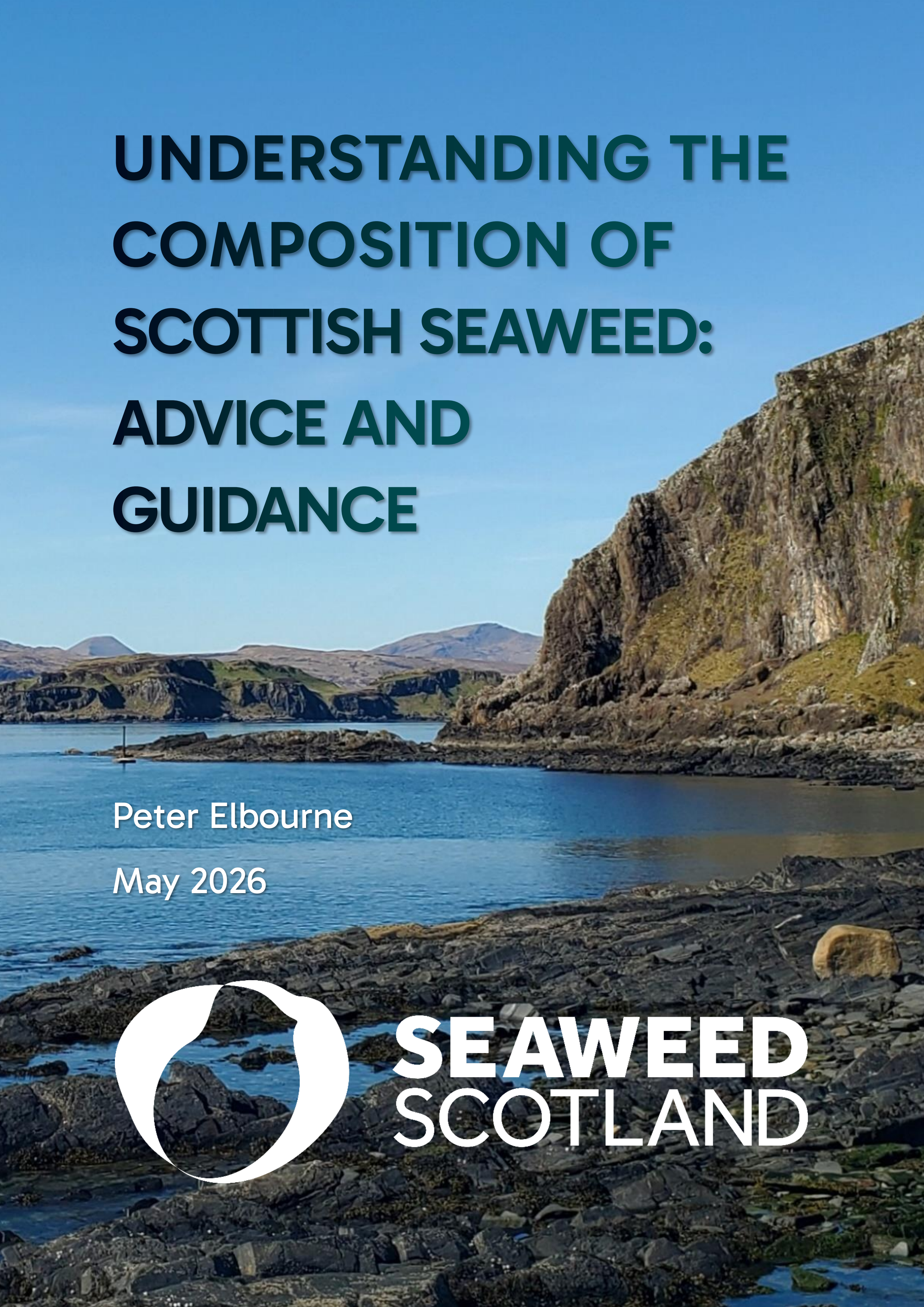
UNDERSTANDING THE COMPOSITION OF SCOTTISH SEAWEED: ADVICE AND GUIDANCE



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SEAWEED SCOTLAND

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1. EXECUTIVE SUMMARY

Background

This report is the outcome of a project by Seaweed Scotland to assess food safety risks linked to sourcing and processing Scottish seaweed. A long held ambition of Seaweed Scotland, funding from Marine Fund Scotland (Scottish Government) has allowed a comprehensive review that will be of value to members and a wider community of stakeholders in the seaweed industry. The project covers a range of relevant subjects, but it also highlights key data gaps.

Scope

This study focuses on hazards in seaweed intended for human consumption. It is also relevant to wider uses, including food supplements, animal feed, cosmetics and bioactive extraction, as shared raw materials and processing can lead to similar exposure pathways and hazards. Findings are intended to support risk assessment across these sectors (e.g. HACCP), while recognising differences in exposure and regulation. Most of the work focuses on element concentrations in seaweed sourced through literature review, covering both essential nutrients and toxic elements, to better understand variability and support safe consumption.

The following subjects are covered in this report:

- Evaluating contamination risks (e.g. pollution sources).
- Emerging risks & regulatory considerations (horizon scanning, relevant regulation on contaminants etc.).
- Units & statistics (e.g. consistency, dry weight and fresh weight, tolerable intake).
- Excess nutrients and toxic elements, analysing a dataset compiled from over 3,000 results sourced from studies of European seaweed across 14 countries. Covering essential trace minerals (iron, manganese, copper, selenium, zinc, cobalt, iodine), beneficial trace minerals (molybdenum, strontium, bromine, chromium, boron, rubidium, vanadium, lithium), characterised toxic trace elements (nickel, aluminium, cadmium, mercury, lead, arsenic) and other toxic trace elements (barium, titanium, silver, tin, thallium, bismuth, beryllium, antimony, uranium, rare earth elements).
- Anthropogenic compounds, including halogenated persistent organic pollutants (e.g. dioxins and PCBs, perfluoroalkyl substances), polycyclic aromatic hydrocarbons and pesticide residues
- Biogenic toxins, particularly mycotoxins from fungi
- Managing allergen risks, especially cross-contamination with major allergens (e.g. crustaceans, molluscs)
- Microbiological hazards, including factors influencing microbial growth (e.g. water activity, temperature) and microorganisms of concern (e.g. pathogenic bacteria and viruses, spoilage yeasts and moulds).
- Exposure to radionuclides in seaweed

- Physical contamination from the environment (e.g. sand, shell fragments) and from processing (e.g. metal, glass), or both (e.g. plastic).
- A summary of results for samples collated by Seaweed Scotland (primarily toxic elements, but also some anthropogenic compounds and mycotoxins).

Evaluating contamination risks

Seaweed operations intended for food use must assess contamination risks. This begins with identifying both diffuse pollution (e.g. agricultural runoff, atmospheric deposition) and point-source pollution (e.g. sewage outfalls, industrial activity, ports). All potential hazards should be assessed in terms of their likelihood and severity, including those considered low risk, to demonstrate a comprehensive evaluation.

Risk assessment should first be conducted at a regional scale, considering sources of contamination that may influence the site from a distance. These include runoff from urban areas, agriculture and major roads, as well as more obvious concerns like industrial discharges. Rivers are particularly important pathways, as they transport pollutants from large catchment areas into coastal environments. Historical contamination, such as pollutants stored in sediments from past industrial activity, may also pose ongoing risks if disturbed. In addition, local geology can naturally contribute elevated levels of toxic elements that seaweed may accumulate. Together, these factors help determine whether a coastline is vulnerable to anthropogenic or natural contamination.

Agriculture on land adjacent to harvest and farm sites should be assessed for contamination risk

If no major concerns are identified regionally, a more detailed site-specific assessment can be progressed. This involves avoiding areas close to known pollution sources and establishing appropriate separation distances based on local conditions, factoring in water flow, topography and usage patterns. Watercourses flowing onto the foreshore are particularly important, as they act as vectors for contaminants, especially from agricultural land. While larger rivers present a clearer risk, smaller streams can also contribute pollution, particularly during heavy rainfall when runoff increases and temporary channels may form. Precautionary measures like avoiding harvesting near freshwater inputs or during periods of intense rainfall can help reduce exposure.

Seawater exchange plays a critical role in determining contamination levels. Open, exposed coastlines benefit from strong wave and tidal action that disperses pollutants, whereas sheltered areas such as bays and estuaries have limited water exchange, allowing contaminants to accumulate. Ocean circulation patterns further influence how pollutants are transported, with currents around Scotland generally moving northward along the west coast and southward along the east coast, meaning some external pollution sources may have a greater regional impact than others.

Contaminants are less likely to accumulate on exposed rocky shores due to high water exchange

Finally, identifying and monitoring pollution sources is supported by regulatory frameworks and mapping tools. Resources from SEPA provide information on authorised discharges and water quality status in Scotland. Almost all Scottish coastal waters are classified as Good or High in the key parameters; there are only five coastal water bodies with a Moderate or Poor status, all of which are in located around central and southern Scotland. Although environmental controls have improved, a wide range of anthropogenic and natural contamination sources still exist, making thorough and site-specific assessment essential for ensuring the safety of seaweed as a food product.

Emerging risks & regulatory considerations

European Rapid Alert System for Food and Feed (RASFF)

The European Rapid Alert System for Food and Feed (RASFF) enables countries to share food safety risks and take rapid action. Its database supports trend analysis and helps identify contamination patterns. Between 2020 and 2025, 914 notifications were recorded for hazardous elements – mainly involving cadmium, mercury and lead (84%) – particularly in seafood and plant products. Biogenic toxins were also commonly reported across several food categories.

For seaweed, there were 63 notifications in the five year period, with high iodine levels accounting for 79% of cases. Other issues—such as cadmium, arsenic and pathogens—were rare. Overall, seaweed-related alerts are limited, with iodine representing the main food safety concern.

Relevant regulation

Food safety is regulated through various laws. When treating seaweed as a food product, most mainstream food legislation is applicable; anyone supplying edible seaweed must adhere to the following principles:

- Ensure food is safe to consume
- Apply controls under a HACCP system
- Comply with rules around labelling and traceability
- Review risk of contaminants, even where no legal limits exist
- Check compliance with novel food regulations

This report provides an overview of the relevant regulations to help support seaweed producers manufacture food-safe products.

Third-party accreditation

Third-party accreditation is increasingly important for UK seaweed producers seeking to supply into established food manufacturing and retail markets. While a producer can legally operate using a documented HACCP plan and basic prerequisite controls, significant customers will often require additional assurance through recognised certification schemes or their own supplier audits (that will likely align with recognised schemes). The two most relevant standards for UK seaweed processors are SALSA and BRCGS. These schemes help demonstrate robust food safety, traceability and process control systems, while also reducing customer concerns around supply chain vulnerability and less familiar ingredients such as seaweed.

BRCGS is the most internationally recognised food safety certification and is commonly required for direct supply into major supermarkets and large manufacturers. It provides a comprehensive framework covering HACCP, supplier approval, traceability, process controls and food safety culture, with strong expectations around senior management involvement and continuous verification. However, implementation is resource-intensive and often requires dedicated technical management. As a result, BRCGS is generally more suitable for medium to large businesses or companies targeting export and large-scale retail markets.

SALSA was developed specifically for small and micro food producers in the UK and represents a more accessible and lower-cost route to accreditation. It is widely accepted by UK wholesalers, foodservice businesses and manufacturers, including some BRCGS-certified businesses. The standard is relatively flexible and has already been successfully applied within the UK seaweed sector. Although SALSA provides a realistic starting point for smaller processors, progression to BRCGS involves a substantial increase in documentation, auditing, supplier management and verification requirements. Many businesses therefore use the transitional scheme BRCGS START! to support phased implementation.

Organic certification represents a separate but complementary area of accreditation for seaweed producers wishing to market products as organic. The term is legally protected and certification is required through an approved control body such as the Soil Association. Organic seaweed production must demonstrate environmentally suitable harvesting waters, sustainable harvesting practices, separation of organic and non-organic material, controlled processing methods and enhanced traceability. Additional requirements also apply to labelling and paperwork around imports and exports. Several UK seaweed businesses have already achieved certification under these standards, demonstrating that compliance is achievable but operationally demanding. Organic certification is recognised as an international accreditation for sustainable, low-impact production. Any seaweed producer aiming to sell on a B2B basis should consider organic accreditation to provide credibility to customers.

Units and statistics

Quantities

While different units are used in contaminant analysis, this report primarily presents results in milligrams per dry kilogram (mg/kg), which is equal to parts per million (ppm). Moisture content (typically 70–90% in fresh seaweed) significantly affects reported concentrations of nutrients and contaminants, making the distinction between wet and dry weight essential for accurate risk assessment and regulatory comparison. As most studies standardise results on a dry weight basis to ensure consistency and comparability, this approach is used throughout this report, with limited conversions from fresh weight where required. While some regulatory limits are set on a fresh weight basis, clear conversion and consistent reporting are necessary to avoid misinterpretation.

Seaweed consumption in the UK and Europe is generally low, reflecting its limited role in traditional cuisine compared to other parts of the world (e.g. east Asia). A 2025 Eurobarometer survey found that 81% of EU consumers eat seaweed or algae products rarely or never, with only a small proportion consuming them weekly, while a French study estimated average intake at just 0.3 dry grams per day. In contrast, daily intake in Japan, South Korea and China – countries where seaweed is a regular dietary component – is estimated at 4–8 dry grams (Zava and Zava, 2011; Hwang et al., 2010; Chen et al., 2018). The lack of reliable European intake data means studies assessing contaminants often adopt intake estimates from Asian populations to reflect exposure for a regular consumer of seaweed. Based on this approach, a daily intake of 5 dry grams is considered a reasonable high-consumption scenario for risk assessment purposes in this report, aligning with values used in previous studies. Although this level of intake could lead to high iodine exposure, iodine levels can be reduced through processing. Overall, 5 dry grams per day is a practical benchmark for evaluating contaminant risks. Comparisons in this report assume a body weight for an adult of 70kg.

Guidance values in food safety and toxicology define the amount of a substance that can be consumed without significant health risk, usually expressed per kilogram of body weight to account for differences between individuals. Regulatory agencies (e.g. the European Food Safety Authority, EFSA) use these values to standardise risk assessments and often convert them into practical daily or weekly intake limits. Key guidance values include Upper Limits (ULs) for nutrients, Tolerable Intakes (TDIs/TWIs) for contaminants, and Reference Doses (RfDs) or Acceptable Daily Intakes (ADIs) for chemicals and food additives. These thresholds are derived from toxicological studies using safety factors to account for uncertainty and variation between species and populations. Regulatory limits in the UK and Europe are generally based on these values and are used to establish safe exposure levels for contaminants and nutrients in foods, including seaweed.

Statistics

The statistical approach in this report is designed to account for the highly variable and often skewed nature of contaminant data in seaweed, where outliers are common due to environmental and analytical factors. The arithmetic mean can be distorted by extreme results, therefore the median (50th percentile) is used as the primary measure of central tendency in this report. Data spread is represented as 25th and 75th percentiles and maximum values are given to highlight potential upper-bound risks, but contextualised alongside average data and ranges.

Results below analytical limits are excluded from quantitative analysis to prevent distortion, although they are discussed where relevant. The report draws on a range of statistical tools for comparative and exploratory analysis, ultimately functioning as a meta-analysis combining data from multiple studies to improve robustness. Lastly, occasional high contaminant values are interpreted within the context of normal variability and regulatory safety margins, recognising that infrequent exceedances do not necessarily indicate a meaningful risk to public health.

Excess nutrients and toxic elements

Building a dataset

Following a literature review, a dataset was compiled for element concentration data from published studies analysing seaweed collected primarily along the Atlantic coasts of Europe. The geographic range extends beyond Scotland and the UK to improve data coverage and reflect the natural distribution of key Scottish species. Studies were included based on defined criteria, including known sampling date, production method (wild or farmed), clear identification of species and harvestable plant parts. To ensure relevance and data quality, only studies published since 2015 were used, with limited exceptions (e.g. informative analysis of Scottish seaweed). Where necessary, data were standardised by grouping closely related or difficult-to-distinguish species (e.g. Ulva spp. and Porphyra spp.). The dataset excludes microalgae and non-Atlantic sources, with limited use of external studies for benchmarking purposes.

Studies were excluded where data reliability or provenance was unclear (e.g. samples from retail, unclear supplier sourcing). Analyses lacking species-level detail, using ambiguous names, or presenting only low-resolution data were also omitted. Studies involving polluted sites or experimentally exposed seaweed were excluded unless appropriate controls or descriptions were provided. Only studies with clear sourcing and methodological detail were included to ensure the results were comparable.

Saccharina latissima is the species with the most results in the literature review dataset, mainly due to research into cultivation

The dataset draws on studies from 14 countries, with Norway contributing the most due to strong research investment in seaweed cultivation (especially Alaria esculenta and Saccharina latissima). Spain and the UK (primarily Scotland) are also well represented, alongside Ireland, France, Iceland and Sweden. Most studies were published from 2021 onwards (61%) and the majority of data relates to wild-harvested seaweed (80%). The species contributing the most results to the dataset is Saccharina latissima (21%).

In total, the dataset contains 3,130 average results and 601 maximum values, derived from an aggregated sample size of over 20,000 measurements. Most results are based on small sample sizes typical of analytical chemistry (two-thirds are for a sample size of three or fewer).

Three categories are used to provide a structured, risk-based interpretation of analytical data in relation recommended upper intake levels. Summarised in Table 1.1, the categories lessen from 'Risk of excess intake via seaweed' though 'Possible risk' to 'Minimal risk'. Relevant limits in regulations are highlighted for elements, even if risk of excess intake is low.

Table 1.1: Categories for risk of excessive intake of a mineral from consuming seaweed.

Category	Contribution to upper intake level	Detail provided
Minimal risk of excess intake via seaweed	Highest levels in any species are <20% of recommendation	Overview of levels
Possible risk of excess intake via seaweed	Highest levels in any species are 20-100% of recommendation	Basic appraisal of variation (e.g. species of concern)
Risk of excess intake via seaweed	Highest levels in any species are >100% of recommendation	Detailed assessment of variation (e.g. countries)

Nutrient elements

Many elements serve as inorganic nutrients essential for physiological function. Essential macro-minerals (specifically: sodium, calcium, magnesium, potassium, chloride and phosphorus) are required in larger amounts. Guidance on excess consumption may not be in place as there is minimal risk of high intake. Macro-minerals are excluded from detailed assessment due to the low risk of excessive intake from seaweed consumption. Although multiple studies have measured macro-minerals in seaweed, comprehensive datasets across Scottish species are limited. Nevertheless, Badmus et al. (2021) demonstrated that even maximum observed levels indicate low risk in 5 dry gram portions.

Essential trace minerals

Essential trace minerals are needed to support specific health functions – but only in small quantities (e.g. 10µg to 100mg) – and recommended upper limits are generally set. They are widely included in seaweed composition studies, providing a large set of data for analysis. Of the seven assessed, the only essential trace mineral of concern is iodine (all others essential trace minerals have a minimal risk of excess intake: iron, manganese, copper, selenium, zinc, cobalt; Table 1.3a).

Iodine

Iodine is a key component of seaweed that is widely studied due to its high variability and potential to cause excessive dietary intake. This report uses the UK and European recommended limit of 600µg per day, although guidance elsewhere in the world is higher (e.g. 1,000µg per day; Joint FAO/WHO Expert Committee on Food Additives, 1989). Across the dataset, median iodine levels are around 650mg/kg, with a strongly skewed distribution and wide range (200–2,674mg/kg interquartile range; mean 1,661mg/kg), indicating substantial variability between species and samples. The European Food Safety Authority (EFSA) has identified seaweed as a risk for excessive iodine exposure and proposed a draft limit of 1,000mg/kg, which is exceeded by 38% of all results in the dataset. Brown kelps, particularly Laminaria species and Saccharina latissima, show the highest concentrations and even small portions can exceed upper intake limits. There is more variation amongst brown wrack species: iodine content can be high in Ascophyllum nodosum and Fucus serratus, whereas levels in Pelvetia canaliculata, Fucus spiralis and Fucus vesiculosus are lower but still represent a possible risk. In contrast, red and green seaweeds generally have lower iodine levels, though some red species show occasional high values (e.g. Chondrus crispus). Overall, iodine content is highly variable within and between species due to environmental and biological factors. Although processing methods can reduce levels, raw dried kelps in particular present a clear risk of excessive iodine intake. Table 1.2 lists seaweed species by their risk category for excess iodine intake. Generally, there is minimal risk for green seaweed, but risk is species dependent for brown seaweeds and green seaweeds.

