the clustering of observations in the records and is sensible from a food safety perspective.

4.2 NEW ZEALAND

Imported seaweed and seaweed products do not require food safety clearance for entry into New Zealand and are therefore not subject to border inspection. Thus, there are no border rejection records for seaweed or seaweed products.

Since 2016, there have been two seaweed product recalls due to high iodine levels, and four recalls due to undeclared allergens (Table 8).

In 2020, a trade level recall of kelp flakes occurred due to product iodine concentrations of 4300 mg/kg. At this concentration, 0.26 grams of product would provide the adult upper level (UL) of iodine intake (Table 13).

In 2022, iodine levels in a baby puree powder, which used kelp as an ingredient, were estimated to be 2.5 times the UL of daily iodine intake for children aged 1-3 years. This resulted in a consumer level recall.

Table 8. New Zealand seaweed related trade and consumer level recalls between 2016 and August 2022

Product type	Issue	Country of origin (Number of records)
Baby puree powder containing kelp ingredient	Excess iodine	New Zealand (1)
Organic kelp flakes	Excess iodine	New Zealand (1)
Prawn cracker snack with seaweed flavouring	Undeclared allergen	Thailand (1)
Seaweed/wakame salad	Undeclared allergen (Soy)	China (2)
Lupine tempeh containing seaweed	Undeclared allergen (Soy)	New Zealand (1)

Source Data provided by Food Compliance Services (NZFS) on 22 August 2022

4.3 AUSTRALIA

The Australian Failing Food Reports website[20] lists imported foods that were checked at the border and were classed as a 'failed food' because they failed an analytical test, contained non-permitted ingredients, or were a prohibited plant or fungus. Australian imported food inspection (section 3.1.1) requires testing of dried, fresh or frozen brown seaweeds for iodine and hijiki seaweed specifically for inorganic arsenic. Food containing brown seaweed as an ingredient (for example soup or salad) are not required to be tested.

Imported seaweed and seaweed products were implicated in 50 reported "failed food" incidents" during the period July 2019 to December 2021, which are summarised in Table 9 and listed in Appendix Table B.2.

Table 9. Failed imported seaweed products identified at the Australian border (July 2019 to December 2021)

Product type	Issue	Country of origin (Number of records)
Dried brown seaweed	Excess iodine	China (8), Chinese Taipei (1), Japan (4), Republic of Korea (10), Viet Nam (1)
Kelp sheets, slices, shreds, knots	Excess iodine	China (6), Japan (1)
Roasted kelp	Excess iodine	China (1)
Kelp powder or flakes	Excess iodine	China (1), Japan (1), Republic of Korea (4)
Seasoned brown seaweed	Excess iodine	Japan (3 from same exporter)
Sea tangle[1]	Excess iodine	Republic of Korea (1)
Seaweed (undefined)	Excess iodine	China (5)
Frozen hijiki	Excess inorganic arsenic	Republic of Korea (1)
Hijiki powder	Excess inorganic arsenic	China (1)
Hijiki (undefined)	Excess inorganic arsenic	Republic of Korea (1)

Note
1 Raw ready-to-eat noodles made with kelp and extracts from brown seaweeds.

Most failures (47 incidents) were due to excess iodine while the remaining three were for excess levels of inorganic arsenic in hijiki seaweed. Excess iodine was found in a wide range of brown seaweed product types, consistently across the time the data were collected.

The FSANZ website contains details of food recalls for the period June 2019 to the present.[21] A single seaweed-related recall occurred during this period, with seaweed flavoured crisps recalled due to the presence of an undeclared allergen (egg).

[20] https://www.awe.gov.au/biosecurity-trade/import/goods/food/inspection-testing/failing-food-reports (Accessed 10 May 2022)
[21] https://www.foodstandards.gov.au/industry/foodrecalls/recalls/Pages/default.aspx (Accessed 28 September 2022)

4.4 CANADA

In 2019, 2018 and 2017, the Canadian Food Inspection Agency[22] made 67, 100 and 134 border rejections, respectively. None of these related to seaweed. Note that, Canada, like the United States, has no seaweed-specific regulatory limits for chemical hazards so there are no border checks done for iodine or heavy metals in seaweed.

No product recalls for seaweed products where located in the last three years when recalls from undeclared allergens such as peanuts, milk or egg were excluded from the search.[23]

4.5 EUROPEAN UNION

Seaweed products have been the subject of several recalls, border rejections or notifications in the EU due to food safety concerns. A search of the EU Rapid Alert System for Food and Feed (RASFF) searchable database[24] for the period 2015 to 2020 returned 38 distinct alerts where seaweed products were recorded in the database. The data were cleaned to reflect information provided in the comment subject field. The 38 alerts are summarised by product type in Table 10 and listed in Appendix Table B.3.

Table 10. Seaweed related alerts recorded in the RASFF database, 2015 to 2020

Product type	Issue [1]	Country of origin (Number of records)
Roasted seaweed	Excess iodine	China (1), Republic of Korea (1)
	Unauthorised herbicide detected	China (1)
Dried seaweed	Excess iodine	China (7), Japan (4), Republic of Korea (9), Spain (2)
	Arsenic, lead and excess iodine	Japan (1)
	Cadmium and excess iodine	Republic of Korea (2)
	Salmonella Idikan	China (1)
	Unauthorised (E102) /undeclared (E133) colouring ingredients [2]	China (1)
Frozen seaweed	Norovirus	China (2) – Public information/not tested
Seaweed salad	Excess iodine	Spain (1)
Seaweed products	Absence of health certificate	China (1), Thailand (1)
Seaweed (unspecified)	Excess iodine	China (2)
	Foreign bodies (shells)	France (1)

Notes

[22] https://inspection.canada.ca/about-cfia/transparency/regulatory-transparency-and-openness/compliance-and-enforcement/refused-entry/eng/1324305448701/1324305531127 (Accessed 10 May 2022)
[23] https://recalls-rappels.canada.ca/en (Accessed 23 June 2022)
[24] https://webgate.ec.europa.eu/rasff-window/screen/search Accessed 10 May 2022

1 Herbicides, unauthorised ingredients and foreign body contamination are outside the scope of the current report but are included for completeness.
2 E102: Tartrazine and E133: Brilliant Blue.

Of the 38 distinct alerts, 25 were for excess iodine in dried seaweed, three were for excess iodine in seaweed (product unknown). There were two alerts due to high levels of cadmium, and one alert due to excess arsenic and lead levels recorded as well as excess iodine. Two alerts reported multiple chemical elements as the reason for the notification.

Norovirus was recorded in two public information notices for frozen seaweed and there is one record of *Salmonella* spp. detected in dried seaweed strips. The remaining eight entries were for the absence of a health certificate or undeclared, unauthorised, or contaminated ingredients.

The type or species of seaweed involved was not recorded in most of the entries. Five alerts for excess iodine recorded kombu seaweed, and one recorded the seaweed as a brown type.

4.6 UNITED STATES

The United States Food and Drug Administration (USFDA) database of border refusals (equivalent to border rejections) from 2014 to 2021 was interrogated[25] and the data were filtered for the presence of "seaweed" in the product description. Similar entries were removed as described above. This resulted in a list of 32 distinct border refusals. Further analysis revealed that 17 of these were due to incorrect or incomplete labelling. The remaining 15 refusals are summarised in Table 11 and listed in Appendix Table B.4.

Table 11. Seaweed related border refusals, excluding labelling related refusals, recorded in the USFDA import refusals database, 2015 to 2021

Product type	Issue	Exporting country (Number of records)
Seaweed with sauce	*Listeria monocytogenes*	China (Single company with four refusals)
	Insanitary or decomposed product	China (1)
Seaweed (dried or paste)	Pesticide residue	Mexico (1)
	Insanitary or decomposed product	China (1), Grenada (1), Republic of Korea (1) and St Lucia (1)
Seaweed (leaf and stem vegetable)	Pesticide residue	Japan (1)
	Poisonous substance	Republic of Korea (2)
	Unsafe food additive	Chinese Taipei (1)
	Unsafe food colourant	Republic of Korea (2), Denmark (1)
Seaweed snack	Unsafe food colourant	China (1)

Notes
1 Pesticide residue, unauthorised or unsafe ingredients and quality of the product are outside the scope of the current report but are included for completeness.

The public version of the USFDA database does not provide detailed information on the type of seaweed products or the hazards detected beyond the descriptions given in Table 11. Note

[25] https://www.accessdata.fda.gov/scripts/ImportRefusals/index.cfm (Accessed 10 May 2022)

that the United States does not have regulatory limits for chemicals in seaweed (section 3.1.3) so there are no border checks done for iodine or heavy metals in seaweed products.

4.7 SUMMARY

The notifications, recalls and border rejections of seaweed products described in this section will be biased to those criteria that are being checked regularly or are being requested to be notified in the system. It was noted that there is no common approach to recording border rejections and recalls among the different countries regarding seaweed products. Each country records data and applies regulatory criteria differently.

Seaweed products included in this section are predominantly from China and the Republic of Korea. This is not unexpected as China and the Republic of Korea, along with Indonesia, are the top three producers of edible seaweed and seaweed products (FAO, 2018).

For those countries that test imported product for iodine concentration, most recalls, notifications or border rejections of seaweed product consignments were due to excess levels of iodine. These have been consistently recorded for products from a range of source countries for the years considered (2015 to 2022).

Also captured in the data were more sporadic border or recall events due to inorganic arsenic, cadmium, lead, herbicide, pesticide, *Listeria* spp., *Salmonella* spp. and norovirus contamination.

5 OUTBREAKS AND CASES OF FOODBORNE ILLNESS ASSOCIATED WITH CONSUMPTION OF SEAWEED PRODUCTS

5.1 OUTBREAKS

In the following sections the definition of an outbreak used in *Guidelines for the Investigation and Control of Disease Outbreaks* (ESR, 2012) has been adopted:

> "a localised increase in cases of illness clearly in excess of that normally expected".

While outbreaks are most often of infectious diseases, localised increases in cases of non-infectious diseases or with adverse health effects may also occur. Due to the timeframes involved, increases in the incidence of chronic diseases are not usually referred to as outbreaks.

Table 12 lists the outbreaks of illness associated with seaweed consumption identified from the scientific literature and includes a short summary of the evidence that seaweed was the source of the illness. More information is provided in the sections following the table.

A search of the New Zealand National Notifiable Disease Database (EpiSurv)[26] undertaken on 5th May 2022 showed that seaweed had not been recorded as a confirmed or possible food source for any pathogen related outbreak or individually notified illness for the previous 15 years (1997 to 2022) in New Zealand.

Note that, due to the incubation period for microbiological illnesses, or the time for adverse health effects for some chemical-associated illnesses to occur, it can be difficult to determine the source of foodborne illness. The original food causing the illness is unlikely to be available for testing, people may have trouble recalling their previous diet and there can be multiple possible foods consumed and other sources. The source of a common source outbreak is more likely to be found in larger outbreaks, using epidemiological investigations.

While *Vibrio* spp. are yet to be implicated in foodborne illness associated with seaweed consumption documented in English language literature, the abstract of Kudaka *et al.* (2008) suggests outbreaks may occur in Japan.

[26] https://surv.esr.cri.nz/episurv/ (Accessed 17 August 2022)

Table 12. Outbreaks associated with seaweed consumption identified from scientific literature review, 1980 to 2020

Year/Country	Seaweed consumed	Hazard	Evidence	Case numbers	Reference
1980 - 1982 Japan	*Gracilaria verrucosa* and *Gracilaria chorda*	Prostaglandin stimulant (PGE2) (Speculated cause of illness)	Common food source, PGE2 detected in the seaweed	10 (2 deaths)	(Fusetani and Hashimoto, 1984)
1991 Guam	*Gracilaria edulis (Polycavernosa tsudai)*	Polycavernoside A and B/Cyanobacterium (Speculated cause of illness)	Only food eaten by all affected persons across several households. Seaweed was locally harvested and sold through one local retailer. Seaweed collected from the same site two months later yielded Polycavernoside A and B.	13 (3 deaths)	(Haddock, 1993; Yotsu-Yamashita *et al.*, 1993)
1992 United States, California	*Grasilariopsis lemanaeformis*	Not specified	Common food source collected off a beach	3	(Hanne *et al.*, 1995)
1993 Japan	*Gracilaria verrucosa* (ogonori)	Prostaglandin stimulant–PGE2 (Speculated cause of illness)	Common food source, PGE2 detected in the seaweed	2 (1 death)	(Noguchi *et al.*, 1994)
1994 United States, Hawaii	*Gracilaria coronopifolia* – washed and boiled up to 4 minutes	Cyanobacteria - Mouse and guinea pig assays revealed that the seaweed contained debromoaplysiatoxin and aplysiatoxin, two toxins that possibly came from the blue-green algae found on the seaweed	Common food source identified by retrospective cohort study. Toxins detected in seaweed.	7	(Hanne *et al.*, 1995; Marshall and Vogt, 1998)
2002 – 2003 Philippines	*Acanthophora specifera* and *Gracilaria edulis (*now named *Polycavernosa tsudai)*	Polycavernoside A/Cyanobacterium (Speculated cause of illness)	Common food source yielded Polycavernoside A	36 (8 deaths)	(Yotsu-Yamashita *et al.*, 2004; Yotsu-Yamashita, 2006)
2004 New Zealand	Kelp in an imported soymilk, origin of product not stated.	Iodine	Thyrotoxicosis evident in cases who had all drunk the same soymilk product. Case control study confirmed food link. Investigation showed the product contained excessive iodine (9 mg/kg) due to kelp added as a flavour enhancer. The product was reformulated in 2004 to meet acceptable iodine levels	5	(O'Connell *et al.*, 2005)

Year/Country	Seaweed consumed	Hazard	Evidence	Case numbers	Reference
2008 – 2010 Australia	Kelp added to soymilk, origin of product not stated	Iodine	Case series investigation of iodine toxicity was linked to the consumption of a soymilk product which contained kelp. In all cases, removing the product from the diet resulted in recovery. The product was withdrawn from the Australian market and only returned after the kombu had been removed from the manufacturing process, resulting in a significant reduction in iodine in the product (from 25,000 µg/L to 15 µg/L)	8	(Crawford *et al.*, 2010)
2012 Republic of Korea	Seasoned green seaweed (*Enteromorpha* spp.)	Norovirus	Implicated by case control study. Samples of green seaweed, seawater used for washing, and seawater collected near company were positive for norovirus. Site was near a wastewater outlet.	91	(Park *et al.*, 2015)
2014 Wales	Welsh laverbread (boiled and minced laver seaweed)	*Salmonella enterica* (serovar not specified)	Common food source. “Strong association”, but not culture-confirmed from the food or its processing environment	17 (3 hospitalised)	(Anonymous, 2014; Public Health Wales, 2014)
2016 United States, Hawaii	Raw fish (poke) containing limu/ogo (not further specified)	*Salmonella* Weltevreden	*Salmonella* Weltevreden was identified in packing and processing tanks as well as in the farm environment. Production area was near a wildlife refuge and harvesting was from uncontrolled streams.	15 (4 hospitalised)	(Nichols *et al.*, 2017)
2017 Japan	Shredded dried laver/nori	Norovirus	Implicated as common food source. Norovirus of the same sequence type was also detected from the shredding process environment. An employee who directly handled the product post cook steps was symptomatic before the outbreak.	Seven separate outbreaks, 2094 total cases	(Kusumi *et al.*, 2017; Sakon *et al.*, 2018)
2019 Norway	Frozen wakame seaweed salad from China	Norovirus	Norovirus confirmed from cases, seaweed implicated epidemiologically. Results of product testing not located in literature	>100	(FAO/WHO, 2020b; Whitworth, 2019)
2020 Japan	*Gigartina tenella* (red seaweed) salad – part of a salad made from six kinds of seaweed rehydrated with water.	*Escherichia coli* O7:H4 - Enteroaggregative *E. coli* heat stable enterotoxin 1 (EAST1)	Common food source, organism confirmed from cases and the food by culture, toxin testing, serotyping and genomic analysis.	2958	(Kashima *et al.*, 2021)

5.1.1 *Gracilaria* spp. seaweed

Gracilaria spp., sometimes known as ogonori, were implicated in a series of disease outbreaks between 1980 and 2002 in Japan, Guam, Hawaii, and the Philippines (Cheney, 2016). The outbreaks were reported to have involved 44 cases with eight fatalities. For earlier outbreaks, it was suggested that the causative agent may have been the high levels of prostaglandin E2 present in *Gracilaria verrucosa* and *Gracilaria chorda* (Fusetani and Hashimoto, 1984; Noguchi *et al.*, 1994). Other studies have suggested cyanobacterial toxins, due to cyanobacteria on the surface of the seaweed, may have been the causative agents (Haddock, 1993; Marshall and Vogt, 1998). Cheney (2016) noted that the outbreaks appeared to be temporally clustered (1980-1982, 1991-1994, and 2002-2003) and that no *Gracilaria*-associated outbreaks had been reported since 2003 (Cheney, 2016). Given the uncertain nature of the aetiology (no hazard definitively identified) of these cases and the lack of any reported cases between 2003 and 2016, these outbreaks were not considered as evidence in selecting prostaglandin E2 or cyanobacterial toxins associated with *Gracilaria* spp. for further hazard profiling in section 7 of this report.

5.1.2 Norovirus

Three norovirus infection outbreaks or outbreak clusters due to seaweed consumption were identified, each affecting >90 cases. Investigations implicated a contaminated growing area in one, contamination during processing in another, and a comprehensive investigation was not located in the literature for the third.

The first outbreak occurred in two schools in the Republic of Korea in February 2012 (Park *et al.*, 2015). A comprehensive investigation was carried out, and a retrospective cohort study in school A (60 cases) showed a significant association of illness with consumption of seasoned green seaweed with radishes. A case-control study of students at school B (31 cases) showed that cases were more likely than controls to have eaten seasoned green seaweed with pears. The green seaweed (*Enteromorpha spp.*) was harvested from an area where wastewater flows into the sea. Both seaweed and seawater used for washing the seaweed were shown to harbour different strains of norovirus and the investigators concluded that only the consumption of uncooked green seaweed could explain these norovirus outbreaks, but the point of contamination could not be confirmed as being in-farm or post-harvest washing. The company supplying the seaweed was subsequently forbidden from selling green seaweed (Park *et al.*, 2015).

Seven geographically separated norovirus outbreaks attributable to the GII.P17-GII.17 strain were reported across Japan during January to March 2017, causing illness in a total of 2,094 cases (Kusumi *et al.*, 2017; Sakon *et al.*, 2018). In each outbreak, shredded, dried nori from a single company was implicated and this product tested positive for norovirus. The nori sheets were produced by one company (company C), shredded and packaged by another (company B) and distributed by another (company A). The nori was heat treated by company C, using a conveyor-type machine for ~7 seconds at 240°C after heating in water for 2 hours at 90°C. An infected worker at company B subsequently handled the seaweed with bare hands during the cutting and packaging process (Kusumi *et al.*, 2017). A comprehensive traceback study showed that all the nori implicated had been shredded and packaged at the one site (company B). Norovirus was subsequently detected in environmental samples collected from this site. The traceback of implicated nori product revealed that norovirus infectivity remained for >2 months at ambient temperature under dry conditions. However, the percentage of exposed persons with gastrointestinal symptoms (the attack rate) gradually decreased from the date of nori production, suggesting a decline in norovirus infectivity over time under dry conditions (Sakon *et al.*, 2018).

The third norovirus outbreak was initially reported in Norway and included >100 cases who had consumed a frozen seaweed salad imported from China (Whitworth, 2019). Goma Wakame Seaweed frozen salad bags produced by Dalian Kowa Foods Co. in China were withdrawn from the market and no further outbreaks linked to seaweed salad were reported. At the same time frozen seaweed salad from China was implicated in norovirus outbreaks in other European countries.

5.1.3 *Salmonella*

Two salmonellosis outbreaks were reported with seaweed consumption as an implicated cause. One was linked to the consumption of a cooked seaweed product and the other to fresh seaweed consumption.

The first salmonellosis outbreak (reported in Wales in 2014) comprised 17 cases, with consumption of laverbread (a boiled, minced seaweed product) “strongly implicated” as the cause (Anonymous, 2014; Public Health Wales, 2014). Consequently, the product was voluntarily withdrawn from the market. However, no comprehensive investigation report could be found in the literature regarding the *Salmonella* strain or the final investigation outcomes.

The second salmonellosis outbreak, due to *Salmonella enterica* serovar Weltevreden, occurred in 2016 in Hawaii (Nichols *et al*., 2017). Similar to the first outbreak, a detailed scientific report could not be located, only a conference abstract. Consumption of a dish including raw fish and seaweed was implicated, with the seaweed traced back to a local aquaculture facility. The authors reported that although the outbreak *Salmonella* strain was distinct from environmental *Salmonella* Weltevreden isolates, based on pulsed-field gel electrophoresis (PFGE) patterns, detection of multiple serotypes and clonal variants throughout the farm suggested conditions permitting *Salmonella* contamination and subsequent dissemination. It was concluded that seaweed should be considered a potential foodborne illness risk because of the tendency for it to be consumed raw and because aquaculture may be susceptible to environmental or human contamination, particularly when conditions are not well-controlled (Nichols *et al.*, 2017).

5.1.4 *Escherichia coli*

The largest seaweed-associated acute gastroenteritis outbreak reported to date, occurred in Japan in 2020, when approximately 3000 school students became ill after consuming seaweed salad, including a red seaweed (*Gigartina tenella*) (Kashima *et al.*, 2021). The seaweed salad was made from six kinds of rehydrated seaweed and boiled vegetables with dressing. *Escherichia coli* O7:H4, carrying the enteroaggregative *E. coli* heat stable enterotoxin 1 (EAST1) gene (*astA*), isolated from cases and the implicated food were indistinguishable by PFGE and by single nucleotide polymorphism analysis using whole genome sequencing (Kashima *et al.*, 2021). A trace back showed the *Gigartina tenella* had been imported to Japan in 2017 (country of origin not stated). The source of the *E. coli* contamination of the seaweed (growing area or later cross-contamination) could not be identified.

Enteroaggregative *E. coli* are distinct from Shiga toxin-producing (STEC), enteropathogenic (EPEC), enterotoxigenic (ETEC), enteroinvasive (EIEC), diffusely adherent (DAEC) and enteroaggregative (EAEC) strains usually discussed in the literature. A study reported in 2001 found the *astA* gene in a variety of Enterobacterales including EPEC, EIEC, EAEC and Salmonellae (de Sousa and Dubreuil, 2001). Outside of Japan, *astA* is not routinely tested for as a primary virulence determinant. This pathotype is not screened for in New Zealand diagnostic laboratories (ESR, unpublished data).

5.1.5 Iodine

Two case series of foodborne thyrotoxicosis caused by excessive iodine intake have been reported from Australasia. The source of the iodine was found to be kelp used as a flavour enhancer in soymilk.

O'Connell *et al.* (2005) reported a New Zealand case series of five adults with thyrotoxicosis who had all drunk the same soymilk product. Investigation showed the product contained excessive iodine (9 mg/kg) due to kelp added as a flavour enhancer. The product was reformulated in 2004 to meet acceptable iodine levels. The report did not state where the soymilk was formulated but noted it was widely distributed throughout Australasia.

Crawford *et al.* (2010) reported an Australian case series of iodine toxicity linked to the consumption of a soymilk product (Bonsoy), which contained kombu (kelp), and had an iodine content of 25 mg/L. Cases presented with thyroid dysfunction and the cause of the toxicity was identified by performing urinary iodine tests, demonstrating levels of up to 11,400 µg/L (reference range < 200 µg/L). In all cases, removing the product from the diet resulted in normalisation. The product was withdrawn from the Australian market and only returned after the reformulation to remove kombu, resulting in a significant reduction in iodine in the product - from 25 mg/L to 0.015 mg/L. Again, the report did not state where the soymilk was formulated.

5.2 OUTBREAKS LINKED TO SUSHI

Data suggests that sushi is the most commonly eaten food containing seaweed in New Zealand (see section 9).

Sushi has been reported as a vehicle of infection in outbreaks of foodborne illness, but the contents rather than the seaweed wrap were implicated or identified as the contaminated ingredient. An outbreak of *Yersinia enterocolitica* infection was reported in New Zealand during 2016, with sushi being the implicated, but not confirmed as the vehicle of infection (King, 2017). Probable sources included an infected food handler(s), contaminated ingredients at the implicated premises and/or a dispersed food ingredient.

An outbreak of *Salmonella* Singapore infection in Queensland, Australia, during 2004 was also linked to sushi (Barralet *et al.*, 2004). The outbreak report concluded “As this outbreak involved food prepared and consumed over an 18-day period, it is likely that *Salmonella* was introduced from a contaminated raw product and used directly as an ingredient or was a constituent of one of the sushi ingredients.” The report did not comment on seaweed as a potential source of contamination.

5.3 SUMMARY

A small number of outbreaks or case series have been reported with seaweed as the suspected or confirmed vehicle.

Before 2003, there were several overseas outbreaks associated with the red seaweed *Gracilaria* spp.; however, the actual agent and vehicle (innate to the seaweed or cyanobacteria on the seaweed) remain unresolved.

Cases of thyrotoxicosis in Australia and New Zealand have been attributed to the use of kelp as an ingredient in soymilk products, due to the high iodine concentration of the seaweed.

Outbreak data show that red, green or brown seaweed could all become contaminated with microbiological hazards, such as norovirus, *Salmonella* spp. and pathogenic *E. coli*, before reaching the consumer (at the growing area or during processing). Outbreaks have been associated with dried, frozen, and fresh seaweed.

6 HAZARD PROFILES AND OCCURRENCE OF SELECTED CHEMICAL HAZARDS DETECTED IN SEAWEED

Seaweeds bioaccumulate high levels of elements, including macronutrients (K, Na, Ca, Mg, and S) and micronutrients (Fe, Zn, I, Cu, Se, Mo, F, Mn, Ni and Co), as compared to their surrounding environment (Todorov *et al.*, 2022). In addition to macronutrients and micronutrients, they also concentrate toxic elements (i.e., Pb, Cd, Hg, Al, As) at levels much higher than the surrounding waters (Todorov *et al.*, 2022). There are many factors which influence the presence of these toxic elements such as seaweed type, physiology, season, harvest and cultivation environment, geography including the location of cultivation, and processing. Industrial activity or other anthropogenic (human) activities, can negatively influence water quality, which can increase the likelihood of hazards in seaweed.

6.1 SELECTION OF CHEMICAL HAZARDS

Chemical hazards were selected for inclusion in the current report based on:

- the existence of standards or other regulatory activity for the hazard in seaweed in any country or country group;
- the occurrence of incidents (recalls, border rejections, disease outbreaks, case reports) related to the hazard in seaweed, or
- the reporting of concentrations of the hazard in seaweed that are high compared to foods that are a normal part of the New Zealand diet (Pearson *et al.*, 2018).

Based on these criteria, four elemental contaminants and one nutrient were selected for inclusion in the study:

- Arsenic (specifically inorganic arsenic); regulatory limit for seaweed in Australia/New Zealand, occasional reason for border rejections of seaweed products and very high concentrations detected in certain seaweed, particularly hijiki (*Sargassum fusiforme*);
- Cadmium; regulatory limit for seaweed-based supplements in Europe and guideline limit for seaweed products in France, occasional reason for border rejections of seaweed products and high concentrations in seaweed products relative to most commonly consumed foods;
- Lead; guideline limit for seaweed products in France, occasional reason for border rejections of seaweed products, and high concentrations in seaweed products relative to most commonly consumed foods;
- Mercury; guideline limit for seaweed products in France, high concentrations in seaweed products relative to most commonly consumed foods, dietary exposure to mercury known to be predominantly from consumption of seafoods; and
- Iodine; guideline or import limits in seaweed products in several countries, most common reason for border rejections of seaweed products, case reports of thyrotoxicosis due to consumption of seaweed products, and very high concentrations in some seaweed products, particularly brown seaweeds.

While there is a regulatory limit for tin in edible seaweed in France (see Table 6), no evidence was found of tin being present in seaweed at levels of concern. Two studies reported only sub-part per million (<1 mg/kg) concentrations of tin in seaweeds (Todorov *et al.*, 2022; van Netten *et al.*, 2000). The major contributors to dietary tin exposure are canned foods, that can contain tin concentrations in excess of 100 mg/kg (Pearson *et al.*, 2018). The typical aluminium content of dried seaweed appears to be in the range 10-100 mg/kg (Corrias *et al.*, 2020; Filippini *et al.*, 2021; Khandaker *et al.*, 2021; Miedico *et al.*, 2017; Munoz and Diaz, 2022; Paz *et al.*, 2019; Rubio *et al.*, 2017; Sharma *et al.*, 2018). While these concentrations are higher than in most foods consumed by New Zealanders (Pearson *et al.*, 2018), estimates of dietary exposure to aluminium from consumption of seaweed suggest seaweed would be a minor contributor (Khandaker *et al.*, 2021; Paz *et al.*, 2019; Rubio *et al.*, 2017). Hazard profiles were not developed for tin or aluminium.

Some border rejections occurred due to the presence of pesticide residues or non-permitted food additives in seaweed products. However, these chemical hazards are outside the scope of this report.

6.2 CHEMICAL HAZARD PROFILES

Detailed hazard profiles for the five chemical hazards are included in Appendix C. A summary of these profiles is shown in Table 13.

Table 13 primarily summarises evaluations carried out by the Joint FAO/World Health Organisation (WHO) Committee on Food Additives (JECFA), the European Food Safety Authority (EFSA) and the US Environmental Protection Agency (USEPA). Evaluations of carcinogenicity performed by the International Agency for Research on Cancer (IARC) result in categorisation of chemicals, rather than establishment of exposure limits. The IARC evaluations are summarised in Appendix C. The US Agency for Toxic Substances and Disease Registry (ATSDR) may develop minimal risk levels (MRLs) for acute, intermediate and chronic exposure durations. While all of these are summarised in Appendix C, only chronic MRLs are included in Table 13Table 13, as these are most relevant to exposure to these elements from the food supply.

Table 13. Summary of clinical evaluations of selected chemical hazards

Element	Pivotal study/effect	PoD (mg/kg bw per day unless otherwise stated)	UF	HBGV (mg/kg bw per day unless otherwise stated)	Reference
Inorganic arsenic	Human studies, hyperpigmentation, keratosis and possible vascular complications	NOAEL: Water concentration of 0.009 mg/L converted to 0.0008 mg/kg bw per day	3	RfD = 0.0003	(USEPA, 1991)
	Human studies, skin lesions, cancers of the skin, urinary bladder and lung	$BMDL_{01}$ ranged from 0.0003 to 0.008	-	NR	(EFSA, 2009a)
	Human studies, increased incidence of lung cancer	$BMDL_{0.5}$ 0.003	-	NR	(JECFA, 2011b)

Element	Pivotal study/effect	PoD (mg/kg bw per day unless otherwise stated)	UF	HBGV (mg/kg bw per day unless otherwise stated)	Reference
	Human studies, development of skin lesions	NOAEL: Water = 0.0008	3	MRL (chronic) = 0.0003	(ATSDR, 2007b)
Cadmium	Human studies involving chronic exposures (significant proteinuria)	NOAEL: food = 0.01	10	RfD = 0.001	(USEPA, 1989)
	Human urinary b-2-microglobulin (B2M; a biomarker of renal tubular damage)	Urinary reference point of 1 µg cadmium/g creatinine	-	TWI = 0.0025 mg/kg bw per week (0.00035 mg/kg bw per day)	(EFSA, 2009c)
Cadmium (continued)	Human urinary b-2-microglobulin (B2M; a biomarker of renal tubular damage)	No evidence of increased B2M urinary excretion at urinary cadmium concentrations less than 5.24 µg/g creatinine	-	PTMI = 0.025 mg/kg bw per month (0.00082 mg/kg bw per day)	(JECFA, 2011a)
Lead	Human studies, effects on child neurodevelopment, haematological effects, reproductive effects	No threshold for some effects	-	No RfD established	(USEPA, 2013)
	Neurodevelopmental effects in children and effects on systolic blood pressure (SBP) in adults	No threshold identified	-	No PTWI established	JECFA, (2011b)
	Neurodevelopmental toxicity in young children and cardiovascular and nephrotoxicity effects in adults	$BMDL_{01}$ (child neurodevelopment) = 0.0005 $BMDL_{01}$ (adult cardiovascular) = 0.0015 $BMDL_{10}$ (nephrotoxicity) = 0.00063	-	NR	(EFSA, 2010a)
Methyl mercury	Human epidemiological studies (developmental neuropsychological impairment)	$BMDL_{05}$ range of 46-79 ppb in maternal blood for different neuropsychological effects in the offspring at 7 years of age, corresponding to a range of maternal daily intakes of	10	RfD = 0.0001	(USEPA, 2001)

Element	Pivotal study/effect	PoD (mg/kg bw per day unless otherwise stated)	UF	HBGV (mg/kg bw per day unless otherwise stated)	Reference
		0.857-1.472 μg/kg bw per day			
	Human, neurodevelopmental effects (foetus)	Determined maternal blood concentrations that were without appreciable adverse health effects and converted to dietary exposure equivalents	1	PTWI = 0.0016 mg/kg bw per week (0.0002 mg/kg bw per day)	(JECFA, 2004; 2007)
	Human, neurodevelopmental effects	NOAEL = 0.0013	4.5	MRL (chronic) = 0.0003	(ATSDR, 1999)
Inorganic mercury	Nephrotoxicity (rat)	$BMDL_{10}$ = 0.06	100	PTWI = 0.004 mg/kg bw per week (0.0006 mg/kg per day)	(JECFA, 2011b)
Iodine	Human studies, elevated thyroid hormone (TSH) levels	LOAEL = 1.7 mg/day	1.5	UL = 1.1 mg/day (adults)	(National Health and Medical Research Council, 2006)

Abbreviations

$BMDL_{01}$	lower 95th percentile confidence limit for a benchmark dose equating to a 1% increase in disease incidence
$BMDL_{0.5}$	lower 95th percentile confidence limit for a benchmark dose equating to a 0.5% increase in disease incidence
$BMDL_{10}$	lower 95th percentile confidence limit for a benchmark dose equating to a 10% increase in disease incidence
bw	body weight
HBGV	health-based guidance value
LOAEL	lowest observed adverse effect level
MRL	minimal risk level
NOAEL	no observed adverse effect level
NR	Not relevant
PoD	point of departure
PTWI	provisional tolerable weekly intake
PTMI	provisional tolerable monthly intake
RfD	reference dose
TWI	Tolerable weekly intake
UF	uncertainty factor
UL	upper limit of intake

6.3 CHEMICAL HAZARD OCCURRENCE IN SEAWEEDS

Data on the prevalence and concentration of the five chemical hazards considered in this review are summarised in Appendix D and discussed in the following sections. Note that the concentrations are usually reported on a dw basis. This is somewhat unusual since food compositional studies most commonly report results on a fresh weight (or wet weight, ww) basis.