Table 1.2: Risk of excessive intake of iodine from consuming different seaweeds.

Category for iodine	Species
Minimal risk of excess intake via seaweed	Himanthalia elongata, Porphyra spp., Ulva lactuca, Ulva intestinalis
Possible risk of excess intake via seaweed	Pelvetia canaliculata, Fucus spiralis, Fucus vesiculosus, Sacchoriza polyschides*, Palmaria palmata, Osmundea pinnatifida*
	Ascophyllum nodosum, Fucus serratus, Alaria esculenta, Chondrus crispus, Mastocarpus stellatus
Risk of excess intake via seaweed	Saccharina latissima, Laminaria digitata, Laminaria hyperborea, Vertebrata lanosa*

* Indicates species with only one result in the dataset and, therefore, less confident categorisation.

Beneficial trace minerals

Beneficial trace minerals are elements that may support health at very small intake levels (e.g. <10µg per day). Indeed, some elements in this category could be regarded as neutral with regard to human health. Although beneficial trace minerals generally have low toxicity, upper intake limits are usually in place. They are often included in seaweed composition studies, but some elements are less well studied. Of the eight elements in this category, only bromine is of concern (all others have a minimal risk of excess intake: molybdenum, strontium, bromine, chromium, boron, rubidium, vanadium, lithium; Table 1.3a).

Bromine

Bromine (as bromide) is widely present in the environment and typically occurs in foods at low levels, with no routine dietary regulation. The EFSA established a reference dose of 28mg per day and has recently reviewed bromide exposure because elevated levels in seaweed can transfer into the human food chain and potentially affect thyroid function by competing with iodine. The dataset suggests bromine concentrations in seaweed are relatively high compared with terrestrial foods, with substantial variability between species. Saccharina latissima in particular shows consistently elevated levels across multiple studies and countries, while some red seaweeds also approach high concentrations. Using a precautionary estimate of 2,000mg/kg, a 5 gram dry portion could contribute up to around 36% of the EFSA acute reference dose. However, excluding high-outlier species such as Saccharina latissima reduces estimated exposure substantially (to around 10%). Overall, there is a potential but uncertain risk of excessive bromine intake from certain seaweeds, though current evidence is limited and iodine exposure remains the more established nutritional concern.

Table 1.3a: Levels of minerals essential or beneficial to health in relevant seaweed species determined through literature review of studies of European seaweed.

Category (function)	Element	Levels in dataset			Sources	Risk from consuming seaweed
		Median	25th - 75th percentiles	90th percentiles		
Essential macro-minerals (core to health)	Potassium, Magnesium, Calcium, etc.	Widely studied but excluded from dataset (not within scope of toxicity)				Minimal risk of excess intake
Essential trace minerals (needed in small quantities to support specific functions; 10µg – 100mg daily)	Iron	172 mg/kg	84 - 366 mg/kg	733 mg/kg	194 results from 65 studies (ΣN=1,351)	Minimal risk of excess intake
	Manganese	18.4 mg/kg	7.8 - 65.9 mg/kg	147 mg/kg	176 results from 56 studies (ΣN=1,031)	Minimal risk of excess intake
	Copper	2.7 mg/kg	1.4 - 6.0 mg/kg	13 0 mg/kg	199 results from 70 studies (ΣN=1,488)	Minimal risk of excess intake
	Selenium	0.14 mg/kg	0.07 - 0.42 mg/kg	4.5 mg/kg	93 results from 28 studies (ΣN=366)	Minimal risk of excess intake
	Zinc	32.0 mg/kg	21.8 - 50.9 mg/kg	73.8 mg/kg	209 results from 70 studies (ΣN=1,412)	Minimal risk of excess intake
	Cobalt	0.36 mg/kg	0.16 - 0.82 mg/kg	1.97 mg/kg	94 results from 28 studies (ΣN=776)	Minimal risk of excess intake
	Iodine	650 mg/kg	200 – 2,674 mg/kg	4,643 mg/kg	247 results from 62 studies (ΣN=1,493)	Risk of excess intake (variation by species)
Beneficial trace minerals (minute intake may be beneficial, but not essential; <10µg daily)	Molybdenum	0.32 mg/kg	0.24 - 0.83 mg/kg	1.76 mg/kg	67 results from 20 studies (ΣN=512)	Minimal risk of excess intake
	Strontium	658 mg/kg	461 - 800 mg/kg	899 mg/kg	28 results from 16 studies (ΣN=296)	Minimal risk of excess intake
	Bromine	664 mg/kg	461 - 981 mg/kg	1587 mg/kg	28 results from 11 studies (ΣN=874)	Possible risk of excess intake (variation by species)
	Chromium	0.98 mg/kg	0.50 - 2.02 mg/kg	6.94 mg/kg	99 results from 39 studies (ΣN=697)	Minimal risk of excess intake
	Boron	132 mg/kg	116 - 158 mg/kg	199 mg/kg	12 results from 6 studies (ΣN=39)	Minimal risk of excess intake
	Rubidium	19.8 mg/kg	12.5 - 27.8 mg/kg	34.0 mg/kg	18 results from 9 studies (ΣN=185)	Minimal risk of excess intake
	Vanadium	1.34 mg/kg	1.25 - 1.63 mg/kg	1.74 mg/kg	13 results from 7 studies (ΣN=97)	Minimal risk of excess intake
	Lithium	0.94 mg/kg	0.51 - 1.76 mg/kg	2.9 mg/kg	17 results from 8 studies (ΣN=158)	Minimal risk of excess intake

Characterised toxic elements

Many elements can cause adverse health effects and are considered toxic. Some may only be toxic if ingested in large amounts, but many are known to damage health at trace quantities. The toxicity of many elements is well understood and they are routinely included in seaweed monitoring programmes. It is likely tolerable intake limits will be in place for these characterised toxic elements, either as daily or weekly recommendations. However, tolerable limits are occasionally withdrawn by authorities when evidence suggests intake should be completely avoided. Risks are often sufficiently understood to warrant legal limits in certain foods.

Nickel

Nickel is naturally occurs in soils, with concentrations influenced by local geology and human activity (e.g. industrial emissions, transport-related pollution). While it has limited biological importance in humans, it is generally regarded as toxic due to potential adverse health effects. The EFSA has established a tolerable daily intake of 0.91 mg/day for adults. Nickel levels in seaweed are generally lower than some foods (e.g. legumes, tea, cocoa). Across seaweed species, most measured concentrations generally low (Table 1.3b) and are well below regulatory limits (30mg/kg; amendment to Regulation, EU, 2023/915). Only a small proportion exceed 10mg/kg and none approach maximum permitted levels. Typical seaweed consumption contributes a small fraction of the tolerable intake, indicating that nickel from seaweed is of minimal risk to health.

Aluminium

Aluminium is a naturally abundant element in soil and water, while anthropogenic sources such as industry and transport also contribute to environmental presence. It has no known biological role in humans and, although only partially absorbed, chronic exposure has been linked to potential health effects. The EFSA has set a tolerable weekly intake equivalent to about 10 mg per day for adults. Aluminium is present in many foods at low levels, but seaweed shows particularly wide variability and generally elevated concentrations compared with most foods. The median level in the dataset is 120mg/kg, but the highest levels are all from seaweed harvested in Scotland and Northern Ireland. Indeed, average levels across species collected in Scotland are roughly double those from Spain (the country with several studies and the next highest average levels). One of the few species consistently tested across Europe is Saccharina latissima. Scottish Saccharina latissima has considerably higher levels than the same species from Sweden or Norway, which indicates there is a particular issue in Scotland regarding aluminium in seaweed. This may be linked to conditions specific to different regions, particularly in peat-rich and granitic areas.

Aluminum levels in Scottish Saccharina latissima appear to be higher than the same species collected in other countries

Table 1.3b: Levels of toxic elements in relevant seaweed species determined through literature review of studies of European seaweed.

Category (function)	Element	Levels in dataset			Sources	Risk from consuming seaweed
		Median	25th - 75th percentiles	90th percentile		
Characterised toxic trace elements (toxic even in small amounts, widely studied)	Nickel	1.77 mg/kg	0.81 - 4.24 mg/kg	7.84 mg/kg	90 results from 30 studies (ΣN=975)	Minimal risk of excess intake
	Aluminium	120.0 mg/kg	25.2 - 356.5 mg/kg	787.0 mg/kg	63 results from 27 studies (ΣN=552)	Possible risk of excess intake (variation by species and location)
	Cadmium	0.59 mg/kg	0.21 - 1.20 mg/kg	2.02 mg/kg	281 results from 79 studies (ΣN=2,397)	Possible risk of excess intake (variation by location)
	Mercury	0.016 mg/kg	0.006 - 0.030 mg/kg	0.050 mg/kg	137 results from 38 studies (ΣN=1,094)	Minimal risk of excess intake
	Lead	0.33 mg/kg	0.16 - 0.83 mg/kg	1.44 mg/kg	244 results from 71 studies (ΣN=1,751)	Possible risk of excess intake (variation by species and location)
	Arsenic (inorganic)	0.21 mg/kg	0.10 - 0.45 mg/kg	0.88 mg/kg	101 results from 25 studies (ΣN=630)	Possible risk of excess intake (variation by species and location) Risk of excess intake for Laminaria digitata
Other toxic trace elements (toxic even in small amounts, rarely studied)*	Barium	12.9 mg/kg	8.4 - 16.3 mg/kg	27.4 mg/kg	38 results from 20 studies (ΣN=245)	Minimal risk of excess intake
	Titanium	12.5 mg/kg	8.8 - 40.8 mg/kg	47.4 mg/kg	10 results from 8 studies (ΣN=89)	Minimal risk of excess intake
	Silver	0.04 mg/kg	0.02 - 0.11 mg/kg	0.21 mg/kg	19 results from 8 studies (ΣN=66)	Minimal risk of excess intake
	Tin	0.03 mg/kg	0.02 - 0.16 mg/kg	0.22 mg/kg	11 results from 6 studies (ΣN=40)	Minimal risk of excess intake

*Various elements are not stated in this category as they feature in fewer than ten studies (e.g. thallium, beryllium, rare earth elements).

While many samples fall within moderate ranges for aluminium content, extreme values can exceed 1,500mg/kg, meaning that even small seaweed portions could approach or exceed daily dietary intake limits. Although elevated levels appear location-specific rather than universal, aluminium in seaweed is recognised as a potential emerging food safety concern due to its variability and capacity for high accumulation. More analysis and research is required to further understand the risks of aluminium in seaweed.

Cadmium

Cadmium is a naturally occurring but toxic metal that is present in the environment at low levels, with higher concentrations often linked to industrial activity, mining, agriculture and acidic soils. It has no known biological function in humans and accumulates over time to affect health, which led the EFSA to set a tolerable weekly intake of 25 µg/day for adults). While cadmium exposure in the general diet is relatively low, seaweed is a recognised source of measurable concentrations due to its ability to absorb metals from surrounding water, though most observed levels remain below regulatory thresholds.

Across studies, seaweed cadmium concentrations are generally moderate (Table 1.3b), with a median concentration of 0.59mg/kg across all species and few high outliers. Almost all results are below 3mg/kg, which is the current limit used for seaweed food supplements (Regulation, EC, 1881/2006) and the lowest of the draft maximum limits for cadmium proposed for edible seaweed in Europe. Some species, particularly Alaria esculenta and occasionally Laminaria digitata and Himanthalia elongata, show higher values depending on location, with northern regions such as Greenland and Iceland tending to have elevated levels compared with others. The results exceeding 3mg/kg are from nine different species collected from five northern Europe countries, which indicates the variability is driven by location.

Typical seaweed consumption would contribute a small proportion of tolerable intake for cadmium, suggesting the hazard is low for average exposure. However, some results for Scottish seaweed exceed the regulatory limit and so there is possible risk for adverse health impacts. Furthermore, ongoing monitoring of cadmium in seaweed is important due to toxicity, variability across environments, legal limits and expectations from customers.

Mercury

Although naturally occurring, mercury is a highly toxic metal that can enter the environment through both geological sources and human activity (e.g. historic coal burning, metal production and industrial processes). Mercury can exist in different forms in the environment, with methylmercury the most toxic due to its high bioavailability and tendency to bioaccumulate in food chains. While seafood is the primary dietary source of methylmercury for humans, methylmercury appears to be a smaller proportion of total mercury content in seaweed. The EFSA set a provisional tolerable intake for mercury equivalent to 40µg per day for an adult.

Across European studies, mercury levels in seaweed are generally low and comparable to or below those found in other seafood, with most samples well under proposed food safety limits. The dataset shows a mean concentration of around 0.03mg/kg, and only a small proportion of results exceed 0.10mg/kg (a reference limit used in France and aligned with EU food supplement guidance, Regulation, EC, 2023/915 and amendments). Occasional higher values have been observed in specific samples and years, but these are not consistent across species or regions, and overall variation appears limited compared with other contaminants.

Exposure from seaweed consumption remains low relative to established tolerable intake levels. A typical portion of dried seaweed at or near regulatory limits would contribute only a small fraction of the provisional intake for mercury, indicating that health risks are minimal at normal consumption levels. However, the well-established toxicity of mercury and its regulation in other food groups makes continued monitoring of seaweed worthwhile. Overall emissions in the UK have declined, but there may be areas with historic contamination concerns that would warrant additional testing.

Lead

Lead contamination in Scotland is generally low in soils and streams, but elevated levels occur in some regions and urban centres due to historical anthropogenic sources (e.g. legacy mining, industrial activity, leaded petrol residues). Because lead is toxic at very low levels with no safe exposure threshold, regulatory bodies such as EFSA recommend keeping exposure as low as reasonably achievable; previous tolerable intake limits have been withdrawn.

Food safety regulations in Europe set maximum lead limits for most foods, typically below 1.0 mg/kg (under Regulation, EC, 2023/915 and amendments). Seaweed is not included, but the use of seaweed in food supplements means it is reasonable to apply a limit of 3.0mg/kg. Draft maximum limits have been proposed for seaweed in Europe, ranging between 0.5mg/kg (for Porphyra species) and 2.0mg (green seaweed species and red seaweeds other than Porphyra species).However, they reflect the precautionary approach to minimise dietary lead exposure

Ulva species appear to have an affinity for lead, but elevated levels may be linked to sourcing in areas with freshwater influence

Lead is widely analysed in seaweed and concentrations are generally moderate (Table 1.3b). Median levels are around 0.1-0.9mg/kg depending on species. The median level across all species is 0.33mg/kg and only 4% of results are above 3.0mg/kg. However, lead levels can occasionally reach much higher levels. Higher lead levels are more likely in seaweed collected from polluted or runoff-affected waters, particularly in species in the Ulva genus. However, elevated concentrations also occur across other genera, indicating that contamination is not species-specific. Overall, typical exposure from seaweed consumption is low, but the higher levels seen in some results suggests there is a possible risk of excess lead intake. This may particularly be the case in areas near sources of industrial or urban pollution. As a result, continued monitoring of lead in seaweed is recommended, with attention to local environmental conditions.

Arsenic

Arsenic occurs naturally in the environment and human activities can contribute to localised arsenic contamination (e.g. coal combustion, industrial processes and historical use in pesticides and wood preservatives). In water, arsenic exists mainly in two forms: trivalent (As^{3+}) dominating in reducing and acidic conditions, and pentavalent (As^{5+}) dominating in oxygenated environments like seawater. The toxicity of arsenic depends strongly on its chemical form. Inorganic arsenic is significantly more toxic than organic forms, with trivalent arsenic being particularly harmful due to its ability to bind to proteins and disrupt cellular processes. Organic arsenic compounds, commonly found in seafood, are generally less toxic and are rapidly excreted by the body. Regulatory bodies such as EFSA have therefore focused on inorganic arsenic when assessing health risks. Rather than setting a safe intake threshold, EFSA established a range of exposure levels associated with increased cancer risk.

Seaweed can contain relatively high levels of total arsenic compared to other foods, particularly brown seaweeds. It is possible for kelps and wracks to exceed European regulatory limits set for animal feed (Directive 2002/32/EC). However, total arsenic measurements alone are not a reliable indicator of risk for human health, as most arsenic in seaweed is present in organic forms with low toxicity. Speciation – the breakdown of arsenic into its different chemical forms – is therefore critical for accurate risk assessment. In seaweed, the dominant compounds are arsenosugars and smaller amounts arsenolipids and methylated arsenicals (DMA and MMA), are also present. Current evidence suggests that arsenosugars largely explain differences in total arsenic levels between seaweed types.

Inorganic arsenic is the most toxic form of arsenic and is increasingly prioritised in food safety assessments. There are limits in the EU for food, which state inorganic arsenic is the sum of trivalent arsenic and pentavalent arsenic (Regulation (EC) No 2023/915). Regulatory attention has grown in recent years: while early EU limits focused on foods like rice, newer legislation has introduced limits for seafood. Proposed European limits for seaweed (0.5 mg/kg for red species and 1.0mg/kg for brown and green species) are significantly lower than the existing French standard of 3.0mg/kg.

Inorganic arsenic levels in seaweed (Table 1.3b) are typically higher than in seafood, but vary widely by species. Most red and green seaweeds, as well as many brown species (e.g. fucoid wracks), contain low to moderate levels that generally fall within proposed regulatory limits. However, occasional elevated values occur, influenced by environmental conditions, geography and possibly harvesting factors (e.g. part harvested). Certain species stand out for higher inorganic arsenic content. Kelp species such as Saccharina latissima and Alaria esculenta can sometimes exceed proposed limits, though most samples remain within acceptable ranges. In contrast, Laminaria digitata consistently shows consistently high inorganic arsenic concentrations across multiple studies and regions, often far exceeding regulatory thresholds. This appears to be an intrinsic species characteristic rather than a result of local environmental conditions; levels can vary even within short distances or different parts of the same plant. Similarly, species in the Sargassaceae family – particularly Sargassum fusiforme (hijiki) – are well known for accumulating high proportions of inorganic arsenic, leading to international consumption advisory notices. While processing methods such as boiling can reduce arsenic levels, they are often insufficient to mitigate risk when initial concentrations are very high.


In contrast to other key seaweed species in Scotland, Laminaria digitata has naturally high levels of inorganic arsenic

In conclusion, there is a risk of excessive inorganic arsenic exposure from consuming Laminaria digitata and other species with naturally high content (e.g. Sargassum fusiforme). Inorganic arsenic levels in the majority of other species are generally below proposed European limits, but occasional exceedances are seen in the dataset (e.g. Saccharina latissima, Alaria esculenta, Palmaria palmata, Porphyra species and Ulva species). This indicates that environmental factors can influence inorganic arsenic content; it is more likely that geology is a more important factor than local anthropogenic contamination. Overall, there is a possible risk of excessive inorganic arsenic exposure from most seaweed species and a regulatory threshold around 3.0mg/kg appears to balance consumer safety with practical considerations for producers. Baseline testing and ongoing monitoring is important, which must analyse inorganic arsenic and not rely on conversions from total arsenic content (as some risk assessments have done in the past). Species-specific risk assessment is essential and Laminaria digitata in particular should be treated as a high-risk species.

Other toxic trace elements

Although many elements are known to be toxic, the risk profile for many is less well understood. This means tolerable upper limits are less likely to be published. Studies of seaweed composition include results for a wide range of elements, some of which can be reviewed for food safety risk. Most of these elements occur naturally in rocks and soils, with local geological variation influencing their presence in the marine environment. Anthropogenic sources – such as industrial activity, wastewater, fossil fuel combustion, and consumer products – can contribute to environmental contamination, though natural sources are dominant for many of these elements.

Barium, titanium, tin, bismuth, beryllium, uranium and antimony are generally present in seaweed at low concentrations (or below quantification limits), and estimated intake from realistic portion sizes is negligible compared to dietary intake or established safety thresholds. Silver and thallium show more variability and potential for elevated concentrations in certain cases, particularly in Ulva species. However, these high values are rare and may reflect local contamination or possible analytical inconsistencies.

Other sets of elements with similar characteristics include rare earth elements (REEs; e.g. neodymium, europium, scandium), platinum group elements (PGEs; e.g. platinum, osmium, palladium) and actinides (e.g. actinium, thorium, protactinium). Studies are starting to include these elements. Although detectable in seaweed, levels are usually extremely low and are of minimal risk as a food safety concern. This is an emerging area of research that must be kept under review, but ongoing testing is not necessary.

Summary of excess nutrients and toxic elements

The review of nutrient and toxic element concentrations in relevant seaweed species has highlighted that there are some with a risk of excess intake, but also in some instances that there is limited data to draw a conclusion from. Figure 1.1 is a matrix of 25 elements by risk of excess intake and the quality of the evidence (over thresholds for number of results, studies and aggregated samples used in analysis). Figure 1.1 excludes elements with fewer than 10 results in the dataset (e.g. antimony, beryllium, rare earth elements) but it is unlikely they are a health concern.

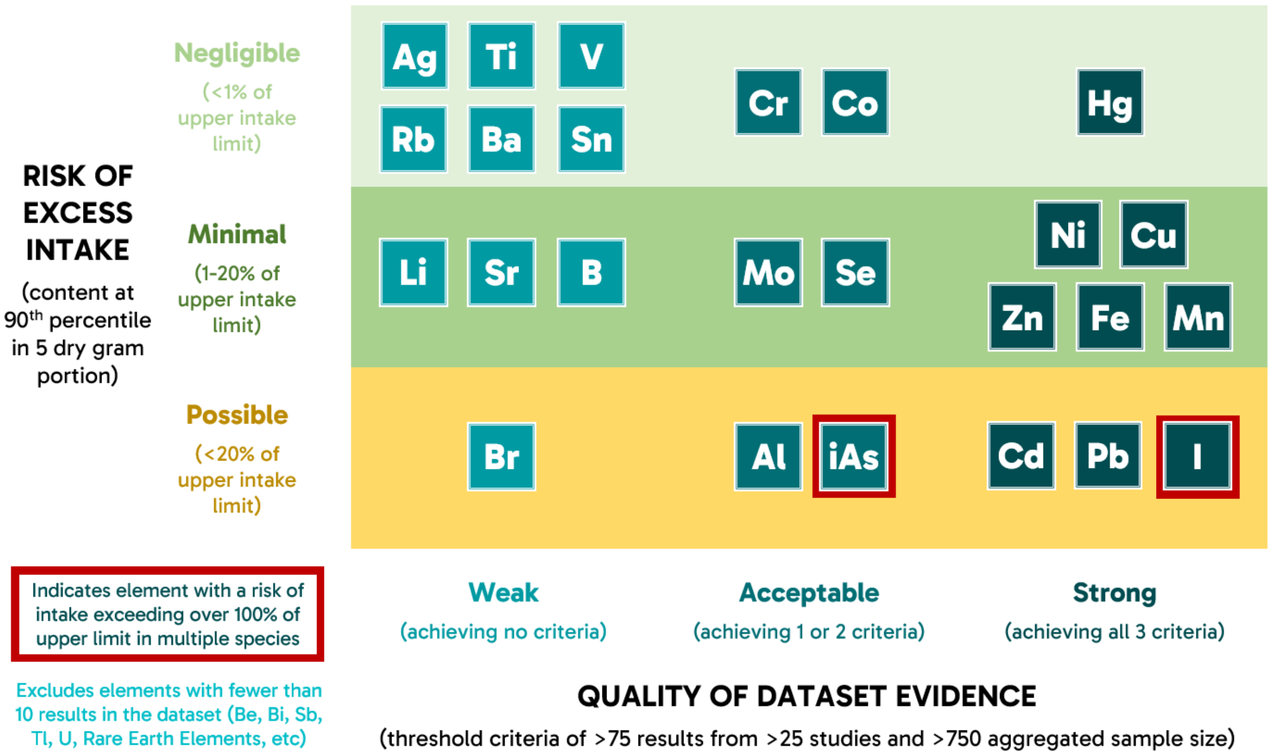


Figure 1.1: Matrix of elements in relevant seaweed species by risk of excess intake and the quality of the evidence determined through literature review.

Using the content at the 90th percentile from the dataset in a 5 dry gram portion as a measure of high likely concentration, there are nine elements of negligible risk of exceeding the appropriate guidance value (i.e. <1% of Upper Limit). Even if more data was sourced through additional testing, it appears unlikely levels will be found that indicate a significant issue for seaweed.

There are ten elements for which the 90th percentile content would represent a minimal risk of excess intake (i.e. 1-20% of the guidance value). There is strong evidence that nickel, copper, zinc, iron and manganese are in this category. The evidence is reasonably conclusive that molybdenum and selenium are of minimal risk. Although high content of lithium, strontium and boron would not exceed 20% of the guidance value, the data is more limited and it is difficult to draw a strong conclusion.

Finally, there are six elements for which the 90th percentile content would represent at least a possible risk of excess intake (i.e. >20% of the guidance value). Cadmium and lead have been widely studied in European seaweed are less likely to exceed guidance values. Bromine and aluminium are also unlikely to exceed guidance values, although they have been less frequently included in seaweed composition studies and are an emerging issue. Iodine and inorganic arsenic are recognised as carrying a clear risk of the guidance value being surpassed in multiple species (bordered in red in Figure 1.1; Table 1.3a&b) and there is strong evidence to draw such a conclusion.

Anthropogenic compounds

A range of contaminants in the marine environment arise from human activity (e.g. agriculture, industry). Substances enter coastal waters, leading to accumulation in marine sediments and uptake by biota. Harmful compounds can also be generated during processing.

Halogenated POPs

Halogenated persistent organic pollutants (POPs) are long-lived environmental contaminants that bioaccumulate in food chains due to their lipophilic nature and resistance to degradation. These compounds can persist in sediments and aquatic environments for extended periods, where they may be remobilised through natural disturbance or human activity. Human exposure is primarily dietary, particularly through animal-derived foods such as meat, dairy and seafood, where these contaminants accumulate in fat tissue. Long-term exposure has been associated with endocrine disruption, immune impairment and increased cancer risk. Although regulatory limits exist in the EU for food and feed, these largely focus on animal products, and monitoring data for seaweed remain limited.

Dioxins, polychlorinated biphenyls and brominated flame retardants

For dioxins, polychlorinated biphenyls (PCBs) and brominated flame retardants (BFRs), available evidence suggests that seaweed generally represents a low exposure risk. These compounds are typically hydrophobic and associated with sediments rather than being efficiently accumulated by seaweed, which has low lipid content. Where contamination has been detected, levels are typically linked to proximity to industrial activity, ports or contaminated sediments. Studies such as Hahn et al. (2022) have reported measurable but relatively low concentrations in Fucus species, while broader reviews (e.g. Banach et al., 2020) highlight the scarcity of robust datasets. Overall, the current evidence base is limited but does not indicate a significant food safety concern for seaweed under typical harvesting conditions.

Per- and polyfluoroalkyl substances

Per- and polyfluoroalkyl substances (PFAS) are a separate class of persistent contaminants of growing concern due to their widespread environmental presence and strong resistance to degradation. PFAS can accumulate in aquatic ecosystems and biota, with dietary exposure linked to adverse health outcomes including endocrine disruption, immune effects and increased cholesterol levels. Regulatory limits in the EU currently apply to selected PFAS in animal products and seafood, but not seaweed. Limited studies indicate that seaweed can accumulate detectable PFAS, particularly near wastewater discharges or contaminated coastal areas, although concentrations reported to date are generally low. This suggests a need for improved monitoring as seaweed consumption increases globally.

Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are another relevant contaminant group, originating either from incomplete combustion (non-alkylated PAHs) or petroleum sources such as oil spills and shipping activity (alkylated PAHs). Seaweed can accumulate PAHs from dissolved and particulate phases, with highest levels observed in polluted coastal environments. Evidence indicates that alkylated PAHs tend to dominate in contaminated seaweed and can reach substantially higher concentrations than non-alkylated forms. In contrast, seaweed from remote or less impacted areas typically shows low or negligible PAH levels. While EU regulations exist for PAHs in food, they focus on combustion-derived compounds and do not specifically address seaweed, highlighting the importance of site selection and environmental context.

Other contaminants

Other contaminants such as 3-monochloropropane-1,2-diol (3-MCPD), glycidyl fatty acid esters, nitrates, melamine and perchlorate are either unlikely to accumulate significantly in seaweed or are present at levels not considered to pose a meaningful food safety risk under current evidence. Some, such as nitrates and perchlorate, can be taken up from marine environments, but exposure assessments suggest intake from seaweed is generally within safe limits under normal consumption scenarios. Overall, while seaweed can interact with a range of environmental contaminants, current data indicate that risk is highly dependent on local environmental conditions, with low risk in well-managed or low-impact harvesting areas.

Pesticides

While pesticides are not directly applied to seaweed, they can be absorbed from the environment and so pose a cross-contamination food safety risk. Pesticide use in Scotland largely driven by agriculture, with around 1,500 tonnes applied annually. The vast majority is used on arable crops that dominate Scottish farmland (e.g. cereals, potatoes and oilseed rape). Fungicides are the most widely used category, accounting for roughly half of all agricultural pesticide use by weight, with key compounds including folpet and prothioconazole. Herbicides such as glyphosate and metsulfuron-methyl are also widely used, while insecticide use is comparatively lower but still significant. Potatoes receive the most intensive treatment, particularly fungicides applied repeatedly to control blight, while other crops vary in application intensity depending on area and pest pressure. Pesticides are also widely used outside terrestrial farming, including in urban areas, gardens, golf courses, forestry and aquaculture. These uses are more spatially dispersed but can still contribute to local environmental contamination, particularly via drainage systems. A wide range of chemicals is involved across these settings, and the diversity of pesticide types and applications continues to expand. Environmental monitoring shows that both legacy and modern pesticides persist in soils, waters and organisms, highlighting the importance of understanding cumulative and multi-source inputs.

Seaweeds have been studied as bioindicators of pesticide contamination. However, research on pesticide residues in seaweed remains limited, mostly restricted to outside Europe and the Atlantic region. Available studies indicate the presence of both modern pesticides and persistent legacy compounds. Evidence from seafood studies, including in Korea, suggests that even when seaweed shows relatively high detection rates, estimated human exposure remains far below acceptable daily intake limits.

Regulation of pesticide residues is governed by EU frameworks that set maximum residue limits (MRLs), based on expected levels from good agricultural practice rather than direct toxicity. MRLs vary between foods and are often set at low detection thresholds. However, detection of residues does not necessarily indicate risk or illegality, as residues may arise from environmental contamination, analytical limitations or rapid chemical degradation patterns. For seaweed, contamination is more likely linked to runoff, rainfall events and proximity to agricultural or aquaculture activities.

Quaternary ammonium compounds (QACs) are commonly used as disinfectants in food production because they are effective against bacteria, fungi and viruses, but residues left on surfaces after cleaning can pose a food safety risk. Seaweed is particularly vulnerable to contamination during washing if QACs are overused or not rinsed away properly, which could lead to regulatory compliance issues although consumer health risks are unlikely.

Overall, managing pesticide risk in seaweed production relies on careful site selection, avoidance of high-risk runoff zones and consideration of day-to-day conditions (e.g. heavy rainfall). Routine monitoring and residue analysis may be appropriate in areas where agricultural intensity is high. While regulatory frameworks and analytical sensitivity continue to improve, the presence of trace residues in seaweed does not automatically imply a food safety concern. It is a more significant consideration for organic certified seaweed production, where detection of pesticide residues will likely trigger investigation.

Additional controls and monitoring for pesticides may be warranted if agricultural fields are adjacent to coastal areas used for seaweed harvesting or cultivation

Biogenic toxins

Naturally occurring toxins can present potential risks to human health. Generally, these are divided between those associated with fungi and plants.

Mycotoxins

Seaweed may act as a substrate for microbial growth both in its natural aquatic environment and during processing, creating conditions where toxin-producing fungi can develop. Mycotoxins are a large and diverse group of toxic compounds produced by moulds that can contaminate crops before harvest or during storage. They are associated with a wide range of harmful impacts, which can be long-term health effects (e.g. organ damage, cancer).

Across food categories, mycotoxins are most commonly associated with cereals and animal products derived from contaminated feed. However, they can also occur in dried foods such as fruits, nuts, herbs and spices. The EU regulates maximum allowable levels of several mycotoxins in food under Regulation No 2023/915, including limits for compounds such as ochratoxin A in dried herbs and spices. However, seaweed is not directly included in these specific regulatory limits, meaning risk assessment is less well defined for this food category.

Research on mycotoxins in seaweed is limited Some studies have detected multiple mycotoxins in edible seaweed species, including a broad range of toxins in fucoid wracks from the White Sea (Burkin et al., 2021; Kononenko et al., 2021, 2022; Burkin & Kononenko, 2023). Because mycotoxins are not always destroyed by food processing, controlling fungal growth in seaweed – particularly through rapid and complete drying – is critical.

While evidence shows that mycotoxins can be present in seaweed, the significance of this as a food safety risk remains unclear. Findings vary by species and region, and data are still limited. Further research is needed to better characterise the hazard, particularly considering how processing methods like drying influence fungal growth. In the meantime, it may be prudent for seaweed processors to include mycotoxin monitoring as part of routine food safety controls.

Other biotoxins

Marine biotoxins are primarily produced by algae, dinoflagellates, cyanobacteria and associated microorganisms. A specific concern for seaweed safety is kainic acid in Palmaria palmata (dulse), a naturally occurring amino acid that can affect the central nervous system at high exposures. Although studies have detected varying levels of kainic acid in commercial products, ordinary dietary consumption is not currently considered likely to pose a health risk. However, uncertainties remain regarding how concentrations vary, the impact of processing and whether future regulation may be required. More broadly, seaweeds may also carry or adsorb shellfish-related marine toxins such as those linked to paralytic, amnesic and diarrhetic shellfish poisoning, particularly when harvested in waters affected by harmful algal blooms.

While seaweeds are considered a lower risk for marine biotoxins than filter-feeding shellfish, increasing commercial production, climate change and the growing frequency of harmful algal blooms have heightened scientific and regulatory interest. There are significant knowledge gaps around toxin accumulation in seaweeds and Scotland is vulnerable to harmful algal blooms. Therefore, it is important to keep the risk of marine biotoxins under review. In addition, although most existing legal limits target biotoxins from terrestrial foods, some regulations relating to herbal infusions be relevant apply to seaweed-derived products and producers may need testing to demonstrate compliance.

Allergens

Food allergens are a significant food safety concern due to their potential to cause severe or life-threatening reactions. In the context of seaweed, allergen risks are complex and closely linked to sourcing, harvesting and processing conditions. As a result, risks cannot be generalised across all products; each food business operator must assess their own supply chain, premises and processes. While UK law (retained from the EU Food Information for Consumers Regulation (EU) No 1169/2011) defines 14 major allergens that require mandatory labelling, the range of foods capable of causing allergic reactions is broader and continues to evolve.

Cross-contamination versus endogenous allergens

Although seaweed itself is not one of the regulated allergens, it is commonly associated with cross-contamination from marine organisms (particularly crustaceans and molluscs, but occasionally fish). These organisms may be physically present on harvested seaweed, especially smaller species such as amphipods and marine snails, and can be impractical to completely remove. The main allergens of concern include tropomyosin (from crustaceans and molluscs) and parvalbumin (from fish), both of which are heat-stable and clinically significant. Studies have shown that low levels of these allergens can be detected in seaweed from NW Europe. While processing can influence allergen levels, it cannot reliably eliminate the risk.

Despite the presence of these allergens, detected levels are generally low and may not always pose a risk to consumers. Tools such as VITAL® (Voluntary Incidental Trace Allergen Labelling) provide a structured, quantitative approach to determine whether precautionary allergen labelling (PAL) is necessary. This helps avoid unnecessary or excessive use of "may contain" statements.

While there is some evidence that seaweed itself may contain compounds that elicit allergenic responses in sensitive individuals, reactions appear to be rare and the risks are poorly characterised. Endogenous allergens are of less concern in seaweed, but producers should review this hazard independently.

Managing allergen risks

The primary focus of allergen management should be on minimising cross-contamination, through good harvesting practices, washing, quality control and supplier checks. Allergen risk assessments should be integrated into HACCP systems. It is likely that product testing is necessary to provide customer reassurance. Laboratory-based methods such as ELISA (Enzyme-Linked Immunosorbent Assay) are considered the most reliable for detecting allergenic proteins. Overall, an evidence-driven approach is essential to ensure both consumer safety and proportionate allergen management in seaweed products. Each FBO must carry out its own risk assessment, as environmental variability means allergen presence can differ between species and batches. Care should also be taken with labelling claims, as "allergen-free" status is difficult to justify for seaweed products due to the natural marine environment.

Microbiological hazards

Microbiological hazards in seaweed arise from naturally occurring marine microorganisms and contamination prior to harvest and during handling and storage. While many are harmless, there are bacteria, viruses, yeasts and moulds can cause spoilage or foodborne illness.

Factors influencing microbial growth

Microbial growth is primarily controlled by water activity, temperature, and pH. Drying is the main preservation method used for seaweed, reducing water activity to levels that inhibit most microorganisms (i.e. <0.60). However, dry-tolerant yeasts and moulds may persist if moisture control is inadequate. Refrigeration is essential for fresh seaweed, while fermentation reduces pH to inhibit the proliferation of many pathogens. Temperature control is particularly important, as many pathogens grow at 5–60°C and rapidly between around 20°C and 50°C.

Microorganisms of concern

Relevant pathogens include bacteria such as Escherichia coli (E. coli), Salmonella, Listeria monocytogenes, Bacillus cereus and Clostridium perfringens. Naturally occurring marine Vibrio species may also be relevant: strains have been detected on Scottish seaweed, but not those highlighted as pathogens. The primary virus of concern is norovirus, which is particularly important in ready-to-eat products and seaweed has been implicated in outbreaks in Asia. Yeasts and moulds mainly affect spoilage, but may present safety risks via mycotoxins.

Managing microbial contamination

Although contaminated seawater is an important source of pathogen microorganisms, improper hygiene, processing and handling can also introduce bacteria, viruses and spoilage fungi. It is possible that integrated multi-trophic aquaculture presents a risk of pathogen transfer to seaweed. Hygiene indicators such as Enterobacteriaceae and E. coli are used to assess process hygiene and potential contamination. Overall, seaweed safety relies on a risk-based HACCP approach, with preventive controls (drying, chilling, sanitation, and water quality management) being more important than end-product testing, which mainly serves as verification and trend monitoring. Each FBO must carry out a comprehensive risk assessment to understand hazards relating to microbiological contamination.

Radionuclides

Radioactive contamination can enter the food chain through water, soil and air following nuclear accidents, industrial activity and poor waste management. When contaminated food is consumed, radionuclides may accumulate in specific tissues and increase the risk of cellular damage and cancer. Seaweed readily absorbs radionuclides from seawater, making it a useful bioindicator for monitoring marine pollution.