6.3.1 Arsenic

Most foods typically contain concentrations of arsenic <0.05 mg/kg as consumed, and many have concentrations <0.01 mg/kg (Pearson *et al.*, 2018). The exceptions are foods of marine origin (fish, shellfish, crustaceans). Arsenic exists in inorganic and organic forms (Cressey, 2015), with the inorganic forms being more toxic (see Appendix C). In foods of marine origin (fish, shellfish and crustaceans), inorganic arsenic typically makes up a very small percentage of total arsenic (1-3%) (Pearson *et al.*, 2018).

The majority of the studies reviewed reported the concentrations of total arsenic (tAs) and inorganic arsenic (iAs) in seaweeds. Some seaweed samples were found to contain a substantial proportion of tAs in the more toxic iAs form (up to 80%). The Australia New Zealand Food Standards Code (Schedule 19)[27] gives a hydration level for seaweed of 85%. On this basis, the ML for inorganic arsenic of 1 mg/kg on a ww basis would equate to 6.7 mg/kg on a dw basis.

Two studies have reported heavy metal content in edible seaweeds in New Zealand. In the first study, the concentrations of tAs and iAs were reported in four commercial seaweeds and six wild-harvested species (Smith *et al.*, 2010). The seaweed products were obtained either from health food shops or directly from the manufacturer and included both fresh and further processed products. Concentrations of tAs and the percentage of arsenic present as iAs in commercial seaweeds were 97 (0.8%), 34 (0.3%), 25 (4.7%), and 36 (4.2%) mg/kg dw for samples of giant kelp (*Macrocystis pyrifera),* wakame (*Undaria pinnatifida), Porphyra* and spiny kelp (*Ecklonia radiata)*, respectively. Inorganic arsenic concentrations were below the ML. The mean concentrations of total arsenic in six wild-harvested edible seaweeds were in the range of 1.9 to 51.3 mg/kg dw. In the second study, the concentrations of tAs were determined in samples of wakame collected from several locations around New Zealand (Marlborough Sounds and Wellington Harbour) and across seasons (Hau, 2012). The monthly means of tAs concentrations across the seasons were in the range of 24 – 46.7 mg/kg dw.

In 2013, FSANZ released a survey on the levels of inorganic arsenic in dried seaweed and products containing seaweed available in Australia (FSANZ, 2013). The typical levels of iAs were below 1 mg/kg, with the exception of one composite sample of dried hijiki seaweed, which contained 7.8 mg/kg of iAs and exceeded the ML for inorganic arsenic in the Australia New Zealand Food Standards Code. The mean (range) iAs concentrations in dried samples of wakame, kombu and nori were 0.18 (0.16-0.20) mg/kg, 0.22 (0.16-0.33) mg/kg and 0.11 (0.09-0.16) mg/kg, respectively. The iAs concentration in single samples of *Sargassum fusiforme*[28] and sea vegetable were 0.32 and 0.10 mg/kg dw. Samples of seaweed products were typically found to have iAs at the concentration of <0.05 mg/kg which is also the limit of reporting.

A survey was conducted by the New South Wales (NSW) Food Authority of seaweed products in the NSW market for levels of tAs and iAs. The mean tAs concentration in 48 seaweed products was 39.0 (8.7-140) mg/kg, as received (dried, shredded, salted, roasted or not stated). The iAs concentrations ranged from less than the limit of reporting (LOR, which was 0.05 mg/kg) to 38 mg/kg, as received (NSW Food Authority, 2010). It should be noted that only one sample of seaweed contained iAs greater than 1 mg/kg, exceeding the

[27] https://www.legislation.gov.au/Details/F2021C00628 Accessed 9 May 2022
[28] Hijiki and *Sargassum fusiforme* are common and scientific names for the same seaweed species. It is uncertain why these were listed separately in the FSANZ report.

ML. This sample also had a very high tAs concentration (140 mg/kg), equating to 27% iAs. For other samples analysed, iAs typically accounted for <2% of tAs.

Internationally, hijiki has been reported to have higher concentrations of tAs and iAs compared with other types of seaweed (Almela *et al.*, 2006; Rose *et al.*, 2007; Todorov *et al.*, 2022). Almela *et al.* (2006) found tAs and iAs concentrations in hijiki that ranged from 68 to 149 mg/kg dw and 44 to 117 mg/kg dw, respectively, with the percentage of tAs present as iAs in the range 46-80%. Similarly, in another study, hijiki was found to have tAs and iAs concentrations that ranged from 95 to 124 mg/kg dw and 69 to 96 mg/kg dw, respectively. The concentrations of iAs in other seaweed types were <0.3 mg/kg dw (LOD) (Rose *et al.*, 2007). While other seaweed species may occasionally contain iAs concentrations above the Australia New Zealand ML, exceedance appears to be more likely with hijiki.

6.3.2 Cadmium

The typical cadmium (Cd) content of most foods is <0.05 mg/kg as consumed, with the exception of shellfish and dehydrated potato products (crisps) (Pearson *et al.*, 2018).

Cd concentrations in seaweed samples collected from several locations in New Zealand (Marlborough Sounds and Wellington Harbour) and across seasons have been reported. The monthly mean Cd concentrations across the seasons were in the range of 1.51 – 2.33 mg/kg dw (Hau, 2012).

In the studies reviewed (Appendix D), the concentration of Cd in seaweeds varied, ranging from below a limit of detection (LOD) of 0.001 mg/kg dw and up to 10 mg/kg dw (Arulkumar *et al.*, 2019; Awheda *et al.*, 2015). The highest concentrations reported were 10.0 and 8.5 mg/kg dw from *Pterocladia capillacea* (a red seaweed) and *Chaetomorpha linum* (a green seaweed), respectively. However, it should be noted that the studies that reported these very high Cd concentrations did not report quality assurance and analytical method performance data (Arulkumar *et al.*, 2019; Awheda *et al.*, 2015). The high concentrations of Cd in both the seaweeds were considered to be due to anthropogenic discharge into the marine and coastal environment. Overall, the typical concentration of Cd in seaweeds was <1 mg/kg. There were no consistent differences observed between seaweed types (brown, red, and green) with respect to Cd concentrations, although some studies have reported that red seaweeds contain higher Cd concentrations than brown seaweeds (Awheda *et al.*, 2015).

6.3.3 Lead

The lead (Pb) content of New Zealand foods is typically low (<0.05 mg/kg), except for shellfish (Pearson *et al.*, 2018). Even in shellfish, data from the New Zealand Total Diet Study (NZTDS) indicate concentrations do not exceed 0.3 mg/kg.

Two studies have reported Pb content for edible seaweeds in New Zealand. The concentrations of Pb in four commercially available seaweeds; wakame, giant kelp, *Porphyra* and spiny kelp were 0.30, 0.30, 0.41 and 0.20 mg/kg dw, respectively. The seaweed products were obtained either from health food shops or directly from the manufacturer and include both fresh and further processed products. In the same study, the mean concentrations of Pb in six wild-collected edible seaweeds were in the range 0.14 to 0.30 mg/kg dw (Smith *et al.*, 2010). In a further study, the concentrations of Pb were determined in samples of wakame collected from several locations in New Zealand (Marlborough Sounds and Wellington Harbour) and across seasons. The monthly means of Pb concentration were in the range 0.21-0.31 mg/kg dw (Hau, 2012).

Internationally, the concentration of Pb in seaweeds has been reported to vary widely, with concentrations in the range from below the LOD of 0.013 to 40 mg/kg dw (Appendix D). The high concentrations of Pb were reportedly due to pollution, as the sampling sites were subjected to industrial, agricultural, sewage and drainage waste (Anbazhagan *et al.*, 2021; Salem *et al.*, 2019).

Consistent differences in Pb content between seaweed types were not evident in the studies reviewed. In a study from an unpolluted environment, Pb concentrations in edible seaweeds ranged from <0.05 mg/kg dw (the LOD) to 2.44 mg/kg dw, with the highest concentrations found in the brown seaweed Japanese kelp (*Undaria pinnatifida*) (Almela *et al.*, 2006). In another study, Pb was found to be low in red and brown algae (up to 0.58 mg/kg dw in *Porphyra dioica*) compared with green algae (up to 3 mg/kg dw in *Ulva intestinalis*) (Biancarosa *et al.*, 2018).

6.3.4 Mercury

Mercury (Hg) is rarely present at measurable concentrations (<0.01 mg/kg) in foods other than fish and shellfish (Pearson *et al.*, 2018). Mercury exists in food in inorganic and organic forms (methylmercury). While both forms are considered toxic, organic mercury can cross physiological barriers such as the placenta.

Two studies have reported the Hg content in edible seaweeds in New Zealand. In the first study, the concentrations of Hg in four commercially available seaweeds (*Undaria pinnatifida*, *Macrocystis*, *Porphyra* and *Ecklonia*) were 0.05, 0.05, 0.01 and 0.17 mg/kg dw, respectively. The seaweed products were obtained either from health food shops or directly from the manufacturer and include both fresh and further processed products. The mean concentrations of Hg in six wild-collected edible seaweeds were in the range 0.03 to 0.17 mg/kg dw (Smith *et al.*, 2010). In the second study, the concentrations of Hg were determined in samples of *Undaria pinnatifida* collected from several locations in New Zealand (Marlborough Sounds and Wellington Harbour) and across seasons. The monthly mean Hg concentrations were in the range 0.021-0.042 mg/kg dw (Hau, 2012).

Overall, the typical concentration of total Hg in seaweeds was <0.05 mg/kg (Appendix D). Occasional higher concentrations are reported. For example, Hg was reported at concentrations up to 0.93 mg/kg dw in green seaweed (*Ulva lactuca)* (Arisekar *et al.*, 2021) and a concentration of 1.08 mg/kg dw was reported in a brown seaweed (*Fucus vesiculosis*) (van Netten *et al.*, 2000).

Some studies reported higher Hg concentrations in brown seaweeds than in red seaweeds, however, there is little evidence for such differences. While the organic form of mercury is of greater concern than the inorganic form, none of the studies reviewed reported the methylmercury content of seaweed. Hence, only total mercury concentrations were reported in the studies reviewed.

6.3.5 Iodine

The iodine content of foods varies markedly, from about 0.001 mg/kg to >1 mg/kg (Pearson *et al.*, 2018). Foods of marine origins (fish, shellfish, seaweed) have some of the highest iodine concentrations, although the use of iodised salt can result in elevated iodine concentrations in some processed foods.

Reviewed studies (Appendix D) indicate a wide range of iodine concentrations can be found in seaweed, from only a few mg/kg to several thousand mg/kg of iodine.

In a New Zealand study, the highest levels of iodine were found in the brown seaweeds; *Ecklonia radiata* (3,990 mg/kg dw in wild-harvested samples and 3,719 mg/kg dw in a commercial sample), *Macrocystis pyrifera* (2,115 mg/kg dw in a commercial sample) and *Hormosira banksii* (1,041 mg/kg dw in a wild-harvested sample) (Smith *et al.*, 2010).

In a survey conducted by FSANZ, the iodine concentration ranges in dried kombu and other dry seaweeds (type not disclosed) were 650-6,800 and 13-4,600 mg/kg dw, respectively. The concentration of iodine in a range of seaweed products (soups, seasoning sauce, rice crackers, desserts, tea, etc.) was 0.01-110 mg/kg on an as purchased or as prepared basis (FSANZ, 2010).

Brown seaweeds (kelps, order Laminariales), which include species such as *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima*, and *Alaria esculenta*, have been reported to have higher iodine concentrations than the green and red seaweeds (Nitschke and Stengel, 2015). In an Irish study, wild-harvested kelps were also found to have the highest quantities of iodine (1,734-10,203 mg/kg dw), suggesting that these species probably are one of the richest natural sources of iodine. Red seaweeds had iodine concentrations approximately one order of magnitude lower than kelps (56–1,530 mg/kg dw). The iodine concentration in green seaweeds (41-79 mg/kg dw) was about 100 times lower than reported for Laminariales species (Nitschke and Stengel, 2015).

6.4 SUMMARY

The drying of seaweed products will increase the concentration of chemical contaminants, by decreasing the mass without influencing the contaminants present and some of the apparently high concentrations of some contaminants are due to this. However, seaweed does appear to have a particular ability to accumulate arsenic and iodine from the marine environment. Unlike other marine organisms, a large proportion of the arsenic present in seaweed can be present in the more toxic inorganic form. Hijiki seaweed was found to have the highest concentrations of inorganic arsenic (up to 117 mg/kg dw). Kelps (order Laminariales) are one of the richest natural sources of iodine and were found to have the highest levels of iodine (up to 10,203 mg/kg dw).

Very high concentrations of cadmium and lead have also been reported in seaweed in some studies. However, in some cases, the studies did not report method performance information and it is uncertain how much weight should be attached to this information. In other studies, seaweeds were intentionally sampled from polluted environments and high cadmium and lead concentrations appear to be study-related, rather than seaweed species-related.

7 HAZARD PROFILES AND OCCURRENCE OF SELECTED BIOLOGICAL HAZARDS IN SEAWEED

7.1 RECENT REVIEWS OF BIOLOGICAL HAZARDS IN SEAWEEDS

Several reviews have assessed the microbiological risks associated with seaweed consumption. The Food Safety Authority of Ireland report: *Safety Considerations of Seaweed and Seaweed-derived Foods Available on the Irish Market* reviewed information on both local and imported seaweed products (FSAI, 2020). The study focussed on dinoflagellates, cyanobacteria, *Vibrio* spp. and norovirus as biological hazards, noting "there are currently insufficient data available to suggest that these contaminants pose a significant risk to consumers in general through the consumption of seaweed or seaweed-based foods".

Banach *et al.* (2020) reported on perceptions of food safety hazards in the European seaweed chain and stratified the perceived biological risks as major (*Salmonella*), moderate (*Bacillus* spp. and norovirus) and minor (marine biotoxins, other pathogenic bacteria, hepatitis E virus).

Løvdal *et al.* (2021) reviewed the microbiological food safety of seaweeds. Bacteria considered were *Bacillus* spp., *Vibrio* spp., *Aeromonas* spp. (putative), *Escherichia coli*; *Salmonella* spp.; *Listeria monocytogenes; Staphylococcus aureus; Campylobacter jejuni, Yersinia enterocolitica; Clostridium* spp., and *Shigella* spp. The viruses included in the food safety review were norovirus and hepatitis A virus. Løvdal *et al.* (2021) concluded "*Bacillus* spp., *Vibrio* spp., and *Aeromonas* spp. were the main inherent bacteria that are of special concern for food safety of seaweed". *Bacillus* spp. were considered a concern due to the production of heat resistant spores and a heat stable toxin, while *Vibrio* spp. and *Aeromonas* spp. were considered a concern due to the possibility of naturally inhabiting the growing waters, combined with their ability to grow under chilling temperatures.

7.2 SELECTION OF BIOLOGICAL HAZARDS

Biological hazards were selected for inclusion in the current report based on:

- the existence of standards or other regulatory activity for the hazard in seaweed in any country or country group;
- the occurrence of incidents (recalls, border rejections, disease outbreaks, case reports) related to the hazard in seaweed, or
- the reporting of possible concern of the hazard in seaweed in the review articles summarised in section 7.1.

Table 14 lists the biological hazards selected for inclusion in the study using the above criteria.

Table 14. Biological hazards selected for inclusion in the study

Hazard	Country with standard [1]	Border rejection, notification or recall [2]	Documented outbreak or cases, either probable or confirmed [3]	Identified as of potential concern in review article
Bacteria (non-spore forming)				
Aeromonas spp.	-	-	-	Løvdal *et al.* (2021)
E. coli (STEC or EAEC)	-	-	Rehydrated seaweed salad (Japan)	-
L. monocytogenes	New Zealand (RTE foods)	US refusal of seaweed with sauce product	-	-
Salmonella spp.	China (dried laver and pre-packaged algae products), France (dried algae) Republic of Korea (RTE foods)	EU notification for dried seaweed strips	Raw seaweed (Hawaii) Boiled seaweed (Wales)	Banach *et al.* (2020)
Shigella spp.	China (dried laver)	-	-	-
S. aureus	China (dried laver), France (dried seaweed), Republic of Korea (RTE foods)	-	-	-
Vibrio spp.	China (dried laver and pre-packaged algae products), Republic of Korea (RTE foods)	-	-	Løvdal *et al.* (2021)
Bacteria (spore forming)				
B. cereus	Republic of Korea (RTE foods)	-	-	Banach *et al.* (2020) Løvdal *et al.* (2021)
C. perfringens	France (dried algae)	-	-	-
Viruses				
Norovirus	-	EU notification for frozen seaweed [4]	Dried laver (Japan) Seasoned seaweed (Republic of Korea) Frozen salad (Norway) [4]	Banach *et al.* (2020) EFSA (2017)
Fungi				
Mould	China (dried laver)	-	-	-
Microorganisms that produce marine biotoxins				
Dinoflagellates	-	-	-	EFSA (2017)
Cyanobacteria	-	-	Boiled seaweed (Hawaii)	-

Notes
1 See section 3 of report for more details.
2 See section 4 of report for more details.
3 See section 5 of report for more details.
4 The EU notification of possible norovirus in frozen seaweed was in the same time period that the outbreak was identified in Norway and are likely connected.

Symbol and abbreviations
- None listed
RTE Ready-to-eat, STEC shiga toxin producing *E. coli*, EAEC enteroaggregative *E. coli*

7.3 BIOLOGICAL HAZARD PROFILES (EXCLUDING ORGANISMS PRODUCING MARINE BIOTOXINS)

Profiles of the biological hazards selected in Table 14 are summarised in Table 15.

For some microbial pathogens, the risk to humans arises from the presence of the microbes themselves, which can infect the human gastrointestinal tract when ingested. For other microorganisms, such as *B. cereus*, *S. aureus*, and moulds (for example, *Aspergillus* spp. and *Penicillium* spp.), it is the production of toxins in food before consumption or in the gut following consumption that causes adverse health effects.

Microbial pathogens on seaweeds for human consumption may originate from the environment in which the seaweed is grown or be introduced during processing from contaminated equipment or water and infected food handlers. Microbial hazards in the aquatic growing environment can occur naturally (*Aeromonas* spp., *C. perfringens* or *Vibrio* spp.) or be present as a result of human or animal activities (anthropogenic, e.g. wastewater inflows, run-off from agricultural land or natural habitats, sewage discharges from boats).

Norovirus, *Shigella* spp. and serovars of *Salmonella* Typhi that cause human illness are species specific, so only human sources can infect humans (Doyle and Beuchat, 2007). Contamination of seaweed with disease causing norovirus, *Shigella* spp. or *Salmonella* Typhi before harvest will be from growing waters contaminated with human sewage.

B. cereus and *C. perfringens* cells are able to form spores which are resistant to heat, radiation, disinfectants, and desiccation (Brynestad and Granum, 2002; Logan, 2012). For these pathogen spores to germinate and grow to levels that are associated with illness, the seaweed product would need to be held at temperatures that would allow germination and growth for a sufficient period of time. Chilled, frozen or dried seaweed would not usually support growth of these pathogens. Although psychrotrophic strains of *B. cereus* have been reported to grow at temperatures below 7°C, toxin production has not been reported at temperatures below 8°C (Lechner *et al.*, 1998; Thorsen *et al.*, 2006). These psychrotrophic strains are now referred to as a separate species, *B. weihenstephanensis* (Lechner *et al.*, 1998).

Like *B. cereus*, *S. aureus* causes illness through the ingestion of a pre-formed toxin. The toxin is produced when concentrations of cells reach levels of 10^5 CFU/cm^2 or ml (Kadariya *et al.*, 2014). *S. aureus* is unlikely to grow on fresh seaweed at any temperature, as *S. aureus* competes poorly with other bacteria. Bacterial communities are part of the normal flora of seaweed surfaces (Singh and Reddy, 2014). *S. aureus* is not expected to grow below 6°C and enterotoxins do not form below 10°C, so toxins will not form in chilled or frozen product. Any pre-formed toxins and cells can survive frozen storage.

None of the studies summarised in section 7.1 identified *Shigella* spp., *Staphylococcus aureus, Clostridium perfringens* or moulds of particular food safety concerns for seaweed and seaweed products. However, this appears to be due to a lack of evidence for their occurrence in seaweed and seaweed products, rather than strong evidence that they are consistently absent from these foods.

Table 15 summarises the characteristics of microbiological hazards with potential relevance to seaweed. Note, the growth and survival characteristics noted in Table 15 and this section are not specific to the microorganisms on a seaweed matrix[29] and the actual growth or survival of microorganisms may be affected by characteristics of the seaweed matrix. A table of the minimum and maximum values for temperature and pH, and minimum water activity required for the growth of these microorganisms under otherwise optimal conditions is provided in Appendix E.

[29] Further information on the bacterial and viral hazards listed in the table can be viewed at https://www.mpi.govt.nz/science/food-safety-and-suitability-research/food-risk-assessment/foodborne-hazard-data-sheets/ (accessed 12 May 2022).

Table 15. Characteristics of the microbiological hazards of potential relevance to seaweed

Organism	Infectious dose [1]	Adverse foodborne health effects in humans	Contamination origin [2]	Characteristics [3] (not seaweed matrix specific)	References
Bacteria					
Aeromonas spp.	< 10^3 cells	Sub-acute gastroenteritis mainly in young children, can be more severe in immunocompromised populations.	Naturally occurring in aquatic environments	• Grow at chilling temperatures • Survive at freezing temperatures • Inactivated at moderate cook temperatures $D_{51°C}$ = 2.3 min in saline solution (0.85% NaCl) • Growth inhibited at 5-6% NaCl • Growth inhibited at pH < 5.5, inactivated at pH ≤ 4.5	(Løvdal *et al.*, 2021; Pessoa *et al.*, 2022; Teunis and Figueras, 2016))
B. cereus	>10^5 cells, or 8 µg preformed toxin per kg body weight	Acute gastroenteritis, diarrhoeal (toxins produced in the gut) or emetic (preformed toxin ingestion)	Environmental (terrestrial and aquatic)	Vegetative cells • Survive or inactivated at chilling temperatures (strain dependent) • Growth inhibited at a_W ≤ 0.92 or pH < 5 • Inactivated at moderate cook temperatures $D_{60°C}$ = 1 min in luncheon meat Spores • Survive at freezing temperatures • Inactivated at high cook temperatures $D_{100°C}$ = 1.2 minutes in rice Emetic toxin will survive high temperature cooking and low a_W or freezing.	(Brynestad and Granum, 2002; Byrne *et al.*, 2006; Logan, 2012)
C. perfringens	>10^6 cells	Acute gastroenteritis, typically mild and short duration (<24 hours)	Anthropogenic/ Environmental/aquatic sediments	Vegetative cells • Survive or inactivated at chilling temperatures, are inactivated at freezing temperatures • Growth inhibited at a_W ≤ 0.93 or pH < 5 • Inactivated at moderate cook temperatures $D_{65°C}$ = 0.9 min in luncheon meat Spores • Survive at freezing temperatures • Inactivated at high cook temperatures $D_{100°C}$ ~ 30 minutes in beef gravy	(Byrne *et al.*, 2006; McClane, 2007)

Organism	Infectious dose [1]	Adverse foodborne health effects in humans	Contamination origin [2]	Characteristics [3] (not seaweed matrix specific)	References
Enteroaggregative *E. coli* (EAEC)	Variable	Acute gastroenteritis with or without blood in stool and little to no vomiting. Can cause prolonged diarrhoea in children (more than 14 days).	Anthropogenic	Unknown if different to other *E. coli.*	(Nataro *et al.*, 1998)
Shiga toxin-producing *E. coli* (STEC)	<50 to 200 cells	Acute gastroenteritis with or without blood in stool, in severe cases haemolytic uraemic syndrome or thrombotic thrombocytopaenia purpura develops	Anthropogenic	• Survive at chilling or freezing temperatures • Inactivated at moderate cook temperatures $D_{60°C}$ < 3 min in broth, milk or ground beef • Growth possible at $a_w \geq 0.95$, some strains survive drying • Growth possible at 6% NaCl, but not 8% • Acid tolerant, growth inhibited at pH < 4	(EFSA, 2020; Molina *et al.*, 2003)
L. monocytogenes	10^5-10^9 cells	Sub-acute gastroenteritis. In pregnancy can lead to serious/fatal foetus/new-born outcomes. Elderly and immunosuppressed may also present with severe systemic infection.	Anthropogenic/ environmental	• Survive or grow at chilling temperatures • Survive or inactivated at freezing temperatures • Inactivated at moderate cook temperatures $D_{60°C}$ < 5 to 8 min in carrot homogenate • Growth possible at $a_W \geq 0.9$, survive $a_W \geq 0.83$ • Growth possible at 12% NaCl • Growth inhibited at pH < 4.6	(Quereda *et al.*, 2021)
Shigella spp.	10^1-10^2 cells	Severe acute gastroenteritis with or without blood in stool.	Anthropogenic	• Survive at chilling or freezing temperatures • Rapidly inactivated at temperature above 65°C • Growth inhibited at 5% NaCl • Inactivated at pH < 4	(Baker-Austin *et al.*, 2018)
Salmonella enterica serovars	10^2 - 10^6 cells	Acute gastroenteritis with or without blood in stool, in severe cases may progress to sepsis	Anthropogenic	• Growth inhibited at chilling temperatures • Survive or slowly inactivated at freezing temperatures • Inactivated at moderate cook temperatures $D_{60°C}$ = 10 min in green pea soup • Growth inhibited at a_W < 0.94, survive well in a dry environment • Inactivated at pH < 3.8	(Eng *et al.*, 2015; Hara-Kudo and Takatori, 2011)
S. aureus	< 1 µg preformed enterotoxin, may be present when ≥ 10^5 cells	Acute gastroenteritis	Anthropogenic /environmental	• Survive at chilling or freezing temperatures • Inactivated at moderate cook temperatures $D_{60°C}$ < 15 min in beans, peas • Growth inhibited at a_W < 0.85 (25% NaCl w/w) • Growth can occur at pH of 4.3	(Kadariya *et al.*, 2014)

Organism	Infectious dose [1]	Adverse foodborne health effects in humans	Contamination origin [2]	Characteristics [3] (not seaweed matrix specific)	References
				• Does not compete well with other bacteria in raw product	
Vibrio spp.	10^3–10^4 cells	Acute gastroenteritis	Naturally occurring in marine environment (water temperature > 13°C)	• Inactivated at chilling temperatures, although psychrotrophic strains have been reported • Survive at freezing temperatures • Inactivation at low cooking temperatures $D_{47°C}$ =3.6 min in broth, $D_{65°C}$ < 1 min in crab meat • Growth inhibited at a_W < 0.93 • Growth inhibited at pH < 4.8 • Salt tolerant, inactivated by distilled water	(Baker-Austin *et al.*, 2018; Lee, 1972)
Viruses					
Norovirus	10^1 - 10^2 virus particles	Acute gastroenteritis	Anthropogenic	• No growth in food or the environment • Survives chilling, freezing and drying • Survive pH of 3.75	(Hall, 2012)
Moulds					
Food safety issues mainly associated with species of *Aspergillus, Fusarium* and *Penicillium*	Issues relate to production of mycotoxins (mould secondary metabolites)	Various health effects dependent on the mycotoxin present. Most health effects result from chronic exposure	Environmental	Most mycotoxins are stable across a wide range of temperatures and other environmental conditions. Mycotoxins may remain following inactivation of the mould	(Council for Agriculture and Technology, 2003; Cressey, 2014)

Notes

1 For all pathogenic bacteria and viruses, the infectious dose is not absolute – it is dependent on the pathogen strain, host immunocompetence and food matrix.

2 Environmental: Naturally occurring in the aquatic growing environment (presence not related to human activity or land-based environmental events, although these might influence abundance).
Anthropogenic: From human or animal waste being introduced into the aquatic growing or processing environment by hygiene failure (for example: poor or failed wastewater infrastructure; high rainfall events in nearby agricultural areas; or, introduced as a result of hygiene failures during harvest and post-harvest processes.

3 General characteristics of pathogen as taken from MPI hazard datasheets, Microorganisms in foods 5 (ICMSF, 1996), Doyle and Beuchat (2007) or provided references.

Abbreviations

a_w water activity
D_x Decimal reduction time; the time for a 90% reduction in microbial concentrations at temperature x
w/w Weight by weight, refers to a percentage, proportion or concentration expressed on a weight basis

7.4 BACTERIAL, VIRAL OR FUNGAL HAZARD OCCURRENCE IN SEAWEEDS

7.4.1 Surveys of hazards in fresh seaweed

Table 16 summarises studies on the prevalence and concentrations of bacterial species found in fresh seaweed. No surveys of virus or mould presence in fresh seaweed were found in the literature.

The most commonly surveyed bacteria were the *Vibrio* spp., *V. parahaemolyticus* and *V. vulnificus,* which have been found in seaweed grown off the coasts of Japan, Italy and the United States (Mahmud *et al*., 2007,2008; Barberi *et al*. 2020 and Ziino *et al*. 2010). An additional Japanese study (only abstract in English) found 18.8% of *Caulerpa lentillifera* (sea grape) samples positive for *V. parahaemolyticus* (Kudaka *et al*., 2008).

In Maine (US), *Salmonella* Typhimurium and *E. coli* O157:H7 were detected by qPCR after enrichment on 83% and 53% of kelp samples, respectively (Barberi *et al*. 2020). The concentration of these pathogens on the seaweed was not determined. Fresh *Chondrus crispus* and *Chondracanthus teedii* seaweed from market stalls in Italy were all contaminated with *Aeromonas* spp., with concentrations up to 5.9 $\log_{10}$ CFU/g (Ziino *et al.*, 2010).

An alternative to testing for specific pathogens not normally associated with the marine environment, is to test for indicators of human or animal faecal contamination. A study of the hygienic quality of edible seaweed was undertaken by the Danish Veterinary and Food Administration (DVFA, 2021). Of the 65 samples taken, samples from eight sites showed *E. coli* concentrations of more than 100 CFU/100 g, with samples from two of the sites that were close to drains (from a field and from a harbour) having *E. coli* levels of >1000 CFU/100 g. *Salmonella* spp. were not detected in any of the samples taken.

Table 16. Selected microbiological surveys of fresh seaweed

Country	Seaweed and collection parameters	Sample	Survey results	Reference
Japan	Washed, fresh seaweed (unspecified species) collected from 12 sites twice per season	96 samples (10 g samples ground, and made up to 100 ml)	*V. parahaemolyticus* (summer and autumn, water temperature 20 to 29°C) • Detected in all samples (LOD = 3 MPN/10g) • Median 460 MPN/10 g, mode > 1100 MPN/10 g (both seasons) *V. parahaemolyticus* (winter and spring, water temperature 10 to 18°C) • Detected in 83% (winter) and 86% (spring) of samples • Median concentration 3 MPN/10g, mode 3 and 21 MPN/10 g (both seasons)	(Mahmud *et al.*, 2007)
Japan	Washed, fresh seaweed (*Porphyra, Undaria, Laminaria* and *Fucus* species) collected from 12 sites twice per season	96 samples (10g samples ground, and made up to 100ml)	*V. vulnificus* (summer and autumn, water temperature 20 to 29°C) • Detected in all samples (LOD 3 MPN/10 g) • Median 460 MPN/10 g, Mode > 1100 MPN/10 g (both seasons) *V. vulnificus* (winter and spring, water temperature 10 to 18°C) • Detected in 46% (winter) and 67% (spring) of samples • Median 3 (winter) and 21 (spring) MPN/10g, mode 21 MPN/10g (both seasons)	(Mahmud *et al.*, 2008)
United States (Maine)	Raw kelp (*Saccharina latissima*) collected over winter months from three aquaculture areas (n=8, 6 and 4 sampling days)	18 samples (8 g mixed samples stomached with100 ml sterile seawater)	Enrichment, then detection by qPCR: *Salmonella* Typhimurium detected in 83% samples *Escherichia coli* O157:H7 detected in 56% samples *V. parahaemolyticus* detected in 78% samples, concentration ranged from 0 to 8 CFU/8 g kelp.	(Barberi *et al.*, 2020)
Italy	*Chondrus crispus and Chondracanthus teedii* from fishmongers or street stalls	20 samples (sample size not given)	*E. coli* detected in 6 samples (0.7 to 2.74 log CFU/g) *Aeromonas* spp. detected in all samples (1 to 5.9 log CFU/g) *Vibrio* spp. detected in 15 samples (1.3 to 4.6 log CFU/g) *V. parahaemolyticus* detected in 2 samples	(Ziino *et al.*, 2010)
Denmark	Raw product (6 species) sampled from at least 28 sites	65 samples (sample size not given)	*Salmonella* spp. not detected in any 25 g samples Eight of the samples had generic *Escherichia coli* > 100 CFU/100 g suggesting some form of faecal contamination of the water (2 of these where from close to field drains and a port, so were expected to be high).	(DVFA, 2021)

Abbreviations LOD: limit of detection, MPN: most probable number, CFU: colony-forming units and qPCR: quantitative polymerase chain reaction.

Three studies further to those included in Table 16, failed to detect pathogens in seaweed samples

(1) A study by Moore *et al.* (2002) did not detect *Campylobacter* spp., *E. coli* O157:H7, *L. monocytogenes*, *Salmonella* spp., *S. aureus*, *Vibrio* spp. or moulds in raw dulse (*Palmaria palmata*) sampled from the coast of Northern Ireland. Samples were tested within one week of collection. The limits of detection of the methods were not clearly stated.

(2) A Food Safety Authority of Ireland report (FSAI, 2020), lists raw seaweed product monitoring data collected during the period 2011 to 2018. While the number of samples tested is not known and does not cover every year, *Bacillus* spp. (LOD = 1000 CFU/g), coagulase-positive *Staphylococcus* spp. (LOD = 10 or 20 CFU/g), *E. coli* (LOD = 10 CFU/g), *L. monocytogenes* (LOD = 10 CFU/g) and *Salmonella* spp. (Present/Absent) were all reported as being below these LODs in the samples taken.

(3) A Norwegian seaweed food safety assessment stated that seaweed "harvested from Norwegian waters have been analysed for the presence of *L. monocytogenes*, pathogenic *Vibrio* spp., enterococci, coliforms and thermotolerant coliforms, and none of these were detected in any of the samples (National Institute of Nutrition and Seafood Research (NIFES), unpublished results)" (Duinker *et al.*, 2016).

7.4.2 Surveys of hazards in processed seaweed products

There is limited information from published surveys of bacterial hazards in seaweed products.

One study, which tested only four 20 g samples of dried laver products from the Republic of Korea, did not detect *B. cereus*, *L. monocytogenes*, *Salmonella* spp., *S. aureus*, or *V. parahaemolyticus* in the products (Son *et al*., 2014).

Another study carried out in the Republic of Korea (Choi *et al*., 2014) tested for *B. cereus*, *E. coli, L. monocytogenes*, *Salmonella* spp., *S. aureus*, and *V. parahaemolyticus* in raw laver sheets and at several points through processing (primary roasting, seasoning, secondary roasting, counting and packaging and final product). Only *B. cereus* was detected during or after processing, but at very low concentrations (≤ 1.5 log CFU/g).