In the UK, radioactive contamination is closely monitored through the Radioactivity in Food and the Environment (RIFE) programme. This annual report compiles data from multiple nuclear, defence and research sites across the UK. Findings consistently show that radiation exposure from artificial sources is very low, contributing less than 0.3% of total public exposure, while natural sources remain the dominant contributor. Most contamination affecting Scottish waters originates from outside Scotland – especially from the Sellafield complex in Cumbria – with ocean currents transporting soluble radionuclides along the west coast.

Seaweed is included in the RIFE monitoring programme: radionuclide concentrations are generally low and often below detection limits. Seaweed tends to accumulate certain radionuclides (e.g. technetium-99 and caesium-137) more readily than fish or shellfish, but levels remain far below safety thresholds and are not considered a health concern, especially given the relatively modest consumption of seaweed compared to other seafood.

There are a few localised cases of radioactive particles in Scotland, notably at Dalgety Bay and near Dounreay, but these pose minimal risk to food safety due to limited mobility and ongoing monitoring and remediation. Regulatory limits for radionuclides in food only apply during radiological emergencies: current measured levels in Scottish seaweed are well below these thresholds.


Often used as a bioindicator species, Fucus vesiculosus is included in the vigorous UK radioactivity monitoring programme

Overall, the evidence shows that radionuclides in Scottish seaweed do not present a food safety risk. Given the extensive national monitoring already in place, additional routine testing by producers is unnecessary, except possibly in southwestern areas of Scotland due to proximity to Cumbria. Even then, Sellafield emissions have fallen dramatically and independent testing may serve primarily to provide reassurance to customers. Continued review of annual RIFE reports is recommended to ensure changes in contamination patterns are identified promptly.

Physical contamination

Physical hazards in seaweed primarily arise from environmental debris and processing equipment, and can cause immediate consumer injury such as choking, dental damage, or internal injury. Although relatively infrequent, they are high-impact hazards: a significant proportion of food recalls linked to physical contamination.

Sand, shell and stone fragments

In seaweed, the main environmental hazards include sand, shell, and stone fragments, which may be introduced during harvesting depending on site conditions and species. While sand is not toxic, it is a major quality issue and can indicate poor washing or unsuitable harvesting locations. Shell and stone fragments are more hazardous due to their potential to cause injury and are influenced by environmental exposure and harvesting methods.

Microplastics

Additional risks include metal, glass and plastic fragments, often introduced through equipment wear, handling, or transport. These are typically low-frequency but high-severity hazards requiring strict control (standard in the food processing industry).

An emerging concern is microplastic contamination, as seaweed can accumulate plastic particles from seawater and aquaculture infrastructure. Studies show measurable microplastic loads in both wild and farmed seaweed, with potential for transfer through the food chain, although the direct human health impact remains under investigation.

Post-harvest controls

Control of physical hazards relies on good harvesting practices, washing, visual inspection and robust processing controls. Post-harvest measures such as washing can reduce debris, while metal detection, magnetic separation, and (where feasible) X-ray systems provide additional safeguards. Overall, effective management depends on preventing contamination at source and applying multiple downstream control steps within a structured food safety system.

Results for Seaweed Scotland member samples

Sample collation

Results were collated by Seaweed Scotland in late 2025 and early 2026. Data came either from analysis of dried samples of seaweed supplied by members or certificates from accredited analytical companies for samples produced by members. In total, results from 95 samples of seaweed were available for review, sourced from eight different members of Seaweed Scotland covering 14 species wild harvested and cultivated from across Scotland.

Excess nutrients & toxic elements

The results for the samples supplied by Seaweed Scotland members can be compared to the dataset created through the literature review of levels in European seaweed.

Essential trace minerals

Iodine levels were similar to the literature review dataset, broadly varying by species as expected. Geographic variation would not be expected, but the results confirm that iodine concentrations in Scottish seaweed are similar to those seen across Europe. Overall, copper results appear to be marginally lower in Scottish seaweed. However, copper is not of concern for food safety.

Toxic trace elements

Table 1.4 summarises the results for toxic trace elements. Concentrations for most toxic trace elements in the Seaweed Scotland member samples were all similar to the results from the literature review (i.e. cadmium, lead, mercury, tin, aluminium). Total arsenic and inorganic arsenic levels varied by species in the Seaweed Scotland member samples as seen in the dataset. Although total arsenic levels are similar, it appears that levels of inorganic arsenic are higher in the Seaweed Scotland member samples. Alaria esculenta is the species for which the most inorganic arsenic results were collated in this project; the median and interquartile range is higher in the Seaweed Scotland samples (0.75, 0.50-1.00) than the dataset from the literature review (0.55, 0.19-0.83). There may be a risk of higher inorganic arsenic in Scottish seaweed, most likely of natural geogenic origin. Given there have been relatively few studies of inorganic arsenic in Scottish seaweed, the data collated in this project are an important addition to the scientific understanding of inorganic arsenic in seaweed.

Levels above recommended limits

No samples exceeded recommended limits for mercury or cadmium. One of 52 samples tested marginally exceeded the recommended limit for lead: Fucus spiralis from the Clyde at 3.4mg/kg (limit 3.0mg/kg). This is not a cause for concern. A few results for tin were supplied by Seaweed Scotland members: all were low. For aluminium, four Seaweed Scotland samples exceeded 500mg/kg, with a maximum of 1,217mg/kg in Alaria esculenta from the west coast. Although there are no limits in place, these levels are high compared to other foods and European seaweed.

Table 1.4: Overview of results for toxic trace elements in samples supplied by Seaweed Scotland members compared with the dataset from the literature review of European seaweed composition.

	Seaweed Scotland member samples				Dataset from literature review				
Toxic trace mineral	**N Results**	**Median**	**25th-75th Percentile Range**	**90th Percentile**	**Median**	**25th-75th Percentile Range**	**90th Percentile**	**N Results above recomm-ended limit**	**Comment on Seaweed Scotland samples**
Arsenic (inorganic)	64	0.66 mg/kg	0.32-1.05 mg/kg	2.38 mg/kg	0.21 mg/kg	0.10-0.45 mg/kg	0.88 mg/kg	5	Marginally higher – variation by species as expected
Arsenic (total)	52	46.1 mg/kg	27.4-57.9 mg/kg	68.1 mg/kg	44.3 mg/kg	20.7-66.0 mg/kg	89.6 mg/kg	N/A	Similar – variation by species as expected
Cadmium	64	0.68 mg/kg	0.21-1.18 mg/kg	1.82 mg/kg	0.59 mg/kg	0.21-1.20 mg/kg	2.02 mg/kg	-	Similar
Lead	52	0.29 mg/kg	0.13-0.62 mg/kg	1.20 mg/kg	0.33 mg/kg	0.16-0.83 mg/kg	1.44 mg/kg	1	Similar
Mercury	63	0.015 mg/kg	0.008-0.021 mg/kg	0.030 mg/kg	0.016 mg/kg	0.006-0.030 mg/kg	0.050 mg/kg	-	Similar
Aluminium	13	130 mg/kg	90-732 mg/kg	731.5 mg/kg	120 mg/kg	25-357 mg/kg	787.1 mg/kg	N/A	Similar
Tin	3	0.07 mg/kg	0.03-0.54 mg/kg*	-	0.03 mg/kg	0.02-0.16 mg/kg	0.22 mg/kg	N/A	Similar – single higher level of no concern

* Lowest and highest values as only three results

Five samples exceeded the recommended inorganic arsenic limit of 3.0mg/kg: one Fucus vesiculosus sample (3.8mg/kg), one Laminaria hyperborea sample (6.7mg/kg) and all three Laminaria digitata samples tested (3.8–46.0mg/kg). The elevated levels in Laminaria digitata match findings from the literature and confirm that this species poses a higher inorganic arsenic risk across Scottish waters, with affected samples from the west, north and east coasts. The Laminaria hyperborea result may reflect accidental harvesting or misidentification with Laminaria digitata. The exceedance in Fucus vesiculosus was only marginal, and the remaining six samples of this species were well below the limit. A further seven samples from four brown seaweed species contained inorganic arsenic between 1.5 and 3.0mg/kg. Red and green seaweeds appear to present lower risk, although testing of these species in this project was limited.

Polycyclic aromatic hydrocarbons (PAHs)

Results for PAHs were available for two samples produced by the membership of Seaweed Scotland. Levels were low, with upper-bound sums of four PAHs at 1.9 and 2.0µg/kg. Although there is no specific regulatory limit for seaweed, these levels are well below limits for comparable dried plant products and supplements. The results suggest PAHs are likely to present a low risk in seaweed, although testing was limited.

Pesticides

A total of 26 samples were sent for pesticide residue screening, which covers a wide range of groups and hundreds of chemicals. There were detections in nine samples across five species and six coastal regions. No clear species or geographic pattern was identified.

Folpet residues were detected in seven samples from six members and one Seaweed Scotland collection. Most results were close to the detection limit, with the highest level at 0.54mg/kg in Alaria esculenta from western Scotland. Folpet is a widely used fungicide in Scottish agriculture, so runoff is the likely source. Although some samples exceeded the default MRL for algae (0.03mg/kg), this limit relates to agricultural practice rather than health risk and folpet toxicity is low. As residues were measured as phthalimide, which may also occur from non-pesticide sources, natural occurrence in seaweed cannot be ruled out. Overall, the detected levels are not considered a health concern.

Dichlobenil, a herbicide commonly associated with non-agricultural weed control, was detected at 0.02mg/kg in one sample of farmed Saccharina latissima, marginally above the default MRL of 0.01mg/kg. Runoff from land is the likely source, but the level detected is not considered a risk to human health.

Diethyltoluamide (DEET), a common ingredient in insect repellents, was detected at 0.03mg/kg in one sample of cultivated Saccharina latissima from western Scotland. As DEET is not used in agriculture, there is no EU MRL for this compound. The low level detected is not considered a human health concern. The most likely source was contamination from insect repellent used by someone handling the seaweed during harvest, which highlights the importance of good hygiene practices.

Quaternary ammonium compounds (QACs)

QACs were detected in 13 of 26 seaweed samples tested for pesticide residues. These compounds, commonly used in disinfectants and cleaning products, are usually associated with hygiene chemicals used in factory settings. Detections occurred across nine species, five regions and most suppliers, with 39 quantified results overall. Most levels were below 0.2mg/kg, although the highest total benzalkonium chloride level was 3.7mg/kg.

QAC contamination often results from inadequate rinsing after sanitisation, particularly in washing equipment. However, detections across six suppliers suggest residues may also originate from environmental contamination. Detection in one sample collected and processed directly by Seaweed Scotland, without entering a factory, confirmed that QACs can occur independently of processing contamination.

Although QACs were found in half the samples, levels were not considered a human health concern. Further work is needed to understand the sources and risks of QACs in seaweed.

Mycotoxins

Three Scottish seaweed samples were tested for mycotoxins: two Saccharina latissima and one Ascophyllum nodosum. No mycotoxins were detected in Saccharina latissima, while aflatoxin B1 was detected in Ascophyllum nodosum at 0.29μg/kg. There is no regulatory limit for mycotoxins in seaweed and the level it is not a health concern. As the positive sample was collected and dried directly by Seaweed Scotland, less controlled drying conditions may have contributed. However, detecting aflatoxin B1 in one of three samples suggests further research into mycotoxin risks in seaweed is needed.

Further research into hazards

Table 1.5 provides a summary of the hazards considered in this report, emphasising the more significant concerns for seaweed producers to control. Unfortunately, limited information is available on certain hazards, making it difficult to draw firm conclusions (as highlighted in Table 1.5). More research is required on the following:

- Bromine (high levels detected, but limited research to date)
- Aluminium (further investigation into elevated levels seen in Scottish seaweed)
- Speciation of arsenic in more species of seaweed, especially toxic forms (i.e. inorganic arsenic)
- Many other toxic trace elements are poorly characterised (e.g. thallium, antimony), although the risk of harm is likely to be low
- Halogenated POPs have been detected in seaweed (e.g. dioxins, PFAS), but research is limited
- PAHs can be found in seaweed collected in areas at risk of pollution, but more research is needed to characterise the risk
- Pesticides residues can be absorbed by seaweed (and were frequently detected in testing of Scottish samples in this project) and further investigation could help control this hazard
- Mycotoxins are a risk for dried seaweed, but has been rarely tested to date
- Additional research into pathogen risks would be welcome, especially reasonable microbiology specifications for seaweed in different formats
- There has been increasing awareness around microplastic pollution in marine habitats and more research would help characterise the risk to seaweed consumers

Table 1.5: Overview of hazards relevant to food safety for seaweed produced in Scotland.

Hazard		Comment	Confidence
Excess nutrients and toxic elements	Essential macro-minerals	No hazard identified (highly unlikely to be consumed to excess)	High
	Essential trace minerals	Only hazard is Iodine (possible risk of excess in most species and clear risk of excess in some species)	High
	Beneficial trace minerals	Only hazard is Bromine (possible risk of excess in some species)	Low
	Characterised toxic trace elements	Only hazards: Aluminium (possible risk of excess in some species, particularly in Scotland) Cadmium (possible risk of excess in many species) Lead (possible risk of excess in some species, particularly by industrial areas) Inorganic arsenic (a possible risk of excess in many species and clear risk of excess in some species)	Medium - High
	Other toxic trace elements	No hazard identified (but difficult to draw firm conclusions due to limited research)	Low
Anthropogenic compounds	Halogenated POPs	Unlikely to be a hazard if basic controls are in place to limit contamination (but detected)	Medium
	PAHs		
	Other contaminants (e.g. 3-MCPD, nitrites)	No hazard identified (unlikely to be relevant to seaweed)	High
	Pesticides	Possible hazard if uncontrolled, but basic controls should to limit contamination (frequently detected in samples of Scottish seaweed)	Medium
Biogenic toxins	Mycotoxins	Unlikely to be a hazard if basic controls are in place to limit contamination (but difficult to draw firm conclusions due to limited research)	Low
	Other biotoxins	Either not relevant to seaweed or unlikely to be a hazard (but detected)	Medium
Allergens*	Molluscs, crustaceans and fish	Unlikely to be a hazard if basic controls are in place to limit contamination (but detected)	Medium
	Nuts and other major allergens	Unlikely to be a hazard, but basic controls must be place to prevent contamination	High
Microbiological hazard*	Pathogenic bacteria and viruses	Possible hazard, but basic controls should minimise risk of contamination	Medium
Radionuclides	Technetium-99, Caesium-137, etc.	No hazard identified (highly unlikely to be consumed to excess)	High
Physical contamination*	Sand and shells	Possible hazard, but basic controls should minimise risk of contamination	High
	Glass and metal fragments	Unlikely to be a hazard, but basic controls must be place to prevent contamination	High
	Microplastics	Unlikely to be a hazard if basic controls are in place to limit contamination (but difficult to draw firm conclusions due to limited research)	Low

* Degree of hazard highly dependent on the nature of the process and contamination controls in place

2. SCOPE

Seaweed Scotland

Formerly the Scottish Seaweed Industry Association (SSIA), Seaweed Scotland is the principal trade and membership body representing Scotland's growing seaweed sector. Established in 2014, the organisation supports businesses involved in wild harvesting, cultivation, processing and product innovation across the seaweed value chain. Seaweed Scotland works to promote sustainable industry development by connecting producers, researchers, policymakers and investors, while also providing guidance on licensing, regulation, and best practice. The association positions seaweed as an important component of Scotland's emerging blue economy with diverse applications.

Scotland's seaweed industry is currently dominated by small and micro-scale enterprises, historically focused on wild harvesting with increasing interest in cultivation. Government and research bodies have highlighted seaweed's economic and environmental value, including its low-carbon production methods, potential contribution to sustainable aquaculture and role in supporting rural and island economies. Seaweed Scotland advocates for responsible expansion of the industry, balancing commercial growth with environmental stewardship and scientific research into marine ecosystems and cultivation practices.

The Code of Good Practice (CoGP) for Seaweed Operations in Scotland was an important milestone for Scottish seaweed. It established shared standards for Scotland's seaweed industry, covering the full supply chain (nurseries, marine farms, wild harvesting and processing facilities). It is designed to promote safe, sustainable and responsible industry growth. The CoGP sets out practical guidance for operators on issues such as biosecurity, habitat protection, harvesting methods, processing standards, and risk management.

As part of the ambition to continuously develop industry insight, Seaweed Scotland successfully applied to Marine Fund Scotland to support a project aiming to provide detailed guidance for seaweed food safety. This has been a long held ambition for the association, which has embarked on various contamination-related projects over the years.

Author

Peter Elbourne is a consultant working on seaweed, food production and a range of innovation and sustainability projects. Formerly a director of New Wave Foods – which launched the SHORE brand in 2018 – and CEO of Horizon Seaweed, Peter has spent nearly 15 years working in the seaweed industry supplying a range of species to diverse sectors. He oversaw the development of a sustainable wild harvest operation, helped pioneer farming at sea in Scotland and established an organic food-grade processing facility accredited by the Soil Association and SALSA. A marine ecologist by training, Peter remained active in applied research and was a co-author on papers studying cultivation technologies (Kerrison et al., 2020) and seaweed composition (Badmus et al., 2021). Peter has been an active member of Seaweed Scotland since 2017, including a term as director (2020-2021).

Concept

This study was undertaken to assess food safety issues associated with the sourcing and processing of seaweed. The primary focus is on hazards relevant to seaweed intended for human consumption, aiming to evaluate current scientific knowledge and identify data gaps. It covers seaweed collected from foreshore or farmed at sea or on land. Although beach-cast seaweed is a resource available in Scotland, there is little consideration of food safety concerns in this report. This is essentially because there are clear additional risks for beach-cast material over freshly harvested seaweed (e.g. mixed species, uncertain origin, decay, marine plastics).

Contamination associated with beach-cast seaweed is generally excluded from this report, given evident food safety risks

While the central scope is seaweed used as a food, the assessment is also relevant to other uses of seaweed. This is especially the case for use of seaweed as food supplements, which is an established application with some longstanding regulatory limits in place. However, the information in this report will be of some relevance to livestock and companion animal feed, bioactive extraction and cosmetic products. This is because many of the same raw materials, harvesting environments and processing steps are shared across these sectors, leading to overlapping exposure pathways and potential hazards. For example, accumulation of heavy metals or persistent organic pollutants in seaweed could pose risks regardless of whether the final product is consumed directly by humans in food, drink and dietary supplements or incorporated into animal feed and cosmetic formulations.

Milled Palmaria palmata – a format and species commonly used in food applications

Accordingly, the findings of this study are intended to provide a broadly applicable evidence base that can inform risk management considerations across multiple end uses of seaweed. However, where relevant, differences in exposure routes, consumption patterns and regulatory requirements will be acknowledged to ensure appropriate interpretation of risks within each specific context.

The majority of the research effort has gone into collating data in the literature related to element concentrations in seaweed. This covers both minerals essential to human health that could be consumed to excess and toxic elements not required to maintain health.

Understanding the levels and variation is crucial for promoting safe intake levels and protecting public health.

This report draws on previous studies covering food safety assessments for seaweed (e.g. Banach et al., 2020, 2024; Duinker et al. 2020; Cavallo et al., 2021; Woźniak & Moya, 2024). There are also several recent analyses of seaweed composition that provide helpful context for anyone using seaweed in food applications (e.g. Jonssen & Karlsson, 2023; Ficheux et al., 2023).

3. EVALUATING CONTAMINATION RISKS

For most applications, a seaweed operation must assess the risk of contamination when planning to licence foreshore for wild harvesting or seabed for cultivation. This is in addition to analysis of conservation constraints, logistics and suitability for target species. This section aims to provide guidance on how to approach an evaluation of contamination, with a particular focus on using seaweed for food.

Assessing sources of pollution

Diffuse and point-source pollution

The assessment should cover both diffuse pollution (e.g. urban runoff, agriculture) and major point source pollution (e.g. industrial discharges, fish farms). Table 3.1 provides a summary of important pollution sources for seaweed in Scotland. Hazards should be risk assessed against severity and likelihood, including unlikely and low impact contamination to evidence evaluation.