A single study was found that investigated mycotoxin (mould toxin) contamination of seaweed (Li *et al.*, 2018). The study analysed 50 dried kelp samples from a local supermarket in Shandong Province, China for seven mycotoxins usually produced by *Fusarium* species (3-acetyl-deoxynivalenol (3AcDON), 15-acetyl-deoxynivalenol (15AcDON), T-2 toxin, fusarenon-X (F-X), deoxynivalenol (DON), nivalenol (NIV) and zearalenone (ZEA)). Only 3AcDON/15-AcDON[30] were detected and were quantified in 43 samples at concentrations in the range 15 to 163 µg/kg. These toxins usually co-occur with DON, with DON being the dominant mycotoxin present. No analyses for the toxin-producing mould species were conducted. The isolated nature of this study and the unexpected mycotoxin profile found suggest that the results of this study should be viewed with caution.

No survey of norovirus in seaweed products was located.

[30] The two mycotoxins were not able to be separated by the method used and were reported collectively

7.5 MARINE BIOTOXIN HAZARD PROFILES

Marine biotoxins and cyanobacterial toxins (collectively termed marine biotoxins from here on) are sometimes classed as chemical hazards and other times as biological hazards, due to their production by biological organisms. In the current document, they have been classified as biological hazards, but have been considered separately to pathogenic microorganisms. While there is little evidence of marine biotoxins being associated with edible seaweed products, their potential presence was highlighted by EFSA as an emerging risk (EFSA, 2017).

Table 17 summarises information on the major dinoflagellate and cyanobacterial toxins and toxin-producing species which have been shown to cause adverse health effects in humans. Additional toxins have been identified with cytotoxic properties, but those included in Table 17 are the toxins commonly considered by regulatory and science advisory organisations.

Table 17. Characteristics of the marine biotoxins of potential relevance to seaweed food safety

Toxin group	Main producing organisms	Adverse health effects in humans	ARfD	Reference
Dinoflagellate toxins				
Okadaic acid (OA)	*Dinophysis* spp. *Prorocentrum* spp.	Diarrhoea, nausea, vomiting, abdominal pain	0.3 µg OA equiv/kg bw	(EFSA, 2008a)
Azaspiracid (AZA)	*Azadinium spinosum* *Amphidoma* spp.	Nausea, vomiting, diarrhoea and stomach cramps	0.2 µg AZA1 equiv/kg bw	(EFSA, 2008b)
Saxitoxin (STX)	*Alexandrium* spp. *Gymnodinium* spp. *Pyrodinium* spp.	Paralytic shellfish poisoning, symptoms varying from a slight tingling sensation or numbness around the lips to fatal respiratory paralysis	0.5 µg STX equiv/kg bw	(EFSA, 2009d)
Domoic acid (DA)	*Chondria* spp. *Pseudo-nitschia* spp.	Amnesic shellfish poisoning, including gastrointestinal (vomiting, diarrhoea or abdominal cramps) and/or neurological symptoms (confusion, loss of memory, or other serious signs such as seizure or coma)	30 µg DA/kg bw	(EFSA, 2009e)
Brevetoxin (BTX)	*Karenia brevis*	Neurologic shellfish poisoning, including nausea, vomiting, diarrhoea, paraesthesia, cramps, bronchoconstriction, paralysis, seizures and coma	No ARfD established	(EFSA, 2010b)
Ciguatoxin (CTX)	*Gambierdiscus* spp.	Gastrointestinal (vomiting, diarrhoea, nausea), neurological (tingling, itching) and cardiovascular (hypotension, bradycardia) effects	No ARfD established	(FAO/WHO, 2020a)

Toxin group	Main producing organisms	Adverse health effects in humans	ARfD	Reference
Cyanobacterial toxins				
Microcystin	*Microcystis* spp. and a variety of other	Hepatotoxicity, although gastrointestinal symptoms have also been reported	TDI (microcystin-LR) = 0.04 µg/kg bw per day	(Chorus and Welker, 2021; WHO, 2003)
Nodularins	*Nodularia* spp.	Hepatotoxicity		(Chorus and Welker, 2021)
Anatoxins	*Microcoleus autumnalis* *Cuspidothrix issatschenkoi*	Neurological symptoms	No health-based guidance value established	(Chorus and Welker, 2021; WHO, 2020a)
Cylindropermopsin	*Raphidiopsis* spp.	Effects on liver, kidneys and erythrocytes	Provisional TDI = 0.03 µg/kg bw per day	(Chorus and Welker, 2021; WHO, 2020b)
Saxitoxins	Various cyanobacteria, in addition to dinoflagellates	See above	See above	(Chorus and Welker, 2021)

Abbreviations
ARfD acute reference dose
bw body weight
equiv equivalents,
TDI tolerable daily intake,

Certain toxins produced by dinoflagellates have long been associated with human illnesses such as paralytic shellfish poisoning, neurotoxic shellfish poisoning, diarrhetic shellfish poisoning and ciguatera poisoning. Ciguatera poisoning can cause gastrointestinal, cardiac and neurological disorders and can sometimes be fatal (FAO/WHO, 2020a).

Some cyanobacteria can be toxic to the hepatic, neurological, gastrointestinal and integumentary systems, while also having embryo-lethal, teratogenic, mutagenic and tumour-promoting activities (Kubickova *et al.*, 2019).

The marine cyanobacterium, *Lyngbya majuscula,* has been implicated in outbreaks of dermatitis following swimming in affected areas, with reports of outbreaks from Hawaii and Okinawa (Osborne *et al.*, 2001). Accidental human oral ingestion of *L. majuscula* while consuming seaweed has been reported and led to an instant burning sensation and, several hours later, the mucous membrane in the anterior portion of the mouth appeared to be scalded (Sims and Zandee van Rilland, 1981). Discomfort lasted for three days and had completely disappeared in three weeks. There are no reports of systemic toxic effects due to this cyanobacterium.

As outlined in Section 5.1.1, toxins were recovered from seaweed associated with outbreaks of illness, including fatalities. The toxins were purified and identified as polycavernoside A and B (Yotsu-Yamashita *et al.*, 2004). Due to the highly sporadic nature of the outbreaks, it was speculated that these toxins may be of cyanobacterial origin, due to their structural similarity to toxins from *Lyngbya bouillonii* (Cheney, 2016). However, the origin, human toxicity and causative role in the outbreaks was never conclusively established.

Outbreaks of illness caused by dinoflagellate or cyanobacterial toxins may be reported to the New Zealand notifiable disease system (EpiSurv). In the period 2011-2020, cases of ciguatera poisoning (*n* = 50) were exclusively associated with imported fish (Horn *et al.*, 2021). The most recent outbreaks of toxic shellfish poisoning in New Zealand were in 2014 (*n* = 13 cases) and 2012 (*n* = 29 cases).

A single outbreak of cyanobacterial poisoning is included in EpiSurv. The outbreak occurred in 2018 and involved 18 cases who had contact with contaminated lake water.

Based on the available evidence, toxins from dinoflagellates or cyanobacteria associated with seaweed remain a potential, rather than an actual cause of human illness. While developments in this topic area should continue to be monitored, biotoxins have not been identified as a seaweed-related issue in New Zealand.

7.6 MARINE BIOTOXIN OCCURRENCE IN SEAWEEDS

Rinsing seaweed blades is an accepted technique for sampling dinoflagellates from the environment (Rhodes *et al.*, 2014a; Rhodes *et al.*, 2014b) suggesting dinoflagellates can be present on the surface of seaweeds.

The dinoflagellate *Gambierdiscus toxicus,* which produces ciguatera toxin, has been found attached to the surface of seaweed. *Gambierdiscus* spp. grow optimally in water ≥29°C (Tester *et al.*, 2010) and toxins can survive freezing. Therefore, the greater risk comes from fresh or frozen contaminated seaweed from tropical regions (FSAI, 2020).

Gambierdiscus species have been identified in New Zealand's coastal waters and *G. polynesiensis*, a known producer of ciguatoxins, has been isolated from Rangitāhua/Kermadec Islands, although the strain isolated was found not to produce ciguatoxins (Rhodes *et al.*, 2017). The warming of the Tasman Sea and the waters around New Zealand's northern subtropical coastline heightens the risk of *Gambierdiscus* occurring in New Zealand's coastal waters. If this occurs, the risk of ciguatera fish poisoning due to consumption of locally caught fish could increase (Rhodes *et al.*, 2020). Likewise, climate change may facilitate the expansion of optimal habitats for *Gambierdiscus* spp. and toxin contamination of seaweed could become a greater risk.

In addition to the major dinoflagellate toxins, *Vulcanodinium rugosum,* the only known producer of pinnatoxins (a class of cyclic imine toxins), has been found attached to the surface of seaweed (*Saccharina latissima*) in cold Norwegian waters (de la Iglesia *et al.*, 2014). Pinnatoxins were also detected, although the toxicological significance of this finding is uncertain.

Cyanobacteria are photosynthetic bacteria that can be found in all bodies of water. While they are mainly associated with freshwater environments, cyanobacteria have been reported to be associated with seaweed (Mutalipassi *et al.*, 2021).

7.7 SUMMARY

A range of microorganisms which could potentially cause adverse health effects can be found on seaweed either through their presence in the marine growing environment (naturally occurring or anthropogenic) or due to them being introduced by contamination during processing. There are limited data available to understand the potential contamination levels present on raw or processed seaweed products.

Based on the seaweed-specific evidence provided in this report, and general microbiological knowledge (which may or may not apply to the seaweed matrix) the following conclusions can be made.

None of the pathogens considered will grow at freezing temperatures, but in general pathogenic *E. coli*, *L. monocytogenes*, *Shigella* spp., *V. parahaemolyticus*, *V. vulnificus*, norovirus, hepatitis A and E viruses are known to survive at freezing temperatures for extended periods. *Salmonella* spp. concentrations will gradually decline over time under freezing conditions. The survival/inactivation rates for these pathogens on frozen seaweed product is not known and the food safety risk will be linked to this as well as the initial levels of contamination.

Norovirus may pose a food safety risk in dried products, based on known outbreaks, where product was contaminated either in the growing area, or later in processing. It is unclear if *Aeromonas* spp., pathogenic *E. coli*, *L. monocytogenes*, *Salmonella* spp., *Shigella* spp., *S. aureus,* hepatitis A or hepatitis E viruses may cause a food safety risk in dried seaweed products. More information is required relating to the potential growth/survival/inactivation of these pathogens in a seaweed matrix during the drying process.

The pathogens considered in this section can all be inactivated by heat treatments to some extent, although bacterial spores may not be inactivated. It is not known how resilience or susceptibility to heat treatment is affected by the seaweed matrix. It is also not clear, which time-temperature combinations are being used by producers. Mycotoxins and marine biotoxins are generally heat stable and can remain in product following inactivation of the producing organism.

Vibrio parahaemolyticus or *Vibrio vulnificus* are inherently present in seawater and have been found in fresh seaweed samples at concentrations that could cause foodborne illness. Psychrotrophic strains have been reported, able to grow at 0°C and above (Morii and Sarukawa, 2000). While these *Vibrio* species are easily inactivated by cooking or drying, they could survive in chilled or frozen products, such as the frozen wakame salads available in New Zealand. These salads may undergo a blanching step, but it is unknown if this would be sufficient to reduce *Vibrio* sufficiently to make the seaweed safe for consumption.

The potential for people to be exposed to biotoxins from dinoflagellates or cyanobacteria or mycotoxins from moulds via seaweed or seaweed products cannot be discounted, although no conclusive evidence is available at this time. The potential for dinoflagellate biotoxins to be present in seaweed is proven whilst human health impact has yet to be reported from their presence in seaweed.

8 SEAWEED PROCESSING AND THE IMPACT OF PROCESSING ON HAZARDS

8.1 INTRODUCTION

In general, seaweed is available to food producers and consumers as a high moisture product (fresh or processed, which may be chilled, frozen or shelf-stable) or in dried (shelf-stable) form. Shelf-stable products can range from simple dried products to more complex products that include seaweed as a minor ingredient, such as dry mix powders and crackers (Ferdouse *et al.*, 2018).

In the following sections, information is summarised for the five main types of products that contain seaweed as a primary ingredient identified in Table 5; dried products that contain seaweed as a primary ingredient other than dried nori, dried nori, frozen seaweed salad, shelf-stable seaweed preparations and seaweed snacks. The impact of individual processing steps on hazards present in the harvested seaweed is also summarised. It should be noted that seaweed-specific information on the impact of processing on hazards is sparse.

The overall food safety of fresh seaweed often reflects the environment from which it is harvested, with regard to biological and chemical hazards (Lupo and Angot, 2020). However, the presence and concentrations of such hazards in products that contain seaweed as a primary ingredient can be impacted by the treatments applied during their processing (Wells *et al.*, 2017). Processing may also introduce additional hazards, due to contaminated processing environments or infected workers. Seaweed processing aims to produce an array of consumer products with desirable characteristics, including increased shelf-life, safety and palatability (Løvdal *et al.*, 2021).

High moisture content, in combination with a dense nutrient composition, makes seaweeds susceptible to growth of microorganisms, including human pathogens, which reduces the shelf-life of raw or minimally processed products that contain seaweed as a primary ingredient (Løvdal *et al.*, 2021). Shelf-life of chilled product is typically between 6 and 12 days depending on the seaweed type and season of harvesting (Nayyar, 2016; Sánchez-García *et al.*, 2021).

Processes such as drying have the potential to concentrate chemical residues such as heavy metals, while processes that include a heat treatment step have the potential to decrease the concentrations of heat-labile residues and the number/growth of pathogenic and non-pathogenic microorganisms. There is also some evidence that heat treatment could alter the chemical forms of elements such as arsenic (Devesa *et al.*, 2008).

8.2 EDIBLE SEAWEED PROCESSING

The main categories of edible products that contain seaweed as a primary ingredient commercially available in New Zealand are summarised in Table 5. The processing of these products can differ considerably between and within product categories, with different process steps applied, and a variety of ingredients added, to produce a wide range of products.

Immediately following harvest, fresh seaweeds will have the holdfast (the attachment of the seaweed to the sea floor or other stable point) and the stipe (the stalk between the holdfast and the blade of the seaweed) removed and will be washed with either seawater or freshwater to remove adhering material (Concepcion *et al.*, 2021). These post-harvest steps are typically applied to various types of seaweed prior to their further processing.

The following sections include a summary of information on the five main types of products that contain seaweed as a primary ingredient and their processing.

8.2.1 Dried seaweed (other than nori)

Drying is a process employed for preservation of most processed products that contain seaweed as a primary ingredient currently available in New Zealand. Examples of common dried products that contain seaweed as a primary ingredient include:

- **Dried hijiki**. Hijiki is an example of a seaweed that is mainly sold as a dried product. Hijiki is cleaned and cut at harvest, and may be sun-dried before transfer to a processing facility (McHugh, 2003). Further processing involves boiling and/or steaming the hijiki for several hours to decrease its bitterness.[31] The resulting product is dried into black, brittle seaweed pieces that require rehydration before use. It is typically used as a stir-fry ingredient or simmered alongside other vegetables (McHugh, 2003).
- **Dried kombu**. Kombu is derived from *Saccharina japonica* and related species of brown algae. A variety of dried kombu products are available (Radmer, 1996), and in most cases the processing involves simply washing of the harvested fresh seaweed with seawater, sun or air drying and folding (McHugh, 2003). It may also be sold pickled in vinegar.
- **Dried dulse.** *Palmaria palmata* (dulse) is predominantly sun-dried straight after harvest and is normally sold in dried whole leaf form (McHugh, 2003).

The methods that can be used for drying are described below.

Solar/sun drying

The use of open-air solar energy to reduce the moisture content of seaweed has no process control over drying conditions. Drying periods may be long and the outdoor nature of the process may result in contamination with airborne contaminants (bacteria, insects, fungi). The drying time varies based on the solar conditions and type of seaweed, but on average ranges from 4-9 days (Cascais *et al.*, 2021; Santiago and Moreira, 2020).

Oven/convection drying

This is the most commonly employed method for drying seaweed (Badmus *et al.*, 2019; Santiago and Moreira, 2020). Drying parameters, such as temperature and time, can usually be controlled by the processor, which results in a more consistent product (Santiago and Moreira, 2020). However, the high temperatures used can reduce the content of desirable heat-labile bioactive and nutrient components of the seaweed (Badmus *et al.*, 2019)

A study on the impact of oven drying temperature on the water activity of dried sugar kelp (*Saccharina latissimi*) examined drying temperatures between 30 and 70°C (Duran-Frontera, 2017). All drying temperatures resulted in final seaweed moisture contents of less than 15%, while water activities were in the range 0.20 to 0.65. These water activities are well below

[31] http://www.kurakonusa.com/hijiki/production_process_of_hijiki.html Accessed 11 August 2022

the minimum required for growth of bacterial pathogens potentially present in seaweed (Appendix E, Table E1).

Air drying

Air drying of seaweed involves drying at ambient temperature in an enclosed space, avoiding contamination from environmental sources, such as from birds. Dehumidifiers may be used to assist the drying process. This process does not appear to be commonly used, however, NZ Kelp[32] state that they use dehumidifiers and controlled airflow to dry the kelp and the ambient temperature in the drying room is kept below 30°C during their process.

Freeze drying

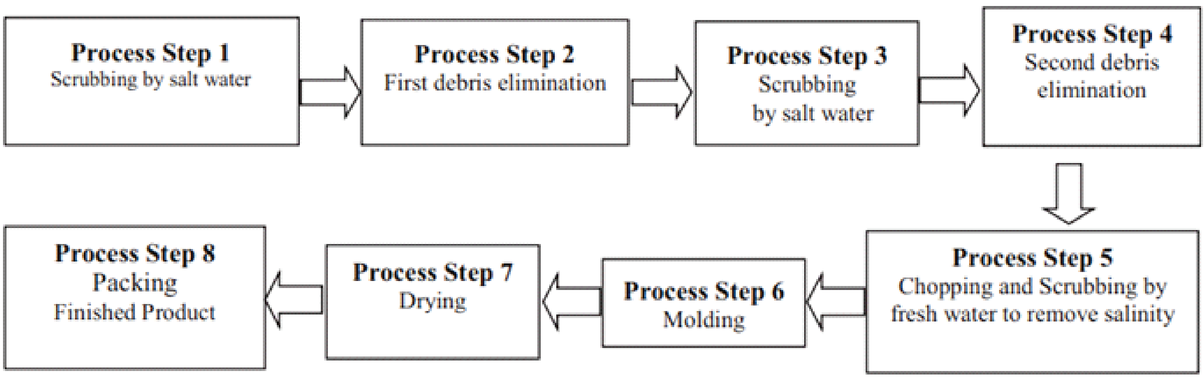
Also known as lyophilisation, freeze-drying works by crystallising the water at low temperatures, and the crystals are then sublimed into the vapour phase under vacuum. Akin to convective drying, the parameters can be set by the producer (Santiago and Moreira, 2020). The low temperatures used for freeze-drying mean that loss of heat labile components is minimised. The use of this method is currently limited by the cost and it appears to be mainly used for the production of high-value seaweed flakes and powders (Cascais *et al.*, 2021).

8.2.2 Dried nori/laver (*Porphyra/Pyropia* species)

Nori is the dried end-product produced from the *Porphyra* species of red seaweed and used for sushi wraps and snacks. The process to create nori is highly mechanised and is similar to a paper-making process (McHugh, 2003).[33] Briefly, the seaweed is cleaned, minced then blended into small pieces, which are finally poured into mats that are dried (most commonly via convection). Sheets are then packaged (Ferdouse *et al.*, 2018; McHugh, 2003).

A typical process is shown in Figure 2 (Son *et al.*, 2014).

Figure 2. Example of dried laver processing steps



Source Adapted from (Son *et al.*, 2014)

The use of sponges in step 7 in this process was reported by the authors to correlate with an increase in the bacterial load of the finished product.

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[32] https://www.nzkelp.co.nz/valere-1 (Accessed 16 May 2022)
[33] A video of dried laver production can be viewed at: Dried Seaweed Laver Processing in Factory - Seaweed Harvesting - Green Laver Factory - YouTube

Some dried laver products may be roasted (sometimes twice) after the drying step and before packaging. There is a large temperature range for such roasting; from 50 to 400°C, with roasting times of 2 to 10 seconds (Choi *et al.*, 2014).

An outbreak report listing the process used to produce the outbreak associated product, stated that the seaweed was heat treated in water for 2 hours at 90°C followed by heat treatment using a conveyor-type machine for ~7 seconds at 240°C after (Kusumi *et al.*, 2017).

The water activity of dried nori is typically 0.65 or less (Choi, 2014; Duran-Frontera, 2017).

8.2.3 Frozen seaweed salad

Little information was found on the processing of frozen seaweed salad. The salads appear to be most commonly made of wakame (*Undaria pinnatifida*) and contain added ingredients, such as oil, vinegar, sesame seeds and chilli pepper. Salads are consumed directly, once thawed.

It is uncertain whether all frozen seaweed salads receive a heat treatment step. Pre-freezing blanching has been shown to improve the colour and technological properties of frozen seaweed (Akomea-Frempong, 2022).

Wakame seaweed harvested in New Zealand by Wakame Fresh[34] undergoes a blanching step straight after harvest, but it is not known if this is sufficient to reliably inactivate *Vibrio* spp. or other pathogens if present on the harvested seaweed to levels which would not cause illness.

Wakame (*Undaria pinnatifida*) is popularly sold as a wet product, which may be chilled or frozen. Provided a low temperature is maintained, the wakame will remain fresh for long periods (Ferdouse *et al.*, 2018; McHugh, 2003). The product is boiled or blanched and salted, which results in the green product[35] that consumers eat, and is commonly included in miso soup and seaweed salads (Ferdouse *et al.*, 2018; Radmer, 1996). An example of wakame processing is blanching at 80°C for one minute and then cooling in water. Salt is added (30% of the seaweed weight) and this is then stored at -10°C.

8.2.4 Shelf-stable seaweed preparations (non-dried)

This category of products that contain seaweed as a primary ingredient includes seasoned, pickled and salted seaweed preparations that can be safely stored under ambient conditions, and retorted products, such as seaweed soups (Table 5). Shelf-stable products depend on the application of one or more 'hurdles' to inhibit the growth of microorganisms (Guerrero *et al.*, 2002). Hurdles may include adjustment of pH (pickling), reduction of water activity (salting), addition of ingredient with antimicrobial characteristics (seasoning), and application of heat.

8.2.5 Seaweed-based snacks

While this category potentially covers a wide range of products, most seaweed snacks appear to be based on dried nori with the addition of condiments, flavourings and other ingredients. Snacks may be baked, fried or roasted.

[34] https://wakamefresh.co.nz/ and https://www.facebook.com/wakamefresh/ (Accessed 16 May 2022)
[35] The green colour is chlorophyll, which has a higher melting point than other seaweed pigments and remains when the other pigment dissolve during the blanching or boiling processes.

Potentially, hazards may be introduced into seaweed snacks as a component of added ingredients, such as spices.

8.3 IMPACT OF PROCESSING ON HAZARDS

The products that contain seaweed as a primary ingredient summarised in the previous sections may involve application of a variable range of processes, each of which may potentially impact on the hazard profile of the finished product.

8.3.1 Washing/soaking (with or without heating)

Chemical elements associated with seaweeds can exist in colloidal-sized particles absorbed to algal surfaces (Wells *et al.*, 2017). Interaction of the seaweed with water through physical processes, such as washing or soaking (with or without heating), may disrupt this attachment and reduce concentrations of elemental contaminants on the seaweed surface.

<u>Microbiological hazards</u>

Microorganisms may also be removed by the physical process of washing, but no information was found on the effectiveness of this process with respect to seaweed.

<u>Chemical hazards</u>

Arsenic

Traditional washing and soaking of hijiki seaweed (*Sargassum fusiforme;* a species that has inherent high inorganic arsenic levels), has been shown to reduce the concentration of total arsenic by up to 60% (Devesa *et al.*, 2008; Hanaoka *et al.*, 2001). Increasing the amount of water used for soaking did not increase arsenic removal, but increasing temperature did, with a linear decrease in arsenic content when the temperature of the soak water was increased from 0 to 60°C (Hanaoka *et al.*, 2001). Ichikawa *et al.* (2006) observed that between 28 and 58% of the total arsenic in hijiki *seaweed* could be removed by soaking in water (5 g seaweed in 20 mL pure water for 30 minutes at room temperature), and that 49-60% of the remaining arsenic could be removed through heating in water for 20 minutes at 90°C. Similarly, a study by Cheyns *et al.* (2017) showed a 28% decrease in arsenic levels through soaking of hijiki, and a 50% decrease in the arsenic levels in hijiki when boiled in water. The decreases in arsenic appear to be due to movement of the arsenic into the soak/cooking water. When nori or hijiki was boiled to produce a soup (i.e. water retained as part of the dish), only negligible decreases in overall arsenic content were observed.

The study of Cheyns *et al.* (2017) demonstrated that the inorganic arsenic species were not chemically altered during soaking or boiling. However, a study in shellfish found that organic arsenic could be converted into inorganic arsenic during boiling (Liao *et al.*, 2018), and it is possible that the same reaction occurs in boiled seaweeds.

Iodine

Chung *et al.* (2013) showed that iodine concentration in kelp could be decreased by 90% when the kelp was boiled for 20 minutes, with the iodine released into the water that the kelp had been boiled in. Nitschke and Stengel (2016) quantified iodine losses in the edible seaweeds *Alaria esculenta* (brown)*, Palmaria palmata* (red), *Ulva intestinalis* (green) during processing. Washing and air-, oven- or freeze-drying only had marginal effects on iodine levels. In a second set of experiments starting with freeze-dried seaweed, rehydration by soaking in water reduced iodine levels by 62%, 15% and 10%, for *Alaria esculenta, Palmaria* *palmata* and *Ulva intestinalis* respectively, when compared to the raw, unprocessed material. Boiling of the seaweeds for 20 minutes further reduced the iodine levels.

Marine biotoxins

No information was found on the impact of washing, soaking or boiling on marine biotoxins associated with seaweed. Marine biotoxins, if present, are likely to be attached to the surface of seaweed. Additionally, the toxins causing diarrhetic shellfish poisoning (DSP) and Amnesic shellfish poisoning (ASP) are water soluble (Visciano *et al.*, 2016). It is likely that the processing described in this section will decrease the concentrations of any marine biotoxins that may be present on seaweed.

8.3.2 Blanching

Blanching involves the immersion of the seaweed into hot water or a steam for a certain amount of time to microorganisms and enzymes that may impact the quality of the product (Løvdal *et al.*, 2021).

Wakame Fresh, state that they wash and blanch their harvested seaweed (*Undaria pinnatifida*) on board the mussel barge, shortly after harvesting and before salting.[36]

Microbiological hazards

Thermal processes, including blanching, boiling and roasting, have the ability to inactivate spoilage and pathogenic microorganisms (Løvdal *et al.*, 2021).

No information was found on the impact of blanching on microbial pathogens in seaweed. Blanching of sugar kelp (*Saccharina latissima*) for 1 or 3 minutes at 100°C had a minimal impact on aerobic plate count, reducing counts from 2.9 log CFU/g to 2.6 and 2.4 log CFU/g, respectively (Akomea-Frempong *et al.*, 2021).

The spores of *Bacillus cereus* and *Clostridium* spp. are very resistant to heat, surviving temperatures 40°C higher than those that inactivate their corresponding vegetative cells (Setlow, 2006). Fernandez *et al.* (1999) have shown that the decimal reduction rate (D-value) of *B. cereus* spores of two enterotoxigenic strains to be 10 minutes at 95°C. Whether or not this would be the case for spores contained within a seaweed matrix is unknown. Any spores not destroyed during processing may germinate when the conditions become favourable, meaning the risk to the seaweed consumer may remain. Viral pathogens, such as norovirus, can be inactivated at temperatures greater than 90°C for >90s (Bosch *et al.*, 2018).

A practical complication of heat application to seaweed is the clumping of seaweed leaves during processing. The resulting uneven seaweed configuration results in difficulties predicting the heat load and the effectiveness of the inactivation of microorganisms (Løvdal *et al.*, 2021). Due to the different physical characteristics of different seaweed types, effective heat treatments will vary between seaweed genera, or even species within a genus.

Chemical hazards

No information was found on impact of blanching on concentrations of chemical hazards in seaweed.

[36] SeaFoodNZ Magazine December 2020, https://www.seafood.co.nz/detail-3/seafood-nz-magazine-december-2020 (Accessed 16 May 2022)

Marine biotoxins

No information was found on impact of blanching on concentrations of marine biotoxins in seaweed.

8.3.3 Salting

Salting refers to the process of adding dry salt or brine to a product, to lower the water activity to inhibit the growth of microorganisms. Salting may be used on its own, or in combination with other processing methods, such as drying, to preserve seaweed.

Microbiological hazards

Salting is a traditional technique used in the preservation of seaweeds. Products may be heavily salted, with salt addition rates as high as 400 g/kg (40%) reported (del Olmo *et al.*, 2019; Perry *et al.*, 2019). Although salting will decrease water activity and may cause hyperosmotic shock in microorganisms, this method may not guarantee microbiological safety, as some pathogens can survive this process (even in combination with refrigeration), depending on the salt concentration and salting period. Regardless, it can be efficient at reducing microbiological growth (del Olmo *et al.*, 2020; Ho and Redan, 2021).

While studies have reported the impact of salting on the microbial load of seaweed, there is a paucity of information on the effects of salting on pathogenic microorganisms in seaweed (del Olmo *et al.*, 2019; Perry *et al.*, 2019).

Chemical hazards

No information was found on impact of salting on concentrations of chemical hazards in seaweed.

Marine biotoxins

No information was found on impact of salting on concentrations of marine biotoxins in seaweed.

8.3.4 Chilling or freezing

Microbiological hazards

Lowering the temperature of seaweed through chilling and/or freezing is a bacteriostatic processing method that prevents the growth of many pathogenic microorganisms. The growth rate of a microorganism will decrease with decreasing temperature until their minimum growth temperature is reached (Løvdal *et al.*, 2021). The minimum growth temperatures of pathogens that may be associated with seaweed are listed in Table E.1 (Appendix E).

Three human pathogens with potential relevance to seaweed, *Aeromonas* spp, *Listeria spp.* and some *Vibrio* spp. are able to grow at chilling temperatures (<5°C) (Løvdal *et al.*, 2021).

Freezing can injure and inactivate bacteria through several mechanisms (El-Kest and Marth, 1992). Norovirus (and other viruses) are relatively resistant to both chilling and freezing (Bosch *et al.*, 2018), with a norovirus outbreak reported in Norway due to imported contaminated frozen wakame seaweed from China (Whitworth, 2019). Bacterial spores (discussed further below) are thermostable, consequently freezing will not affect spore viability (Lupo and Angot, 2020).

No scientific information was found on the impact of freezing on pathogenic or indicator microbial species on seaweed.

Chemical hazards

No information was found on the impact of chilling or freezing on chemical contaminants in seaweed.

Marine biotoxins

No information was found on the impact of chilling or freezing on marine biotoxins in seaweed.

8.3.5 Drying

Drying is the most common method used for preserving seaweed (see sections 8.2.1 and 8.2.2) (del Olmo *et al.*, 2019). Drying reduces the water activity of the seaweed to a level unfavourable for microbial growth or survival.

Microbiological hazards

Drying inhibits microbiological growth, but bacteria that are resistant to desiccation may survive and be able to proliferate if the dried seaweed is rehydrated (del Olmo *et al.*, 2020).

The effectiveness of drying in controlling hazards varies depending on the method employed (Cascais *et al.*, 2021), and factors such as the drying temperature and time, the drying rate and the final moisture content achieved. Reduction of the water activity to below 0.6 can also inhibit growth of yeasts and moulds (Løvdal *et al.*, 2021).

Vairappan and Suzuki (2000) dried sea lettuce (*Ulva reticulata*) for 31 days at 28°C and 85% humidity which resulted in a gradual reduction in water activity from 0.98 to 0.89. The freshly harvested sea lettuce was found to be naturally contaminated with *E. coli, A. hydrophila,* and *V. parahaemolyticus.* Weekly sampling showed concentrations of all three bacteria increased by a factor of at least 6 in the first week, followed by a gradual decline. The *A. hydrophila* concentration was ~1300 CFU/cm^2 at day 7, and gradually decreased to ~100 CFU/cm^2 at day 31. *E. coli* concentrations dropped from ~2550 CFU/cm^2 at day 7 to ~800 CFU/cm^2 at day 28 and 31. It is not clear if these concentrations would have continued to drop, beyond 31 days if the experiment had continued. The *V. parahaemolyticus* concentration was ~300 CFU/cm^2 at day 7 and the organism was not detected by day 21.

Other pathogens that may survive on dried seaweed based on their general characteristics include *E. coli*, *Salmonella* spp., *S. aureus* and norovirus.

Son *et al.* (2014) reported that sponges are used to help the drying process in Korean dried laver production (section 8.2.2). The sponges used to aid in drying are replaced every 2-3 days. As the sponges are moist, stored at room temperature and contain nutrients (from contact with the seaweed), bacterial growth may occur in the sponges, which subsequently come into contact with seaweed. Increases in total viable counts and total coliforms were seen during the later stages of laver processing and it was concluded that this was due to contamination from used sponges. It is therefore conceivable that the sponges could introduce pathogens during the drying process.

Chemical hazards

Air drying (23°C), oven drying (60°C) and freeze-drying (temperature not stated) of washed pieces of winged kelp (*Alaria esculenta)* resulted in no significant decrease in iodine content

(Nitschke and Stengel, 2016). In contrast, freeze-drying of *Saccharina latissimi* (sugar kelp) significantly decreased total iodine compared to drying at 25°C, with final iodine concentrations of 3,000 and 5,900 mg/kg dw, respectively (Stevant *et al.*, 2018). The mechanism by which iodine was lost was not discussed in this publication.

<u>Marine biotoxins</u>

No literature was identified on the impact of drying on marine biotoxins in or on seaweed. EFSA has speculated that processing of shellfish could lead to an increase in the apparent concentration of lipophilic marine biotoxins, due to the decrease in weight of the shellfish flesh and the stability of the toxins (EFSA, 2009b).

8.3.6 Thermal processing

A range of thermal processes may be applied to seaweed for various technological reasons. Soaking in hot water (section 8.3.1) and blanching (section 8.3.2) are discussed in previous sections. Other thermal processes, such as frying, baking and roasting, have the potential to inactivate microorganisms present on the seaweed but may also increase the concentration of heat-stable components by reducing the water content of the seaweed.

<u>Microbiological hazards</u>

A study by Choi *et al.* (2014), investigated the microbiological quality of seasoned roasted laver (a dried product) from six different producers using two separate roasting steps at various temperatures, as described in Section 8.2.2. Coliforms and *B. cereus* were detected in the dried laver prior to processing. For all six producers, these two roasting steps achieved products that had no detectable coliforms. *B. cereus* spores were detected on some of the final products which did not correlate with lower roasting temperatures.

<u>Chemical hazards</u>

No information was found on the impact of thermal processing on chemical contaminants in seaweed.

<u>Marine biotoxins</u>

No information was found on the impact of thermal processing on marine biotoxins in seaweed.

8.3.7 Fermentation

Lactic acid fermentation of seaweed is a recent development in the processing and preservation of seaweed and limited information is available on culture conditions (Løvdal *et al.*, 2021). The absence of natural lactic acid bacteria (LAB) and simple sugars in most seaweeds may have limited commercial uptake of this technology for the development of fermented seaweed products. However, fermented seaweed products are commercially available[37], although such products are not explicitly mentioned in Table 4 and may not be available in New Zealand.

<u>Microbiological hazards</u>

The fermentation of seaweed results in a decrease in pH to below 4.3; a level at which most pathogens are inactivated (Løvdal *et al.*, 2021). Norovirus is an exception, which can

[37] https://fermentationassociation.org/fermented-seaweed-products-make-use-of-2020s-super-ingredient/ Accessed 18 August 2022

withstand pH levels less than 1 (Løvdal *et al.*, 2021). The pH maxima/minima for other human pathogens associated with seaweed are listed in Table E.1.

Uchida *et al.* (2007) investigated the performance of different lactic acid bacteria during the fermentation of dried *Undaria*. While fermentation did lower the pH, this was only to a range of 4.3 – 5.3, which is still within the pH range for survival of many of the pathogenic microorganisms that may be associated with seaweed (Table 13). Moreover, the authors concluded that the natural microbiota of *Undaria* (both before and after fermentation) posed significant challenges for the control of the fermentation process and the safety of the resulting food product, primarily due to the presence of *B. subtilis*.

A further study showed that while fermentation can reduce the number of viable coliforms present in a fermented kelp product, it does not completely inactivate them (Skonberg *et al.*, 2021). These results, in combination with the paucity of literature on successful fermentation (Scieszka and Klewicka, 2019; Uchida *et al.*, 2007; Uchida *et al.*, 2014), suggest that currently the use of fermentation is not sufficiently well-characterised to ensure products are safe for human consumption.

Chemical hazards

No information was found on the impact of fermentation on chemical contaminants in seaweed.

Marine biotoxins

No information was found on the impact of fermentation on marine biotoxins in seaweed.

8.3.8 Novel processes

A number of other food processes may occasionally or potentially be applied to seaweed. Some of these processes and their impact on hazards in seaweed are summarised in the following sections. It is unknown whether these processes have been applied to any products that contain seaweed as a primary ingredient currently available in New Zealand.

Irradiation

Irradiation with gamma rays is the most widely accepted form of radiation sterilisation and may be used when food matrices cannot be heated to high temperatures for sterilisation (WHO, 1999). It is unknown whether gamma irradiation is currently being used on seaweed products. Standard 1.5.3 of the Australia New Zealand Food Standards Code[38] permits irradiation of fruits and vegetables, herbs and spices and plant material for herbal infusions. Irradiated foods must be labelled to the effect that the food has been treated with ionising radiation.

Scientific studies have demonstrated the ability of gamma irradiation to decrease concentrations of viruses (Park *et al.*, 2016) and bacteria (Jo *et al.*, 2005; Lee *et al.*, 2018) on seaweed. While no information was found, it is improbable that concentrations of elemental contaminants or marine biotoxins would be influenced by irradiation.

Microwave hydro-diffusion and gravity

Compared to other drying technologies, microwave hydro-diffusion and gravity (MHG) significantly reduces the time, energy consumption and environmental impacts (Lopez-Hortas *et al.*, 2022). This technology works by removing water from the algal cells through

[38] https://www.legislation.gov.au/Details/F2021C00766 Accessed 18 August 2022

microwave heating combined with earth gravity at atmospheric pressure (Lopez-Hortas *et al.*, 2022). This method does not result in significant differences in heavy metal concentrations compared to other drying methods (Lopez-Hortas *et al.*, 2022). While experimental studies have been carried out on the application of this technique to seaweed drying, it is unknown whether it is being applied in commercial operations.

High pressure processing (HPP)

HPP is a useful procedure for improving the microbiological quality of seaweeds as it is able to inactivate microorganisms without the need for high temperatures (del Olmo *et al.*, 2019). HPP involves subjecting the seaweed to pressure which can result in the inactivation of microbes and viruses (Tao *et al.*, 2014). This was shown by del Olmo *et al.* (2019) where HPP (400 or 600 MPa for 5 minutes) outperformed both salting and freezing with regard to microbiological quality of fresh (untreated) *Laminaria ochroleuca* (kombu). HPP was effective immediately after treatment and maintained this microbiological quality throughout a 180-day storage period. The definition used for microbiological quality in this study was total microbiological burden measured by a range of bacteriological plate counts, rather than the presence or absence of pathogenic bacteria.

In studies on other food matrices, HPP treatment was not found to be effective against bacterial spores (Reineke *et al.*, 2013).

While there is no information on whether HPP causes alterations to concentrations of chemical hazards or marine biotoxins in seaweeds, it seems unlikely.

8.4 SUMMARY

The safety of products that contain seaweed as a primary ingredient will depend on the type and extent of the initial contamination on the fresh seaweed (Lupo and Angot, 2020) and the impact of any processing treatments applied during production of the final consumer product.

Five main product groups have been identified as available in New Zealand. The processing of these products can differ considerably between and within product categories, with different process steps applied, and a variety of ingredients added, to produce a wide range of products. Processes such as blanching and drying may be applied to products in any of the categories.

There are many data gaps involving seaweed processing and its consequences on hazards (chemical and microbiological) present in the final product. Only a few of the hazards identified in this review (e.g., microbiological, arsenic and iodine) have been studied using seaweed as the food matrix. While the likely impact of some processing steps can be inferred from their impact in the processing of other foods, caution should be exercised in extrapolating findings to seaweed.

Only drying and roasting have been studied for their impact on microbial contamination of seaweed, with drying shown to decrease pathogen concentrations over time, while roasting appeared to be ineffective for inactivation of bacterial spores.

Soaking in hot or cold water has been shown to decrease concentrations of inorganic arsenic and iodine in seaweed, presumably through solubilisation of the elements into the soak water.

There are hazards (e.g., lead, cadmium, mercury, parasites, cyanobacteria, dinoflagellates) for which no literature was identified describing how processing methods may decrease or remove said hazards. As consumers continue to demand minimally processed food, free from food additives, new processing methods will need to be developed and these will change the risk profile (Tao *et al.*, 2014).

9 CONSUMPTION OF SEAWEED PRODUCTS

9.1 FOOD BALANCE SHEETS

Food balance sheets (FBS) provide a high-level picture of a country's food supply. The FBS include elements of supply (production, importation) and utilisation (exports, use as feed, use as seed, other non-food uses, tourist consumption and food supply). Table 18 summarises the FBS information for New Zealand for the most recent available year (2019) for the food category 'aquatic plants' which includes plants other than seaweed.[39] However, the International Standard Statistical Classification of Fishery Commodities (ISSCFC) suggests that 'aquatic plants' and 'seaweed products' are largely synonymous.[40]

Table 18. Food balance sheet data for aquatic plants for New Zealand, 2019

Element (units of measurement)	Value
Production (1000 tonnes)	2.46
Import quantity (1000 tonnes)	0.7
Export quantity (1000 tonnes)	0.18
Domestic supply quantity (1000 tonnes)	**2.98**
Other uses (non-food) (1000 tonnes)	2.98
Food supply quantity (Kg/capita)	<0.01

The data in Table 18 suggest that human consumption of seaweed is minor in the general New Zealand population. In a survey commissioned by New Zealand Food Safety however, many seaweed products were found to be available only through ethnic retail outlets (Christine Esquerra, New Zealand Food Safety, personal communication) and it is plausible that there are sub-populations within New Zealand with substantially higher seaweed consumption levels than the general population. It should be noted that the import quantities listed in Table 18 are consistent with import data for the same year (Section 2), which reports a total of 897,089 kg of seaweed imported in the 2019 year, equal to 0.9 x 1000 tonnes.

9.2 NATIONAL NUTRITION SURVEYS

Data are potentially available from three New Zealand National Nutrition Surveys (NNSs), noting that the most recent of these was carried out over a decade ago so does not reflect current food consumption trends:

- 1997 National Nutrition Survey (1997NNS; adults 15+ years)
- 2002 National Children's Nutrition Survey (2002CNS; children 5-14 years)
- 2008/09 Adult Nutrition Survey (2008ANS; adults 15+ years)

The NNSs included collection of 24-hour dietary recall (24HDR) records from the participants in the studies. The 24HDR is a detailed record of what the participant remembers they ate

[39] https://www.fao.org/faostat/en/#data/FBS Accessed 14 April 2022
[40] https://www.fao.org/3/bt967e/bt967e.pdf Accessed 4 August 2022

during a 24-hour period, including detailed descriptions of the foods and an estimate of the amount consumed. For a proportion of the participants, a second 24HDR was collected. The survey days for the 24HDRs were randomised with respect to the day of the week and time of the year. For each participant, a survey weight was calculated. The survey weights align the survey population to the national population, with respect to age, gender and ethnicity.

Across the three NNSs approximately 11,000 unique food descriptors have been used. Some descriptors identify individual foods, while some identify recipes, such as sandwiches, hamburgers, and curries.

The NNSs provide little direct information on consumption of seaweed. The 2002CNS includes four records of seaweed consumption (dried or boiled), relating to three respondents (0.1% of the survey cohort) (MoH, 2003). Daily consumption amounts were in the range 1-43 g. The 2009ANS contains six records of seaweed (dried) consumption, relating to four survey respondents (0.1% of the survey cohort). Daily consumption amounts were in the range 0.5-2 g (University of Otago and Ministry of Health, 2011).

Considerably more information is available on consumption of seaweed as a component of sushi. Sushi is wrapped in a layer of nori (*Pyropia*/*Porphyra* spp). Table 19 summarises information from the 2002CNS and 2009ANS on sushi consumption.

Table 19. Information on sushi consumption from 2002CNS and 2009ANS

Parameter [1]	2009ANS	2002CNS
Number of servings	95	9
Number of respondents	4721	3275
Number of consumers	72	9
% Consumers	1.5	0.3
Servings/consumer/day	1.3	1.0
Consumer mean (g/person/day)	194.6	256.7
Respondent mean (g/person/day)	3.0	0.7
Mean serving size (g)	147.5	256.7
Median serving size (g)	112.0	135.0
95th percentile serving size (g)	360.0	570.8

Abbreviations
2009ANS 2008-2009 Adult Nutrition Survey
2002CNS 2002 National Children's Nutrition Survey

Note
1 Consumers are those within the survey cohort who consumed the specified food in the survey data. Respondents refers to the whole survey cohort.

The United States Department of Agriculture (USDA) Food Data Central website[41] includes information on the composition of foods, including the ingredients and their proportions in composite foods. While the filling components of different sushi types vary, the composition given in the database is based on a standard recipe made up of:

- Rice, white, glutinous, unenriched, cooked 290 g
- Vinegar, distilled 19.5 g
- Sugars, granulated 3.75 g
- Salt, table, iodised 3.6 g
- Seaweed, laver, raw 5.2 g
- Filling ingredients 104 g

On the basis of this recipe, seaweed constitutes 1.2% of the sushi, by weight. The USDA database also gives a portion size of 30 g for sushi.

A French study reported a mean nori percentage in sushi of 1.4% (Ficheux *et al.*, 2022).

9.3 OTHER INFORMATION SOURCES

The FAO FBS database only reports three countries as having levels of aquatic plant consumption of note: the Republic of Korea (33.4 kg/capita/year or 91.5 g/capita/day), China (12.3 kg/capita/year or 33.7 g/capita/day) and Japan (0.93 kg/capita/year or 2.5 g/capita/day).

Similarly, the FAO/WHO Chronic Individual Food Consumption database summary statistics (CIFOCOss)[42] contains information on consumption of several types of seaweed (brown algae, eucheuma, hijiki, kombu, laver, red algae, sea lettuce, wakame). However, with the exception of data from the Republic of Korea, the proportions of consumers reported as consuming the seaweeds are small. Table 20 summarises CIFOCOss data for the Republic of Korea.

Table 20. Consumption of seaweed in the Republic of Korea, 2015, general population

Seaweed type	Consumers/total respondents [1] (%)	Consumer mean, g/kg bw per day	Consumer 95th percentile, g/kg bw per day	Total mean, g/kg bw per day	Total 95th percentile, g/kg bw per day
Brown algae	1505/20671 (7.2)	0.082	0.42	0.0060	0.0078
Laver	7492/20671 (36)	0.073	0.23	0.026	0.13
Other algae	190/20671 (0.9)	0.32	1.17	0.0030	-
Sea lettuce	364/20671 (1.8)	0.26	1.07	0.0045	-
Wakame	3081/20671 (15)	0.22	0.79	0.032	0.16

Abbreviations
bw body weight

Note
1 Consumers are those within the survey cohort who consumed the specified food in the survey data.

[41] https://fdc.nal.usda.gov/ Accessed 14 April 2022
[42] https://apps.who.int/foscollab/Download/DownloadConsco Accessed 30 August 2022

For comparison, consumption of sushi by adult New Zealanders, assuming 1.2% seaweed content and a nominal 70 kg body weight, would equate to a consumer mean of 0.033 g/kg bw per day, with a total population mean of 0.00051 g/kg bw per day.

A French study assessed seaweed consumption through an on-line survey of 780 French adults (18+ years) (Ficheux *et al.*, 2022). At a total population level, the mean consumption was estimated as 0.29 g/capita per day or 0.0041 g/kg bw per day, for a nominal 70 kg adult. Approximately half of the seaweed consumed was in the form of 'tartar' which appears to be a mix of seaweeds eaten on its own or as a flavouring for other foods and can be made with fresh or dried seaweeds.

9.4 SUMMARY

While it is likely that the consumption of seaweed is increasing in New Zealand based on import data, seaweed would currently be considered as a very minor food in the New Zealand diet. Although it is reasonable to assume that the consumption of prepared foods such as sushi is increasing, the seaweed component of this food is quite small. However, it should be noted that the available information is limited and somewhat dated.

10 CONCLUSIONS

This project has collated, analysed and reviewed information on seaweed and seaweed products commercially available in New Zealand for human consumption and selected microbiological and chemical hazards associated with the harvested seaweed and processing products with seaweed as a primary ingredient.

10.1 SOURCES OF EDIBLE SEAWEED PRODUCTS

Domestic production of edible seaweeds is currently characterised by a few operations serving niche markets. Wakame (*Undaria pinnatifida)*, kombu (*Saccharina japonica)* and giant kelp (*Macrocystis pyrifera*) are currently commercially harvested and processed in New Zealand. Prior to the Kaikōura earthquake in 2016, nori (*Porphyra*/*Pyropia* spp.) was also harvested along the Kaikōura coast. Seaweed is commercially harvested in New Zealand for human consumption, either by wild-harvest or collected from shellfish farm lines.

Seaweed is also commercially harvested for use in the agricultural or horticultural sectors, with smaller amounts being used in products for the beauty or health and well-being markets.

Most edible seaweed and seaweed products that are commercially available in New Zealand are imported. New Zealand predominantly imports seaweed products from China, the Republic of Korea and Japan. Hazards observed in overseas surveys of seaweed or seaweed products are relevant when considering the potential food safety risk to the New Zealand public.

Most of the seaweed products imported in 2021 were of a dried form, 71% of imports (by weight) were dried products. The greatest proportion of dried products were nori (53% of total imported products). Other common imported products included frozen salad (mainly wakame) (13%) and products grouped as dried or frozen seaweed of unknown species (10%). Other imported product types included seaweed-based snacks, and food containing seaweed as a minor ingredient, such as crackers, nut and seed mixes, soups, instant noodles, and seasoning and flavouring products.

10.2 CONSUMPTION OF SEAWEED

The available evidence suggests that seaweed is not a commonly consumed food in New Zealand. However, there is suggestive evidence that consumption may be higher in some ethnic groups. It is likely that consumption of seaweed in New Zealand will increase.

The amount of seaweed and seaweed products imported annually and intended for consumption as a food was approximately 1,000 tonnes in 2021, equating to 0.2 kg/capita/year. The amount of imported seaweed has increased from 2019, when 900 tonnes were imported.

There were minimal records for individuals' seaweed consumption from national nutritional surveys. However, these surveys are now out-dated (2002 for children and 2008-2009 for adults) and are unlikely to accurately represent current consumption patterns. Based on the national nutrition surveys, sushi is the most commonly eaten food containing seaweed, with 1.5% of adult survey respondents reporting consumption of sushi on the survey day. Standard recipes indicate that the nori (laver) wrap used in sushi accounts for just over 1%

of the product by weight. Seaweed soups, salads and stir-fries will result in higher servings of seaweed.

10.3 RISK MANAGEMENT

Regulatory or guideline limits for microbiological or chemical hazards in seaweed and seaweed products are uncommon internationally and the maximum limits for hazards vary between jurisdictions. Inorganic arsenic is the hazard for which maximum limits are most frequently established.

Border rejections and product recalls of seaweed and seaweed products in New Zealand, Australia, North America and the European Union have been most frequently due to the presence of excessive levels of iodine in the food. Less frequently, incidents have related to excessive level of elemental contaminants (inorganic arsenic, lead, cadmium), or the presence of microbial pathogens (norovirus, *Salmonella*, *L. monocytogenes*) or non-permitted pesticides or additives. The frequency of hazard detection in seaweed or seaweed products will in part be related to which hazards are being monitored.

10.4 HAZARD PATHWAYS

The available evidence suggests that there are three pathways by which hazards can contaminate or accumulate in seaweed and seaweed products:

4. The hazard may be a naturally occurring component of seaweed (e.g. iodine). The concentration of iodine is generally higher in brown seaweeds (*Ochrophyta*).
5. Seaweed can bioaccumulate chemical hazards (inorganic arsenic, lead, cadmium, mercury) present in the marine environment. Bioaccumulation of chemical hazards can be seaweed species dependent, such as the accumulation in inorganic arsenic by hijiki (*Sargassum fusiforme*)
6. Bacteria or viruses can contaminate seaweed if present in the marine environment (e.g. *Aeromonas* spp*, C. perfringens* and *Vibrio* spp.) or can be introduced during processing from contaminated equipment, water supplies or infected food handlers. These factors are unlikely to be seaweed-specific but will be process-specific or be dependent on harvesting waters contaminated with human or animal faecal matter. Mycotoxins and marine biotoxins can also potentially contaminate seaweed products, but the evidence for this occurring is scarce.

10.5 SEAWEED PROCESSING AND ITS IMPACT ON HAZARDS

Imported seaweed products that contain seaweed as a primary ingredient can be classified into five main product categories: dried seaweed (other than nori), dried nori, frozen seaweed salads, shelf-stable seaweed products (non-dried) and seaweed-based snacks. The processing of these products can differ considerably between and within product categories, with different process steps applied, and a variety of ingredients added, to produce a wide range of seaweed products.

Specific information on the impact of seaweed processing on pathogenic microorganisms, marine biotoxins and mycotoxins is generally lacking. Most of the comments in the following section are based on the general characteristics of the organisms and substances, rather than on seaweed-specific studies.

All seaweeds are washed following harvest, and this has the potential to remove surface-adhering hazards, such as microorganism and biotoxin-producing dinoflagellates. Soaking (with or without heat) has been shown to decrease the inorganic arsenic and iodine levels of seaweed by up to 60 and 90%, respectively.

Chilled seaweed products that have not undergone a heat treatment step represent a potential food safety risk, as *L. monocytogenes, Aeromonas* spp. and some *Vibrio* spp. strains can grow at chilling temperatures. It is not clear if the shelf-life of fresh seaweed is short enough to preclude these bacteria as a risk. It is unknown whether they will grow on the seaweed matrix. Pathogenic *E. coli*, *Shigella* spp., *Salmonella* spp., *V. parahaemolyticus*, *V. vulnificus*, norovirus, in chilled seaweed products all pose a possible risk depending on their initial contamination concentrations.

Seaweed products are often salted and salting will inhibit the growth of microorganisms. However, while studies have reported the impact of salting on the microbial load of seaweed, there is a paucity of information on the effects of salting on pathogenic microorganisms in seaweed (del Olmo *et al.*, 2019; Perry *et al.*, 2019).

It is likely that most seaweed products receive some level of heat treatment, ranging from short duration blanching to boiling for several hours. These heat treatments should inactivate most microorganisms, although may be insufficient to inactivate bacterial spores.

The majority of imported seaweed products are dried, which should prevent growth of microorganisms and contribute to their inactivation. The single study that examined the behaviour of microbial pathogens (*E. coli, A. hydrophila* and *V. parahaemolyticus*) of seaweed (sea lettuce (*Ulva reticulata*)) samples during drying demonstrated an initial increase in bacterial numbers, followed by a steady decline (Vairappan and Suzuki, 2000).

10.6 POTENTIAL CHEMICAL HAZARDS

Chemical hazards included in the current report and a summary of their hazard profiles, with respect to seaweed and seaweed products, are included in Table 21. High concentrations of iodine and inorganic arsenic are related to particular types of seaweed, while high concentrations of the other contaminant elements appear to be related to levels of contamination in the growing environment.

Of the hazards included in Table 21, only iodine has been associated with adverse health effects in humans due to its presence in seaweed. This is probably not surprising as effects of excessive iodine on thyroid function can occur after a relatively short period of exposure (days to weeks), while adverse effects due to other chemical hazards occur after chronic exposure to high levels of the hazards.

Table 21: Chemical hazards in seaweed and seaweed products

Hazard	Product likely to be affected	Epidemiological evidence	Occurrence evidence
Iodine	Brown seaweed and brown seaweed products	Case series of thyrotoxicosis linked to seaweed ingredients (Australia and New Zealand)	• Concentrations up to 13,000 mg/kg dw (Appendix D) • Multiple border rejections/recalls
Arsenic (inorganic)	Hijiki seaweed and hijiki seaweed products	No reported evidence of adverse effects due to inorganic arsenic in seaweed	• Concentrations up to 110 mg/kg dw (Appendix D) • Border rejections
Cadmium	Any seaweed harvested from contaminated environment	No reported evidence of adverse effects due to cadmium in seaweed	• Concentrations up to 10.0 mg/kg dw (Appendix D) • Occasional border rejections
Lead	Any seaweed harvested from contaminated environment	No reported evidence of adverse effects due to lead in seaweed	• Concentrations up to 43 mg/kg dw (Appendix D) • Occasional border rejections
Mercury	Any seaweed harvested from contaminated environment	No reported evidence of adverse effects due to mercury in seaweed	• Concentrations up to 1.1 mg/kg dw (Appendix D)

10.7 POTENTIAL BIOLOGICAL HAZARDS

Biological hazards included in the current report and a summary of their hazard profile, with respect to seaweed and seaweed products, are included in Table 22. Only *Salmonella* has been both detected in surveys of seaweed and confirmed as the causative organism for a seaweed-associated outbreak. However, there are only a few microbiological surveys of seaweed and seaweed products available for review.

Of the biological hazards listed in Table 22, *B. cereus*, *C. perfringens* and *S. aureus* are unlikely to be a risk in seaweed products, unless fresh or rehydrated seaweed or seaweed products are held at temperatures which would promote the growth of cells. The review has found no documented evidence that *Shigella* spp., or moulds in dried products have historically been a seaweed-associated food safety risk and it is not known if these hazards are a potential risk. It is also unclear if marine biotoxins are a food safety concern for seaweed or seaweed product consumption.

Table 22: Potential biological hazards in seaweed and seaweed products

Hazard	Products likely to be affected	Epidemiological evidence	Occurrence evidence
Bacteria			
Aeromonas spp.	Chilled or frozen seaweed, without a heat treatment step	No seaweed associated cases or outbreaks reported	Detected in fresh seaweed surveys
B. cereus	Not likely, unless product handling allows spores to germinate and vegetive cells to grow	No seaweed associated cases or outbreaks reported	Spored detected in dried and roasted seaweed product at low concentrations
C. perfringens	None, unless product handling allows spores to germinate and vegetive cells to grow	No seaweed associated cases or outbreaks reported	Not included in any seaweed surveys reviewed
Enteroaggregative *E. coli* (EAEC)	Chilled, frozen, or dried if contaminated after any heat treatment	Seaweed associated outbreak reported	Not included in any seaweed surveys reviewed
Shiga toxin-producing *E. coli (*STEC*)*	Chilled or frozen seaweed, without a heat treatment step or chilled, frozen, or dried if contaminated after any heat treatment	No seaweed associated cases or outbreaks reported	Detected in fresh seaweed surveys
L. monocytogenes	Chilled fresh or processed RTE	No seaweed associated cases or outbreaks reported	Included, but not detected in surveys of fresh seaweed
Salmonella enterica serovars	Chilled, frozen, or dried seaweed, if contaminated after any heat treatment	Seaweed associated outbreaks reported	Detected in fresh seaweed surveys
Shigella spp.	Chilled, frozen, or dried seaweed, if contaminated after any heat treatment	No seaweed associated cases or outbreaks reported	Not included in any seaweed surveys reviewed
S. aureus	None, unless product handling at unsafe temperatures allowing cell growth	No seaweed associated cases or outbreaks reported	Included in seaweed survey, but not detected in fresh seaweed
Vibrio spp.	Chilled or frozen seaweed, without a heat treatment step	No seaweed associated cases or outbreaks reported	Detected in fresh seaweed surveys

Hazard	Products likely to be affected	Epidemiological evidence	Occurrence evidence
Viruses			
Norovirus	Chilled or frozen seaweed, without a heat treatment step or chilled, frozen, or dried if contaminated after any heat treatment	Seaweed associated outbreaks reported	Not included in any seaweed surveys reviewed
Mould in dried seaweed product			
Food safety issues mainly associated with species of *Aspergillus, Fusarium* and *Penicillium*	Uncertain. Many mould species have a limited host range	No seaweed associated cases or outbreaks reported	No reports of specific mould species in seaweed. One report of mycotoxins in kelp but the finding is questionable
Marine biotoxins			
Various dinoflagellate and cyanobacterial toxins	Uncertain. Host specificity of organisms not investigated	No seaweed associated cases or outbreaks reported. Cyanobacterial toxins implicated in *Gracilaria* associated outbreaks, but association not confirmed	Except for finding of purported cyanobacterial toxins in *Gracilaria*, no toxins reported in seaweed. No surveys conducted

Aeromonas spp. can survive and grow in chilled foods and survive freezing, suggesting this hazard could be a food safety risk in chilled or frozen products. Infection by *Aeromonas* spp.is normally associated with more susceptible populations such as children or immunocompromised people.

L. monocytogenes can survive and grow in chilled foods and may survive freezing. It is not known if the spoilage shelf-life of chilled seaweed products (6 to 12 days) is short enough to restrict any increase in *L. monocytogenes* concentration to ensure the safety of the product. Unless the initial concentration of *L. monocytogenes* on the product is high, it is not envisaged that frozen products would present a high risk of illness, as no growth is predicted to occur. It is possible seaweed contaminated by *L. monocytogenes,* could have increasing counts during early drying, but it is not clear how long *L. monocytogenes* would survive or how quickly it would die during drying or storage.

Pathogenic *E. coli* and Salmonellae can survive in chilled and frozen foods and Salmonellae have the potential to survive for long periods of time in a desiccated state, on work surfaces and equipment, as well as in food (Finn *et al.*, 2013).

Some *V. parahaemolyticus* or *V. vulnificus* have been shown to survive chilling or freezing in sterile seawater or shellfish flesh. Psychrotrophic strains have been identified and were shown to be able to grow in broth containing 25% seawater at temperatures of 0°C or above (Morii and Sarukawa, 2000). *V. parahaemolyticus* or *V. vulnificus* are inactivated by cooking ($D_{65°C}$ < 1 minute), drying, or suspension in distilled water (Lee, 1972). *V. parahaemolyticus* or *V. vulnificus* could survive in fresh, chilled, or frozen seaweed products that do not include a wash, cook or blanch step sufficient to inactivate the *Vibrio* cells. *V. parahaemolyticus* or *V. vulnificus* require seawater temperatures above 13°C to grow in the harvesting area.

The low infectious dose for norovirus (10-100 virus particles) and the ability to survive freezing for extended periods of time, means norovirus is a potential hazard for any fresh, chilled or frozen product that does not have a cook step to inactivate the virus.

It is not known how long norovirus survives on dried seaweed products, but it survives up to 12 days on environmental surfaces. If an infected food handler contaminates the seaweed product after a thermal inactivation step, it is likely the norovirus will survive on the product. An example of this transmission route caused an outbreak in Japan (section 5.1.2).

10.8 EMERGING ISSUES

Vibrio spp. and the dinoflagellate *Gambierdiscus* spp. may become endemic in regions where they were not formerly seen, due to sea temperature warming.

If the popularity of seaweed consumption increases in New Zealand, there may be a need for public education around suitable serving sizes or frequency of consumption given the potentially high iodine concentrations in brown seaweed. Guidance is currently included in the MPI advice for safe eating for pregnancy[43].

In 2016, EFSA identified the following potential emerging health risks associated with the potential higher popularity and demand for edible seaweeds in Europe post 2016 (EFSA, 2017).

[43]https://www.mpi.govt.nz/food-safety-home/food-pregnancy/list-safe-food-pregnancy/ (accessed 26 May 2022)

(i) Increased risk of iodine toxicity.

(ii) High arsenic levels in foods.

(iii) Toxic effects from seaweed bioaccumulation of metals.

(iv) Norovirus contamination.

(v) Risks associated with opportunistic dinoflagellates producing toxins that can be isolated from edible seaweed and the epiphytic growth of filamentous cyanobacteria on edible seaweed.

10.9 DATA GAPS

The following data gaps have been established during this research project:

- Up to date information on consumption of seaweed products in New Zealand. Serving sizes of different seaweeds or seaweed products and frequency of consumption. This information underpins chemical or biological acceptable levels in consumer products.
- Information on processing methods used for different products, including time temperature profiles of blanching and cook steps.
- More information is needed on how chemical concentrations change during heating and drying processes.
- Information on how the seaweed matrix influences the growth, survival or inactivation of biological hazards under different temperature (chilling, freezing and cooking) and water activity conditions, specific to seaweed processing and storage.
- Information on how the structure of the fresh seaweed affects thermal inactivation/reduction times compared to results from inactivation studies using broth or other food matrices.
- Information on concentrations of chemical and biological hazards in processed seaweed products.
- Information on occurrence of mycotoxins and marine biotoxins in seaweed and seaweed products.
- Information from non-English language literature, given the high proportion of seaweed production and consumption in Asia.

These data gaps have impacted the ability of this report to inform the risk management questions listed in section 1.1. In particular, the shortage of occurrence data on microbial pathogens in seaweed and seaweed products makes it difficult to assess the potential risks and inform country-specific or product-specific risk management measures.

11 FUTURE SURVEY SCOPE RECOMMENDATIONS

11.1 OCCURRENCE OF HAZARDS

11.1.1 Chemical hazards

The current study has focussed on the elemental species, inorganic arsenic, cadmium, iodine, lead and mercury in seaweed and seaweed products. While other chemical contaminants have not been assessed at this time, the possibility of new knowledge identifying further contaminants of importance cannot be excluded.

Of the chemical hazards considered in the current study, iodine and inorganic arsenic are of the greatest concern. Adverse health effects have been observed due to consumption of seaweed-containing products and their associated iodine content. The adverse health effects due to chronic exposure to inorganic arsenic are well established and the consumption of certain seaweed species has the potential to add substantially to dietary exposure to this contaminant. High concentrations of other chemical contaminants (cadmium, lead and mercury) appear to be primarily due to harvesting of seaweed from polluted growing environments and is likely to be a more sporadic issue.

With regard to the potential value of a survey for iodine and inorganic arsenic in seaweed products:

- Iodine is an established health issue for brown seaweeds. Elevated iodine concentrations are confirmed in products being identified through monitoring of products imported into Australia and other countries as well as surveys described in the literature. There is no reason to expect seaweeds and seaweed products imported into New Zealand to be substantially different to those traded elsewhere and it is appropriate and relevant for New Zealand to use these data in assessing risks.
- Similarly, inorganic arsenic may be present in seaweed at elevated concentrations, as confirmed by surveys and import monitoring. Hijiki seaweed has been identified internationally as a seaweed type which can have elevated levels of inorganic arsenic.

However, seaweeds containing high concentrations of iodine or inorganic arsenic may be included as ingredients in processed foods and in such cases, it may be difficult to predict the levels of these chemicals in the processed products. Recommendations for a survey of chemical hazards include:

- Identification of processed foods containing brown seaweed or hijiki material and their analysis for iodine and inorganic arsenic.
- Given the relatively low marginal cost of additionally analysing samples for cadmium, lead and mercury, analysis of samples collected for these analytes, as an intelligence gathering exercise, is recommended if resources permit.

11.1.2 Biological hazards

The greatest concern for biological hazards is from fresh chilled seaweed. However, there is no chilled category in the imported foods data. The next greatest concern will be for frozen seaweed salads. *Aeromonas* spp., STEC, *Salmonella* spp., norovirus and *Vibrio* spp. are all able to survive freezing and have infectious doses that could be present at the point of freezing. All five of these pathogens have been detected in seaweed or seaweed products (Table 22) and *Salmonella* spp. and norovirus outbreaks have been associated with seaweed products.

Based on previous detection in seaweed or seaweed products or association with outbreaks and ability to survive drying - STEC, norovirus and *Salmonella* spp. should be considered for inclusion if sampling dried products which do not include a lethal cook step during processing.

It is not recommended to sample for *B. cereus*, *C. perfringens, Shigella* spp. and *S. aureus* While *B. cereus* spores have been detected in seaweed products, *B. cereus*, *C. perfringens* and *S. aureus* are unlikely to be a food safety issue, unless the raw product is held at temperatures suitable for significant growth of the organisms for sufficient time. *Shigella* spp. have not been included in surveys of fresh produce or associated with outbreaks.

Recommended survey of biological hazards would include:

- frozen seaweed salad for some or all of *Aeromonas* spp., STEC, *Salmonella* spp., norovirus and *Vibrio* spp; and
- dried (but uncooked) seaweed products for STEC, *Salmonella* spp., and norovirus.