Table 3.1: Diffuse and point-source pollution most relevant to contamination of seaweed produced in Scotland.

Category	Source	Examples of contaminants
Diffuse pollution (from widespread sources carried by soil erosion or runoff into rivers and, eventually, the sea)	Agriculture	Fertiliser, pesticides, veterinary treatments, slurry, spilled fuels
	Forestry	Fertiliser, pesticides, spilled fuels
	Urban fabric	Spilled fuels, litter
	Atmospheric deposition	Nitrogen compounds, products of combustion
Point-source pollution (from a single, identifiable location)	Sewage treatment	Pathogenic microorganisms, litter
	Fish farms	Waste feed, veterinary treatments, nitrogen compounds
	Industrial discharge	Chemical plants, distilleries, factories, power stations
	Ports and harbours	Spilled fuels, litter

The first step is to evaluate risks at a regional level (e.g. within 50km from the site). This would focus on runoff from major cities (e.g. urban runoff) and agriculture, together with point-source pollution from industrial production, high-traffic roads, etc. Rain will wash contaminants from different sources into rivers and, ultimately, the sea. Major rivers will carry a greater risk given the large catchment area, but there are also many fast-flowing, short rivers in Scotland that can quickly transport contaminants to the sea. The water chemistry within a loch system may also change the availability of natural elements, converting them into a form more readily absorbed by seaweed once the freshwater discharges into a coastal setting.

Historic pollution may present an ongoing problem: contaminants residing in sediment can be disturbed and reabsorbed into the surrounding seawater. This means it is important to consider former industrial activity (e.g. disused mines). A regional evaluation would also benefit from assessment of the natural geology. It is possible that local bedrock could be naturally high in toxic elements that seaweed is prone to accumulate. The results of this assessment will determine if coastline in the area is vulnerable to anthropogenic and/or geogenic contamination.

If there are no major pollution concerns at the regional level, the next step would be consideration of contamination affecting individual harvest or farm sites. For example, the initial review may have highlighted important point-source pollution to avoid and, therefore, at-risk areas could be removed from the licensed foreshore or seabed to minimise the hazard. Although harbours and jetties are helpful for extraction of seaweed, the possibility of contaminants from vessels and road vehicles mean it is worthwhile excluding adjacent foreshore from harvest or avoiding siting a farm close by. Exact separation distances would be site specific, considering natural topography, water exchange and frequency of use.

Harvest and farm sites should be located at a distance from harbours to mitigate contamination risk

Watercourses as vectors for contaminants

Any watercourse flowing onto foreshore will carry contaminants over seaweed and must be carefully assessed. Watercourses act mainly as a vector for diffuse pollution linked to land use in the catchment area. While watercourses also receive point-source pollution (e.g. a pipe discharging effluent into a river), contaminants would be considered diffuse pollution once reaching the foreshore. Short streams and burns will have a small catchment area and the land use may present minimal risk (e.g. natural woodland). Longer and larger watercourses will carry pollutants from a wide area. On the basis that urban fabric has been avoided at the outset, the most problematic land use may be agriculture. Outfalls – a structure or pipe through which water is discharged – can include treated wastewater from sewage treatment works, storm overflows that release excess rainwater or surface water drainage. All outfalls near a site should be identified and avoided.

Outfalls must be identified and separation distances maintained

Separation distances should be considered to minimise risk that seaweed will absorb diffuse pollution. A river will likely have an established route where it meets the sea, with freshwater influence limiting seaweed growth. This will facilitate demarcation of areas to exclude from harvest. Smaller watercourses will tend to follow transient routes, to the extent that they can be difficult to accurately map. Nevertheless, separation distances should be in place. Many species of seaweed will tolerate freshwater influence when emersed at low tide and so it is possible that contamination from a small watercourse will go unnoticed. It is likely that only major rivers will be of significant concern for seaweed cultivation, given immediate dilution upon entering the sea.

Even on remote coastline, watercourses can be a vector for terrestrial pollution

During heavy rainfall, soil cannot absorb water quickly and surface runoff will wash pollutants into watercourses. There is also increased connectivity between small burns and larger rivers. The high average rainfall in western Scotland combines with steep terrain to cause rapid washing of contaminants into the sea, amplifying low intensity pollution. Importantly for seaweed, ephemeral streams will form during intense rainfall. This may require additional precautions during periods of inclement weather (e.g. avoiding harvesting species from the upper shore).

Seawater exchange

Seawater exchange plays a crucial role in determining how contaminants behave in coastal environments. Exposed beaches facing open seas are continually flushed by waves and tidal currents, helping to disperse pollutants and reduce their concentration. This natural dilution helps reduce the accumulation of harmful substances. In contrast, sheltered or enclosed coastal areas experience lower exchange and contaminants are more likely to accumulate over time. Therefore, bays and estuaries are more liable to degraded water quality and, consequently, increased risks to human health. Therefore, the degree of exposure and water circulation is a key factor in how pollution impacts a coastal region.

Pollution is less likely to affect seaweed harvested on open coastline exposed to waves

Research has found higher levels of heavy metals in seaweed collected from sheltered or enclosed coastal environments, particularly near estuaries and pollution sources where water exchange is limited. Samarasinghe et al. (2021) analysed contaminants in Ulva sp. from two locations in Denmark: Mariager Fjord (around 35km from the western extent the open sea of the Kattegat) and Skive Fjord (~100km inland from the open North Sea). While there were two months between sampling at the two sites, it is likely that the sheltered location led to many elements being detected in the Skive Fjord sample at concentrations at least double those in the Mariager Fjord sample (nickel, barium, cobalt, zinc, manganese, copper, inorganic arsenic). This demonstrates the importance of seawater exchange in controlling pollutant retention in coastal ecosystems. Furthermore, this highlights a particular risk with Ulva species given they can thrive in brackish water (unlike many other key species).

Seawater from the Atlantic Ocean generally passes northwest of Scotland and above Shetland, with circulation through to the North Sea. Coastal circulation around the west of Scotland and in the North Sea is primarily wind driven and will vary in strength and positioning across different seasons. Generally, circulation is mainly northwards from the Irish Sea, up along the west coast and through the Minch. Turning east through the Pentland Firth and into the North Sea, circulation moves to a southerly direction along the east coast of Scotland. Therefore, pollutants originating from the northwest of England are of more concern to Scottish coastline than pollutants discharged from the northeast of England.

Identifying pollution sources

The Controlled Activities Regulations (CAR) cover water discharges that can cause pollution. Simple Registration covers low-risk activities. Complex Registration covers longer term activities with greater potential for impact, with the application requiring consideration of local conditions. A CAR Licence is required for activities that are likely to have significant impacts, requiring detailed assessment and greater scrutiny from SEPA. There can be overlap with other systems managed by SEPA: lower risk waste and industrial sites require permits under Environmental Authorisations (Scotland) Regulations (EASR) and large, high-polluting sites require permits under Pollution Prevention and Control (PPC).

Table 3.2: Status of the five coastal water bodies in Scotland that are not achieving Good or High classification in one or more parameters (SEPA, 2025).

Coastal water body	Overall status	Overall Ecology	Water Quality
Clyde Estuary Outer	Moderate	Moderate	Moderate
Solway Estuary	Moderate	Moderate	Moderate
Irvine Bay	Moderate	Moderate	Good
Middle Forth Estuary	Moderate	Moderate	Good
Leith Docks – Port Seton	Poor	Poor	Good

SEPA publish a Dynamic Map covering authorised pollution sources, which can be used to determine licences and registration under CAR, EASR and PPC in the vicinity of harvest sites. SEPA's Water Classification Hub maps the status of water bodies. Almost all of the seas around Scotland are classified as Good or High in the key parameters; there are only five coastal water bodies with a Moderate or Poor status, all of which are in central and southern Scotland (summarised in Table 3.2). Classifications of rivers can also be checked. Although the majority are unclassified, the tool can help identify any watercourses that have failed for levels of toxic metals (e.g. cadmium, chromium, lead), herbicides (e.g. simazine, pendimethalin, mecoprop, diuron), insecticides (e.g. dimethoate, diazinon, chlorpyrifos), fungicides (e.g. chlorothalonil), veterinary medicine (e.g.

permethrin, cypermethrin), PAHs (e.g. napthalene, fluoranthene, benzo-a-pyrene) and POPs (e.g. hexachlorobutadiene, hexachlorobenzene, hexabromocyclododecane).

Although pollution controls have become more rigorous over time, there are many potential sources for potentially hazardous elements in the UK. Tables 3.3a&b list anthropogenic sources for the majority of the elements that are relevant to food safety and seaweed contamination. The list is not exhaustive, but it provides an indication of pollution sources to consider in a local assessment. Tables 3.3a&b also highlight which elements are may be naturally elevated due to local geology, either common across the UK or localised.

Table 3.3a: Major sources of toxic trace minerals and selected occasionally beneficial trace minerals in the UK that are relevant to seaweed contamination (Aluminium to Copper).

Element	Natural geology	Metal prod-uction (plating, smelting)	Waste consumer goods (electric items, batteries)	Agri-culture (feed, sprays)	Fossil fuel com-bustion (coal, oil, diesel)	Mining and quarry-ing	Waste water (pipes, treating)	Incinera-tion	Vehicle wear (tyre, brakes)	Other
Aluminium	Common					✓	✓			
Antimony		✓	✓					✓	✓	Flame retardants
Arsenic (inorganic)	Localised			✓	✓	✓				Tanneries
Barium	Localised		✓							Drilling fluids
Beryllium	Localised	✓			✓			✓		
Boron	Localised		✓	✓						
Cadmium		✓	✓	✓		✓		✓		
Chromium		✓	✓							Wood preservation, tanneries, cement
Cobalt	Trace	✓	✓							Pigments
Copper				✓			✓		✓	Marine antifoulants*

* Legacy of historic applications

Table 3.3b: Major sources of toxic trace minerals and selected occasionally beneficial trace minerals in the UK that are relevant to seaweed contamination (Lead to Zinc).

Element	Natural geology	Metal production (plating, smelting)	Waste consumer goods (electric items, batteries)	Agriculture (feed, sprays)	Fossil fuel combustion (coal, oil, diesel)	Mining and quarrying	Waste water (pipes, treating)	Incineration	Vehicle wear (tyre, brakes)	Other
Lead			✓			✓	✓			Paint*, Leaded petrol*, fishing tackle, ammunition
Lithium	Localised		✓				✓			
Manganese	Common	✓	✓		✓	✓				
Mercury		✓	✓		✓					
Molybdenum	Common	✓		✓	✓	✓				
Nickel	Trace	✓			✓				✓	
Rubidium	Common		✓			✓				
Selenium	Localised	✓		✓	✓					
Silver		✓	✓				✓			
Strontium	Common	✓		✓	✓					
Thallium		✓			✓					Cement
Tin	Localised		✓		✓	✓				
Titanium	Common		✓				✓			Paint residue
Uranium	Localised				✓	✓				Phospate processing
Vanadium		✓			✓					
Zinc		✓		✓			✓		✓	

* Legacy of historic applications

4. EMERGING RISKS & REGULATORY CONSIDERATIONS

For seaweed food producers, horizon scanning and regulatory compliance are essential to both risk management and market access. As scientific understanding evolves, regulators are moving toward more specific and stringent controls on contaminants. Proactive horizon scanning – monitoring emerging legislation, scientific publications, industry opinions and market expectations – is essential for anticipating change rather than reacting to it. Effective compliance is ongoing process that integrates regulatory awareness, supply chain control and product testing to ensure both consumer safety and continued access to increasingly regulated markets.

Horizon scanning

Horizon scanning plays a critical role in food safety management. It enables organisations to proactively identify emerging risks, regulatory changes and scientific developments before they threaten food safety concern for their operation. Rather than reacting to incidents after they occur, horizon scanning is a forward-looking approach: considerations of wider industry trends are particularly important in this emerging sector due to the unique risk profile. Factors relevant to seaweed include:

- Limits for heavy metals and variation by territory
- Novel food regulations
- Specific toxicity associated with seaweed
- Consumer consumption patterns, which will influence dietary exposure

Scientific literature, regulatory updates, environmental data and industry trends can be used to anticipate issues associated with edible seaweed and, if necessary, proactively introduce appropriate controls. The majority of food safety accreditation standards now require evidence of ongoing horizon scanning.

Food Standards Scotland alerts

The Food Standards Agency (FSA) issues food alerts and recalls, with Food Standards Scotland (FSS) responsible for dissemination in Scotland. As a matter of course, all food business operators should subscribe to email alerts from FSS. Risk assessments and committee reports on longstanding and emerging issues are also available from both FSA and FSS. Unfortunately, there will be very little information relating to seaweed as at is not a significant contributor to the average diet. It is unlikely that any alerts or recalls will be issued for seaweed.

Yue et al. (2023) analysed over 1,000 food recalls in the UK over the six years to 2021. The majority related to allergens (58%), followed by microbiology (19%) and physical contaminants (17%). The most common allergenic groups were milk (25%), cereals containing gluten (17%), nuts (11%) and soya (10%). Over the period, there were just 6-9 recalls annually for crustacean, mollusc and fish allergies (mean 7.7 per year; ~4% of all recalls). Improper labelling of allergens is the most common reason for recall (mostly omitted allergens, but also unemphasised ingredients and false 'free from' claims).

It is important to note that the frequency of recalls are indicative only. They reflect consumption patterns in the UK. For example, the limited number of recalls for seafood-related allergens is likely due to clear labelling of the ingredients (unlike traces of milk, gluten and nuts that may be overlooked). Nevertheless, the findings presented by Yue et al. (2023) demonstrate the importance of allergens for UK food manufacturing.

European Rapid Alert System for Food and Feed

The Rapid Alert System for Food and Feed (RASFF) was created to enable exchange information on health risks derived from food or feed between European Union countries, helping support rapid responses by food safety authorities. The service can lead to product recall, preventing consumers from harm. It is still used by UK food businesses after Brexit. Crucially, the expanded coverage provides a larger dataset for horizon scanning purposes.

The online database is called RASFF Window, which allows searching through keywords in past notifications and trend analysis. This can provide some indication of risks associated with specific products and patterns across contaminant categories. Food producers can identify trends such as contamination events, adulteration or non-compliance with regulatory standards. Incorporating RASFF Window into routine horizon scanning activities supports proactive management. Reviewing alerts, border rejections and information notifications can help hazard identification.

In December 2025, RASFF Window was interrogated for notifications linked to minerals and elements. While the RASFF Window database goes back to the end of 2019, notification records became more numerous in late 2020. Therefore, the time period was set to 1 December 2020 to 30 November 2025 (60 months, 5 years). Results were screened to remove duplicated entries, references to metal as physical contaminants (e.g. aluminium foil fragments) and contaminants to an approved compound of an element (e.g. pesticides in zinc sulphate for feed). Metals are frequently notified for migration from food contact materials, which is not relevant to contamination in food products (over 200 notifications removed). There were also checks to text to ensure the notification referenced metal contamination (e.g. lead mentioned within “misleading allergen label”). If multiple elements were referenced, the notification was duplicated to ensure each was captured. Groups were created from the assorted categories within the database.

Notifications for elements

After screening, there were a total of 914 notifications across the 5 year period for potentially hazardous elements (ranging from 153 to 206 per 12 months). There were zero results for many elements (e.g. antimony, barium, strontium, beryllium). Titanium was only mentioned as the banned whitening agent titanium dioxide (over 100 notifications in data prior to screening). Nine elements were referenced fewer than five times each over the 5 year period – boron, lithium, chromium, manganese, cobalt, molybdenum, rubidium, vanadium, bismuth – with most notifications linked to food supplements (71%).

Certain elements and groups dominate the screened RASSF notifications for toxic metals:

- Three elements account for 84% of the 914 RASSF notifications for potentially hazardous metals (Figure 4.1a); cadmium (34%), mercury (33%) and lead (17%) are commonly termed 'the toxic trio'. Their careful regulation in food and feed for consumer safety may lead to more frequent RASSF notifications.
- Three food categories account for 70% of all notifications (Figure 4.1b): fish and seafood (41%), fruits and vegetables (16%) and food supplements (12%).
- Three combinations of element and category account for 53% of all notifications: mercury in fish and seafood (29%), cadmium in fruits and vegetables (13%) and cadmium in fish and seafood (11%).

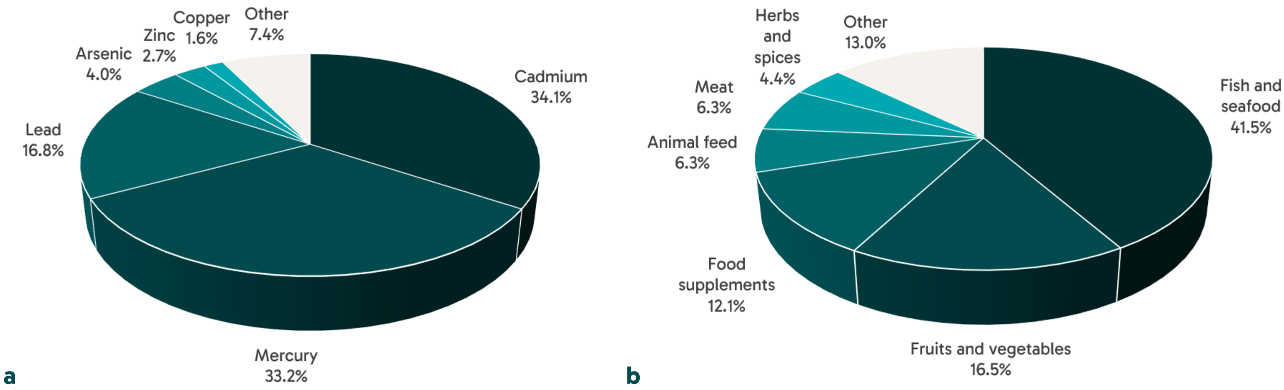


Figure 4.1: Screened notifications on RASFF Window database over five years (1 December 2020 to 30 November 2025): a) notifications by chemical elements, b) notifications by category.

Notifications for biogenic toxins

Across the five year period, there are almost as many notifications in RASFF for biogenic toxins as potentially hazardous elements, although none refer to seaweed. The majority of the 326 notifications for plant toxins are for pyrrolizidine alkaloids (76%) and largely reported in herbs and spices (60%) and cereal and bakery products (13%). The majority of the 553 notifications for mycotoxins are for ochratoxin A (84%) and it is fairly common for notifications to report multiple mycotoxins (13%). Common categories for notifications are fruits and vegetables (54%), cereals and bakery products (18%) and herbs and spices (11%).

Biogenic toxins are frequently reported in the RASFF system, but it is understandable there are none linking to seaweed as it is a food currently with limited consumption and relevant regulation. This highlights the importance of maintaining awareness.

Notifications for seaweed

There were 63 notifications that refer to seaweed in the five year period (Figure 4.2). Interestingly, 50 of those notifications were for elevated iodine levels (79% of the seaweed notifications; the 914 screened notifications for potentially hazardous elements do not include iodine). While two-thirds of the notifications describe the seaweed as dried or dehydrated, stated or inferred formats include nori sheets (18%), salads (10%) and kelp or kombu (6%). The majority of the iodine reports are for Asian seaweed (82%; 56% of which from China and Hong Kong, 39% of which from South Korea). The trends in format and origin are indicative of Asian products driving European consumption of seaweed.

It is clear that elevated iodine is the most likely reason for a seaweed food safety alert to be issued via RASFF. Only two other hazardous elements were reported in seaweed:

- High cadmium in animal feed (two notifications in 2021, both from Europe but seemingly different sources).
- High inorganic arsenic in an organic algae blend (one notification in 2025, from China).

There were five notifications linked to the presence of pathogens, all of which were linked to Asian seaweed salad. Although the RASFF Window database states that one report came from a product of European origin, the description indicates that the raw material may have been from Asia. Three pathogens were reported – hepatitis E, Salmonella spp. and norovirus (two samples) – with one non-specific notification.