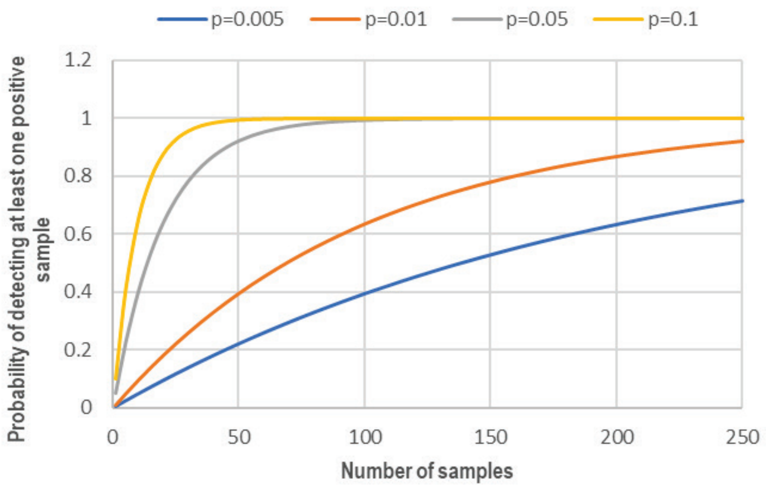
While marine biotoxins have been identified as potential hazards in seaweed and seaweed products (EFSA, 2019), they have not been detected to date. Given the complexity and cost of analysing for the range of potential marine biotoxins, it is not recommended that they be included in a survey at this stage.

11.1.3 Occurrence sampling considerations

Heavy metals, pathogenic microorganisms, marine biotoxins and mycotoxins could potentially occur in fresh seaweed products sporadically, due to contamination in the harvesting/farm area or due to contamination during processing from infected food handlers or the environment.

From the data collected in this review it would not be possible to estimate the likely prevalence of any of these hazards in seaweed and seaweed products for use in survey sample size calculations. Any sample size calculations for a survey would need to be based on the probability of detecting a positive sample given defined underlying proportions of positive samples. For example, Figure 3 gives the probability of detecting at least one positive sample for different combinations of sample size and true proportion positive (p).

Figure 3. Probability of detecting at least one positive sample given a true proportion positive (p) and sample size



It is recommended that any survey of heavy metal or biological hazard in seaweed and seaweed products be viewed as a snapshot, with a reasonable expectation that no hazards will be detected.

Analyses for marine biotoxins and mycotoxins are very specialised, with analytical methods usually focussed on a narrow range of toxins. Without any reliable intelligence to identify toxins likely to be present in seaweed and seaweed products, a survey of marine biotoxins and/or mycotoxins is unlikely to be cost-effective. There is also a strong probability that no toxins would be detected.

Current norovirus methodology would need to be validated for the seaweed matrix and it is likely cost will be a limiting factor for the inclusion of norovirus in a survey. There is currently no standard test for EAEC in food in New Zealand, however a test has been proposed by the EU Reference Lab.[44]

Any survey for specific hazards, should collect information on both the presence and concentration of the hazard in the product. For microorganisms, this should include the concentration of live organisms. This will allow the product hazard concentrations to be compared against dose response relationships or chemical limits to determine the possible risk to health.

Pacific Harvest do regular testing of the imported seaweed they package in New Zealand. They test for inorganic arsenic, cadmium, lead, mercury, tin, total bacterial counts, coliform bacteria, *E. coli*, *Salmonella*, *S. aureus*, moulds, and yeasts. This could be another source of survey data for sporadic hazards.

11.2 PROCESSING STEPS AND PHYSICAL PROPERTIES

Given the limited power of a survey to detect sporadically occurring hazards, an alternative approach is to improve understanding of the seaweed or seaweed product matrix and processing steps. This would help to evaluate the potential for hazards to be at a level to

[44] Public health risks associated with Enteroaggregative *Escherichia coli* (EAEC) as a food-borne pathogen | EFSA. Available at https://www.efsa.europa.eu/en/efsajournal/pub/4330 (Accessed 30 August 2022).

cause a risk to human health, in the product at the point of consumption or when being prepared with other RTE foods (cross-contamination potential).

This review has identified data gaps in terms of both the seaweed matrix and processing steps. Recommended surveys to fill these data gaps could include:

1. Survey of domestic processors and importing processors to better understand:
    a. Generic steps taken during processing
    b. Specific process parameters, such as: temperature of the seaweed during any cook step and the cook duration, blanching processes including temperatures and times; seaweed cleaning processes, drying temperature/humidity profiles. Preservatives used and when introduced.
2. Survey of physical properties of seaweed products available in New Zealand:
    a. Fresh, frozen, fermented, and dried (not cooked)
    b. pH, water activity, seasoning, packaging atmosphere, preservatives.

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APPENDIX A: INFORMATION RETRIEVAL

Part 1

A Boolean search string was constructed including keywords used to define the scope of the review. This string was then used in PubMed:

((Seaweed) AND (Food safety) AND ((food ingredients) OR (food additives) OR (heavy metals) OR (iodine) OR (microbiome) OR (foodborne disease) OR (pathogens) OR (virus) OR (food regulations) OR (mould) OR (fungi) OR (processing methods) OR (processing treatments) OR (human hazards) OR (adverse health effects) OR (human consumption) OR (nori) OR (zicai) OR (gim) OR (gamet) OR (laver) OR (Pyropia) OR (Porphyra) OR (wakame) OR (sea mustard) OR (undaria) OR (kombu) OR (konbu) OR (kelp) OR (saccharina) OR (sugar kelp) OR (agar-agar) OR (gracilaria) OR (gelidium) OR (sea grapes) OR (caulerpa) OR (dulse) OR (pulmaria plamata) OR (hijiki) OR (biotoxins))

This search resulted in 268 articles. Removal of articles not in English resulted in 256 articles.

The same search string was used in Web of Science and returned 48 results:

(with formatting changes as follows: "Seaweed" AND "Food safety" AND ("food ingredients" OR "food additives" OR "heavy metals" OR "iodine" OR "microbiome" OR "foodborne disease" OR "pathogens" OR "virus" OR "food regulations" OR "mould" OR "fungi" OR "processing methods" OR "processing treatments" OR "human hazards" OR "adverse health effects" OR "human consumption" OR "nori" OR "zicai" OR "gim" OR "gamet" OR "laver" OR "Pyropia" OR "Porphyra" OR "wakame" OR "sea mustard" OR "undaria" OR "kombu" OR "konbu" OR "kelp" OR "saccharina" OR "sugar kelp" OR "agar-agar" OR "gracilaria" OR "gelidium" OR "sea grapes" OR "caulerpa" OR "dulse" OR "pulmaria plamat" OR "hijiki" OR "biotoxins"))

The two lists of articles were combined, and duplicates were removed, resulting in 280 articles.

These 280 articles formed the basis of the literature search. As it was likely that the initial search missed important references, reference lists of papers were also checked for papers covering key topics. Such papers were included where appropriate.

Part 2

Part 2 searches predominantly involved grey literature sources and were heavily informed by information gathered from overseas regulatory agencies. Particular sources included:

Evaluations (human health effects):

Joint FAO/WHO Expert Committee on Food Additives (JECFA)
https://apps.who.int/food-additives-contaminants-jecfa-database/search.aspx

Border rejections, recalls, alerts:

European Rapid Alert System for Food and Feed (RASSF)
https://ec.europa.eu/food/food/rasff-food-and-feed-safety-alerts_en

USFDA recalls, market withdrawals and safety alerts system
https://www.fda.gov/industry/actions-enforcement/import-refusals

Australian border rejections
https://www.agriculture.gov.au/import/goods/food/inspection-compliance/failing-food-reports

Regulatory documents:

Codex standards
https://www.fao.org/fao-who-codexalimentarius/codex-texts/list-standards/en/

Code of Federal Regulation
https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=556

European Commission standards
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31990R2377

Australia and New Zealand standards
https://www.foodstandards.gov.au/code/Pages/default.aspx

APPENDIX B: NOTIFICATIONS, BORDER REJECTIONS AND RECALLS

Table B.1. New Zealand product recalls, 2019 to July 2022

Product	Issue	Origin	Date	Action
Baby puree powder containing kelp ingredient	Excess iodine	New Zealand	14/07/2022	Consumer recall
Kelp flakes	Excess iodine	New Zealand	21/01/2020	Trade recall
Wakame Salad	Undeclared allergen (soy)	China	13/10/2021	Consumer recall
		China	26/10/2021	Consumer recall
Prawn cracker snack with seaweed flavouring	Undeclared allergen (crustacea, soy and fish)	Thailand	23/06/2021	Consumer recall
Lupine tempeh containing seaweed	Undeclared allergen (soy)	New Zealand	04/02/2020	Trade recall

Table B.2. Failed seaweed products from testing at the Australian border and food recalls, July 2019 to December 2021

Product	Issue	Exporting Country	Date	Action
Dried kelp	Excess iodine	Republic of Korea	12/11/2021	Border rejection
			28/10/2021	Border rejection
			20/10/2021	Border rejection
			14/10/2021	Border rejection
			15/09/2021	Border rejection
			28/07/2021	Border rejection
			7/01/2021	Border rejection
			8/02/2019	Border rejection
		Chinese Taipei	7/02/2019	Border rejection
Dried kelp knots	Excess iodine	China	12/08/2019	Border rejection
Dried seaweed	Excess iodine	China	2/06/2021	Border rejection
			15/04/2021	Border rejection
			15/03/2021	Border rejection
			19/05/2020	Border rejection
		Japan	4/05/2021	Border rejection

Product	Issue	Exporting Country	Date	Action
			15/04/2021	Border rejection
			1/11/2019	Border rejection
			4/10/2019	Border rejection
		Republic of Korea	28/06/2021	Border rejection
			8/01/2021	Border rejection
		Viet Nam	29/06/2021	Border rejection
Dried seaweed slices	Excess iodine	China	2/04/2019	Border rejection
			6/02/2019	Border rejection
Dried seaweed strip	Excess iodine	China	15/04/2021	Border rejection
Kelp powder	Excess iodine	China	29/08/2019	Border rejection
		Republic of Korea	15/12/2020	Border rejection
			15/10/2020	Border rejection
Seaweed powder (Kelp)	Excess iodine	Japan	9/10/2020	Border rejection
Kelp knots	Excess iodine	China	17/06/2019	Border rejection
Kelp sheets	Excess iodine	China	17/06/2019	Border rejection
Kelp shreds	Excess iodine	China	7/02/2020	Border rejection
			12/08/2019	Border rejection
		Japan	3/11/2021	Border rejection
Kelp slices	Excess iodine	China	12/08/2019	Border rejection
Seaweed knot	Excess iodine	China	5/11/2020	Border rejection
Organic kelp flakes	Excess iodine	Republic of Korea	12/02/2020	Border rejection
			24/12/2019	Border rejection
Roasted kelp	Excess iodine	China	12/05/2020	Border rejection
Sea tangle (kelp)	Excess iodine	Republic of Korea	29/04/2020	Border rejection
Seasoned seaweed	Excess iodine	Japan	2/11/2021	Border rejection
			29/11/2019	Border rejection
			3/09/2019	Border rejection
Seaweed	Excess iodine	China	21/09/2021	Border rejection
			10/09/2020	Border rejection
			12/06/2020	Border rejection
Kelp	Excess iodine	China	3/08/2021	Border rejection

Product	Issue	Exporting Country	Date	Action
			4/06/2021	Border rejection
Frozen hijiki seaweed	Excess inorganic arsenic	Republic of Korea	26/10/2021	Border rejection
Hijiki seaweed	Excess inorganic arsenic	Republic of Korea	22/12/2020	Border rejection
Hijiki seaweed powder	Excess inorganic arsenic	China	19/05/2020	Border rejection
Seaweed flavoured crisp chips	Undeclared allergen (egg)	China	2/04/2021	Food recall

Table B.3. Notifications, border rejections and recalls of seaweed products relating to food safety issues other than labelling requirements; European Union (RASFF[1]), 2015 to 2019

Product	Issue	Origin[2]	Date	Action
Dried and roasted seaweed	Excess iodine	China	23/10/2018	Withdrawal
		Republic of Korea	3/12/2018	Withdrawal
Roasted seaweed	Unauthorised herbicide detected	China	26/02/2015	Border Rejection
Dried seaweed	Arsenic, lead and Iodine	Japan	11/08/2020	No action taken
	Excess iodine	China	10/09/2019	Relabelled
			17/05/2019	Destruction
			12/04/2019	None recorded
			12/02/2019	Consumer Recall
			11/09/2018	Withdrawal
			24/08/2018	Withdrawal
			23/03/2015	Consumer Recall
		Japan	17/09/2019	Relabelled
			27/07/2018	Withdrawal
			11/07/2018	Informed recipients
			11/06/2015	Withdrawal
		Republic of Korea	23/11/2020	alert
			20/05/2020	Withdrawal
			21/01/2019	Withdrawal
			17/01/2019	Informed recipients
			7/01/2019	Withdrawal
			31/08/2018	Public warning
			21/08/2018	Withdrawal

Product	Issue	Origin[2]	Date	Action
			6/07/2018	Consumer Recall
			15/12/2016	Consumer Recall
		Spain	4/06/2018	Consumer Recall
			25/08/2016	Withdrawal
Dried seaweed	Excess iodine and cadmium	Republic of Korea	19/01/2016	Withdrawal
			31/12/2015	Consumer Recall
Dried seaweed (cont)	*Salmonella* spp.	China	5/04/2018	Informed recipients
	Unauthorised ingredient	China	10/03/2015	Border Rejection
Frozen seaweed	Norovirus	China	22/08/2019	Public Warning
			13/08/2019	Informed recipients
Seaweed	Excess iodine	China	5/09/2019	Relabelled
			20/08/2019	Withdrawal
	Foreign bodies (Shells)	France	23/03/2018	Withdrawal
Seaweed noodles	Absence of health certificate	Thailand	11/05/2015	Destruction
Seaweed peanuts	Absence of health certificate	China	10/08/2016	Destruction
Seaweed salad	Excess iodine	Spain	19/07/2019	Withdrawal

Notes
1: European Rapid Alert System for Food and Feed (RASSF) https://ec.europa.eu/food/food/rasff-food-and-feed-safety-alerts_en
2: Origin refers to the source country of the seaweed before further processing or re-distribution.

Table B.4. Border refusals of seaweed products relating to food safety issues other than labelling requirements; USFDA, 2015 to 2021

Product	Issue	Exporting Country	Date	Action
Seaweed with sauce	*Listeria monocytogenes*	China	Aug and Sept 2017	Border refusal
	Insanitary or decomposed product	China	Apr 2016	Border refusal
Seaweed (leaf and stem vegetable)	Pesticide residue	Japan	Nov 2021	Border refusal
	Poisonous substance	Republic of Korea	Mar 2016	Border refusal
			Dec 2015	Border refusal
	Unsafe food additive	Chinese Taipei	Jan 2019	Border refusal
	Unsafe colourant	Republic of Korea	Jan 2020	Border refusal
			Mar 2016	Border refusal

Product	Issue	Exporting Country	Date	Action
		Denmark	Jan 2015	Border refusal
Seaweed snack	Unsafe colourant	China	May 2017	Border refusal
Seaweed (dried or paste)	Insanitary or decomposed product	Grenada	Dec 2021	Border refusal
		St Lucia	Feb 2021	Border refusal
		Republic of Korea	Jun 2021	Border refusal
		China	Oct 2014	Border refusal
	Pesticide residue	Mexico	Nov 2015	Border refusal

APPENDIX C: CHEMICAL HAZARD PROFILES

C.1 ARSENIC

Arsenate (As^{V}, pentavalent inorganic arsenic) is rapidly reduced to the more reactive arsenite (As^{III}, trivalent arsenic), mainly by the enzyme glutathione reductase (EFSA, 2009a). In mammals, arsenite undergoes oxidative methylation in the liver, catalysed by the enzyme arsenic-methyltransferase, to give methylarsonate (MMA^{V}). MMA^{V} is then reduced to MMA^{III} by the enzyme glutathione-S-tranferase ω1. Formation of MMA^{III} facilitates further oxidative methylation to give dimethylarsinate (DMA^{V}).

The main organic arsenic compound in foods, arsenobetaine, is not metabolised in humans and is excreted unchanged. Arsenosugars and arsenolipids appear to be completely metabolised to DMA^{V}, the same end product as inorganic arsenic (EFSA, 2009a).

In humans, arsenic is mainly excreted in urine, with a typical excretion profile made up of 10–30% iAs, 10–20% MMA^{V} and 60–70% DMA^{V} (EFSA, 2009a). However, the profile of arsenic metabolites excreted can vary considerably from person to person and this is believed to reflect variations in methylation efficiency. It has been suggested that methylation efficiency may be a risk factor for carcinogenesis, with higher proportions of MMA in urine associated with increased risk of lung and bladder cancers (Melak *et al.*, 2014).

While inorganic trivalent arsenic and trivalent arsenic compounds are generally considered to be more toxic than their pentavalent equivalents, the co-occurrence of both forms and their interconversion under a range of environmental and physiological conditions means they are generally considered collectively (EFSA, 2009a).

Laboratory animals appear to be substantially less susceptible to the toxic effects of iAs than humans and most information on the adverse health effects of arsenic exposure comes from human epidemiological investigations. These investigations have usually assessed arsenic exposure in terms of the concentration of arsenic in the water supply and, therefore, relate to iAs. Studies have focussed on five regions (south-west and north-east Taiwan, northern Chile, the Cordoba region of Argentina, Bangladesh and the West Bengal region of India) with particularly high water arsenic concentrations (IARC, 2012).

Rodent LD_{50} for arsenate and arsenite have been reported in the range 15 to 175 mg/kg bw (ATSDR, 2007b), while LD_{50} for the organic arsenic species monomethylarsonic acid (MMA), dimethylarsinic acid (DMA) and roxarsone[45] have been reported in the range 102 to 3184 mg As/kg bw (ATSDR, 2007b). Arsenobetaine (AB) and trimethylarsine oxide (TMAO) have been reported to be virtually non-toxic following acute administration, with LD_{50} greater than 10,000 mg/kg bw (JECFA, 2011b).

Inorganic arsenic (iAs) can be lethal to animals and humans. Inorganic arsenic is acutely toxic in humans and ingestion of large doses leads to gastrointestinal symptoms, disturbances of cardiovascular and central nervous system functions, multiorgan failure and eventually death. The minimum lethal dose of iAs in human is approximately 2 mg/kg bw (ATSDR, 2007b). However, acute arsenic poisoning is usually associated with accidental, suicidal, homicidal, or medicinal ingestion of arsenic-containing powders or solutions. No

[45] Roxarsone is an organoarsenic compound that may be added to poultry feed as a coccidiostat. Roxarsone has been voluntarily withdrawn from use in the USA and is not registered for use in the EU or New Zealand.

information has been reported on human deaths following ingestion of organic arsenic species (ATSDR, 2007b; EFSA, 2009a).

Subacute oral exposure to iAs is associated with gastrointestinal, haematological (such as hematopoietic and immune system changes) cardiovascular and respiratory effects, plus effects on the reproductive and nervous systems and dermal effects (such as skin lesions including hyperkeratinisation and hyperpigmentation of the skin) (ATSDR, 2007b). Chronic lung disease, peripheral neuropathy, hepatomegaly and peripheral vascular disease have frequently been reported in cases of chronic exposure to arsenic (IARC, 2012). In various epidemiological studies, peripheral vascular effects such as cyanosis, Raynaud's disease (episodes of ischaemia resulting from spasms in vessels, usually in the arteries of the fingers) and tissue necrosis on the extremities (Blackfoot disease) were described after long-term inhalation exposure to iAs (ATSDR, 2007b).

Inorganic arsenic compounds produce lung tumours in both animals and humans, following inhalation, oral or parenteral exposures. Exposure to high levels of iAs compounds in drinking water has been associated with skin, lung and urinary tract or bladder cancer in humans. Tumours at other sites including the adrenal glands and liver have also been reported in some animal studies (ATSDR, 2007b).

Skin lesions, including hyperpigmentation and hyperkeratosis, are sensitive indicators of chronic iAs arsenic exposure (EFSA, 2009a). Significant associations between skin alterations and risks of skin cancer have also been identified.

Effects on foetal development (increased risk of spontaneous abortion, stillbirth, preterm birth and neonatal death, birth defects, lower birth weight, lower head or chest circumference), child health and development (neurobehavioural deficits, central nervous system disorders), neurotoxicity (peripheral neuropathy, central nervous system toxicity), cardiovascular disease, and abnormal glucose metabolism and diabetes have all been associated with water iAs levels in regions with high water arsenic (>100 μg/L) (EFSA, 2009a). However, these associations have not been demonstrated in regions with lower water arsenic concentrations.

No human toxicity data are available for organoarsenic compounds.

Toxicological assessment

Five key toxicological assessments of arsenic have been carried out, with particular focus on iAs (ATSDR, 2007b; EFSA, 2009a; IARC, 2012; JECFA, 2011b; USEPA, 2010). It should be noted that the USEPA assessment is still in draft form and has not been summarised here. The previous assessment by USEPA established an RfD of 0.3 μg/kg bw per day based on hyperpigmentation of the skin (USEPA, 1991).

IARC

IARC concluded that there was:

- Sufficient evidence that iAs compounds cause cancer of the lung, urinary bladder and skin. A positive association was noted to have been observed between exposure to arsenic and iAs compounds and cancer of the kidney, liver, and prostate.
- Sufficient evidence in experimental animals for the carcinogenicity of iAs compounds.

Based on these conclusions, arsenic and iAs compounds were classified as Group 1 (carcinogenic to humans). DMA and MMA of pentavalent arsenic were classified as possibly carcinogenic to humans (Group 2B), while AB and other organic arsenic compounds are not metabolised in humans and are not classifiable as to their carcinogenicity to humans (Group 3).

EFSA

EFSA identified a range of values for the 95 % lower confidence limit of the benchmark dose of 1% extra risk ($BMDL_{01}$), instead of a single reference point, for use in the risk characterisation for iAs. The $BMDL_{01}$ values for the relevant health endpoints, skin lesions, cancers of the skin, urinary bladder and lung, ranged from 0.3 to 8 µg/kg bw per day. The estimated dietary exposures for European populations to iAs for average and high-level consumers were within the range of the $BMDL_{01}$ values identified, and therefore there was little or no margin of exposure (MOE), and the possibility of a risk to some consumers could not be excluded. Exposure estimates for potentially highly exposed population sub-groups (high consumers of rice or algae-based products) were also within the range of the $BMDL_{01}$ values identified.

EFSA noted that the available data on mean and median urinary arsenic in European populations, without specific high-level exposure to arsenic, are in the region of 5 to 6 µg/L. This concentration range is close to, or below, the concentrations in the reference populations in the epidemiological studies providing the basis for the $BMDL_{01}$ values. However, data on European sub-groups with high dietary iAs exposure were not available.

Because of the lack of data on the toxicity and food concentrations of arsenosugars, arsenolipids, MMA and DMA (pentavalent) it was not possible for the risks associated with exposure to these compounds to be characterised.

EFSA recommended that:

- Dietary exposure to iAs should be reduced.
- Speciation data for different food commodities should be produced to allow refinement of risk assessment.
- The suitability of arsenic speciation methods needs to be established for a range of food samples and/or arsenic species.
- There is a need for robust validated analytical methods for determining iAs in a range of food items.
- Certified reference materials, especially for iAs in products such as water, rice and seafood, are required.
- Future epidemiological studies should incorporate better characterisation of exposure to iAs, including food sources.
- There is a need for more information on critical age periods of arsenic exposure, in particular in early life. Studies should include effects later in life of early life arsenic exposure.
- There is a need for improved understanding of the human metabolism of organoarsenicals in foods (arsenosugars, arsenolipids, etc.) and the human health implications.

JECFA

JECFA based their risk characterisation on an iAs BMDL for a 0.5% increased incidence of lung cancer. The $BMDL_{0.5}$ was determined by using a range of assumptions to estimate exposure from drinking water and food with differing concentrations of iAs. The $BMDL_{0.5}$ was estimated to be 3.0 µg/kg bw per day (2.0–7.0 µg/kg bw per day based on the range of estimated total dietary exposure). It should be noted that this range is within the EFSA range of values for their $BMDL_{01}$. The JECFA Committee noted that the previously derived Provisional Tolerable Weekly Intake (PTWI) of 15 µg/kg bw (2.1 µg/kg bw per day) is in the region of the $BMDL_{0.5}$ and therefore was no longer appropriate and withdrew the previous PTWI.

Mean dietary exposure to iAs in the United States and various European and Asian countries was reported to be in the range 0.1 to 3.0 µg/kg bw per day. Drinking-water was a major contributor to iAs dietary exposures and, depending on the concentration, can also be an important source of arsenic in food through food preparation and possibly through irrigation of crops. The proportion of total exposure to iAs due to food consumption relative to the proportion from water intake increases as the concentration of iAs in the water decreases.

JECFA recommended that:

- There is a need for validated methods for selective extraction and determination of iAs in food matrices and for certified reference materials for iAs.
- There is a need for improved data on occurrence of different arsenic species in, and their bioavailability from, different foods as consumed in order to improve the estimates of dietary and systemic exposure.
- Further information on the toxicity of arsenic species found in food is also required.
- Future epidemiological studies of the health impacts of arsenic should incorporate appropriate measures of total exposure to iAs, including from food and from water used in cooking and processing of food.
- Epidemiological studies should not only focus on relative risks, but also analyse and report the data such that they are suitable for estimating exposure levels associated with additional (lifetime) risks, so as to make their results usable for quantitative risk assessment.

It is worth noting that there is a high level of agreement between the recommendations made by EFSA and JECFA.

Agency for Toxic Substances and Disease Registry (ATSDR)

ATSDR have derived estimates of exposure posing minimal risks to human (minimal risk level, MRL). An MRL is defined as an estimate of daily human exposure to a substance that is likely to be without an appreciable risk of adverse effects (non-carcinogenic) over a specified duration of exposure.

For iAs, ATSDR derived:

- an MRL of 5 μg/kg bw per day for acute-duration (14 days or less) oral exposure, based on human poisoning case studies;
- an MRL of 0.3 μg/kg bw per day for chronic-duration (365 days or more) oral exposure, based on a NOAEL for development of skin lesions in a Taiwanese study.

For organoarsenic compounds, ATSDR derived:

- an MRL of 100 μg/kg bw per day for intermediate-duration (15–364 days) oral exposure to MMA, based on a benchmark dose (BMD) for a 10% increase in the incidence of diarrhoea in animal studies;
- an MRL of 10 μg/kg bw per day for chronic-duration (365 days or longer) oral exposure to MMA, based on a BMD for a 10% increase in the incidence of progressive glomerulonephropathy in animal studies;
- an MRL of 20 μg/kg bw per day for chronic-duration (365 days or longer) oral exposure to DMA, based on a BMD for a 10% increase in the incidence of vacuolisation of the urothelium in the urinary bladder in animal studies.

No MRLs were derived for roxarsone, due to a lack of appropriate toxicological data.

Proposed mechanisms of carcinogenicity

Several modes of action have been proposed to explain the carcinogenicity of iAs (ATSDR, 2007b; EFSA, 2009a; JECFA, 2011b). It is likely that multiple mechanisms may be involved and that, at least, some of them may also have relevance for non-cancer endpoints. Proposed modes of action include:

- Oxidative stress, through the production of reactive oxygen species.
- Genotoxicity. While iAs is only weakly mutagenic, it appears to be capable of inducing DNA damage, such as strand break.
- Altered growth factors, leading the cellular proliferation and promotion of carcinogenesis.
- Modification of expression of genes involved in cell growth and defence (epigenetic mechanisms).
- Alteration of binding of nuclear transcription factors.

In vitro studies were considered with epidemiological evidence to elucidate the mode of action of arsenic with respect to bladder cancer (Gentry *et al.*, 2014). Studies in cell lines exhibited a transition in gene expression with increasing exposure to arsenic from an adaptive response to frank toxicity. At low arsenic doses changes in gene expression related to pre-inflammatory responses and delay of apoptosis (Gentry *et al.*, 2010). At intermediate arsenic doses gene expression changes were observed related to oxidative stress, proteotoxicity, inflammation, proliferative signalling and induction of apoptosis, while at high arsenic doses expression changes in genes associated with apoptosis dominate. This suggests that linear extrapolation from high to low doses may not be appropriate for bladder carcinogenicity due to arsenic and an effect threshold was proposed. It was also noted that this finding is consistent with meta-analyses that have failed to establish a relationship between water arsenic and bladder cancer at water arsenic concentrations below 100 μg/L (Mink *et al.*, 2008).

Carcinogenic potency of inorganic arsenic

The USEPA has derived several estimates of carcinogenic potency for arsenic over the last 30 years. The potency is usually expressed as the cancer slope factor or unit risk and is the slope of the low dose relationship derived between arsenic exposure and cancer incidence. The first of these was a cancer slope factor of 1.5 (mg/kg bw/day)$^{-1}$ for skin cancer, based on data from a Taiwanese study (USEPA, 2010). USEPA amended this cancer slope factor to 3.67 (mg/kg bw/day)$^{-1}$ in 2006 (USEPA, 2006). Subsequent assessments have focussed on internal cancers (lung and bladder) and the current draft USEPA assessment has proposed a cancer slope factor of 25.7 (mg/kg bw/day)$^{-1}$ for lung and bladder cancer combined (USEPA, 2010).

In an assessment of the global burden of disease from foodborne arsenic, cancer slope factors, also known as cancer potency factors or unit risk factors, were consolidated for the three main cancer types causally associated with arsenic exposure (Oberoi *et al.*, 2014). Slope factors are multiplied by estimates of exposure to give a probability of excess cancer; a larger slope factor indicates greater cancer potency. Slope factors are summarised in Table C.1.

Table C.1. Cancer slope factors for lung, bladder and skin cancers due to inorganic arsenic exposure

Cancer type	Slope factor (increased population risk per µg iAs/day)	
	Males	Females
Lung	0.0000137	0.0000194
Skin	0.000015	0.000015
Bladder	0.0000127	0.0000198

The slope or cancer potency factors are quite similar across the different cancer types. For comparison, assuming a 70 kg body weight, the USEPA cancer slope factor would equate to a value of 0.000367 (µg/day)$^{-1}$.

C.2 CADMIUM

Acute toxicity data for cadmium in humans are very scarce and there are no reliable human studies following acute-duration oral exposure. Acute exposure to high doses of cadmium in laboratory animals results in a variety of effects, including altered haematological parameters, focal necrosis and degeneration of the liver, focal necrosis in renal tubular epithelium, necrosis and ulceration in the stomach and intestines, decreased motor activity, and testicular atrophy and necrosis.

Cadmium is primarily toxic to the kidneys and bones after repeated exposure in animals and humans (EFSA, 2009c). Chronic exposure to cadmium by the oral or inhalation routes has produced proximal tubule cell damage, proteinuria, glycosuria, amino aciduria, polyuria, decreased absorption of phosphate, and enzymuria in humans and in a number of laboratory animal species. The clinical symptoms result from the degeneration and atrophy of the proximal tubules, or (in worse cases) interstitial fibrosis of the kidney. After prolonged and/or high exposure the tubular damage may progress to decreased glomerular filtration rate, and eventually to renal failure. Cadmium can also cause bone demineralisation, either through direct bone damage or indirectly as a result of renal dysfunction. In severe cases this may result in itai-itai disease[46], involving osteomalacia and osteoporosis (JECFA, 2011a).

IARC has classified cadmium as a human carcinogen (Group 1) on the basis of occupational studies (IARC, 2012). Newer data on human exposure to cadmium in the general population have been statistically associated with increased risk of cancers such as in the lung, endometrium, bladder, and breast.

Toxicological assessment

EFSA

EFSA considered cadmium in 2009 (EFSA, 2009c). The EFSA Panel did not consider the dose-response data for cancer as a sufficient basis for quantitative risk assessment and based their assessment on kidney effects. A meta-analysis was conducted on the relationship between urinary cadmium (a measure of cadmium body burden) and urinary β-2-microglobulin (B2M; a biomarker of renal tubular damage). A urinary reference point of 1 μg cadmium/g creatinine was derived, equating to a tolerable weekly intake (TWI) of 2.5 μg/kg bw per week. Creatinine enters urine at a fairly constant rate and is used to standardise biomarker measurements.

EFSA subsequently reviewed the approach and assumptions used in deriving the TWI and compared them to the approach and assumptions employed by JECFA (see below) (EFSA, 2011a; b). The JECFA health-based guidance values (HBGV) is more than twice the EFSA value, when considered in the same time frame.

EFSA noted that adult dietary cadmium exposure in Europe was close to or slightly exceeded the TWI and, for some population subgroups, could be two-fold higher than the TWI.

EFSA recommended that:

- More detailed food consumption information should be acquired to allow calculation of the impact of individual foods or food groupings on overall exposure to cadmium.
- There is a need for representative occurrence data in food commodities, including total diet studies to reduce the uncertainty in the exposure assessment. In addition, it would be valuable to establish exposure-based sampling procedures in the food monitoring and surveillance programmes to reduce uncertainties due to sampling adjustment factors.
- More data are required to evaluate the effects of cadmium on reproduction and development as well as the possible effect on cancer incidence (especially hormone-related cancers) and mortality.
- The vulnerability of diabetics and patients with kidney disease needs to be ascertained with regard to cadmium effects on kidney function.
- Collection of biomonitoring data from diverse European populations should be promoted.

[46] The disease was the name given to the mass cadmium poisoning of Toyama Prefecture, Japan, starting around 1912. The term "*itai-itai* disease" was coined by locals for the severe pains (Japanese: 痛い *itai*) victims felt in the spine and joints (https://en.wikipedia.org/wiki/Itai-itai_disease)

JECFA

JECFA published an addendum to their assessment of cadmium in 2011 (JECFA, 2011a). JECFA followed a similar approach to EFSA but concluded that for those aged 50 years or older (a point at which cadmium in the body would have achieved a steady state) there was no evidence of increased B2M urinary excretion at urinary cadmium concentrations less than 5.24 μg/g creatinine. This equates to a provisional tolerable monthly intake (PTMI) of 25 μg/kg bw per month.[47] The tolerable intake was defined on a monthly basis as daily variation in cadmium exposure was considered to have negligible impact on body burden.

All estimates of dietary exposure derived by JECFA were less than the PTMI.

IARC

In 2012, IARC reviewed their monograph on cadmium and cadmium compounds and concluded that:

"There is sufficient evidence in humans for the carcinogenicity of cadmium and cadmium compounds. Cadmium and cadmium compounds cause cancer of the lung. Also, positive associations have been observed between exposure to cadmium and cadmium compounds and cancer of the kidney and the prostate."(IARC, 2012).

The link between cadmium exposure and lung cancer is derived from studies of occupational cohorts, where exposure is largely by the respiratory route.

USEPA

The US EPA has established reference doses (RfD) in water and food of 0.005 and 0.001 mg/kg bw per day, based on a chronic intake that would result in a kidney concentration of 200 μg/g wet weight (USEPA, 1989).

Proposed mechanisms of toxicity

The molecular mechanisms by which cadmium exerts its toxicity have not been fully elucidated. However, it has been suggested that disruption of DNA repair mechanisms, generation of reactive oxygen species and associated oxidative stress and induction of apoptosis are important to cadmium toxicity (EFSA, 2009c; Rani *et al.*, 2014).