RASFF notifications for seaweed in the 5 year period also included more technical issues (i.e. insufficient allergen labelling, unauthorised substances, inclusion of a novel food).

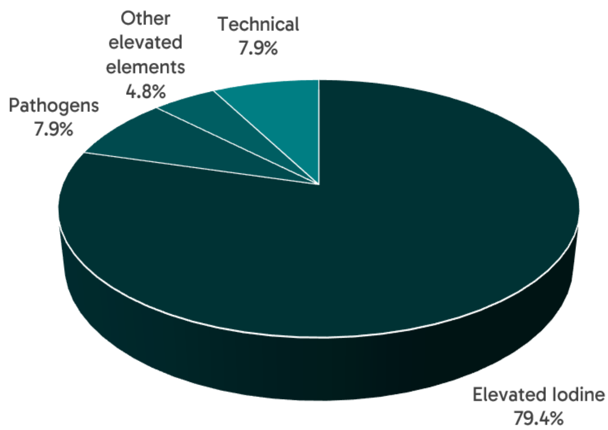


Figure 4.2: Notifications on RASFF Window database over five years (1December 2020 to 30 November 2025) for seaweed (total 63 reports).

Industry and scientific intelligence

Reports, updates and analyses are issued by various commercial entities (e.g. Campden BRI) and industry bodies (e.g. Food and Drink Federation). These can be used to provide additional context. Commercial horizon scanning platforms are available, but are generally unnecessary for seaweed producers. Given the emerging nature of seaweed as a food product, it is likely that papers published scientific journals will be particularly useful for horizon scanning. The importance of the European market for UK producers means that information issued by the European Food Safety Authority (EFSA) are relevant. Indeed, opinions and risk assessments by the EFSA are likely to be the best source of evidence.

Seaweed Scotland serves as a conduit of information relating to seaweed and food safety. This includes connecting in to seaweed regulations in other territories.

Relevant regulation

For a seaweed producer in the UK, food safety is governed by a mix of general food law, hygiene regulations, contaminant limits and specific rules for novel foods, traceability and labelling. The key point is that seaweed is treated as a food product and most mainstream food legislation is applicable: a seaweed producer supplying edible seaweed is a food business operator (FBO) and must adhere to the following:

- Ensure food is safe under general food law
- Apply HACCP-based hygiene controls

- Comply with labelling and traceability rules
- Consider contaminants like iodine and heavy metals, even where no specific limits exist
- Check whether products fall under novel food regulations

Key legislation in food law

Responsibilities of Food Business Operators (FBOs)

The Food Safety Act 1990 is the foundation of UK food law, making the sale of food that is contaminated, unsafe or not of the nature/quality expected an offence. The Retained EU Regulation (EC) No. 178/2002 (General Food Law) sets out core principles around food safety, traceability and the fact that producers are responsible for food placed on the market. Under this legislation, a Food Business Operator (FBO) has a specific legal meaning: the natural or legal person responsible for ensuring that food law requirements are met within a food business under their control. This is the person that has effective control over food safety and compliance decisions (e.g. production, hygiene, distribution), not an individual delegated to undertake a particular task. It can be a sole trader, company or partnership.

Food hygiene regulations

In Scotland, the Food Hygiene (Scotland) Regulations 2006 and Food Hygiene (Scotland) Amendment Regulations 2008 outline enforcement powers and penalties, including the main retained EU hygiene laws. For example, Regulation (EC) No. 852/2004 states food hygiene requirements for producers. In summary, a producer of seaweed food products must follow the following practices:

- Hygienic handling during harvesting and processing
- Documented food safety management procedures based on HACCP
- Clean equipment and facilities, including quality of water used on the premises

Weighing regulations

The Weights and Measures Act 1985 is the main UK law regarding units of measurement, how goods are weighed and the accuracy of equipment. Seaweed products intended for the final consumer must be weighed using trade-approved, verified scales. The packs must be filled under the average weight system, where the declared weight must be met on average within small defined tolerances. An additional point for fresh seaweed is that it can lose moisture, which means a seaweed producer may need to slightly overfill fresh packs.

Different measurement rules apply if seaweed is sold to another FBO (e.g. as an ingredient for a food manufacturer; also known as Business-to-Business or B2B). Goods must still be accurately weighed, but tolerances and compliance are driven by commercial agreements. Overall, B2B sales are more flexible.

Labelling regulations

Retained EU Regulation (EU) No. 1169/2011 (Food Information to Consumers) requires food producers to accurately label products. Food labels must include certain information:

- Food name (only common name of seaweed required, but best practice is to include the scientific name for clarity).
- Net quantity, in metric units (i.e. grams, kilograms). If a product is packed in liquid or ice then the label must show the drained net weight.
- Shelf-life date, generally a 'best before' (e.g. dried seaweed), but sometimes a 'use by' (e.g. fresh seaweed).
- Ingredients list (if more than one ingredient), listed in weight order. The percentage inclusion of an ingredient needs to be included if highlighted or inferred in the product name (e.g. dulse spice blend would require a percentage declaration of dulse).
- Allergens, if present (i.e. the 14 major allergens defined in law), highlighted using a different font, style or background colour.
- Storage instructions necessary to retain product integrity (e.g. cold storage of fresh seaweed).
- Instructions for use where needed (e.g. for a product that must be cooked).
- Country of origin of the food, not the premises it was packed (there is an overarching principal that consumers should not be misled on origin).
- Lot or batch code to allow traceability.
- Name and address of the UK Food Business Operator responsible for the information.
- Additional warnings may apply (e.g. for modified atmosphere packaging).

There are also formatting rules (e.g. minimum font size) to ensure legibility and visibility.

It is important to state that there are rules for labelling fishery products that do not apply to seaweed. Fishery products are defined in Regulation (EC) No 853/2004 as all seawater or freshwater animals, whether wild or farmed, and including all edible forms, parts and products of such animals. Although there are exceptions for certain animals subject to different legislation (e.g. live bivalve molluscs, all mammals), it is clear that plants are not considered fishery products. This avoids mandatory inclusion of certain label elements (e.g. scientific name, sea area of production).

Nutrition labelling

Nutrition labelling is not required for certain foods. This includes unprocessed foods (e.g. vegetables, herbs) and it is reasonable to assume this applies to seaweed, unless it is sold as a blend with other ingredients.

There are rules in place for nutrition labelling of prepacked products. It is possible that these will not apply to small seaweed producers (i.e. <10 employees) only supplying locally (e.g. within the local authority). However, it is prudent to follow the requirements to avoid unnecessary market restrictions. The mandatory nutrients must be listed (i.e. energy, fat, saturated fat, carbohydrates, sugars, protein, salt). There is a standardised format and order of presentation and conditions are in place for additional information.

Claims on labels

Certain rules must be followed if any claim is included on a label. The definition of claim includes both written and spoken information, covering text and graphics. A FBO cannot claim or imply that food can treat, prevent or cure any disease or medical condition. Both the UK and EU still rely heavily on the same original framework within EU Regulation (EC) 1924/2006 on nutrition and health claims. The EU register was copied into a UK system after Brexit: the Great Britain Nutrition and Health Claims (NHC) Register. UK authorities now control approvals and enforcement. Although the two systems are similar currently, differences may arise regarding functional health claims (e.g. probiotics) and marketing language.

The principal for claims is that the substance is proven to influence health, that it is present or absent to a sufficient degree in a relevant portion size of the product. Only authorised claims listed on the NHC Register can be used. Language is controlled (e.g. low in fat can only be claimed for a solid food where the product contains no more than 3g of fat per 100g). Health claims must follow the wording stated on the NHC Register and can only be used where the food is at least a source of the nutrient.

General claims are those that do not relate to nutrition or health (e.g. hand-harvested seaweed). There are no specific rules for such claims, but all statements on a food product (e.g. label) or any commercial communication (e.g. website) must be true. If not, it could be considered misleading and this is considered an offence.

Direct to consumer versus wholesale

There is an important distinction to make between seaweed products intended for the final consumer versus seaweed products being supplied to another FBO. This drives what must physically appear on-pack rather than what can be supplied as accompanying information. A general guide is that full retail compliance is required if a consumer can pick it up and buy it as it is. However, the necessary information can be supplied in separate documents (e.g. specifications, datasheets) if it is an intermediate product supplied to another FBO. For example, a seaweed producer may sell 500g packs to both food factories and bulk health food outlets; labelling all 500g packs to be retail-compliant will avoid generating different labels.

The key principal is that information must be passed on to the next FBO to ensure the final seller has the necessary details to correctly label end products. In practice, this allows labelling of B2B products to be simplified down to:

- Food name
- Net quantity
- Shelf-life date
- Storage instructions
- Lot or batch code

Upstream suppliers must ensure accurate information transfer. In practice, the recipient FBO is likely to require additional information on labels to support their quality control and food safety systems. One clear example is allergen labelling: it is now standard practice to highlight the content of allergens on food products sold on a B2B basis.

In addition, labels must undergo careful controls to ensure legal compliance (e.g. version control, internal authorisation). There is more flexibility regarding wholesale labels, but labels for retail products must often be carefully designed and should not be frequently amended.

Contaminant compliance

This report does not consider details in food additives regulations (if seaweed is processed into ingredients like thickeners) or animal feed regulations (if seaweed is sold for feed rather than food), unless it provides context for certain contaminants (e.g. total arsenic in animal feed). Food supplements are defined in Directive 2002/46/EC as a concentrated source of nutrients or other substances with a nutritional or physiological effect, marketed in dose form (such as capsules, tablets, powders, or liquids) and intended to supplement the normal diet. When seaweed (or seaweed-derived material) is used in this way, the product is treated as a food supplement rather than as a conventional food. This report frequently makes references to food supplements alongside use of seaweed as food: both are applications for edible seaweed.

The key framework around contaminants in food is retained EU law: Regulation (EC) No 1881/2006 and Regulation (EU) 2023/915. This sets maximum levels (MLs) for contaminants in specific foods and FBOs cannot place unsafe food on the market. Importantly, this rule includes food that is unsafe even if no specific limit is in place and a FBO must assess the risks of their product, following the ALARA principle (as low as reasonably achievable). Regulators (e.g. Food Standards Scotland) would expect evidence that seaweed products supplied are safe, which will include testing where appropriate. Local authorities manage enforcement with input from regulators.

The configuration of the limits in Regulation (EU) 2023/915 is given in Table 4.1, which also includes broad explanations of sources and foods at risk. There are only limits stated for seaweed in relation to metals:

- Cadmium in food supplements consisting of seaweed (3.2.21.2)
- Nickel in seaweed used as food (3.6.8).

There are limits in place for similar products and food categories. They provide useful references for portion sizes (e.g. salt), context for seafood (e.g. fishery products) and, in some cases, relevant applications for seaweed (e.g. food supplements, dried products for herbal teas). Contaminant limits are often in place for unspecified herbs and spices. While seaweed does not necessarily fit in this category, it is reasonable to compare against these levels as small quantities are typically used.

One important point is that many contaminants have limits in place for food intended for babies, infants or young children. Therefore, including seaweed in a formulation for young consumers may result in an elevated mineral level beyond a limit in Commission Regulation (EU) 2023/915. This is understandable, given assessments of tolerable intake are based on body weight. Anyone sourcing of supplying seaweed for infant food should be mindful of these limits, which are usually lower than other foods.

Regardless of the legislation specified for seaweed, the general principle in Regulation (EC) No 178/2002 applies: FBOs are responsible for ensuring that their food products are safe to consume.

Table 4.1: Summary of contaminants for which maximum limits (MLs) are stated in Regulation (EU) 2023/915 that are relevant to seaweed.

Section	Contaminants	Source	Foods at risk	MLs for seaweed	MLs for similar products and categories
1 Mycotoxins	1.1 Alfatoxins 1.2 Ochratoxin A 1.3 Patulin 1.4 Deoxynivalenol 1.5 Zearalenone 1.6 Fumonisins 1.7 Citrinin 1.8 Ergot sclerotia and ergot alkaloids	Produced by certain fungi and molds, contaminating food during growth, harvest or storage	Cereals (maize, rice, wheat), nuts, seeds, legumes, fruit dried herbs and spices, animal products (via contaminated feed)	None	Dried spices (1.1.14; 1.2.17) Dried herbs (1.2.5)
2 Plant toxins	2.1 Erucic acid 2.2 Tropane alkaloids 2.3 Hydrocyanic acid 2.4 Pyrrolizidine alkaloids 2.5 Opium alkaloids 2.6 Delta-9-tetrahydrocannabinol equivalents	Natural products from certain plant families (e.g. Brassicaceae, Solanaceae, Papaveraceae)	Oils from brassica seeds, nuts, fruits, cereals, herbal teas, herbs and spices	None	Dried herbs (2.4.2) Dried products for herbal teas (2.2.7, 2.4.7) Food supplements containing botanical preparations (2.4.10)
3 Metals and other elements	3.1 Lead 3.2 Cadmium 3.3 Mercury 3.4 Arsenic (inorganic) 3.5 Tin (inorganic) 3.6 Nickel	Anthropogenic (mainly)	Cereals, potatoes, vegetables, nuts, seeds, fishery products	Food supplements consisting of seaweed (3.2.21.2) Seaweed as food (3.6.8)	Dried spices (3.1.12) Fishery products (3.1.15, 3.2.14, 3.3.1, 3.4.5, 3.4.6, 3.4.7, 3.4.8) Salt (3.1.23, 3.2.16, 3.3.3, 3.4.9) Food supplements (3.1.28; 3.3.2)
4 Halogenated persistent organic pollutants	4.1 Dioxins and PCBs 4.2 Perfluroalkyl substances	Anthropogenic	Meat, fishery products, dairy products, eggs	None	Fishery products (4.1.5, 4.2.2)
5 Processing contaminants	5.1 Polycyclic aromatic hydrocarbons 5.2 3-MCPD 5.3 Sum of 3-MCPD and fatty esters 5.4 Glycidyl fatty acid esters	Anthropogenic	Cocoa, meat, fishery products, oils and fats, herbs and spices	None	Dried herbs (5.1.3) Dried spices (5.1.10) Smoked fishery products (5.1.7) Food supplements (5.1.16)
6 Other contaminants	6.1 Nitrates 6.2 Melamine 6.3 Perchlorate	Anthropogenic	Vegetables, tea	None	Food products (6.2.1) Dried herbal infusions (6.3.2)

Proposed EU limits for seaweed

The EU developed proposed limits for seaweed through consultations in 2025 as part of a broader effort to address food safety concerns linked to increasing awareness and consumption. This work follows scientific advice from the EFSA, with the aim of expanding Regulation (EU) 2023/915 to cover contamination risks linked to seaweed.

The proposal focuses primarily on four key substances: cadmium, lead, inorganic arsenic and iodine. Although not all final limits had been fixed during the 2025 consultation phase, the proposals build on existing benchmarks already applied to certain seaweed products (e.g. food supplements). A key feature of the proposal is the recognition of seaweed as a distinct food category requiring tailored regulation, rather than treating it like seafood or terrestrial vegetables. The EU is also moving toward a more risk-based approach, taking into account typical consumption patterns and overall dietary exposure rather than assessing seaweed in isolation.

The proposed limits for elements are stated in the Excess nutrients and toxic elements section of this report. Overall, the direction of travel is clear: the EU intends to introduce stricter, more comprehensive controls on contaminants in seaweed, reflecting both its growing popularity and its potential to contribute significantly to dietary exposure to certain harmful substances.

Novel foods

Novel food regulation is particularly relevant for seaweed because some species or extracts may not have a documented history of consumption and therefore require pre-market approval. In Europe, Regulation (EU) 2015/2283 established a centralised system in which any food not consumed to a significant degree before 1997 must undergo a scientific risk assessment (by EFSA). Once approved, the food is added to the Union List of novel foods with defined specifications and labelling requirements. This framework ensures that novel foods are assessed for toxicological risks, nutrition and potential contaminants before being placed on the market.

The EU Novel Foods Catalogue states all species confirmed as not novel as either a food or a food supplement. Table 4.2 gives the status of all 43 seaweed species listed on the Novel Food Status Catalogue, broken down by relevant Scottish species, other species found in NW Europe and species from the rest of the world. The majority of the key seaweed species are on the Novel Food Status Catalogue and so are not novel foods.

Osmundea pinnatifida is not included in the Novel Food Status Catalogue and so is a novel food

Table 4.3 lists species not included in the Novel Food Status Catalogue and, therefore, are novel foods. This includes some common seaweed species around Scottish waters (e.g. Pelvetia canaliculata, Saccorhiza polyschides, Osmundea pinnatifida, Vertebrata lanosa). Although Porphyra dioica and Ulva fenestrata are included in Table 4.3, the Porphyra and Ulva genera are hard to speciate and it is likely there is no issue for these two species.

Table 4.2: Species listed on the Novel Food Status Catalogue (accessed March 2026).

Category	Group	Status	Species
Relevant Scottish seaweed species	Brown	Authorised novel food	Fucus vesiculosus - fucoidan extract
		Not novel in food	Alaria esculenta, Ascophyllum nodosum, Fucus serratus, Fucus spiralis, Fucus vesiculosus, Himanthalia elongata, Laminaria digitata, Laminaria hyperborea, Saccharina latissima
	Green		Ulva intestinalis, Ulva lactuca, Ulva prolifera, Ulva compressa
	Red		Chondrus crispus, Palmaria palmata, Porphyra purpurea, Porphyra umbilicalis
		Not novel in food supplements	Mastocarpus stellatus
Other NW European seaweed species	Brown	Authorised novel food	Undaria pinnatifida - fucoidan extract
		Not novel in food	Undaria pinnatifida
	Red		Erythroglossum lacinatum, Gelidium corneum, Gracilaria verrucosa, Gracilariopsis longissima, Phymatolithon calcareum
		Not novel in food supplements	Alsidium helmintochorton, Corallina officinalis, Gracilaria gracilis
Other seaweed species	Brown	Authorised novel food	Ecklonia cava - phlorotannin extract
		Not novel in food supplements	Durvilaea antarctica, Ecklonia cava, Macrocystis pyrifera
		Not novel in food	Eisenia bicyclis, Laminaria longicruris, Saccharina japonica, Sargassum fusiforme
	Green		Monostroma crispata, Ulva australis, Ulva ohnoi
	Red		Gelidium amansii, Neopyropia leucosticta, Neopyropia yezoensis, Pyropia tenera
		Not novel in food supplements	Eucheuma denticulatum, Euchema horridum

Table 4.3: Species found in Scotland and NW Europe characterised as novel foods as they are not listed on the Novel Food Status Catalogue (accessed March 2026).

Category	Group	Species
Relevant Scottish seaweed species	Brown	Halidrys siliquosa, Pelvetia canaliculata, Saccorhiza polyschides
	Green	Ulva fenestrata
	Red	Osmundea pinnatifida, Vertebrata lanosa, Porphyra dioica
Other NW European seaweed species	Brown	Bifurcata bifurcata, Chorda filum, Sargassum muticum, Laminaria ochroleuca
	Green	Chaetomorpha linum, Codium fragile
	Red	Dilsea carnosa

Following Brexit, the United Kingdom retained this regulatory framework in domestic law but introduced an independent approval system. Responsibility for risk assessment and authorisation now sits with the Food Standards Agency (FSA) and advisory bodies. As a result, businesses must submit separate applications for the UK and EU markets, even for the same product, creating a dual regulatory pathway.

The existence of separate UK and EU novel food authorisation systems has created divergence in both approval timelines and permitted products. As a result, some foods approved in the EU are not yet authorised for sale in the UK. This is particularly evident in the case of edible insects, where EU regulations now permit products like house cricket and mealworm powders, while UK legislation remains less clearly defined. There is no divergence for seaweed species currently. Over time, this divergence is expected to increase as each system evolves independently, although both retain the core principle of requiring robust safety evidence prior to market placement. For seaweed producers, this means additional regulatory complexity, particularly where novel species, extracts, or fortified products are concerned, and highlights the importance of compliance strategies.