With respect to cadmium's renal toxicity, cadmium has been shown to down-regulate gene expression of ubiquitin-conjugating enzyme E2D (UBE2D) forms in human proximal tubular cells (Lee *et al.*, 2016). The decreased activity of these enzymes results in an increase in p53 tumour suppressor protein levels and induction of apoptosis in proximal tubular cells. Post-translational ubiquitination of proteins by UBE2D enzymes is also thought to play a role in DNA repair mechanisms and inhibition of these enzymes by cadmium may also play a role in disruption of DNA repair.

C.3 LEAD

The acute toxicity of lead is low (JECFA, 2011a). Ingestion of large amounts of lead can produce gastrointestinal symptoms, including colic, constipation, abdominal pain, anorexia and vomiting. Exposure to lead during pregnancy has been associated with toxic effects on the human foetus, including increased risk of preterm delivery, low birthweight, and impaired mental development, including decreased IQ scores. Human studies are inconclusive

[47] This equates to approximately 6 μg/kg bw/week, compared to the EFSA TWI of 2.5 μg/kg bw/week

regarding the association between lead exposure and other birth defects, while animal studies have shown a relationship between high lead exposure and birth defects (ATSDR, 2007a).

Studies of lead exposure in humans as well as laboratory animal studies have reported effects on the nervous system, cardiovascular effects, renal effects, immune system effects, haematologic effects, reproductive and developmental effects and cancer (EFSA, 2010a; JECFA, 2011a; USEPA, 2013).

Human studies are inconclusive regarding lead exposure and an increased cancer risk. Animal studies have reported kidney tumours in rats and mice exposed to lead via the oral route.

<u>Toxicological assessment</u>

The toxicity of lead has been assessed a number of times by various international organisations. Recent assessments by JECFA, EFSA, USEPA, ATSDR and IARC were reviewed.

JECFA

At their 30th meeting, JECFA established a provisional tolerable weekly intake (PTWI) of 25 µg/kg body weight for lead, for exposure of infants and children (JECFA, 1987). A PTWI is the amount of contaminant that can be ingested per week over a lifetime without adverse health effects. At JECFA's 41st meeting, this PTWI was extended to all age groups (JECFA, 1993).

JECFA reassessed lead most recently at their 73rd meeting (JECFA, 2011a). JECFA concluded that:

- exposure to lead is associated with a wide range of effects, including neurodevelopmental effects, mortality, impaired renal function, hypertension, impaired fertility and adverse pregnancy outcomes. Neurodevelopmental effects in children and effects on systolic blood pressure (SBP) were considered to provide an appropriate basis for dose-response analysis;
- due to neurodevelopmental effects, foetuses, infants and children are the most sensitive groups to the toxic effects of lead;
- the previously established PTWI of 25 µg/kg body weight was no longer considered to be health protective and was withdrawn;
- the dose-response analyses did not provide any indication of a threshold for the key toxicological effects of lead and no new PTWI could be established.

EFSA

EFSA's Panel on Contaminants in the Food Chain (CONTAM) considered lead in 2010 (EFSA, 2010a). EFSA concluded *inter alia* that:

- cereals, vegetables and tap water were the most important contributors to lead exposure in the general European population;
- neurodevelopmental toxicity in young children and cardiovascular and nephrotoxicity effects in adults form an appropriate basis for risk assessment;

- the (then) current PTWI of 25 µg/kg body weight was no longer appropriate and there was no evidence for a threshold for a number of critical toxicological endpoints, including neurodevelopmental and renal effects;
- based on a margin of exposure analysis, the possibility of effects in some consumers at current dietary exposure levels cannot be excluded.

USEPA

The USEPA considered the strength of evidence for a causal relationship between lead exposure and various adverse health endpoints and concluded there was sufficient evidence for a causal relationship in relation to (USEPA, 2013):

- cognitive function decrements in children;
- attention-related behavioural problems in children;
- hypertension;
- coronary heart disease;
- decreased red blood cell survival and function;
- altered haem synthesis;
- development;
- male reproductive function.

For a number of other endpoints, the relationship to lead exposure was classified as likely to be causal.

The USEPA assessment supported earlier conclusions that neurodevelopmental effects in children and cardiovascular effects in adults were of greatest public health concern, as the evidence suggests that these adverse effects occur at the lowest blood concentrations of lead (PbB).

The USEPA did not derive a reference dose for inorganic lead as the critical effects that occur as a result of exposure to lead (changes in levels of certain blood enzymes, elevation of blood pressure, and neurobehavioural deficits in children) occur at exposure levels (measured as blood lead) so low as to be essentially without a threshold. Therefore, the EPA's RfD Work Group considered it inappropriate to develop an RfD. The CDC identified 10 µg/dL as the blood lead level of concern in children in their 1991 report "Preventing Lead Poisoning in Young Children" and provided risk management options for categories of blood lead levels higher than 10 µg/dL (USEPA, 2004).

ATSDR

ATSDR produced a toxicological profile for lead in 2007 (ATSDR, 2007a). The document is extensive and does not contain a distinct summary. The following relevant points were made:

- The most sensitive targets for lead toxicity are the developing nervous system (children only), the haematological and cardiovascular systems, and the kidneys.
- Of major concern are the cognitive and neurobehavioural deficits in children exposed to lead.
- A clear threshold for some of the more sensitive effects of lead in humans has not been identified.

IARC

IARC considered the evidence for carcinogenicity of lead most recently in 2006 (IARC, 2006). IARC concluded that:

- there was sufficient evidence in experimental animals for the carcinogenicity of inorganic lead;
- there is limited evidence in humans for the carcinogenicity of inorganic lead;
- inorganic lead compounds are probably carcinogenic to humans.

A non-DNA reactive mode of action for the carcinogenicity of inorganic lead has been suggested, with lead inhibiting DNA repair mechanisms (JECFA, 2011a).

Proposed mechanisms of toxicity

Many of the toxic effects of lead are attributed to its high affinity for thiol (-SH) groups and other organic ligands in proteins (ATSDR, 2007a; EFSA, 2010a; JECFA, 2011a). The mechanisms presented below for particular toxicological endpoints are the currently supported dominant mechanisms. In each case other mechanisms have been proposed.

While lead can affect the nervous system by multiple mechanisms, it is believed that the neurotoxicity of lead is due to disruption of calcium homeostasis, through activation of protein kinase C enzymes (ATSDR, 2007a; EFSA, 2010a). It has been suggested that this may increase neuronal calcium levels, causing excessive calcium influx to mitochondria, resulting in free radical production and neuronal damage.

Oxidation stress (ATSDR, 2007a) and direct constrictive effects on vascular smooth muscle (EFSA, 2010a) have been proposed as mechanisms of lead-associated hypertension. Hypertension is associated with depletion of nitrous oxide, which plays an important role in regulating blood pressure.

Renal effects of lead toxicity involve the formation of intranuclear inclusion bodies in the renal proximal tubule. It has been proposed that formation of lead-protein complexes plays a role in formation of these bodies (ATSDR, 2007a; EFSA, 2010a). A further consistent feature of lead-induced renal toxicity is the occurrence of structural abnormalities in the mitochondria of the renal proximal tubules, which may be associated with lead-induced inhibition of calcium uptake.

Toxicological studies suggest that oxidative stress is a major contributor to the effects of lead on the male reproductive system (Salawu *et al.*, 2009; USEPA, 2013).

The concentrations of lead in the bones (tibia, patella) of people have been correlated with levels of DNA hypomethylation (Ray *et al.*, 2014). DNA hypomethylation is an epigenetic alteration that inhibits gene expression. However, any correlation between the level of DNA hypomethylation and adverse health outcomes still needs to be established.

C.4 MERCURY

Humans can be exposed to mercury in three different chemical forms: elemental, inorganic and organic. However, only the latter two forms are relevant to dietary exposure. The overwhelmingly predominant organic form of mercury present in foods is methylmercury.

Definitive data regarding the potential carcinogenicity of mercury and mercury compounds in humans are not available. In animal studies, there is limited and sufficient evidence of carcinogenicity for mercuric chloride and methylmercury (IARC, 1993). Dietary exposure to methylmercuric chloride in mice revealed increased incidence of renal adenomas, adenocarcinomas and carcinomas. The tumours were observed at a single site and in a single species and single sex. Based on the available animal data, IARC classified methylmercury as possibly carcinogenic to humans (Group 2B) (IARC, 1993).

Inorganic mercury

Human and animal studies indicate that approximately 10–30% of inorganic mercury is absorbed from the gastrointestinal tract (ATSDR, 1999), with most estimates in the range 10–15% (JECFA, 2011b). Studies in rats have suggested that monovalent mercury may be absorbed less well than divalent mercury, probably due to lower solubility (JECFA, 2011b).

The lethal dose of inorganic mercury following acute oral exposure has been estimated to be 29–50 mg/kg, with death attributed to renal failure, cardiovascular collapse and severe gastrointestinal damage (ATSDR, 1999).

The effects of chronic exposure depend, to a degree, on the form of inorganic mercury (mercury(I) or mercury(II)). In general, chronic inorganic mercury exposure is associated with a classic triad of signs, including tremor, neuropsychiatric disturbances and gingivostomatitis (JECFA, 2011b).

Central nervous system signs and symptoms include emotional lability (particularly irritability and excessive shyness), delirium, headache, memory loss, insomnia, anorexia and fatigue. Renal dysfunction is also prominent and can be manifested in forms ranging from asymptomatic proteinuria.

In children, a variety of neurological effects have also been reported following inorganic mercury intoxication, including developmental delay and regression, poor sleep, affective disturbance and self-directed aggression.

Organic mercury

Organic mercury is readily absorbed following oral exposure, with indirect evidence suggesting as much as 95% of methylmercury being absorbed. Selenium is known to reduce the toxicity of methylmercury through formation of a bismethylmercury selenide complex (ATSDR, 1999).

Evidence suggests that, following absorption, methylmercury is converted to inorganic mercury, specifically divalent mercury (ATSDR, 1999). However, this process may not be rapid, as mercury found in the brain has been ascribed to organic or elemental mercury, which can pass the blood-brain barrier, rather than inorganic mercury, which cannot (JECFA, 2011b).

The main adverse effect due to methylmercury exposure is neurodevelopmental deficits due to prenatal exposure to methylmercury, due to high levels of fish consumption by the mother (Davidson *et al.*, 1998; Debes *et al.*, 2006; JECFA, 2011b).

Toxicological assessment

Inorganic mercury

ATSDR

ATSDR derived an acute duration minimal risk level (MRL) for inorganic mercury by the oral route of exposure of 0.007 mg/kg bw/day (7 μg/kg bw/day), based on a NOAEL of 0.93 mg/kg bw/day for increases in relative and absolute kidney weights and increased incidence of renal tubular necrosis in a 14 day study in rats (ATSDR, 1999). Factors of ten, for extrapolation from animals to humans, and ten, for human variability, were applied.

ATSDR derived an intermediate duration MRL for inorganic mercury by the oral route of exposure of 0.002 mg/kg bw/day (2 μg/kg bw/day), based on a NOAEL of 0.23 mg/kg bw/day for increases in relative and absolute kidney weights and increased incidence of renal tubular necrosis in a 26 week study in rats (ATSDR, 1999). Factors of ten, for extrapolation from animals to humans, and ten, for human variability, were applied.

JECFA

JECFA derived a chronic Provisional Tolerable Weekly Intake (PTWI) of 0.004 mg/kg bw/day, based on the same 26-week rat study used by ATSDR (JECFA, 2011b). However, JECFA used dose-response modelling to derive a benchmark dose for a 10% increase in relative kidney weight of 0.06 mg/kg bw/day and applying a 100-fold uncertainty factor.

The PTWI for inorganic mercury was considered applicable to dietary exposure to total mercury from foods other than fish and shellfish.

Organic mercury

ATSDR

ATSDR derived a chronic duration MRL for methylmercury by the oral route of exposure of 0.0003 mg/kg bw/day (0.3 μg/kg bw/day), based on a NOAEL of 0.0013 mg/kg bw/day from a 66-month study of children in the Seychelles (ATSDR, 1999). Factors of three, for human pharmacodynamics and pharmacokinetic variability, and 1.5, for domain-specific findings, were applied.

JECFA

JECFA derived a PTWI for methylmercury of 0.0016 mg/kg bw/week based on neurodevelopmental effects in humans (JECFA, 2007). This equates to a daily exposure of 0.0002 mg/kg bw/day; very similar to the ATSDR MRL.

JECFA noted that life stages other than the embryo and foetus might be less sensitive to the adverse effects of methylmercury.

USEPA

The US EPA has established a reference dose (RfD) for methyl mercury (oral) of 0.0001 mg/kg bw per day based on neurodevelopmental effects on the foetus (USEPA, 2001). Maternal blood concentrations associated with no adverse effects were converted to dietary exposure equivalents.

C.5 IODINE

Iodine as an essential element

Iodine is necessary for normal growth and development because it is a component of essential thyroid hormones. Disorders arising from iodine deficiency include goitre, mental, nerve and muscular impairment, increased foetal and infant mortality, combined deaf mutism and impaired fertility. The most severe form of iodine deficiency is congenital hypothyroidism, previously known as cretinism (Deshpande, 2002; Expert Group on Vitamins and Minerals, 2003; Hetzel and Maberley, 1986).

New Zealand provides a naturally low-iodine environment. Goitre was endemic in many areas of New Zealand at the beginning of the 20th century but has virtually disappeared since the introduction of iodised salt. Iodised salt was first introduced in 1924, with an iodine level of 4 mg/kg. The iodine level was increased to the current level of 40–80 mg/kg in 1934. Iodine intakes were also increased by widespread use of iodine-containing sanitisers in the dairy industry. Fortification of bread with iodine has been mandatory since 2009.[48] Grain products now contribute 40-55% of dietary iodine intake by New Zealanders, with the exception of infants (Pearson *et al.*, 2018).

The physiological role of iodine

The only known physiological role of iodine is in the synthesis and action of the thyroid hormones; thyroxine 3,5,3',5'-tetraiodothyronine (T_4) and 3,5,3'-triiodothyronine (T_3). Iodine in the thyroid gland also occurs in the form of monoiodotyrosine (MIT), diiodotyrosine (DIT), thyroglobulin, polypeptides containing T_4, inorganic iodine, and probably other iodinated compounds (Hetzel and Maberley, 1986).

About 70–80% of the body's iodine is found in the thyroid gland, which effectively traps and stores iodine. The iodine content of the thyroid gland reflects iodine intakes. Iodine from the diet is rapidly absorbed from the gut. Intake in excess of requirement, estimated at 150 μg per day for adult men, is excreted by the kidneys. Urinary iodine, iodine intakes and thyroid iodine levels are well correlated.

The major role of iodine in nutrition arises from the importance of thyroid hormones in the growth and development of humans and animals. In the foetus, neonate and child, thyroid hormones have a major influence on cellular differentiation, growth and development (Hetzel and Maberley, 1986). Thyroid hormones also induce stimulation of oxygen consumption and basal metabolic rate in tissues.

Nutrient reference values for iodine

Nutrient reference values for Australia and New Zealand were published in 2006 (National Health and Medical Research Council, 2006). Reference values are expressed in terms of:

- EAR – Estimated average requirement, the daily nutrient intake level estimated to meet the requirements of half of the healthy individuals in a particular life stage and gender group.
- RDI – Recommended dietary intake, the average daily dietary intake level that is sufficient to meet the nutrient requirements of nearly all (97–98%) healthy individuals in a particular life stage and gender group.

48 https://www.mpi.govt.nz/food-business/bakery-and-grain-based-products/iodine-fortification/ Accessed 28 June 2022

- AI – Adequate intake, used when an RDI cannot be determined. The average daily nutrient intake level based on observed or experimentally determined approximations or estimates of nutrient intake by a group (or groups) of apparently healthy people, that are assumed to be adequate.
- UL – Upper level of intake, the highest average daily nutrient intake level likely to pose no adverse health effects to almost all individuals in the general population. As iodine intakes increase above the UL, the potential risk of adverse effects increases.

Nutrient reference values for various life stages are given in Table C.2.

Table C.2. Nutrient reference values for iodine by life-stage and gender in New Zealand (µg/day)

Group	Age	AI	EAR	RDI	UL
Infants	0 - 6 months 7 - 12 months	90 110	* *	* *	* *
Toddlers	1 - 3 years	-	65	90	200
Young children	4 – 8 years	-	65	90	300
Children	9 – 13 years	-	75	120	600
Adolescents	14 - 18 years	-	95	150	900
Adults	19+ years	-	100	150	1100
Pregnant women	14 - 18 years 19 – 50 years	- -	160 160	220 220	900 1100
Lactating women	14 - 18 years 19 – 50 years	- -	190 190	270 270	900 1100

Source From National Health and Medical Research Council (2006)

Symbols * Not possible to establish, - Not listed (AI only used when RDI cannot be determined)

<u>Iodine deficiency</u>

Iodine deficiency may result in endemic goitre, a swelling of the thyroid gland. Apart from goitre, a study has revealed that iodine deficiency is associated with a great variety of other effects on human growth and development (WHO, 2007). A summary of disorders associated with iodine deficiency is given in Table C.3. For convenience, the disorders have been described in relation to four different stages of the life cycle.

Cases of congenital hypothyroidism have never been reported in New Zealand and iodine deficiency in childhood typically results in goitre (Skeaff *et al.*, 2002). Iodine status of individuals may be assessed by measurement of median urinary iodine concentration (MUIC) (FSANZ, 2006). For school-age children a MUIC of <20 µg/L is indicative of severe iodine deficiency, 20–49 µg/L moderate iodine deficiency and 50-99 µg/L mild iodine deficiency (FSANZ, 2006).

Table C.3. Iodine deficiency disorders

Age group	Disorder
Foetus	Abortions Stillbirths Congenital anomalies Increased perinatal mortality Congenital iodine-deficiency syndrome
Neonate	Neonatal hypothyroidism Endemic mental retardation Increased susceptibility of the thyroid gland to nuclear radiation
Child and adolescent	Goitre (Subclinical) hypothyroidism (Subclinical) hyperthyroidism Impaired mental function Retarded physical development Increased susceptibility of the thyroid gland to nuclear radiation
Adult	Goitre and its complications Hypothyroidism Impaired mental function Spontaneous hypothyroidism in the elderly Iodine-induced hyperthyroidism Increased susceptibility of the thyroid gland to nuclear radiation

Source (WHO, 2007)

A study of 300 New Zealand children aged 8-10 years found a median MUIC of 66 µg/L, with 31.4% less than 50 µg/L (Skeaff *et al.*, 2002). Ultrasonography was used to measure the volume of the thyroid gland and it was assessed that 11–12% of children had enlarged thyroid glands. Cut-off values for thyroid volume have recently been revised and application of the new values to the study of Skeaff *et al*. (2002) would result in an estimate of approximately 30% of children having enlarged thyroid glands (Zimmerman *et al.*, 2004).

The 2002 National Children's Nutrition Survey included MUIC measurements of 1,793 New Zealand children, aged 5-14 years, with 25% of males and 31% of females having MUICs <50 µg/L (MoH, 2003). Skeaff *et al.* (2005) reported a median MUIC of 99 µg/L for 51 formula-fed infants, with 13.7% below 50 µg/L, while 43 breast-fed infants had median MUIC of 44 µg/L with 51.2% less than 50 µg/L.

Iodine toxicity

Humans are tolerant to high levels of iodine intake and have several biological mechanisms to protect against iodine toxicity. For this reason, most people can tolerate high doses of iodine without developing thyroid abnormalities. For normal persons who have not been conditioned to iodine deficiency, a Lowest Observable Adverse Effect Level of 1,700 µg/day of iodine has been identified (FNB, 2001).

Despite having tolerance to high levels of iodine, there have been reports of adverse symptoms resulting from both acute and chronic iodine toxicity. Acute iodine toxicity can lead to vomiting, diarrhoea, acid accumulation, seizure, iodide mumps, rashes and fever (Backer and Hollowell, 2000; Expert Group on Vitamins and Minerals, 2003). Chronic and sub-chronic toxicity may disrupt thyroid function, resulting in under activity of the thyroid (hypothyroidism) or excessive activity, known as hyperthyroidism or thyrotoxicosis (Expert Group on Vitamins and Minerals, 2003). There is also concern that iodine may induce autoimmune thyroid disease and thyroid cancer (Dunn, 1998; Koutras, 1996).

In Korea, “breastmilk-fed preterm infants often develop hypothyroidism because of excessive maternal iodine ingestion in the form of brown seaweed soup” (Chung *et al.*, 2009; Jin *et al.*, 2020). In 2011, Rhee *et al*. stated “A careful dietary history should be part of the evaluation and follow-up of postpartum Korean women and their infants, especially in the setting of signs and/or symptoms of thyroid dysfunction, thyroid autoimmunity, nodular thyroid anatomy, or pre-existing thyroid dysfunction. In addition, Korean women should consider refraining from seaweed soup consumption in the postpartum period if their infants are born before 37 weeks of gestational age” (Rhee, 2011).

However, in 2021 a case was reported of transient congenital hypothyroidism in a Dutch woman without Asian background (Vlaardingerbroek, 2021). The woman had consumed a bowl of wakame miso soup daily, hijiki or arame seaweed once a week and nori seaweed once a week during pregnancy and lactation. This case highlights that in families of non-Asian background, high maternal intake of iodine-rich seaweed can also occur and result in transient or permanent hyper-thyrotropinemia in the neonate with risk of impaired neurodevelopmental outcome if untreated.

APPENDIX D: OCCURRENCE OF CHEMICAL HAZARDS IN SEAWEED AND SEAWEED PRODUCTS

Unless otherwise stated the seaweed for which data are presented in Tables D.1 to D.5 were harvested from the wild or from aquaculture. In all cases, results are presented on a dry weight basis, either through samples being dried before analysis or through analytical results being corrected for the moisture content of the seaweed. Retail samples are mostly of dried seaweed. As drying does not affect elemental species, these results should be viewed as largely equivalent to results for harvested seaweed, when corrected for differences in moisture content.

Table D.1. Concentrations of arsenic in seaweed and seaweed products

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
New Zealand	**Wild seaweeds** *Ecklonia radiata* *Ulva stenophylla* *Durvillaea antarctica* *Hormosira banksii* *Porphyra spp.* *Undaria pinnatifida*	1 each	ICP-OES	 51.3 1.9 27.1 31.7 12.9 35.6		(Smith *et al.*, 2010)
New Zealand	**Commercial samples** Wakame (*Undaria pinnatifida*) *Macrocystis pyrifera* *Porphyra* spp. *Ecklonia radiata*	1 each	ICP-OES	 35 97 25.2 36	 0.30 0.82 4.7 4.2	(Smith *et al.*, 2010)
New Zealand	*Undaria pinnatifida*	114	ICP-AES	23.8 – 46.7 [2]		(Hau, 2012)
Australia	**Retail seaweed products** Wakame (dried) Kombu (dried) Hijiki (dried)	 4 4 1	ICP-MS	Inorganic arsenic 0.18 (0.16-0.20) 0.22 (0.16-0.33) **7.8**		(FSANZ, 2013)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
	Sargassum fusiforme (dried) Nori (dried) Other seaweed (dried) Seaweed-containing products	1 4 2 11		0.32 0.11 (0.09-0.16) 0.0 (<0.05-0.12) (<0.05-0.14)		
Australia (New South Wales)	Retail seaweed products (dried, shredded, roasted)	48	Not stated	39 (8.1-140)	1.5 (0.1-27)	(NSW Food Authority, 2010)
Bangladesh	*Hypnea musciformis* *Hypnea pannosa* *Jania rubens* *Gelidium pusillum* *Padina tetrastromatica* *Sargassum oligocystum* *Padina boryana* *Caulerpa racemose* *Enteromorpha intestinalis* *Ulva compressa*	16 each	Energy-dispersive X-ray fluorescence (EDXRF) spectroscopy (LOD: 0.02)	0.6 1.6 0.76 1.7 11.9 10.6 1.7 2.27 0.84 1.72		(Rakib *et al.*, 2021)
Brazil	*Canistrocarpus cervicornis* *Dictyopteris delicatula* *Ceratodyction variabilis* *Palisada* spp. *Zonaria tournefortii* *Gracilaria* spp. *Padina gymnospora* *Palisada perforata*	Not stated	ICP-OES (LOD: 5)	27.61 (16.56–49.52) 27.62 (23.45–32.89) 10.64 (5.73–17.35) 17.42 (13.67–21.66) 53.26 (38.11–66.48) 40.82 (30.36–55.34) 112.3 (101.2–117.9) 118.8 (107.9–136.4)		(Santos-Silva *et al.*, 2018)
Canada (product from British Columbia,	**Retail seaweed products** Bull kelp (*Nereocytis leutkeana*) Wakame *(Undaria pinnatifida)* Arame *(Eisenia bicyclis)*	1 each	ICP-MS (LOD: 0.5)	 79 55 31		(van Netten *et al.*, 2000)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
Japan, Norway)	Hijiki *(Hizikia fusiformis)* Asakusa-nori *(Porphyra tenera)* Makombu *(Laminaria japonica)* Asakusa-nori *(Porphyra tenera)* Wakame *(Undaria pinnatifida)* Bladderwrack *(Fucus vesiculosis)* Kelp tablets (Species not listed) Split Kelp *(Laminaria Setchellii)* Sugar kelp *(Laminaria saccharina)* Winged kelp *(Alaria marginate)* Giant kelp *(Macrocystis integrifolia)* Bull kelp *(Nereocytis leutkeana)*			88 29 29 29 20 20 17 58.5 76.2 39.5 53.1 66.3		
Chile	*Durvillaea antarctica* *Macrocystis pyrifera* *Lessonia nigrescens*	1 each	ICP-MS	47.75 40.75 16.92		(Caballero *et al.*, 2021)
China	*Sargassum fusiforme*	3	ICP-MS	28.2–64.2		(Zhu *et al.*, 2022)
Greece	*Cystoseira barbata* *Cystoseira compressa* *Padina pavonica* *Gracilaria* spp. *Gracilaria gracilis* *Hypnea musciformis* *Codium fragile* *Ulva intestinalis* *Ulva rigida* *Ulva fasciata*	9 each	ICP-MS (LOD: 0.01; LOQ: 0.04)	**55** 16.8 1.5 12.2 7.1 5.0 39 4.3 2.7 2.2	49 19 18 4.5 9.5 1.0 0.84 10	(Pell *et al.*, 2013)
Greenland	*Agarum clathratum* *Alaria esculenta* *Ascophyllum nodosum*	3 9 8	ICP- MS (LOD: 0.023; LOQ: 0.078)	46.1 33 29.8		(Kreissig *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
	Fucus distichus *Fucus* spp. *Fucus vesiculosus* *Hedophyllum nigripes* *Laminaria solidungula* *Palmaria palmata* *Saccharina latissima* *Saccharina longicruris*	8 7 16 5 6 2 11 2		40.1 26.6 33.3 63.1 47.6 6.93 45.2 61.9		
India	*Stoechospermum marginatum* *Padina tetrastromatica* *Sargassum wightii* *Dictyota dichotoma* *Gracilaria corticata* *Gracilaria verrucosa* *Acanthophora spicifera* *Caulerpa racemosa* *Ulva lactuca*	6 each	ICP-MS	2.24 (1.59 – 2.81) 4.63 (3.09 – 5.29) 6.46 (5.22 – 7.94) 1.37 (1.05 – 1.63) 0.65 (0.35 – 0.90) 1.19 (0.78 – 1.72) 0.36 (0.22 – 0.51) 0.62 (0.49 – 0.72) 0.25 (0.13 – 0.41)		(Arisekar *et al.*, 2021)
Italy	*Ulva rigida* *Gracolaria gracilis* *Grateloupia doryphora* *Porphyra leucosticta* *Fucus virsoides* *Undaria pinnatifida* *Cystoseira barbata*	1 each	GFAAS	7 (2 - 12) 15 (<1 – 32) 31 (2 – 56) 13 (<1 – 27) 70 (47 – 93) 40 (8 – 73) 242 (148 – 360)		(Caliceti *et al.*, 2002)
Italy	*Padina pavonica* *Cystoseira mediterranea*	54 each	ICP-OES (LOQ: 0.05)	<LOQ <LOQ		(Corrias *et al.*, 2020)
Italy	**Retail products** Brown seaweed *Himanthalia sp*	 8	ICP-MS (LOD: 0.002; LOQ: 0.005)	 4.6	 8.5	(Filippini *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
	Saccharina *Undaria* *Ascophyllum* *Laminaria* Red seaweed *Porphyra* *Palmaria* Green seaweed *Ulva*	15 10 1 1 13 9 5		5.2 6.7 11 **44** 10 0.70 0.62	16 20 0.8 17 13 13 19	
Italy (product from China, Japan, Republic of Korea, and Hong Kong)	*Laminaria japonica* *Porphyra yezoensis* *Undaria pinnatifida*	16 54 22	ICP-MS (LOQ: 0.01)	0.073 (0.05 – 0.092) 0.026 (0.012 – 0.37) 0.040 (0.015 – 0.068)		(Miedico *et al.*, 2017)
Republic of Korea	Sea Mustard (*Undaria pinnatifida*) Laver Green Laver Sea Tangle (*Laminaria digitata)*	1 each	ICP-AES	52 16 3.6 52	4.2 3.8 nd 5.5	(Cui *et al.*, 2013)
Republic of Korea	**Retail dried seaweed** Laver Brown seaweed Kelp Lettuce	125 153 102 46	ICP- OES (LOD: 0.021 µg/ml)	 13.0 (<LOD to 25.3) 18.5 (0.293–88.8) 23.3 (0.097–68.1) 12.5 (0.88–22.9)		(Hwang *et al.*, 2010)
Republic of Korea	**Retail seaweed** Laver (*Porphyra tenera)* Sea tangle (*Laminaria japonica*)	 53 45	ICP- OES (LOD: 0.00001; LOQ: 0.00004)	 2.07 3.04		(Khan *et al.*, 2015)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
	Sea mustard (*Undaria pinnatifida*) Hijiki (*Hizikia fusiforme*) Gulf weed (*Sargassum fulvellum*)	58 27 15		1.84 4.49 6.48		
Republic of Korea	*Pyropia yezoensis*	1	ICP-MS	33.40 (30.18 – 39.05) [3]		(Son *et al.*, 2014)
Malaysia	*Eucheuma cottoni*	3	ICP- OES (LOD: 0.004)	Inorganic arsenic 4.40		(Khandaker *et al.*, 2021)
Norway	*Laminaria hyperborea*	1	ICP-MS	56.3		(Noriega-Fernández *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
Norway	Irish moss *(Chondrus crispus)* Clawed fork weed *(Furcellaria lumbricalis)* Grape pip weed *(Mastocarpus stellatus)* Dulse *(Palmaria palmata)* Black laver *(Porphyra dioica)* Purple laver *(Porphyra purpurea)* Tough laver *(Porphyra umbilicalis)* Common green branched weed *(Cladophora rupestris)* Gut weed *(Ulva intestinalis)* Sea lettuce *(Ulva lactuca)* Wing kelp *(Alaria esculenta)* Egg wrack *(Ascophyllum nodosum)* Slimy whip weed *(Chordaria flagelliformis)* Serrated wrack *(Fucus serratus)* Spiral wrack *(Fucus spiralis)* Bladder wrack *(Fucus vesiculosus)* Sea oak *(Halidrys siliquosa)* Thong weed *(Himanthalia elongate)* Sea girdle *(Laminaria digitata)* Channel wrack *(Pelvetia canaliculate)* Sugar tang *(Saccharina latissimi)*	1 each	ICP-MS (LOQ: 0.01)	24 6.4 11 9.2 24 11 20 10 6.4 7.2 59 35 26 67 21 45 24 37 120 29 58	0.88 1.1 0.55 0.22 1.0 0.36 0.20 2.5 6.9 5.4 0.09 0.26 0.92 0.05 0.14 0.24 10 0.11 0.92 0.31 0.43	(Biancarosa *et al.*, 2018)
Norway	*Palmaria palmata* *Alaria esculenta* *Saccharina latissima*	12 each	ICP-MS	8.8 (7.19-12.0) 57 (38-97) 70 (52-99)		(Roleda *et al.*, 2019)
Norway	*Ulva fenestrata*	Not stated	ICP-MS	6.72 (n/a-11.4) [3]		(Roleda *et al.*, 2021)
Norway	Sugar kelp (cultivated and wild *Saccharina latissima*)	7	ICP-MS	50.5 (23.3 - 92.5)		(Sharma *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
Netherlands (product from China, Japan and Korea)	**Retail seaweed products** Hijiki seaweed (*Sargassum fusiforme*) Kombu seaweed (*Laminaria japonica*) Laminaria seaweed (*Laminaria* spp.) Nori seaweed (*Porphyra* spp.) Wakame seaweed (*Undaria pinnatifida*)	Not stated	ICP-MS (LOQ: 0.002–0.010 As species; (LOQ: 0.050 total As)	 **19** 6.3 5.5 1.4 4.4	 54 nd nd nd nd	(Brandon *et al.*, 2014)
Portugal	Flax brick weed (*Chaetomorpha linum)* Rooting green thread weed (*Rhizoclonium riparium)* Gut weed (*Ulva intestinalis)* Sea lettuce (*Ulva lactuca)* *Ulva prolifera*	1 each	ICP-MS	6.4 5.2 6.3 4.1 4.0		(Afonso *et al.*, 2018)
Spain (product from Spain, Chile, China, Republic of Korea and Japan)	**Retail seaweed products** **A) Edible seaweed** *Enteromorpha* spp. *Ulva pertusa* *Porphyra* spp. *Palmaria* spp. Sea lettuce flakes (*Palmaria palmata)* *Rhodymenia palmata* Carrageen *(Chondrus crispus)* *Laminaria* spp. Royal kombu *(Laminaria japonica)* Oarweed *(Laminaria digitata)* Arame *(Eisenia bicyclis)* Japanese kelp *(Undaria pinnatifida)* Hijiki *(Hizikia fusiforme)* Bladderwrack *(Fucus vesiculosus)* Seaweed spaghetti *(Himanthalia elongate)*	52 in total	AAS (LOD: 0.025 for tAs; LOD: 0.014 for iAs)	 2.2 3.2 29.5 (18.4 - 58.3) 13.0 12.6 8.2 14.4 44.0 110 65.7 20.9 (4.1 - 26.6) 40.1 (28.0 - 46.2) **110 (68.3 - 149)** 40.4 25.4	 16 8.3 0.78 3.5 4.7 1.8 4.2 0.3 0.8 0.4 2.1 1.2 67 0.7 0.07	(Almela *et al.*, 2006)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
	Rimurapa *(Durvillaea antartica)*			15.2	2.1	
	B) Foods (tofu, hamburger, instant soups, sesame snacks & biscuits, sauces etc) *Porphyra* spp. *H. fusiforme* *Laminaria* spp. *Himanthalia* spp. *Arame (Eisenia bicyclis)* *Japanese kelp (Undaria pinnatifida)* *Laminaria* spp. *Fucus* spp.	28 in total	AAS (LOD: 0.025 for tAs; LOD: 0.014 for iAs)	 0.26 1.19 (0.056 – 2.38) 0.16 (0.03 – 0.44) 8.6 0.90 1.2 (0.09 – 1.6) 0.42 50.3	 19 60 64 1.7 4.5 14 12 1.2	(Almela *et al.*, 2006)
Spain	Nori (*Porphyra umbilicalis*) Kombu (*Laminaria ochroleuca*) Wakame (*Undaria pinnatifida*) Sea lettuce (*Ulva rigida*)	Not stated	ICP-MS	23.5 53.4 46.5 5.3		(García-Sartal *et al.*, 2011)
Spain	Salmon maki (8% seaweed; type not specified) Tuna maki (5% seaweed; type not specified) Eel nigiri (1% seaweed; type not specified) Eel maki (5% seaweed; type not specified)	15 15 9 9	ICP-MS	0.024 (0.018 – 0.034) 0.025 (0.016 – 0.032) 0.025 (0.019 – 0.031) 0.023 (0.018 – 0.029)		(González *et al.*, 2021) [4]
United Kingdom	**Retail seaweed products** Hijiki Arame Kombu Nori	31	ICP-MS (LOD: 0.02 for total arsenic; LOD: 0.3 for inorganic arsenic)	 **109** 30 50 24	 71 nd nd nd	(Rose *et al.*, 2007)
United Kingdom	*Fucus serratus* *Fucus vesiculosus* *Solieria chordalis* *Enteromorpha intestinalis*	3-4	ICP-MS	1.57 (1.15 - 2.36) [3] 1.5 (1.12 - 1.9) 0.28 (0.14 - 0.42) 0.37 (0.22 - 0.64)		(Pawlik-Skowrońska *et al.*, 2007)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
	Rhizoclonium tortuosum			3.89		
	Gracilaria gracilis			0.32		
United Kingdom	*Colpomenia marina*	1	ICP-MS	16.1	0.31	(Taylor and Jackson, 2016)
	Ascophyllum nodosum	3		23.1	0.35	
	Ascophyllum nodosum	4		23.7	0.25	
	Fucus spiralis	2		16.3	0.25	
	Fucus vesiculosus	2		29.0	0.21	
	Fucus vesiculosus	2		32.8	nd	
	Agarum clathratum	1		61.8	nd	
	Alaria esculenta	4		34.5	0.09	
	Laminaria digitata	1		107	nd	
	Laminaria digitata	5		**50.4**	16.5	
	Laminaria longicruris	3		74.1	0.16	
	Saccharina latissima	1		56.3	nd	
	Porphyra umbilicalus	1		20.7	0.58	
	Heterosiphonia japonica	1		8.2	5.7	
	Polyiphonia lanosa	1		14.0	1.9	
	Chondrus crispus	2		12.1	0.58	
	Chondrus crispus	1		6.1	0.98	
	Phyllophora pseudoceranoides	1		4.2	3.4	
	Gracliaria vermiculophylla	1		11.8	2.0	
	Palmaria palmata	4		9.0	0.67	
	Chaetomorpha picquotiana	1		6.7	1.4	
	Gayralia oxysperma	1		12.7	1.3	
	Ulva lactuca	1		5.3	2.4	
	Ulva lactuca	1		4.1	0.48	
	Ulva prolifera	1		14.7	0.82	