Third-party accreditation in the UK

Third-party accreditation is often essential for UK manufacturers aiming to supply into the food industry. The most widely recognised schemes are SALSA and BRCGS, which could be considered as essential for any seaweed producer aiming to trade with significant customers. In the absence of accreditation, the seaweed producer will be subject to customer audits covering paperwork (likely remote) and on-site inspections. Indeed, many serious customers will carry out their own inspections irrespective of third-party accreditation. Supply chain vulnerability is of increasing important in food safety systems, which means larger manufacturers will require additional steps for less familiar ingredients and processes. Although a seaweed producer can legally operate with just a documented HACCP plan and basic prerequisite controls, third-party accreditation helps alleviate customer concerns.

BRCGS

BRCGS is one of the most recognised global food safety standards. BRCGS stands for Brand Reputation Compliance Global Standards. This acronym evolved from the organisation's original identify within the British Retail Consortium. BRCGS is recognised by the majority of the world's largest retailers, quick-service restaurants and manufacturers. BRCGS is commonly required for direct supply into major UK supermarkets and international retailers.

BRCGS is a comprehensive food safety and quality management system, with a strong emphasis on HACCP review, traceability, supplier approval and process controls. There is also an expectation of demonstrable senior management commitment and a strong food safety culture. The BRCGS standards are generally clear in what producers should and should not do. Audits are annual, or more frequent for certain grades. BRCGS accredited facilities tend to be medium and large manufacturers. It is more likely to be of value for a business exporting products as it is recognised by the Global Food Safety Initiative (GFSI). However, it requires significant effort to implement and maintain. Often, a dedicated role is required to manage quality during production (i.e. it is harder to outsource technical functions to consultants).

SALSA

SALSA (Safe and Local Supplier Approval) was developed specifically for UK small and micro food producers. It is designed as an accessible and lower-cost certification scheme for businesses that may not yet be ready for BRCGS-level systems. SALSA is widely accepted by UK retailers, wholesalers and foodservice buyers. Although SALSA may not be enough to supply products directly into a major UK supermarket, it is often sufficient to meet the requirements of a BRCGS-accredited manufacturer that does supply directly. SALSA is a more realistic level of accreditation for smaller producers.

The SALSA standards are designed with a degree of flexibility, which facilitates integration of seaweed processing. However, this requires some interpretation to ensure effective systems are implemented. The standards evolve over time, reissued every few years incorporating important food safety developments. Version 7 of the SALSA standard is due for release in summer 2026. It is expected to expand on food safety culture, allergen management controls, food defence and fraud controls.

Several seaweed processing facilities in the UK have achieved SALSA accreditation. SALSA has a lower implementation and audit cost than BRCGS, making it an easier entry point for small manufactures even when there is ambition for future scaling. However, it is less recognised internationally.

The jump from SALSA to BRCGS is substantial, particularly around documentation, verification and management systems. Common gaps include:

- Documented food safety culture programmes and senior management review
- Robust internal auditing systems
- Verification and validation records
- Risk-based supplier approval
- Detailed corrective action systems
- More extensive traceability exercises and challenges
- Higher standards for building fabric and zoning

Many businesses use BRCGS START!: a tool to support transition between SALSA to BRCGS. This route can help stagger implementation of new systems and reduce operational disruption.

Organic certification

The term "organic" is legally protected under organic food regulations and can only be used on food products that have been certified by an approved organic control body. Businesses must comply with strict rules before they can market products as organic. The UK has several approved organic certification bodies that inspect and certify food producers, processors, manufacturers, importers and retailers against UK organic regulations. While all operate to the same legal baseline, they differ in market recognition, additional standards, support services and sector focus.

The leading UK organic certification body is the Soil Association. They have certified several seaweed producers in the UK against their organic seaweed standards. Waters must be free from significant contamination and not exposed to pollutants, with maps and risk assessments in place. Production must not damage the marine ecosystem or reduce regeneration capacity. It will be important to manage separation of organic and non-organic material. There will be restrictions on hygiene chemicals and methods of processing and cleaning. There will be extra demands on traceability, executed during the annual inspection. In particular, labelling rules are strict as products must carry specific wording and logos. There are also additional steps to take regarding imports and exports of organic products. This can complicate international order fulfilment.

Organic certification is globally recognised as accreditation for sustainable food production. Anyone aiming to supply products on a B2B basis should consider organic accreditation, because it is common within the seaweed industry and is relevant to a range of markets (including non-food applications beyond the scope of organic food production standards).

5. UNITS & STATISTICS

Consistent units

Sources use different units to report levels of contaminants. This can create unnecessary confusion, but it is often appropriate to use separate units for abundant nutrients (e.g. calcium, potassium) and trace contaminants (e.g. dioxins, PFAS). This report primarily reports results in milligrams per dry kilogram (mg/kg), which is equal to parts per million (ppm).

Parts-per nomenclature		Amount per kilogram		Amount per per gram		Log-10 notation	Examples
1 per cent	=	10g per kg	=	10mg per g	=	$\times10^{-2}$	Sodium, Potassium
		↓ Divide by 10,000 / ↑ Multiply by 10,000					
1 part per million	=	**1mg per kg**	=	**1µg per g**	=	$\times10^{-6}$	Selenium, Cadmium
		↓ Divide by 1,000 / ↑ Multiply by 1,000					
1 part per billion	=	1µg per kg	=	1ng per g	=	$\times10^{-9}$	Pesticides
		↓ Divide by 1,000 / ↑ Multiply by 1,000					
1 part per trillion	=	1ng per kg	=	1pg per g	=	$\times10^{-12}$	PFAS

Quantities

Dry weight and fresh weight

Working to either dry weight or wet weight is a critical consideration in the safety and regulatory assessment of food. Seaweed has a naturally high and variable moisture content, typically 70–90% in fresh material. As a result, the concentration of nutrients and hazardous substances will differ markedly depending on whether results are expressed on a wet weight or dry weight basis. The distinction is particularly important when comparing regulatory limits, toxicological reference values or published scientific studies. Failure to account for this can lead to misinterpretation of risk. Clearly defining and consistently applying either dry or wet weight measurements ensures accuracy, transparency and comparability of data. Dry weight basis is generally used in food chemistry and analytical chemistry, with moisture content also reported for reference.

The range of moisture content in fresh seaweed means that most scientific studies on algal composition report results on a dry weight basis. The benefit of sample standardisation means this can be the case even when a study is investigating change in composition of fresh seaweed. In almost all cases, levels in this report are stated on a dry weight basis. There are a few studies that have reported levels in fresh seaweed which were converted to dry weight using the stated moisture content (e.g. Sartipiyarahmadi et al., 2023, Dahlstedt et al., 2026). Some fields use fresh weight by convention (e.g. radioactivity monitoring). Importantly, many regulatory limits for contaminants are on a fresh weight basis. This can cause some confusion when comparing seaweed to other products (e.g. mercury limits for seafood), but there is increasing clarity where limits need to be adjusted to dry weight as appropriate.

Amount of seaweed consumed

There is limited information on how much seaweed is consumed in the UK and Europe, which is understandable given seaweed is not commonly used in European cuisine. The Eurobarometer Consumer Habits Survey published in 2025 showed that in only seven EU Member States did more than 10% of consumers report eating seaweed or algae products at least once a week. Across all respondents around the EU, 81% of consumers ate seaweed or algae products either less than once a month of never. Ficheux et al. (2022) carried out a small online survey on seaweed consumption in France, with intake of seaweeds in food estimated to be equivalent to 0.3 dry g per day. They found that 89% of participants had consumed seaweed products in the last year, noting that that the survey respondents were not likely to be representative of the wider population.

Seaweed is more commonly used in Asian cuisine. Zava and Zava (2011) collated data from studies of seaweed consumption in Japan to understand iodine intake. Over 20 species of red, green and brown seaweed are used in Japanese cuisine, with approximately 21% of meals containing seaweed. Only 1-2% of adults aged 40-79 rarely consume seaweed. Overall, seaweed consumption in Japan is estimated to be 4-7 dry grams per day. This is similar to other Asian nations where seaweed is eaten regularly. Dietary exposure studies have used 8.5 dry grams per day in South Korea (Hwang et al., 2010) and 5.2 dry grams per day in China (Chen et al., 2018).

Figure 5.1: Representation of5 dry grams of seaweed in different species and formats to approximate scale: a) two nori sheets, Porphyra spp; b) coarse flakes of Palmaria palmata, approx. 3-7mm; c) fine flakes of Fucus vesiculosus, approx. 1-3mm; d) milled Fucus serratus, approx. 0.5-1.0mm.

Given this assessment focuses on risk of excessive intake from contaminants, it is reasonable to assume a scenario of relatively high intake for a seaweed consumer. In the absence of reliable

European data, Roleda et al. (2019) used the 5.2 dry grams figure for China (Chen et al., 2018) in their exposure assessment of heavy metals. Other studies have used low and high intake scenarios. In an assessment of edible seaweed available in Italy, Desideri et al. (2016) used an average daily consumption of 3.3 dry grams and a maximum portion of 12.5 dry grams. For their arsenic study of seaweed purchased in Spain, Yu et al. (2024) assumed 2 dry grams for low intake and 8 dry grams for high intake. Therefore, a daily intake of 5 dry grams will be used in this assessment. This matches a recent assessment of seaweed bought commercially in the UK (Casas-Agustench et al., 2024).

Figures 5.1a-d represent 5 dry grams of different species and formats. This intake of seaweed would usually result in a high iodine intake, which is explored further in the Iodine Section of this report. Given there are methods to reduce iodine content, it is practical to use the 5 dry grams intake to assess contaminant risk.

Guidance values and body weight

Guidance values in food safety and toxicology estimate how much of a substance can be consumed without significant health risk. Body weight is a key factor in the establishment of guidance levels because it allows exposure limits to be scaled to physiological capacity to tolerate and eliminate a substance. Regulatory bodies such as the EFSA typically express guidance values as a dose per kilogram of body weight (e.g. mg/kg), which accounts for differences in vulnerability between children and adults and enables a standardised risk assessment across populations. These values are then converted into absolute daily or weekly intakes for reference by applying a standard adult body weight, commonly 70kg in European assessments. For example, an intake of 10μg per kilogram of body weight would correspond to 700μg per week for an adult weighing 70kg (approximately 0.1mg per day). This approach ensures that safety thresholds reflect both relative exposure (per unit of body mass) and practical dietary guidance, while still allowing for adjustments where populations differ significantly in body size or susceptibility. This report assumes a 70kg weight for adults.

There are different guidance values relevant to food safety assessment:

- **Upper Limit (UL)**

  A UL refers specifically to nutrients and is sometimes referred to as an Upper Intake Limit (UIL) or a Tolerable Upper Limit (TUL). It defines the maximum daily intake unlikely to cause adverse effects in the general population. They are calculated for most nutrients, although some elements may exhibit minimal toxicity and so there is no reason to issue a UL.

- **Tolerable Intake (TI)**

  Tolerable Intake will usually be stated daily (TDI) or weekly (TWI). It is applied to contaminants or environmental chemicals where some exposure is unavoidable. It is equivalent to UL, but for a contaminant not a nutrient.

- **Reference Dose (RfD) and Acceptable Daily Intake (ADI)**

  RfD and ADI values estimate the amount of a chemical or contaminant that can be consumed daily over a lifetime without noticeable health effects. They are usually expressed as milligrams per kilogram of body weight. ADI is used primarily in food safety considerations by WHO/FAO. In contrast, RfD is used in environmental health by the US Environmental Protection Agency and will consider different routes of exposure (e.g. skin contact), so Oral Reference Dose is the most relevant for the diet.

These values are typically derived from toxicological studies by identifying a no-observed-adverse-effect level (NOAEL) or benchmark dose, then applying uncertainty or safety factors to account for differences between animals and humans and variation within human populations. Together, these guidance values provide a scientific basis for risk assessment, regulatory limits, and the establishment of safe exposure thresholds in food safety management.

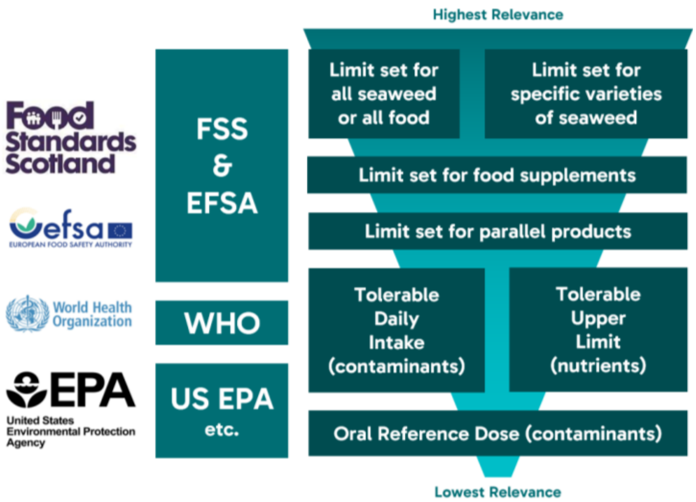


Figure 5.2: Relevance of limits and guidance values.

Regulatory limits are set for some contaminants in some foods. Seaweed is increasingly included in limits, but sometimes this is only for certain applications (e.g. use of seaweed as a dried botanical in herbal tea). Regulatory limits are generally aligned in the UK and Europe and will be based on TIs or ULs: this is the primary source of information for a food safety assessment carried out in the UK. Sometimes, there will be limited assessment of a nutrient or contaminant in Europe. In which case, the next most relevant assessment will likely be the WHO (or FAO, JECFA). As a last recourse, the US EPA or regulator in another developed country will often have completed an assessment and provided an oral RfD. The hierarchy and relevance of different limits and guidance values are summarised in Figure 5.2.

Statistics

In this report, statistical methods were selected to reflect the highly variable and often skewed nature of contaminant concentrations in seaweed. Environmental contaminant data frequently include outliers, which can arise from various factors (e.g. analytical technique, localised pollution, species-specific accumulation, seasonal variation). This creates skewed datasets with non-parametric distribution. As a result, the use of the arithmetic mean can be misleading, as it is disproportionately influenced by high values and may not accurately represent the typical concentration within a dataset.

Use of median levels

The median value (i.e. 50th percentile) has been used as the primary average measure in this report, which provides a more robust estimate of the typical value in the dataset. In addition, the 25th and 75th percentiles are included to give an indication of the central range of the data distribution. Reporting percentiles enables a more transparent representation of the spread and skewness of the data.

Arithmetic mean values are frequently provided in this report. Most studies report their results as mean averages and number of samples; few studies list the levels of individual measurements from the analysis. For example, 76% of the results in the Excess Nutrients and Toxic Elements Dataset are mean averages and just 7% are medians (17% of results are single measurements). Very often, commentary on individual results (e.g. levels detected in a study of Scottish seaweed) refers to mean averages.

Maximum values

In addition to measures of central tendency and distribution, maximum values have been reported to capture the highest observed concentrations of contaminants within the dataset. This is particularly relevant in the context of food safety, where upper-bound concentrations may be important for identifying potential risk scenarios and informing monitoring considerations. However, it is important to acknowledge that maximum values likely represent isolated observations and not typical levels.

To provide appropriate context, maximum values are presented alongside median and percentile data, allowing comparison between typical and extreme observations. Where relevant, potential explanations for unusually high values are discussed. This combined approach ensures that maximum concentrations are transparently reported without overstating their representativeness, supporting a balanced and scientifically robust interpretation of the data.

Minimum values and analytical limits

The limits of detection (LOD) and limits of quantification (LOQ) are important parameters for interpreting low-level measurements. The LOD represents the lowest concentration of an element that can be reliably distinguished from background noise. Results falling below the LOD indicate that the analyte cannot be confirmed as present and are reported as not detected (i.e. <LOD). The LOQ defines the lowest concentration that can be quantified with acceptable accuracy and precision (i.e. higher than the LOD). Therefore, values between the LOD and LOQ indicate that the analyte is present. In this report, the uncertainty of a result between LOD and LOQ is resolved by only included results above the LOQ.

For the purposes of comparative analysis, results below analytical limits can be included in by substituting a chosen fraction of the LOQ (e.g. 0.5×LOQ). However, this report generally excludes all results below analytical limits from analysis while including commentary on results below LOD and LOQ where appropriate. This ensures that low-level measurements do not disproportionately influence summary statistics. The sensitivity of analytical techniques increase over time, which means some trace elements that were once rarely above LOD and LOQ are now accurately measured.

For clarity, the minimum values reported in this study are the lowest levels reported in studies above the LOD and LOQ for that specific analysis. If an element was included in a study but only reported at below the LOD or LOQ, it may not have been recorded in the dataset and certainly will not be included analysis.

Statistical analysis

Analytical methods can be used to compare contaminant levels between species, locations or harvest times (e.g. Kruskal-Wallis for non-parametric data). Correlation and regression analyses help identify relationships between elements or environmental factors. Multivariate techniques, such as principal component analysis (PCA), can explore patterns and sources of contamination.

The majority of statistical techniques rely on several technical assumptions (e.g. homogeneity of variance, independence of observations, linear relationships between variables). Across all methods, it is assumed that samples are representative of the population and that analytical measurements are accurate, precise and free from systematic bias.

A meta-analysis is an approach used to combine and assess the results of multiple independent studies addressing the same research question. Pooling data from different sources increases the overall sample size and statistical power, allowing for more robust and reliable conclusions than any single study alone. Collation is essential to understand the variation in seaweed contamination, especially for infrequently analysed elements and known harmful substances. This report is in essence a meta-analysis, but the imperfect collation of results means that it is inappropriate to apply advanced statistical comparative techniques.

Low frequency exceedances

The occasional detection of elevated levels of contaminants in food products should be interpreted within the context of normal variability and analytical measurement. Isolated exceedances, when infrequent and not indicative of a consistent pattern, do not necessarily represent a meaningful risk to public health.

Food safety regulations are designed with conservative thresholds: monitoring frameworks account for such variability. These limits are designed around chronic exposure and incorporate substantial safety margins to ensure consumer protection, even in the presence of sporadic deviations. An example is pesticide residue monitoring in Europe. Annual reports are prepared by EFSA on over 13,000 products sampled across member states. The most recent report (EFSA, 2025) found that maximum residue limits were exceeded in 2% of samples, of which 1% were classed as non-compliant (due to measurement uncertainty). The EFSA state that the risk to consumers is low despite these exceedances. In reality, rare exceedances will be expected in large datasets.

A result above a limit should trigger evaluation to confirm the cause and to verify that they do not reflect systemic issues in production or supply chains. It is important to interpret the result relative to exposure and toxicological relevance.

6. EXCESS NUTRIENTS & TOXIC ELEMENTS

Minerals and elements are essential to human health, playing vital roles in metabolism, nerve function, development and bone formation. However, many minerals are required only in trace amounts. Excessive intake – whether through intake via food or water, dietary supplementation or environmental exposure – can lead to toxicity and adverse health effects. This section explores elements that are either toxic at trace levels or may become harmful when consumed in excess. Understanding these risks is crucial for promoting safe intake levels and protecting public health. The properties of seaweed cause them to accumulate elements from seawater, even if the water itself is not polluted. The majority of seaweed composition studies include nutrient minerals and toxic elements, which provides a rich dataset for analysis.