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg)	Total arsenic unless otherwise stated, mean (range), mg/kg dry weight unless otherwise stated [1]	Percent inorganic arsenic (%)	Reference
United States	**Retail seaweed samples**		ICP-MS			(Todorov *et al.*, 2022)
	Arame (unable to genetically type)	2		37.5		
	Hijiki (unable to genetically type)	3		93.2		
	Kombu (*Saccharina* spp.)	6		67.4		
	Knotted wrack (*Ascophyllum nodosum, Silvetia babingtonii*)	2		47.1		
	Oarweed (*Laminaria digitata*)	2		73.0		
	Wakame, leaves (*Undaria pinnatifida*)	9		44.1		
	Wakame, stems (*Undaria pinnatifida*)	3		20.4		
	Dulse (*Palmaria palmata*)	4		14.8		
	Irish moss (*Chondrus crispus*)	2		10.4		
	Sea moss (*Chondrus crispus, Kappaphycus alvarezii*)	1		3.1		
	Nori (*Pyropia yezoenis*)	8		17.3		
	Laver (*Porphyra umbilicalis, Pyropia haitanensis*)	2		45.6		
	Sea Lettuce (*Ulva* spp.)	2		9.0		

Notes:
1 Bolded figures would exceed the Australia New Zealand maximum limit (1 mg/kg on a fresh weight basis or 6.7 mg/kg on a dry weight basis)
2 Range of monthly means
3 Mean concentrations in samples/finished products from different locations/processing facilities.
4 Concentration on wet weight basis

Abbreviations:
AAS: Atomic absorption spectroscopy, CV-AAS: Cold Vapor Atomic Absorption Spectroscopy, CV-AFS: Cold vapour atomic fluorescence spectroscopy, EDXRF: Energy-dispersive X-ray fluorescence spectroscopy, ENAA: epithermal neutron activation analysis, GC-ECD: Gas Chromatography – Electron Capture Detector, GFAAS: Graphite furnace atomic absorption spectrometry, HPLC: High Performance Liquid Chromatography, ICP-MS: Inductively coupled plasma mass spectrometry, ICP-OES: Inductively coupled plasma - optical emission spectrometry, LOD: Limit of Detection, LOQ: Limit of Quantification, nd: not detected

Table D.2. Concentrations of cadmium in seaweed and seaweed products

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
New Zealand	*Undaria pinnatifida*	114	ICP-AES	1.51 – 2.33 [2]	(Hau, 2012)
Brazil	*Cottonii (K.alvarezii)* Semi Refined Carrageenan product	Not stated	AAS	 1.0	(Dewi and Darmanto, 2012)
Brazil	*Canistrocarpus cervicornis* *Dictyopteris delicatula* *Ceratodyction variabilis* *Palisada* spp. *Zonaria tournefortii* *Gracilaria* spp. *Padina gymnospora* *Palisada perforata*	Not stated	ICP-OES (LOD: 0.04)	0.15 (< 0.04–0.29) 0.18 (< 0.04–0.23) <LOD <LOD 1 (0.95–1.04) 0.17 (0.15–0.18) 0.27 (< 0.04–1.08) 0.25 (0.23–0.26)	(Santos-Silva *et al.*, 2018)
Canada (product from British Columbia, Japan, Norway)	**Retail seaweed products** Bull kelp (*Nereocytis leutkeana*) Wakame *(Undaria pinnatifida)* Arame *(Eisenia bicyclis)* Hijiki *(Hizikia fusiformis)* Asakusa-nori *(Porphyra tenera)* Makombu *(Laminaria japonica)* Asakusa-nori *(Porphyra tenera)* Wakame *(Undaria pinnatifida*) Bladderwrack *(Fucus vesiculosis)* *Kelp tablets* (Species not listed) Split Kelp *(Laminaria Setchellii)* Sugar kelp *(Laminaria saccharina*) Winged kelp *(Alaria marginate*) Giant kelp (*Macrocystis integrifolia)* Bull kelp (*Nereocytis leutkeana*)	1 each	ICP-MS (LOD: 0.01)	 2.76 0.71 0.57 0.32 0.27 0.02 0.83 0.51 0.34 0.13 0.10 2.80 0.45 0.90 0.30	(van Netten *et al.*, 2000)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Canary Islands, Spain (China, Thailand)	**Retail seaweed products** Wakame (*Undaria pinnatifida*) Wakame algae salad (*Undaria pinnatifida*)	 10 10	ICP – OES (LOQ: 0.001 mg/L)	 1.11 0.06	(Paz *et al.*, 2019)
Canary Islands, Spain (Spain)	Wakame (*Undaria pinnatifida*) Sea spaghetti (*Himanthalia elongata*) Kombu (*Laminaria ochroleuca*) Seaweed	15 15 15 8		0.04 0.11 0.08 0.12	
Chile	*Durvillaea antarctica* *Macrocystis pyrifera* *Lessonia nigrescens*	1 each	ICP-MS	6.15 3.97 6.0	(Caballero *et al.*, 2021)
China	*Sargassum fusiforme*	3	ICP-MS	0.31–0.80	(Zhu *et al.*, 2022)
Egypt	*Ulva linza* *Ulva fasciata* *Colpomenia sinuosa* *Sargassum vulgare* *Amphiroa rigida* *Corollina officinalis* *Pterocladia capillacea* *Jania rubens*	Not stated	AAS	0.12 1.67 (0.12-8.15) [3] 2.28 (0.26 – 4.31) [3] 3.15 0.124 1.00 3.42 (1.70-5.14) [3] 1.80	(Salem *et al.*, 2019)
Greenland	*Agarum clathratum* *Alaria esculenta* *Ascophyllum nodosum* *Fucus distichus* *Fucus* spp. *Fucus vesiculosus* *Hedophyllum nigripes* *Laminaria solidungula* *Palmaria palmata* *Saccharina latissima*	3 9 8 8 7 16 5 6 2 11	ICP-MS (LOQ: 0.0022; LOD: 0.0007)	0.208 1.32 0.293 0.952 0.826 1.42 0.168 0.134 0.600 2.96	(Kreissig *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Saccharina longicruris	2		1.25	
India	*Amphiroa* spp. *Gracilaria edulis* *Gracilaria folifera* *Halymenia* spp. *Hypnea musciformis* Chnoospora minima *Sargassum polycystum* *Sargassum wightii* *Spatoglossum asperum* *Stoechospermum marginatum*	4 each	AAS	0.59 0.79 0.63 4.14 0.46 0.23 0.38 0.42 0.51 0.51	(Anbazhagan *et al.*, 2021)
India	*Stoechospermum marginatum* *Padina tetrastromatica* *Sargassum wightii* *Dictyota dichotoma* *Gracilaria corticata* *Gracilaria verrucosa* *Acanthophora spicifera* *Caulerpa racemosa* *Ulva lactuca*	6 each	ICP-MS	0.14 (0.04 – 0.24) 0.47 (0.40 – 0.56) 0.17 (0.06 – 0.32) 0.19 (0.12 – 0.31) 0.16 (0.07 – 0.29) 0.26 (0.09 – 0.53) 0.16 (0.08 – 0.31) 0.11 (0.02 – 0.26) 0.07 (0.01 – 0.12)	(Arisekar *et al.*, 2021)
India	*Sargassum whitti* *Turbinaria conoides* *Hypnea musciformis* *Gracilaria edulis* *Gracilaria verrucosa* *Gracilaria corticata* *Sarconema filiforme* *Kappaphycus alverizii*	5 each	AAS	7.67 1.92 5.59 4.56 2.66 2.39 4.70 5.68	(Arulkumar *et al.*, 2019)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Acanthophora muscoides *Ulva lactuca* *Ulva reticulata* *Caulerpa scalpelliformis* *Chaetomorpha linum*			1.85 0.87 8.62 3.54 8.51	
India	*Ulva compressa* *Ulva fasciata*	4 each	GFAAS	nd nd	(Hyderali and Eswaran, 2019)
India	*Caulerpa taxifolia* *Caulerpa racemosa* *Caulerpa scalpelliformis* *Chaetomorpha linum* *Ulva lactuca* *Halimeda macroloba* *Halimeda tuna* *Valoniopsis pachynema* *Ulva compressa* *Codium fragile*	4 each	AAS	0.58 (0.44 – 0.80) 2.88 (0.90 – 1.30) 0.96 (0.32 – 1.63) 0.66 (0.23 – 0.57) 0.24 (0.05 – 0.42) 0.33 (0.11 – 0.49) 0.49 (0.34 – 0.55) 0.57 (0.28 – 0.74) 0.71 (0.61 – 0.81) 1.1 (0.64- 2.31))	(Rajaram *et al.*, 2020)
India	*Ulva reticulata*	1	ICP-MS (LOD: 0.1)	<LOD	(Gomathi and Sheba, 2018)
Indonesia	*Eucheuma cottonii*	2	ICP-OES	0.14	(Aras, 2020)
Italy	*Ulva rigida* *Gracolaria gracilis* *Grateloupia doryphora* *Porphyra leucosticta* *Fucus virsoides* *Undaria pinnatifida* *Cystoseira barbata*	1 each	GFAAS	0.2 (<0.1 – 0.7) 0.4 (0.1 - 0.6 0.2 (<0.1 – 0.3) 0.1 (<0.1 - 0.2) 0.1 (<0.1 – 0.1) 0.6 (0.4 – 0.8) 0.1 (<0.1 – 0.2)	(Caliceti *et al.*, 2002)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Italy	*Padina pavonica* *Cystoseira mediterranea*	54 each	ICP-OES (LOQ: 0.05)	0.033 (0.01 – 0.07) 0.06 (0.02 – 0.08)	(Corrias *et al.*, 2020)
Italy	**Retail seaweed products** Brown seaweed *Himanthalia* spp. *Saccharina* spp. *Undaria* spp. *Ascophyllum* spp. *Laminaria* spp. Red seaweed *Porphyra* spp. *Palmaria* spp. Green seaweed *Ulva* spp.	 8 15 10 1 1 13 9 5	ICP-MS (LOD: 0.002) (LOQ: 0.005)	 0.07 0.04 0.16 0.03 0.21 1.56 0.02 0.02	(Filippini *et al.*, 2021)
Italy (product from China, Japan, Republic of Korea and Hong Kong)	**Retail seaweed products** *Laminaria japonica* *Porphyra yezoensis* *Undaria pinnatifida*	 16 54 22	ICP-MS (LOQ: 0.0012)	 0.54 (0.234 – 1.22) 2.85 (0.254 – 6.80) 3.67 (0.90 – 7.33)	(Miedico *et al.*, 2017)
Republic of Korea	**Retail seaweed products** Laver Brown seaweed Kelp Sea lettuce	 125 153 102 46	ICP- OES (LOD: 0.001 µg/ml)	 0.60 (<LOD to 2.421) 0.50 (<LOD to 2.468) 0.30 (<LOD to 1.040) 0.71 (<LOD to 2.931)	(Hwang *et al.*, 2010)
Republic of Korea	**Retail seaweed products** Laver (*Porphyra tenera)* Sea tangle (*Laminaria japonica*) Sea mustard (*Undaria pinnatifida*)	 53 45 58	ICP- OES (LOD: 0.021 ppb; LOQ: 0.070 ppb)	 0.109 0.038 0.072	(Khan *et al.*, 2015)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Hijiki (*Hizikia fusiforme*) Gulf weed (*Sargassum fulvellum*)	27 15		0.119 0.114	
Republic of Korea	*Pyropia yezoensis*	1	ICP-MS	0.007 (0.005 – 0.009) [3]	(Son *et al.*, 2014)
Libya	*Sargassum vulgar* *Pterocladia capillacea*	1 each	AAS	7.5 10.0	(Awheda *et al.*, 2015)
Malaysia	*Eucheuma cottoni*	3	ICP- OES (LOD: 0.00215)	1.63	(Khandaker *et al.*, 2021)
Norway	Irish moss *(Chondrus crispus)* Clawed fork weed *(Furcellaria lumbricalis)* Grape pip weed *(Mastocarpus stellatus)* Dulse *(Palmaria palmata)* Black laver *(Porphyra dioica)* Purple laver *(Porphyra purpurea)* Tough laver *(Porphyra umbilicalis)* *Cladophora rupestris* Gut weed *(Ulva intestinalis)* Sea lettuce *(Ulva lactuca)* Wing kelp *(Alaria esculenta)* Egg wrack *(Ascophyllum nodosum)* Slimy whip weed *(Chordaria flagelliformis)* *Serrated wrack (Fucus serratus)* Spiral wrack *(Fucus spiralis)* Bladder wrack *(Fucus vesiculosus)* Sea oak *(Halidrys siliquosa)* Thong weed *(Himanthalia elongate)* Sea girdle *(Laminaria digitata)* Channel wrack *(Pelvetia canaliculate)* Sugar tang *(Saccharina latissimi)*	1 each	ICP-MS	0.28 0.07 0.2 0.37 0.32 0.17 3.1 0.16 0.18 0.12 2.5 0.32 2.6 1.2 0.45 0.86 0.28 0.56 0.033 0.30 0.59	(Biancarosa *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Norway	*Laminaria hyperborea*	1	ICP-MS	0.6	(Noriega-Fernández *et al.*, 2021)
Norway	*Palmaria palmata* *Alaria esculenta* *Saccharina latissima*	12 each	ICP-MS	0.82 (0.024-2.457) 1.58 (0.601-2.622) 0.60 (0.209-0.989)	(Roleda *et al.*, 2019)
Norway	*Ulva fenestrata*	Not stated	ICP-MS	0.155 (n/a-0.26) [3]	(Roleda *et al.*, 2021)
Portugal	Flax brick weed (*Chaetomorpha linum)* Rooting green thread weed (*Rhizoclonium riparium)* Gut weed (*Ulva intestinalis)* Sea lettuce (*Ulva lactuca)* *Ulva prolifera*	1 each	ICP-MS	0.02 0.43 0.06 0.14 0.06	(Afonso *et al.*, 2018)
Spain (product from Spain, Chile, China, Republic of Korea and Japan,)	**Retail seaweed products** **A) Edible seaweed** *Enteromorpha* spp. *Ulva pertusa* *Porphyra* spp. *Palmaria* spp. Sea lettuce flakes (*Palmaria palmata)* *Rhodymenia palmata* Carrageen *(Chondrus crispus)* *Laminaria* spp. Royal kombu *(Laminaria japonica)* Oarweed *(Laminaria digitata)* Arame *(Eisenia bicyclis)* Japanese kelp *(Undaria pinnatifida)* Hijiki *(Hizikia fusiforme)* Bladderwrack *(Fucus vesiculosus)* Seaweed spaghetti *(Himanthalia elongate)* Rimurapa *(Durvillaea antartica)*	52 in total	GFAAS (LOD: 0.003)	 0.02 0.19 0.88 (0.089 - 3.19) 0.14 0.87 0.13 (0.079 - 0.181) 0.57 (0.722 - 0.18) 0.356 (0.327 - 0.385) 0.491 (0.908 - 0.074) 0.343 0.522 (0.383 - 0.571) 1.20 (0.227 - 2.15) 1.03 (0.511 - 1.53) 0.412 0.33 (0.222 - 0.395) 2.46	(Almela *et al.*, 2006)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Spain (product from Spain, Chile, China, Republic of Korea and Japan,)	**B) Foods (tofu, hamburger, instant soups, sesame snacks & biscuits, sauces etc)** *Porphyra* spp. *Hizikia fusiforme* *Laminaria* spp. *Himanthalia* spp. *Arame (Eisenia bicyclis)* *Japanese kelp (Undaria pinnatifida)* *Laminaria* spp. *Fucus* spp.	28 in total	GFAAS (LOD: 0.003)	 0.105 (0.02 - 0.19) 0.038 (0.025 - 0.049) 0.035 (0.02 - 0.059) 0.286 (0.035 - 0.537) 0.027 0.0412 (<LOD - 0.118) 0.03 0.505	(Almela *et al.*, 2006)
Spain	Salmon maki (8% seaweed; type not specified) Tuna maki (5% seaweed; type not specified) Eel nigiri (1% seaweed; type not specified) Eel maki (5% seaweed; type not specified)	15 15 9 9	AAS (LOD: 0.1)	nd nd nd nd	(González *et al.*, 2021) [4]
Spain	**Retail dried seweed products** *Chondrus* spp. *Eisenia* spp. *Gelidium* spp. *Palmaria* spp. *Porphyra* spp. *Himanthalia* spp. *Laminaria* spp. *Undaria* spp.	 3 6 2 4 10 6 6 4	ICP-OES (LOD: 0.0003 mg/L; LOQ: 0.001 mg/L)	 0.29 0.19 0.008 0.16 0.58 0.82 0.07 0.06	(Rubio *et al.*, 2017)
UK	*Fucus serratus* *Fucus vesiculosus* *Solieria chordalis* *Enteromorpha intestinalis* *Rhizoclonium tortuosum*	3-4 each	ICP-MS	0.013 (0.008 – 0.016) [3] 0.012 (0.005 – 0.007) [3] 0.015 (0.001 – 0.002) [3] 0.005 (0.003 – 0.007) [3] 0.006	(Pawlik-Skowrońska *et al.*, 2007)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Cadmium concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Gracilaria gracilis			0.011	
United States	**Retail seaweed products**		ICP-MS (LOQ: 0.02)		(Todorov *et al.*, 2022)
	Arame (unable to genetically type)	2		1.01	
	Hijiki (unable to genetically type)	3		1.53	
	Kombu (*saccharina* spp.)	6		0.765	
	Knotted wrack (*Ascophyllum nodosum, Silvetia babingtonii*)	2		1.43	
	Oarweed (*Laminaria digitata*)	2		0.13	
	Wakame, leaves (*Undaria pinnatifida*)	9		1.85	
	Wakame, stems (*Undaria pinnatifida*)	3		0.272	
	Dulse (*Palmaria palmata*)	4		0.688	
	Irish moss (*Chondrus crispus*)	2		0.442	
	Sea moss (*Chondrus crispus, Kappaphycus alvarezii*)	1		0.258	
	Nori (*Pyropia yezoenis*)	8		1.42	
	Laver (*Porphyra umbilicalis, Pyropia haitanensis*)	2		2.76	
	Sea Lettuce (*Ulva* spp.)	2		0.382	

Notes
1 The LOD/LOQ provided if reported
2 Range of monthly means
3 Mean concentrations in samples/finished products from different locations/processing facilities
4 Concentration on wet weight basis

Abbreviations
AAS: Atomic absorption spectroscopy, CV-AAS: Cold Vapor Atomic Absorption Spectroscopy, CV-AFS: Cold vapour atomic fluorescence spectroscopy, EDXRF: Energy-dispersive X-ray fluorescence spectroscopy, ENAA: epithermal neutron activation analysis, GC-ECD: Gas Chromatography – Electron Capture Detector, GFAAS: Graphite furnace atomic absorption spectrometry, HPLC: High Performance Liquid Chromatography, ICP-MS: Inductively coupled plasma mass spectrometry, ICP-OES: Inductively coupled plasma - optical emission spectrometry, LOD: Limit of Detection, LOQ: Limit of Quantification, nd: not detected

Table D.3. Concentrations of lead in seaweed and seaweed products

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
New Zealand	**Wild seaweeds** *Ecklonia radiata* *Ulva stenophylla* *Durvillaea antarctica* *Hormosira banksii* *Porphyra* spp. *Undaria pinnatifida*	1 each	ICP-OES	 0.61 1.83 0.14 0.61 0.98 0.23	(Smith *et al.*, 2010)
New Zealand	**Commercial samples** Wakame (*Undaria pinnatifida)* *Macrocystis pyrifera* *Porphyra* spp. *Ecklonia radiata*	1 each	ICP-OES	 0.30 0.30 0.41 0.20	(Smith *et al.*, 2010)
New Zealand	*Undaria pinnatifida*	114	ICP-AES	0.21 – 0.31 [2]	(Hau, 2012)
Bangladesh	*Hypnea musciformis* *Hypnea pannosa* *Jania rubens* *Gelidium pusillum* *Padina tetrastromatica* *Sargassum oligocystum* *Padina boryana* *Caulerpa racemose* *Enteromorpha intestinalis* *Ulva compressa*	16 each	EDXRF (LOD: 0.02)	0.60 0.62 0.71 4.5 4.24 10.63 0.4 0.77 2.76 1.0	(Rakib *et al.*, 2021)
Brazil	*Canistrocarpus cervicornis* *Dictyopteris delicatula* *Ceratodyction variabilis* *Palisada* spp.	Not stated	ICP-OES (LOD: 0.28)	1.33 (<0.28–3.20) 1.47 (0.28–6.60) 0.95 (<0.28-1) 1.30 (<0.28-2.11)	(Santos-Silva *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Zonaria tournefortii *Gracilaria* spp. *Padina gymnospora* *Palisada perforata*			1.03 (0.8–1.25) <0.28 4.0 (< 1.37–5.1) 7.86 (7.54–8.38)	
Canada (product from British Columbia, Japan, Norway)	**Retail seaweed products** Bull kelp (*Nereocytis leutkeana*) Wakame *(Undaria pinnatifida)* Arame *(Eisenia bicyclis)* Hijiki *(Hizikia fusiformis)* Asakusa-nori *(Porphyra tenera)* Makombu *(Laminaria japonica)* Asakusa-nori *(Porphyra tenera)* Wakame *(Undaria pinnatifida*) Bladderwrack *(Fucus vesiculosis)* *Kelp tablets* (Species not listed) Split Kelp *(Laminaria Setchellii)* Sugar kelp *(Laminaria saccharina*) Winged kelp *(Alaria marginate*) Giant kelp *(Macrocystis integrifolia)* Bull kelp (*Nereocytis leutkeana*)	1 each	ICP-MS (LOD: 0.01)	 <0.01 0.14 0.31 0.16 0.28 0.22 0.14 0.21 0.38 0.57 <0.01 <0.01 0.64 0.19 0.08	(van Netten *et al.*, 2000)
Canary Islands, Spain (China, Thailand)	**Retail seaweed products** Wakame (*Undaria pinnatifida*) Wakame algae salad (*Undaria pinnatifida*)	 10 10	ICP – OES (LOQ: 0.001 mg/L)	 0.31 0.50	(Paz *et al.*, 2019)
Canary Islands, Spain (Spain)	Wakame (*Undaria pinnatifida*) Sea spaghetti (*Himanthalia elongata*) Kombu (*Laminaria ochroleuca*) Seaweed salad	15 15 15 8		0.30 0.23 0.38 0.27	
Chile	*Durvillaea antarctica* *Macrocystis pyrifera*	1 each	ICP-MS	7.33 1.45	(Caballero *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Lessonia nigrescens			2.73	
China	*Sargassum fusiforme*	3	ICP-MS	0.31–1.29	(Zhu *et al.*, 2022)
Egypt	*Ulva linza*	Not stated	AAS	34.39	(Salem *et al.*, 2019)
	Ulva fasciata			37.50 (28.19 – 44.05) [3]	
	Colpomenia sinuosa			34.62 (23.83 – 45.42) [3]	
	Sargassum vulgare			38.87	
	Amphiroa rigida			11.73	
	Corollina officinalis			43.0	
	Pterocladia capillacea			33.06 (25.45-40.57) [3]	
	Jania rubens			33.85	
Greenland	*Agarum clathratum*	3	ICP-MS (LOQ: 0.06; LOD: 0.02)	0.337	(Kreissig *et al.*, 2021)
	Alaria esculenta	9		0.474	
	Ascophyllum nodosum	8		0.111	
	Fucus distichus	8		0.243	
	Fucus spp.	7		1.59	
	Fucus vesiculosus	16		0.101	
	Hedophyllum nigripes	5		0.158	
	Laminaria solidungula	6		0.329	
	Palmaria palmata	2		0.251	
	Saccharina latissima	11		0.207	
	Saccharina longicruris	2		0.641	
India	*Amphiroa* spp.	4 each	AAS	13.40	(Anbazhagan *et al.*, 2021)
	Gracilaria edulis			5.31	
	Gracilaria folifera			8.02	
	Halymenia spp.			8.11	
	Hypnea musciformis			8.91	
	Chnoospora minima			9.82	
	Sargassum polycystum			12.39	
	Sargassum wightii			12.69	

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Spatoglossum asperum *Stoechospermum marginatum*			10.30 6.62	
India	*Stoechospermum marginatum* *Padina tetrastromatica* *Sargassum wightii* *Dictyota dichotoma* *Gracilaria corticata* *Gracilaria verrucosa* *Acanthophora spicifera* *Ulva lactuca* *Caulerpa racemosa*	6 each	ICP-MS	0.32 (0.02 – 0.52) 0.16 (0.05 – 0.24) 0.10 (0.04 – 0.17) 0.15 (0.07 – 0.24) 0.18 (0.11 – 0.27) 0.50 (0.11 – 0.21) 0.15 (0.11 – 0.21) 0.31 (0.17 – 0.56) 0.07 (0.02 – 0.14)	(Arisekar *et al.*, 2021)
India	*Sargassum whitti* *Turbinaria conoides* *Hypnea musciformis* *Gracilaria edulis* *Gracilaria verrucosa* *Gracilaria corticata* *Sarconema filiforme* *Kappaphycus alverizii* *Acanthophora muscoides* *Ulva lactuca* *Ulva reticulata* *Caulerpa scalpelliformis* *Chaetomorpha linum*	5 each	AAS	2.68 2.09 2.36 0.86 1.55 0.90 0.94 2.58 2.46 1.49 0.40 0.58 5.24	(Arulkumar *et al.*, 2019)
India	*Ulva compressa* *Ulva fasciata*	4 each	GFAAS	<1 - <5 1.28 - <5	(Hyderali and Eswaran, 2019)
India	*Caulerpa taxifolia* *Caulerpa racemosa*	4 each	AAS	8.73 (7.01 – 9.61) 9.93 (7.13 – 12.43)	(Rajaram *et al.*, 2020)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Caulerpa scalpelliformis *Chaetomorpha linum* *Ulva lactuca* *Halimeda macroloba* *Halimeda tuna* *Valoniopsis pachynema* *Ulva compressa* *Codium fragile*			11.2 (10.46 – 12.55) 8.16 (7.19 – 9.0) 10.75 (7.04 – 14.14) 7.36 (3.88 – 10.08) 10.83 (6.54 – 16.41) 9.68 (6.54 – 12.40) 6.19 (3.54 – 8.52) 13.54 (11.28 – 18.09)	
India	*Ulva reticulata*	1	ICP-MS (LOD: 0.1)	<LOD	(Gomathi and Sheba, 2018)
Indonesia	*Eucheuma cottonii*	2	ICP-OES	0.058	(Aras, 2020)
Indonesia	*Eucheuma cottonii* Semi Refined Carrageenan product	Not stated	AAS	 6.2	(Dewi and Darmanto, 2012)
Italy	**Retail seaweed products** Brown seaweed *Himanthalia* spp. *Saccharina* spp. *Undaria* spp. *Ascophyllum* spp. *Laminaria* spp. Red seaweed *Porphyra* spp. *Palmaria* spp. Green seaweed *Ulva* spp.	 8 15 10 1 1 13 9 5	ICP-MS (LOD: 0.002) (LOQ: 0.005)	 0.06 0.17 0.10 0.11 0.11 0.17 0.14 0.16	(Filippini *et al.*, 2021)
Italy	*Ulva rigida* *Gracolaria gracilis* *Grateloupia doryphora*	1 each	GFAAS	7.3 (0.7 – 17.6) 6.9 (2.8 – 20.6) 3.0 (0.6 – 5.6)	(Caliceti *et al.*, 2002)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Porphyra leucosticta *Fucus virsoides* *Undaria pinnatifida* *Cystoseira barbata*			2.7 (2.1 – 3.9) 2.2 (0.5 – 4.4) 1.6 (1.2 – 2.0) 3.2 (1.4 – 5.6)	
Italy	*Padina pavonica* *Cystoseira mediterranea*	54 each	ICP-OES (LOQ: 0.05)	0.35 (0.11 – 0.75) 1.63 (0.13 – 0.92)	(Corrias *et al.*, 2020)
Italy (product from China, Japan, Republic of Korea, and Hong Kong)	**Retail seaweed products** *Laminaria japonica* *Porphyra yezoensis* *Undaria pinnatifida*	 16 54 22	ICP-MS (LOQ: 0.0019)	 3.07 (0.163 – 28.40) 0.188 (0.088 – 0.66) 0.86 (0.14 – 1.43)	(Miedico *et al.*, 2017)
Republic of Korea	**Retail seaweed products** Laver Brown seaweed Kelp Lettuce	 125 153 102 46	ICP- OES (LOD: 0.002 µg/ml)	 0.71 (<LOD to 2.36) 0.77 (<LOD–2.71) 0.66 (<LOD–1.70) 0.539 (<LOD–1.71)	(Hwang *et al.*, 2010)
Republic of Korea	**Retail seaweed products** Laver (*Porphyra tenera)* Sea tangle (*Laminaria japonica*) Sea mustard (*Undaria pinnatifida*) Hijiki (*Hizikia fusiforme*) Gulf weed (*Sargassum fulvellum*)	 53 45 58 27 15	ICP- MS (LOD: 0.013 ppb; LOQ: 0.042 ppb)	 0.063 0.032 0.050 1.0 0.409	(Khan *et al.*, 2015)
Libya	*Sargassum vulgar* *Pterocladia capillacea*	1 each	AAS	42.5 30.0	(Awheda *et al.*, 2015)
Malaysia	*Eucheuma cottoni*	3	ICP- OES (LOD: 0.011)	7.69	(Khandaker *et al.*, 2021)
Norway	Irish moss *(Chondrus crispus)* Clawed fork weed *(Furcellaria lumbricalis)* Grape pip weed *(Mastocarpus stellatus)*	1 each	ICP-MS (LOQ: 0.01)	0.3 0.22 0.28	(Biancarosa *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Dulse *(Palmaria palmata)* Black laver *(Porphyra dioica)* Purple laver *(Porphyra purpurea)* Tough laver *(Porphyra umbilicalis)* *Cladophora rupestris* Gut weed *(Ulva intestinalis)* Sea lettuce *(Ulva lactuca)* Wing kelp *(Alaria esculenta)* Egg wrack *(Ascophyllum nodosum)* Slimy whip weed *(Chordaria flagelliformis)* *Serrated wrack (Fucus serratus)* Spiral wrack *(Fucus spiralis)* Bladder wrack *(Fucus vesiculosus)* Sea oak *(Halidrys siliquosa)* Thong weed *(Himanthalia elongate)* Sea girdle *(Laminaria digitata)* Channel wrack *(Pelvetia canaliculate)* Sugar tang *(Saccharina latissimi)*			0.14 0.58 0.44 0.08 1.5 3.0 1.0 0.14 0.10 0.36 0.32 0.27 0.25 <LOQ 0.046 0.12 0.24 0.21	
Norway	*Palmaria palmata* *Alaria esculenta* *Saccharina latissima*	12 each	ICP-MS	8.83 (7.19-12.02) 57.0 (38.0-97.0) 70.0 (52.17-99.11)	(Roleda *et al*., 2019)
Norway	*Ulva fenestrata*	Not stated	ICP-MS	0.52 (n/a-1.1) [3]	(Roleda *et al*., 2021)
Norway	Sugar kelp (cultivated and wild *Saccharina latissima*)	7	ICP-MS	1.12 (0.1 – 4.5)	(Sharma *et al*., 2018)
Portugal	Flax brick weed (*Chaetomorpha linum)* Rooting green thread weed (*Rhizoclonium riparium)* Gut weed (*Ulva intestinalis)* Sea lettuce (*Ulva lactuca)* *Ulva prolifera*	5	ICP-MS	1.66 1.47 2.03 1.45 0.62	(Afonso *et al*., 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Spain (product from Spain, Chile, China, Republic of Korea and Japan,)	**Retail seaweed products** **A) Edible seaweed** *Enteromorpha* spp. *Ulva pertusa* *Porphyra* spp. *Palmaria* spp. Sea lettuce flakes (*Palmaria palmata)* *Rhodymenia palmata* Carrageen *(Chondrus crispus)* *Laminaria* spp. Royal kombu *(Laminaria japonica)* Oarweed *(Laminaria digitata)* Arame *(Eisenia bicyclis)* Japanese kelp *(Undaria pinnatifida)* Hijiki *(Hizikia fusiforme)* Bladderwrack *(Fucus vesiculosus)* Seaweed spaghetti *(Himanthalia elongate)* Rimurapa *(Durvillaea antartica)*	52 in total	GFAAS (LOD: 0.05)	 0.205 <LOD 0.49 (0.12 – 1.24) <LOD 1.52 0.19 (0.23 – 0.15) 0.53 (0.72 – 0.34) 0.13 (<LOD – 0.26) <LOD 0.106 0.20 (<LOD – 0.24) 1.0 (<LOD – 2.44) 0.45 (<LOD – 2.06) 0.90 0.14 (0.11 – 0.19) <LOD	(Almela *et al.*, 2006)
	B) Foods (tofu, hamburger, instant soups, sesame snacks & biscuits, sauces etc) *Porphyra* spp. *Hizikia fusiforme* *Laminaria* spp. *Himanthalia* spp. Arame *(Eisenia bicyclis)* Japanese kelp *(Undaria pinnatifida)* *Laminaria* spp. *Fucus* spp.	28 in total	AAS (LOD: 0.05)	 <LOD 0.14 (0.11 – 0.20) 0.13 (0.05 – 0.23) <LOD <LOD 0.33 (<LOD – 0.44) <LOD 1.21	(Almela *et al.*, 2006)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Spain	Salmon maki (8% seaweed; its type not specified) Tuna maki (5% seaweed; its type not specified) Eel nigiri (1% seaweed; its type not specified) Eel maki (5% seaweed; its type not specified)	15 15 9 9	AAS (LOD: 0.05)	(<0.05 – 0.09) (<0.05 – 0.21) (<0.05 – 0.22) (<0.05 – (<0.05)	(González *et al.*, 2021) [4]
Spain	**Retail seaweed products** *Chondrus* spp. *Eisenia* spp. *Gelidium* spp. *Palmaria* spp. *Porphyra* spp. *Himanthalia* spp. *Laminaria* spp. *Undaria* spp.	 3 6 2 4 10 6 6 4	ICP-OES (LOD: 0.0003 mg/L; LOQ: 0.001 mg/L)	 0.07 0.03 0.05 0.05 0.15 0.02 0.07 0.07	(Rubio *et al.*, 2017)
UK	*Fucus serratus* *Fucus vesiculosus* *Solieria chordalis* *Enteromorpha intestinalis* *Rhizoclonium tortuosum* *Gracilaria gracilis*	3-4	ICP-MS	0.005 (0.003 - 0.007) [3] 0.004 (0.003 - 0.006) [3] 0.040 (0.074 - 0.005) [3] 0.042 (0.014 - 0.071) [3] 0.23 0.012	(Pawlik-Skowrońska *et al.*, 2007)
United States	**Retail seaweed products** Arame (unable to genetically type) Hijiki (unable to genetically type) Kombu (*saccharina* spp.) Knotted wrack (*Ascophyllum nodosum, Silvetia babingtonii*) Oarweed (*Laminaria digitata*) Wakame, leaves (*Undaria pinnatifida*) Wakame, stems (*Undaria pinnatifida*) Dulse (*Palmaria palmata*) Irish moss (*Chondrus crispus*)	 2 3 6 2 2 9 3 4 2	ICP-MS	 0.28 1.5 0.571 0.30 0.054 0.322 0.142 0.279 0.837	(Todorov *et al.*, 2022)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Lead concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Sea moss (*Chondrus crispus, Kappaphycus alvarezii*) Nori (*Pyropia yezoenis*) Laver (*Porphyra umbilicalis, Pyropia haitanensis*) Sea Lettuce (*Ulva* spp.)	1 8 2 2		0.127 0.115 0.551 1.458	

Notes
1 The LOD/LOQ provided if reported
2 Range of monthly means
3 Mean concentrations in samples/finished products from different locations/processing facilities
4 Concentration on wet weight basis

Abbreviations
AAS: Atomic absorption spectroscopy, CV-AAS: Cold Vapor Atomic Absorption Spectroscopy, CV-AFS: Cold vapour atomic fluorescence spectroscopy, EDXRF: Energy-dispersive X-ray fluorescence spectroscopy, ENAA: epithermal neutron activation analysis, GC-ECD: Gas Chromatography – Electron Capture Detector, GFAAS: Graphite furnace atomic absorption spectrometry, HPLC: High Performance Liquid Chromatography, ICP-MS: Inductively coupled plasma mass spectrometry, ICP-OES: Inductively coupled plasma - optical emission spectrometry, LOD: Limit of Detection, LOQ: Limit of Quantification, nd: not detected

Table D.4. Concentrations of mercury in seaweed and seaweed products

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Mercury concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
New Zealand	**Wild samples** *Ecklonia radiata* *Ulva stenophylla* *Durvillaea antarctica* *Hormosira banksii* *Porphyra* spp. *Undaria pinnatifida*	1 each	ICP-OES	 0.17 0.10 0.04 0.05 0.03 0.03	(Smith *et al.*, 2010)
New Zealand	**Commercial samples** Wakame (*Undaria pinnatifida)* *Macrocystis pyrifera* *Porphyra* spp. *Ecklonia radiata*	1 each	ICP-OES	 0.05 0.05 0.01 0.17	(Smith *et al.*, 2010)
New Zealand	*Undaria pinnatifida*	114	ICP-AES	0.021 – 0.024 [2]	(Hau, 2012)
Brazil	*Ulva inteslinalis* *Ulva lactuca* *Fucus spiralis* *Fucus vesiculosus* *Gracilaria* spp. *Osmundea pinnatifida*	2	CV-AFS	0.042 0.034 0.049 0.032 0.031 0.082	(Fabre *et al.*, 2020)
Brazil	*Canistrocarpus cervicornis* *Dictyopteris delicatula* *Ceratodyction variabilis* *Palisada* spp. *Zonaria tournefortii* *Gracilaria* spp. *Padina gymnospora* *Palisada perforata*	Not stated	Mercury analyser (LOD: 0.011)	0.022 (<0.011–0.041) <0.011 <0.011 <0.011 <0.011 <0.011 <0.011 0.044 (0.043–0.046)	(Santos-Silva *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Mercury concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Canada (product from British Columbia, Japan, Norway)	**Retail seaweed products** Bull kelp (*Nereocytis leutkeana*) Wakame *(Undaria pinnatifida)* Arame *(Eisenia bicyclis)* Hijiki *(Hizikia fusiformis)* Asakusa-nori (*Porphyra tenera)* Makombu (*Laminaria japonica)* Asakusa-nori (*Porphyra tenera)* Wakame *(Undaria pinnatifida*) Bladderwrack *(Fucus vesiculosis)* Kelp tablets (Species not listed) Split Kelp *(Laminaria Setchellii)* Sugar kelp *(Laminaria saccharina*) Winged kelp *(Alaria marginate*) Giant kelp *(Macrocystis integrifolia)* Bull kelp (*Nereocytis leutkeana*)	1 each	ICP-MS (LOD: 0.05)	 <0.05 0.24 <0.05 0.32 0.44 0.40 0.24 <0.05 1.08 0.24 <0.05 <0.05 <0.05 <0.05 <0.05	(van Netten *et al.*, 2000)
Canary Islands, Spain (China, Thailand)	**Retail seaweed products** Wakame (*Undaria pinnatifida*) Wakame algae salad (*Undaria pinnatifida*)	 10 10	CV-AAS	 0.011 < undefined LOQ	(Paz *et al.*, 2019)
Canary Islands, Spain (Spain)	Wakame (*Undaria pinnatifida*) Sea spaghetti (*Himanthalia elongata*) Kombu (*Laminaria ochroleuca*) Seaweed salad	15 15 15 8		0.012 0.015 0.024 0.016	
Chile	*Durvillaea antarctica* *Macrocystis pyrifera* *Lessonia nigrescens*	1 each	ICP-MS	0.012 0.026 0.021	(Caballero *et al.*, 2021)
Greenland	*Agarum clathratum* *Alaria esculenta* *Ascophyllum nodosum*	3 9 8	ICP-MS (LOQ: 0.078; LOD: 0.023)	< 0.023 < 0.078 < 0.078	(Kreissig *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Mercury concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Fucus distichus *Fucus* spp. *Fucus vesiculosus* *Hedophyllum nigripes* *Laminaria solidungula* *Palmaria palmata* *Saccharina latissima* *Saccharina longicruris*	8 7 16 5 6 2 11 2		< 0.023 < 0.023 < 0.023 < 0.078 < 0.078 < 0.023 < 0.078 < 0.023	
India	*Stoechospermum marginatum* *Padina tetrastromatica* *Sargassum wightii* *Dictyota dichotoma* *Gracilaria corticata* *Gracilaria verrucosa* *Acanthophora spicifera* *Ulva lactuca* *Caulerpa racemosa*	6 each	ICP-MS	0.09 (0.01 – 0.19) 0.12 (0.02 – 0.27) 0.16 (0.09 – 0.24) 0.06 (0.01 – 0.11) 0.17 (0.05 – 0.32) 0.10 (0.02 – 0.19) 0.08 (0.02 – 0.15) 0.36 (0.11 – 0.93) 0.15 (0.09 – 0.25)	(Arisekar *et al.*, 2021)
India	*Ulva compressa* *Ulva fasciata*	4 each	GFAAS	nd nd	(Hyderali and Eswaran, 2019)
Indonesia	*Euchuma cottonii* Semi Refined Carrageenan product	Not stated	AAS	nd	(Dewi and Darmanto, 2012)
Italy	*Padina pavonica* *Cystoseira mediterranea*	54 each	ICP-OES (LOQ: 0.05)	<LOQ <LOQ	(Corrias *et al.*, 2020)
Italy	**Retail seaweed products** Brown seaweed *Himanthalia* spp. *Saccharina* spp. *Undaria* spp. *Ascophyllum* spp.	 8 15 10 1	ICP-MS (LOD: 0.002) (LOQ: 0.005)	 - 0.01 0.02 0.01	(Filippini *et al.*, 2021)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Mercury concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Laminaria spp. Red seaweed *Porphyra* spp. *Palmaria* spp. Green seaweed *Ulva* spp.	1 13 9 5		0.03 0.01 - -	
Italy (product from China, Japan, Republic of Korea, and Hong Kong)	**Retail seaweed products** *Laminaria japonica* *Porphyra yezoensis* *Undaria pinnatifida*	 16 54 22	ICP-MS (LOQ: 0.0012)	 0.05 (0.028 – 0.068) 0.017 (0.004 – 0.036) 0.02 (0.006 – 0.032)	(Miedico *et al.*, 2017)
Republic of Korea	**Retail seaweed products** Laver Brown seaweed Kelp Lettuce	 125 153 102 46	ICP- OES (LOD: 0.0047 ng)	 0.006 (0.002–0.050) 0.015 (0.001–0.043) 0.016 (0.006–0.037) 0.005 (0.003–0.009)	(Hwang *et al.*, 2010)
Republic of Korea	**Retail seaweed products** Laver (*Porphyra tenera)* Sea tangle (*Laminaria japonica*) Sea mustard (*Undaria pinnatifida*) Hijiki (*Hizikia fusiforme*) Gulf weed (*Sargassum fulvellum*)	 53 45 58 27 15	Mercury analyser (LOD: 0.00006; LOQ: 0.0002)	 <LOD 0.006 <LOD <LOD <LOD	(Khan *et al.*, 2015)
Republic of Korea	*Pyropia yezoensis*	1	ICP-MS	0.007 (0.005 – 0.009) [3]	(Son *et al.*, 2014)
Norway	Irish moss (*Chondrus crispus*) Clawed fork weed (*Furcellaria lumbricalis*) Grape pip weed (*Mastocarpus stellatus*)	1 each	ICP-MS	0.005 0.004 <LOQ	(Biancarosa *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Mercury concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Dulse (*Palmaria palmata*) Black laver (*Porphyra dioica*) Purple laver (*Porphyra purpurea*) Tough laver (*Porphyra umbilicalis*) Common green branched weed (*Cladophora rupestris*) Gut weed (*Ulva intestinalis*) Sea lettuce (*Ulva lactuca*) Wing kelp (*Alaria esculenta*) Egg wrack (*Ascophyllum nodosum*) *Chordaria flagelliformis* Serrated wrack (*Fucus serratus*) Spiral wrack (*Fucus spiralis*) Bladder wrack (*Fucus vesiculosus*) Sea oak (*Halidrys siliquosa*) Thong weed (*Himanthalia elongate*) Sea girdle (*Laminaria digitata*) Channel wrack (*Pelvetia canaliculate*) Sugar tang (*Saccharina latissima*)			0.003 0.008 0.005 0.007 0.01 0.005 0.005 0.005 0.014 0.002 0.003 0.005 0.007 0.006 <LOQ 0.009 0.035 0.010	
Norway	*Laminaria hyperborea*	1	ICP-MS (LOD: 0.01)	<0.01	(Noriega-Fernández *et al.*, 2021)
Norway	*Palmaria palmata* *Alaria esculenta* *Saccharina latissima*	12 each	ICP-MS	0.06 (0.004-0.313) 0.05 (0.004-0.257) 0.03 (0.001-0.105)	(Roleda *et al.*, 2019)
Norway	*Ulva lactuca*	4	ICP-MS	<LOQ[d]	(Roleda *et al.*, 2021)
Norway	Sugar kelp (cultivated and wild *Saccharina latissima*)	7	ICP-MS	<0.1	(Sharma *et al.*, 2018)
Spain	Salmon maki (8% seaweed; type not specified) Tuna maki (5% seaweed; type not specified) Eel nigiri (1% seaweed; type not specified)	15 15 9	AAS	0.042 (0.0015 – 0.005) 0.10 (0.006 – 0.218) 0.012 (0.002 – 0.2)	(González *et al.*, 2021) [5]

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Mercury concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Eel maki (5% seaweed; type not specified)	9		0.014 (0.001 - 0.03)	
Spain	Wakame Sea-spaghetti Hijiki	1 each	ICP-MS (LOD: 0.02 µg/kg for Hg (II) and 0.007 µg/kg for MeHg)	0.07 (14.3%) [4] 0.17 (35.3%) 0.07 (14.3%)	(Jinadasa *et al.*, 2021)
United States	**Retail seaweed products** Arame (unable to genetically type) Hijiki (unable to genetically type) Kombu (*saccharina* spp.) Knotted wrack (*Ascophyllum nodosum, Silvetia babingtonii*) Oarweed (*Laminaria digitata*) Wakame, leaves (*Undaria pinnatifida*) Wakame, stems (*Undaria pinnatifida*) Dulse (*Palmaria palmata*) Irish moss (*Chondrus crispus*) Sea moss (*Chondrus crispus, Kappaphycus alvarezii*) Nori (*Pyropia yezoenis*) Laver (*Porphyra umbilicalis, Pyropia haitanensis*) Sea Lettuce (*Ulva* spp.)	 2 3 6 2 2 9 3 4 2 1 8 2 2	ICP-MS	 0.05 0.04 0.02 0.03 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02	(Todorov *et al.*, 2022)

Notes
1 The LOD/LOQ provided if reported
2 Range of monthly means
3 Mean concentrations in samples/finished products from different locations/processing facilities
4 Values represent total mercury (% organic mercury)
5 Concentration on wet weight basis

Abbreviations

AAS: Atomic absorption spectroscopy, CV-AAS: Cold Vapor Atomic Absorption Spectroscopy, CV-AFS: Cold vapour atomic fluorescence spectroscopy, EDXRF: Energy-dispersive X-ray fluorescence spectroscopy, ENAA: epithermal neutron activation analysis, GC-ECD: Gas Chromatography – Electron Capture Detector, GFAAS: Graphite furnace atomic absorption spectrometry, HPLC: High Performance Liquid Chromatography, ICP-MS: Inductively coupled plasma mass spectrometry, ICP-OES: Inductively coupled plasma - optical emission spectrometry, LOD: Limit of Detection, LOQ: Limit of Quantification, nd: not detected

Table D.5. Concentrations of iodine in seaweed and seaweed products

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
New Zealand	**Wild seaweeds**	1 each	ICP-OES		(Smith *et al.*, 2010)
	Ecklonia radiata			3990	
	Ulva stenophylla			27	
	Durvillaea antarctica			291	
	Hormosira banksii			1041	
	Porphyra spp.			64	
	Undaria pinnatifida			171	
New Zealand	**Commercial samples**	1 each	ICP-OES		(Smith *et al.*, 2010)
	Wakame (*Undaria pinnatifida)*			100.7	
	Macrocystis pyrifera			2115	
	Porphyra spp.			45.0	
	Ecklonia radiata			3719	
Australia	**Retail seaweed products**		ICP-MS		(FSANZ, 2010)
	Kombu, dried	2		3200 (2100-4300)	
	Kombu, frozen	1		110	
	Kombu, cooked	2		195 (190-200)	
	Kombu, broth	2		200 (190-210)	
	Hijiki, dried	1		790	
	Hijiki, cooked	1		160	
	Hijiki, broth	1		9	
	Sargassum fusiforme, dried	2		1020 (140-1900)	
	Sargassum fusiforme, cooked	2		89 (17-160)	
	Sargassum fusiforme, broth	2		85 (1-170)	
	Nori, dried	2		(9-20)	
	Wakame, dried	2		250 (220-280)	
	Wakame, frozen	1		1.2	
	Wakame, cooked	2		29 (27-31)	
	Wakame, broth	2		0.4 (0.3-0.5)	

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Arame, dried Arame, cooked Arame, broth Other seaweed, dried Other seaweed, cooked Other seaweed, broth Seaweed-containing foods	1 1 1 2 2 2 24		540 31 21 2650 (2500-2800) 86 (76-96) 143 (96-190) (0.2-110)	
Canada (British Columbia, Japan, Norway)	**Retail seaweed products** Bull kelp (*Nereocytis leutkeana*) Wakame *(Undaria pinnatifida)* Arame *(Eisenia bicyclis)* Hijiki *(Hizikia fusiformis)* Asakusa-nori *(Porphyra tenera)* Makombu *(Laminaria japonica)* Asakusa-nori *(Porphyra tenera)* Wakame *(Undaria pinnatifida*) Bladderwrack *(Fucus vesiculosis)* *Kelp tablets* (Species not listed) Split Kelp *(Laminaria setchellii)* Sugar kelp *(Laminaria saccharina*) Winged kelp *(Alaria marginate*) Giant kelp *(Macrocystis integrifolia)* Bull kelp (*Nereocytis leutkeana*)	1 each	ICP-MS (LOD: 1)	 734 102 600 436 17 2110 185 60 732 815 1070 238 151 240 80	(van Netten *et al.*, 2000)
Chile	*Durvillaea antarctica* *Macrocystis pyrifera* *Lessonia nigrescens*	1 each	ICP-MS	0.10 0.082 0.10	(Caballero *et al.*, 2021)
China	*Codium fragile* *Ulva pertusa*	1 each	ENAA	154 13.0	(Hou *et al.*, 1997)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Monostroma nitidum *Gracilalia confervoides* *Sargassum kjellmanianum* *Dictyopteris divaricata* *Laminatia japonica*			63.6 353 273 28.8 3040	
Fiji	*Caulerpa lentillifera* *Gracilaria maramae*	4 4	Spectrophotometric kinetic method LOD: 1.54 ng/mL LOQ: 4.9 ng/mL	1.18 (0.85 – 1.52) 6.70 (2.43 – 11.0)	(Chandra *et al.*, 2019)
Greenland	*Agarum clathratum* *Alaria esculenta* *Ascophyllum nodosum* *Fucus distichus* *Fucus* spp. *Fucus vesiculosus* *Hedophyllum nigripes* *Laminaria solidungula* *Palmaria palmata* *Saccharina latissima* *Saccharina longicruris*	3 9 8 8 7 16 5 6 2 11 2	ICP-MS (LOQ: 167; LOD: 50)	280 502 670 212 234 188 3323 4478 113 3124 1466	(Kreissig *et al.*, 2021)
Hong Kong	Retail seaweed products (species not specified)	18	ICP-MS	460 (0.084 – 2900)	(Chung *et al.*, 2013)
Ireland	*Saccharina latissima* *Laminaria digitata* *Laminaria hyperborea* *Pelvetia canaliculata* *Fucus spiralis* *Ascophyllum nodosum* *Fucus vesiculosus* *Fucus serratus*	3 each	HPLC	4549 (3341- 6130) 6600 (3340 - 10203) 5661 (1734 - 8976) 248 211 706 (608 – 785) 905 (509 – 1530) 1264	(Nitschke and Stengel, 2015)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Sargassum muticum *Himanthalia elongata* *Cystoseira tamariscifolia* *Porphyra umbilicalis* *Chondrus crispus* *Mastocarpus stellatus* *Ulva intestinalis* *Ulva lactuca* *Codium fragile*			506 135 165 56 296 579 79 63 41	
Ireland	*Saccharina latissima* *Alaria esculenta* *Palmaria palmata*	27 22 11	HPLC	4652 (1556-7208) 530 (181-1070) 183 (72-293)	(Roleda *et al.*, 2018)
Italy	**Retail seaweed products** **Brown seaweed** *Himanthalia* spp. *Saccharina* spp. *Undaria* spp. *Ascophyllum* spp. *Laminaria* spp. **Red seaweed** *Porphyra* spp. *Palmaria* spp. **Green seaweed** *Ulva* spp.	 8 15 10 1 1 13 9 5	ICP-MS (LOD: 0.002) (LOQ: 0.005)	 11.55 304.0 55.56 430.7 6770 12.02 22.43 10.66	(Filippini *et al.*, 2021)
Kuwait	*Chondria* spp. *Codium papillatum* *Colpomenia sinuosa*	Not stated	ICP-MS	129.04 49.60 66.9	(Al-Adilah *et al.*, 2020)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Dictyota dichotoma *Iyengaria stellata* *Padina boergesenii* *Feldmannia indica* *Sargassum ilicifolium*			85.47 44.55 52.54 229.42 476.13	
Norway	**A) Wholefood seaweed** Brown algae (Oarweed, kombu, sugar kelp, arame, bladderwrack, toothed wrack, wakame, winged kelp and sea spaghetti) Red algae (dulse, nori.) Mixed algae (Oarweed, sugar kelp, winged kelp and dulse; dulse, sea lettuce and nori ; sugar kelp, winged kelp, dulse and nori; sugar kelp, winged kelp and dulse; and wakame, kombu and nori) **B) Foods containing macroalgae** Brown algae (Oarweed, sugar kelp, winged kelp, hijiki, wakame,sea spaghetti, bladderwrack, toothed wrack and rockweed) Red algae (Dulse, nori and truffle seaweed) Mixed algae (Oarweed, sugar kelp, dulse and winged kelp)	43 30 8 5 39 24 9 2	ICP-MS	 1651 (5 - 12000) 240 (15 - 1400) 1052 (140 - 2300) 276 (0.7 - 2500) 57 (5 - 350) 21 (0.3 - 42)	(Aakre *et al.*, 2021)
Norway	*Saccharina latissima*	3	ICP-MS (LOQ: 37 µg/g)	4605	(Nielsen *et al.*, 2020)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Norway	Sugar kelp (cultivated and wild *Saccharina latissima*)	7	ICP-MS	3.21 (1.6 – 4.2)	(Sharma *et al.*, 2018)
Norway	*Ulva lactuca*	Not stated	Ion chromatography	0.30 (0.01-0.08) [2]	(Roleda *et al.*, 2021)
Norway	*Laminaria hyperborea*	1	ICP-OES	7340	(Noriega-Fernández *et al.*, 2021)
Portugal	*Caulerpa racemosa* *Dasycladus vermicularis* *Ulva intestinalis* *Ulva lactuca* *Ulva* spp. *Asparagopsis armata* *Asparagopsis taxiformis* *Asparagopsis taxiformis* *Asparagopsis taxiformis* *Corallina officinalis* *Chondrus crispus* *Galaxaura rugosa* *Grateloupia lanceola* *Halopithys incurva* *Halopithys incurva* *Laurencia obtusa* *Nemalion elminthoides* *Cystoseira compressa* *Cystoseira humillis* *Cystoseira usneoides* *Dictyopteris polypodioides* *Dictyota dichotoma* *Halopteris filicina* *Halopteris scoparia* *Lobophora variegata*	1 each	ICP-MS (LOD: 0.0017; LOQ: 0.005)	220 53 63 129 26 9387 8331 8135 11627 181 221 418 136 425 618 136 139 132 68 58 100 82 660 713 642	(Nunes *et al.*, 2019)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
	Padina pavonica *Sargassum vulgare* *Zonaria tournefortii* *Isochrysis galbana* *Asparagopsis taxiformis* *Cystoseira humillis* *Galaxaura rugosa* *Grateloupia lanceola* *Halopteris scoparia* *Padina pavonica* *Ulva intestinalis* *Zonaria tournefortii*			67 623 169 3 12680 57 245 82 858 57 56 154	
Portugal	*Ulva rigida* *Chondracanthus teedei* var. Lusitanicus, *Chondrus crispus* *Gracilaria gracilis* *Grateloupia turuturu* *Osmundea pinnatifida* *Bifurcaria bifurcata* *Fucus vesiculosus* *Saccorhiza polyschides* *Undaria pinnatifida*	1 each	ICP-AES (LOD: 0.24 mg/L; LOQ: 0.48 mg/L)	33 126 206 94 47 302 391 352 139 63	(Milinovic *et al.*, 2021)
Portugal	Flax brick weed (*Chaetomorpha linum)* Rooting green thread weed (*Rhizoclonium riparium)* Gut weed (*Ulva intestinalis)* Sea lettuce (*Ulva lactuca)* *Ulva prolifera*	1 each	ICP-MS	93.3 281.5 45.1 114.0 120.3	(Afonso *et al.*, 2018)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Spain	Salmon maki (8% seaweed; its type not specified) Tuna maki (5% seaweed; its type not specified) Eel nigiri (1% seaweed; its type not specified) Eel maki (5% seaweed; its type not specified)	15 15 9 9	AAS	0.37 (0.13 – 68) 0.04 (0.023 – 0.058) 0.15 (0.047 – 0.36) 0.46 (0.176 - 0.842)	(González *et al.*, 2021) [3]
Spain	Dulse *(Palmaria palmata)* Nori *(Porphyra umbilicalis)* Sea lettuce *(Ulva rigida)* Wakame *(Undaria pinnatifida)* Sea spaghetti *(Himanthalia elongata)* Kombu *(Laminaria ochroleuca)* Canned seaweed *(cooked Himanthalia elongata* and *Saccorhiza polyschides)*	1 each	ICP-MS	77 43 66 306 117 6138 37	(Romarís-Hortas *et al.*, 2012)
Spain	Nori *(Porphyra umbilicalis)* Dulse *(Palmaria palmata)* Nori *(Porphyra umbilicalis)* Sea spaghetti *(Himanthalia elongata)* Kombu *(Laminaria ochroleuca)* Wakame *(Undaria pinnatifida)*	1 each	ICP-MS LOD: 0.12 µg/L; LOQ: 0.41 µg/L)	66–137 77–128 35–102 63–266 3703–7088 63–326	(Romarís-Hortas *et al.*, 2009)
Taiwan	**Retail seaweed products** Nori (*Porphyra*) Wakame (*Undaria*) Kombu (*Laminaria*)	10 each	GC-ECD	 37.0 (29.3 – 31.1) 140.0 (94.0 – 165.1) 2523 (241 – 4384)	(Yeh *et al.*, 2014)
United States	**Retail seaweed products** Kombu *(Laminaria ochroleuca)* Wakame *(Undaria pinnatifida)*	Not stated	ICP-MS	 4170 226	(Shah *et al.*, 2005)
United States (product from United States, Canada,	**Retail seaweed products** Arame (*Eisenia bicyclis)* Dulse (*Palmaria palmata)* Hijiki (*Hizikia fusiforme)*	Not stated	Colorimetric analysis	 586 72 629	(Teas *et al.*, 2004)

Country of survey (also country of origin unless otherwise stated)	Type or species of seaweed	Number of samples (N)	Method of analysis (LOD/LOQ, mg/kg) [1]	Iodine concentration, mean (range), mg/kg dry weight unless otherwise stated	Reference
Namibia, Tasmania, Japan)	Kelp/kombu Nori (*Porphyra tenera*) Wakame (*Alaria esculenta)*			1542 16 66	

Notes

1 The LOD/LOQ provided if reported
2 Mean concentrations in samples/finished products from different locations/processing facilities
3 Concentration on wet weight basis

Abbreviations

AAS: Atomic absorption spectroscopy, CV-AAS: Cold Vapor Atomic Absorption Spectroscopy, CV-AFS: Cold vapour atomic fluorescence spectroscopy, EDXRF: Energy-dispersive X-ray fluorescence spectroscopy, ENAA: epithermal neutron activation analysis, GC-ECD: Gas Chromatography – Electron Capture Detector, GFAAS: Graphite furnace atomic absorption spectrometry, HPLC: High Performance Liquid Chromatography, ICP-MS: Inductively coupled plasma mass spectrometry, ICP-OES: Inductively coupled plasma - optical emission spectrometry, LOD: Limit of Detection, LOQ: Limit of Quantification, nd: not detected

APPENDIX E: MICROORGANISM SUPPLEMENTARY INFORMATION

E.1 PUBLISHED OPTIMUM GROWTH CONDITIONS

Table E.1 shows the minimum and maximum values for temperature, pH and water activity for growth to occur for selected microorganisms under optimum growth conditions.

Note that growth would be very slow at these extremes, and other environmental or seaweed matrix factors will influence the ability of microorganisms to grow.

Table E.1. Minimum and maximum values for temperature and pH, and minimum water activity recorded for the growth of selected microorganisms under otherwise optimum growing conditions.

Microorganism	Temperature (°C)		pH		Water activity (a_w)
	Minimum	Maximum	Minimum	Maximum	Minimum
Aeromonas hydrophilia	0	42	6	7.2	0.97
Bacillus cereus	4	55	4.3	9.3	0.92
Escherichia coli	6.5	49.4	4	9	0.95
Listeria monocytogenes	-0.4	45	4.4	9.4	0.92
Salmonella enterica serovars	5.2	42.6	3.7	9.5	0.94
Staphylococcus aureus Toxin production (cells > ~10^5/cm^2)	7 10	50 48	4 4.5	10 9.6	0.83 0.87
Vibrio parahaemolyticus	5	~44	4.8	~11	0.94
Vibrio vulnificus	10	~44	4.4	~9	0.96
Aspergillus spp. (Toxin production)	10	34	2	>8	0.81
Penicillium spp. (Toxin production)	0	37	unknown	unknown	0.86

Source Løvdal *et al.* (2021) and ICMSF 5 (1996)

Note that norovirus, hepatitis A and hepatitis E do not grow in foods or the environment.

E.2 MICROORANISMS IN PROJECT SCOPE BUT NOT SELECTED FOR FURTHER INVESTIGATION

E.2.1 *Campylobacter* spp.

Campylobacter spp. are the leading cause of notifiable gastrointestinal illness in New Zealand and are also found in a number of animals including birds; therefore, any contamination event which allowed human or animal faecal material to enter a seaweed-growing or processing environment could contaminate the seaweed. However, infection with this organism has not been reported as being associated with seaweed consumption, possibly because it is sensitive to salt and desiccation (Kim *et al.*, 2021).

E.2.2 *Yersina* spp.

The main *Yersinia* species detected in foodborne illness are *Yersinia enterocolitica* and *Yersinia pseudotuberculosis*. Both species have caused outbreaks in New Zealand with *Y. enterocolitica* being implicated in a sushi outbreak in New Zealand in 2016 (King, 2017).

Y. enterocolitica is a natural inhabitant of the gastrointestinal tract of a wide range of animal species. Any contamination event which allowed human or animal faecal material to enter a seaweed-growing or processing environment could contaminate the seaweed. Types of *Y. enterocolitica* can also be found in terrestrial and freshwater environments, but many environmental isolates lack markers for bacterial virulence (Doyle and Beuchat, 2007).

Yersiniae are psychrotrophic (so will grow at chilling temperatures) and show good growth in up to 5% salt regardless of temperature. Growth is inhibited at 7% salt concentration. The minimum pH for growth is between 4.2 and 4.4, but the presence of organic acids reduce the ability of *Y. enterocolitica* to multiply at low pH (Bari *et al.*, 2011).

E.2.3 Hepatitis A virus (HAV) and Hepatitis E virus (HEV)

No outbreak or survey information was available for hepatitis A or E viruses. Like norovirus, they will not grow in food, water, or the environment and have a low infectious dose (10 to 100 virus particles).

Contamination of seaweed could occur from growing waters contaminated with faeces. Human faeces can contain HAV or HEV. Pigs and wild boar are also known carriers of HEV and excrete virus in their faeces. Like norovirus (or indeed any foodborne pathogenic microbe), these viruses can also be introduced onto food by infected food handlers (noting that the majority of HEV infections are asymptomatic) (King *et al.*, 2018).

Hepatitis A and E viruses will survive freezing. Hepatitis A virus can survive well in chilled produce and has a $D_{60°C}$ of 4.6 minutes in spinach.[49]

E.2.4 Protozoan parasites

Protozoan parasites *Giardia lamblia* and *Cryptosporidium* spp. were not discussed in any of the literature reviewed but are known to survive in a marine sediment. Any contamination event which would allow human or animal faecal material to enter a seaweed-growing or processing environment would give potential for a seaweed-borne infection to arise from either of these pathogenic protozoa. *Cryptosporidium* oocysts are particularly resilient, especially under cool, moist conditions. Infectivity can be retained for months, especially in low water temperatures.

[49] https://www.mpi.govt.nz/dmsdocument/11027-Hepatitis-A-virus-Microbial-pathogen-data-sheet (mpi.govt.nz) (Accessed 12 May 2022)

Giardia cysts and *Cryptosporidium* oocysts are sensitive to standard pasteurisation techniques, will die at freezer temperatures and are sensitive to drying at ambient temperatures therefore, they would only be of concern for fresh seaweed products.[50]

[50] https://www.mpi.govt.nz/dmsdocument/11045-Cryptosporidium-parvum-and-Cryptosporidium-hominis-Microbial-pathogen-data-sheet and https://www.mpi.govt.nz/dmsdocument/11024-Giardia-intestinalis-Microbial-pathogen-data-sheet (Accessed 12 May 2022)