Data sourcing

Qualifying studies

Element concentrations are routinely analysed in seaweed during research into nutrition, processing and contamination. The data in this section is drawn from published studies, including supplementary data when available. A study can only qualify for inclusion in the Dataset if it meets the following criteria:

- **Seaweed from the Atlantic coasts of Europe**
  Limiting analysis to only Scottish seaweed would create a restricted pool of data: only 12 studies in the dataset sampled seaweed harvested in Scotland. This would have weakened conclusions, even providing no levels for many elements (e.g. antimony, bromine, vanadium). Extension to the UK would have only added a few other studies and so the geographic coverage expanded to the Atlantic coasts of Europe. This broadly aligns with the natural range of most of the key species in Scotland.
  A few studies are included that harvested seaweed from the Baltic. Greenland is included because there are several high quality studies published by researchers linked to Denmark (e.g. Kressig et al., 2021; Wegeburg et al. 2023). Although many species are also found in Canada and the northwestern states of the US (e.g. Saccharina latissima, Ascophyllum nodosum), no results from the western Atlantic are included in the dataset. France and Spain have coastline on both the Mediterranean and Atlantic. It is important to highlight that only studies using seaweed from the Atlantic coast were included in the dataset as the conditions and species assemblages are markedly different in the Mediterranean (and less relevant to seaweed). However, some Mediterranean studies are referenced to aid benchmarking of certain contaminants. Care was taken to avoid studies carried out in overseas territories (e.g. Guadeloupe, France).
- **Date of sampling**
  Most studies state the month and year that seaweed was taken from a farm or shoreline. This is because there is known seasonal variation in seaweed composition (e.g. Ometto et al., 2018; Maribu et al., 2025). Some data report concentrations in time series, in which case average levels were taken or most recent taken as appropriate.

- **Production method**

  Studies almost always state whether the seaweed was harvested from the wild or farmed. If not unambiguously stated, origin could often be inferred from the sampling description.

- **Sections relevant for harvesting**

  Different parts and sections of one individual seaweed specimen may possess different concentrations of elements (e.g. Kreissig et al., 2021; Garcia-Seoane et al., 2021; Barrat et al., 2024). Results are assumed to be for the harvestable part of the plant, unless clearly stated otherwise. Levels in different sections are recorded to allow comparison and further interrogation as required.

- **Publication since 2015**

  Only studies published since 2015 are included in the dataset, notwithstanding some earlier studies analysing Scottish seaweed or elements of particular interest. Older studies may have results that skew the data. There is a worldwide trend of declining metal pollution, which began following implementation of environmental policies in the 1970s (Aboal et al., 2023). Analytical techniques continuously improve over time. This is particularly important for trace elements (i.e. previously below level of detection, but now quantifiable) and speciation of metals (e.g. discerning inorganic and organic arsenic). In addition, research publication latency means that results are issued typically several years after the samples were collected.

- **Seaweed species stated**

  The majority of reports provide the scientific names to allow identification to species level, although studies sometimes refer to Fucus species. The taxonomic diversity of Ulva means that species determination through morphology is challenging. Steinhagen et al. (2019) conducted DNA analysis and determined that the morphological concepts for identification of Ulva species in northern Germany were not aligned with the inventory of local species present. This has justified some studies of seaweed contamination grouping species of Ulva (e.g. Samarasinghe et al., 2021). Generally, data for species are added to the dataset using the taxonomic name given in the study. Analysis is typically presented as generic Ulva spp., notwithstanding commentary around the two primary species used in Europe: Ulva lactuca (sea lettuce) and Ulva intestinalis (gut weed).

  Similarly, the combination of environmental variability, morphology, complex life cycles and evolving taxonomy makes species-level identification within the Porphyra genus difficult. Identification often requires specialist expertise and genetic analysis for confirmation. Three common species are Porphyra umbilicalis, Porphyra purpurea and Porphyra dioica. Although Biancarosa et al. (2018) reported levels for all three species, the results for Porphyra species are generally grouped to the genus.

  For clarity, this report only covers seaweed (macroalgae) and does not include any data for microalgae.

It is important to recognise that there is some leniency regarding inclusion. The materials and methods section may provide almost all the qualifying information. In many cases, the month of harvest is stated – as the authors recognise the importance of seasonal variation – but the year is not expressly given. Such instances are generally included as they are likely to align with the aim to feature only recently published research.

Seaweed is almost always washed prior to analysis, given the risk of contaminants bonding to particulates. All results in the dataset are for washed seaweed. Concentrations after treatment are not included, but levels prior to treatment are included (e.g. content prior to blanching).

Results are taken from tables and body text, with some data occasionally taken from charts for instances where the Dataset would be strengthened. An example is research into arsenic speciation in seaweed (e.g. Ownsworth et al., 2019; Sim et al., 2023). Results from charts are recorded to an appropriate level of accuracy (e.g. nearest 1mg/kg for total arsenic concentration).

Exclusion of studies

Reasons that studies were excluded from the Dataset include:

- Items purchased from the open market of uncertain provenance (e.g. Desideri et al., 2015; Asensio et al., 2021). Researchers will rarely be able to trace the raw material to source.
- Statement of supplier without reassurance of local seaweed sourcing for study (e.g. Mohammed et al., 2022). This is particularly important given seaweed is traded at a wholesale level between countries.
- Analysis where seaweed groups are reported rather than individual species (e.g. Sim et al., 2024b) or only a common name is given that could be attributed to different species (e.g. sea lettuce).
- Data reported only in low-resolution charts, without corresponding data tables (e.g. Pandey et al., 2023).
- Analysis of seaweed from a location with prior knowledge of pollution risk, although the results may be captured for purposes of comparison with unpolluted sites in the same study or included if there is no evidence of elevated concentration (e.g. García-Seoane et al 2020b).
- Analysis of seaweed exposed to known concentrations of dissolved elements (e.g. Kumblad et al., 2024), unless the study included a control unexposed sample with clear provenance.

For example, there are many studies that have analysed the elemental composition of seaweed used to feed animals. They often state supplier and country of origin, but results are only included in the Dataset if there is additional information to clarify provenance (e.g. year of harvest, statement if wild or cultivated origin).

Overview of dataset

The studies covered seaweed samples sourced from 14 different countries (Figure 6.1). The country featured in the most studies is Norway (37). Over the past decade, Norwegian seaweed cultivation has been supported through public research funding and collaborative innovation programmes. More recently, funding has increasingly aligned with climate mitigation and sustainable food production. This research activity has yielded a substantial amount of data on seaweed composition. Although the majority of studies sampled at least one the two key cultivated species – Alaria esculenta and Saccharina latissima – around one-third of the studies covered other species, many of which were comprehensive assessments (e.g. Biancarosa et al., 2018; Ometto et al., 2018; Duinker et al., 2020). Most of the 17 studies across the UK sampled Scottish seaweed. Spain also was featured in 17 studies. Other countries in 10 or more studies were Ireland, France, Iceland and Sweden.

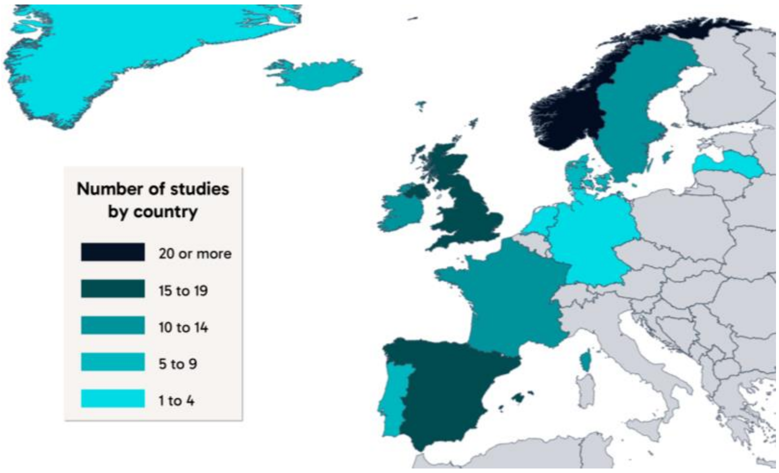


Figure 6.1: Representation of countries featuring in studies in the dataset (created with PaintMyMap.com; Equal Earth projection).

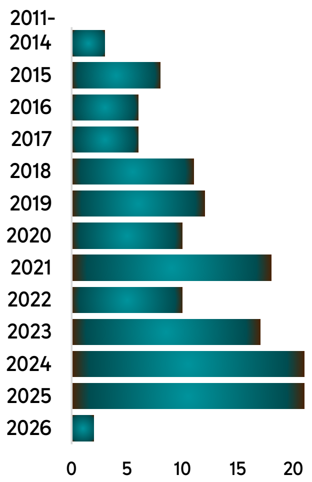


Figure 6.2: Number of studies by publication year.

Most of the studies in the dataset were published from 2021 onwards (61%; Figure 6.2). Three studies were included despite being published prior to 2015. Anakastasis (2011) sampled kelps near Oban, providing useful data in a key location in Scotland and including lithium and boron in the analysis. Villares et al. (2013) covered seasonal variation in metals in wracks in Spain. Kuepper et al. (2014) analysed bromine in French seaweed, a rarely reported element. None of the results in these three papers were obvious outliers in the dataset.

The total number of results in the Dataset is 3,130. This is the combined single, median and mean levels of elements reported across all species and locations by qualifying studies. For example, Jönsson & Nordberg Karlsson (2024) analysed 18 elements in different sections of four species from Sweden, Norway and/ Ireland. This corresponded to transfer of 132 mean results to the Dataset. Concentrations measured by Jönsson & Nordberg Karlsson (2024) following different processing treatments were not included as they were not representative of raw seaweed.

In addition, there are 601 maximum levels captured in the Dataset. These are excluded from the calculation of a statistic to represent the levels of a contaminant (i.e. median), but included in the summary and commentary where appropriate (especially where maximum levels exceed the highest reported average levels).

Over 20,000 samples were measured across the 3,130 average results. Two-thirds of average results in the Dataset are for single, duplicate and triplicate samples (Figure 6.3); 32% of results are for three measurements as this is a standard sample size in analytical chemistry. There are many studies that analysed a larger number of samples for each species (11% of results have a sample size of 15 and above).

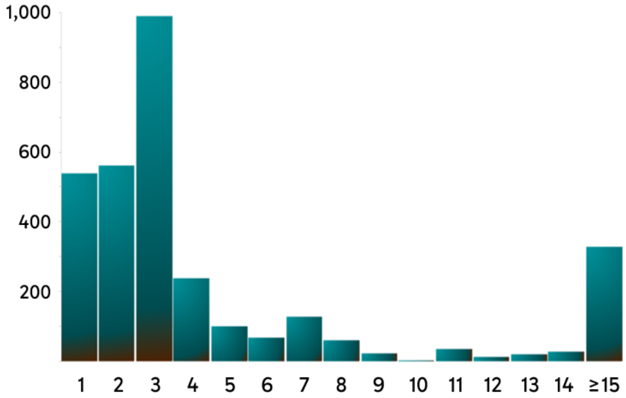


Figure 6.3: Histogram of number of samples analysed for each of the 3,130 results in the Dataset.

The majority of the results in the dataset are for samples of wild seaweed (80%). Indeed, wild harvest is the only origin for most species. The only species for which the majority of results were from cultivated stock was Saccharina latissima (55%). A handful of studies analysed pooled samples from wild and farmed seaweed (e.g. van Tuinen et al., 2023).

Categorising minerals and risk

Minerals and trace elements

In nutrition, the term 'mineral' refers to an essential inorganic nutrient required for physiological function, whereas the term 'element' denotes the chemical substance itself. Accordingly, essential dietary minerals are composed of elements, but not all elements present in foods are considered minerals. Terminology is needed to grade elements as those essential for health and those that are toxic (as Cabrita et al., 2016, did in their analysis of mineral contents of 15 species of Portugese seaweeds. This report uses the following groups:

- Essential macro-minerals (e.g. calcium, magnesium)
- Essential trace elements (e.g. iron, copper)
- Beneficial trace elements (e.g. molybdenum, vanadium)
- Characterised toxic trace elements (e.g. cadmium, lead)
- Other toxic trace elements (e.g. thallium, antimony)

These categories are appropriate for this review and are expanded on in Table 6.4.

Risk categories for elements

Three categories are used to provide a structured, risk-based interpretation of analytical data in relation to Tolerable Upper Intake (TUI) values, or equivalent. They support a consistent approach to evaluating potential consumer exposure, justifying superficial interrogation (i.e. lower risk) or detailed assessment (i.e. higher risk). Generally, a more conservative category will be applied if there is uncertainty around the strength of evidence (e.g. limited data for relevant species). Relevant limits in regulations will be highlighted, irrespective of risk category.

Table 6.4: Categories of minerals according to quantities needed and benefit.

Category	Function	Examples	Requirements		Recommended maximum intake
			Daily intake	Recommended levels	
Essential macro-minerals	Central to biochemical processes and body tissues	Potassium, Sodium, Calcium, Magnesium	>100mg	In place	Guidance may be in place
Essential trace minerals	Needed in small quantities to support specific functions	Iodine, Zinc, Manganese, Selenium	10µg to 100mg	Likely to be in place	Guidance likely to be in place and legal limits may be in place
Beneficial trace minerals	Minute intake may be beneficial, but not widely thought essential	Cobalt, Nickel, Boron, Strontium	<10µg	May be in place	
Characterised toxic trace minerals	Not needed and toxic even in small amounts	Cadmium, Mercury, Lead, Aluminium	-	Never	Risks well understood, with legal limits likely
Other toxic trace minerals		Beryllium, Thallium, Barium, Antimony			Tolerable intakes likely, but not legal limits

Table 6.5: Categories for risk of excessive intake of a mineral from consuming seaweed.

Category	Contribution to upper intake level	Detail provided
Minimal risk of excess intake via seaweed	Highest levels in any species are <20% of guidance level	Basic overview with comparisons where relevant
Possible risk of excess intake via seaweed	Highest levels in any species are 20-100% of guidance level	Overview with assessment of variation (e.g. species of concern)
Risk of excess intake via seaweed	Highest levels in any species are >100% of guidance level	Detailed assessment of variation (e.g. species, countries, levels in seafood)

Essential macro-minerals

The essential macro-minerals calcium, magnesium, phosphorous and potassium are excluded from detailed assessment as there is little-to-no risk of excess intake from seaweed consumption. Sodium is an essential macro-mineral that is consumed in excess in most diets, leading to widely understood impacts that drive public health policies around the world. Therefore, high sodium intake is a population-level chronic disease risk and not linked to toxicity. Chloride is also essential for human health, with intake correlated with sodium through salt (sodium chloride). Sulphur is also important in the diet, contributing to amino acid metabolism and other essential processes. Seaweed contains sulphur in proteins (e.g. methionine) and sulphated polysaccharides (e.g. fucoidan, ulvan).

The maximum levels of essential macro-minerals are listed in Table 6.6. Chloride is excluded as its negative health effects are linked to sodium (as sodium chloride). Sulphur is excluded as there are no recommended intake levels or upper limits. Multiple essential macro-minerals are usually included in elemental analysis of seaweed. However, there are few studies that measure all the macro-minerals in numerous samples across the species of seaweed found in Scotland. Two of the most useful published studies are:

- Badmus et al. (2021): measurements of calcium, magnesium, potassium and sodium in 8 species of Scottish seaweed (from 8-38 samples per species)
- Biancarosa et al. (2018): measurements of calcium, magnesium, phosphorous, potassium and sodium in 21 species of Norwegian seaweed (in duplicate)

The maximum mean levels of macro-minerals detected in relevant species are useful reference points to demonstrate that negative health impacts are improbable. Even at the highest levels observed, a 5 dry gram portion of seaweed would only contribute up to around one-third of recommended daily intake (e.g. calcium from Laminaria digitata: Badmus et al., 2021; magnesium from Ulva lactuca: Biancarosa et al, 2018; Table 6.6). This qualifies why macro-minerals were not included in the detailed analysis of seaweed composition in this review.

Table 6.6: Essential macro-minerals found in relevant seaweed species

Essential macro-mineral	Highest level usually seen in seaweed	Adequate or Recommended Intake		Recommended Upper Intake	
		Amount per day	Contribution from 5g dry portion at highest level	Amount per day (adults)	Rationale
Calcium	74.8g/kg (Laminaria digitata[a])	1,000mg	37%	2,500mg (from total intake)	Excess calcium disrupts absorption of other minerals and increases the risk of kidney stones
Magnesium	27.0g/kg (Ulva lactuca[b])	420mg	32%	350mg (only from supplements / medication)	Excess magnesium in food does not cause issues in healthy individuals
Phos-phorous	3.7g/kg (Alaria esculenta[b])	700mg	3%	4,000mg (from total intake)	Excess phosphorous disrupts calcium metabolism and bone mineralisation
Potassium	100.0g/kg (Saccharina latissima[b])	3,400mg	15%	None in place	Excess potassium is excreted by the kidney in health individuals
Sodium	43.4g/kg (Himanthalia elongata[a])	1,500mg	14%	2,300mg (from total intake)	Excess sodium linked with cardiovascular disease and hypertension

[a] Badmus et al., 2021; [b] Biancarosa et al, 2018.

Essential trace minerals

Essential trace minerals are needed in small quantities to support health. Recommended intake levels and upper limits are likely to be in place given the element is linked to specific functions in the body.

Iron

Iron is not generally considered a contaminant, with focus mainly on iron as a nutrient. The recommended daily intake in the UK is 8.7mg for adults, rising to 14.8mg per day for menstruating women (Scientific Advisory Committee on Nutrition, 2010). However, there were insufficient data to establish an UL for iron in the UK and Europe. The National Academy of Medicine in the US have stated a UL for iron in adults is 45 mg per day, based on posing no risk of adverse effects in healthy individuals (e.g. gastrointestinal distress from excess iron supplementation). This is aligned to a statement from the EFSA in 2024 that 40mg is likely to be a safe intake level.

Iron is not one of the trace metals included the UK Diet Survey. A study by Bruggraber et al. (2012) of plant-based foods showed variable levels (e.g. wholemeal wheat flour: 66mg/kg: tofu: 30mg/kg), with fortified cereal significantly higher (e.g. cornflakes 148mg/kg). Fresh thyme had one of the highest iron levels (836mg/kg).

Iron 194 results across all species ΣN=1,351 from 65 studies	
Mean	433mg/kg
Minimum	9mg/kg
25%	84mg/kg
Median (50%)	172mg/kg
75%	366mg/kg
90%	733mg/kg
Maximum	8,520mg/kg
Minimal risk of excess intake via seaweed	

The levels of iron in seaweed are highly variable. Some very high levels can be detected (8% of the dataset is over 1,000mg/kg), which skews the mean content across all species. Seaweed varieties with lower iron levels include Himanthalia elongata (max 146mg/kg) and Fucus serratus (max 440mg/kg). Kelp species tend to have higher levels (Alaria esculenta: max 3,351mg/kg; Laminaria digitata: max 5,197mg/kg). The maximum levels seen were in Ulva intestinalis (5,800mg/kg) and Chondrus crispus (8,520mg/kg), which suggests that a range of species are vulnerable to elevated concentrations. It is clear than iron is an element that is readily absorbed from the surrounding environment, making species differences may be less important. This is evidenced by the eight results over 1,000mg/kg coming from eight different species (across five different studies).

Although seaweed can contain iron at 5,000mg/kg, this would be just 25mg in a 5 dry g portion (i.e. 56-63% of the maximum levels suggested). It is more likely than consumed seaweed will have an iron level at least an order of magnitude less, which means an intake of under 10% of the recommended safe levels. While iron is consumed in the diet already, it is highly unlikely that the highest possible iron content in seaweed could have any negative impact on health. Therefore, there is no need to have a limit in place for iron in seaweed.

Manganese

Manganese is an abundant trace metal, with higher concentrations associated with mineral soils, and so is commonly found in soil, rock, air and water. There are generally lower levels in groundwater in the Highlands and the Southern Uplands, with higher levels in Aberdeenshire and Strathclyde, the Moray Firth, Caithness and Orkney (Macdonald et al., 2005). Sources of manganese pollution include metal production, waste consumer goods, combustion and leaching from historically contaminated land (Table 3.3).

The daily Reference Intake for manganese in the UK is 2mg for adults, which is similar to the ESFA Adequate Intake of 3mg for adults. There is a weak evidence base for ill effects from high manganese consumption and so there is no formal UL in the UK and Europe. However, the Food and Nutrition Board (FNB) at the US National Academies of Sciences, Engineering, and Medicine state a UL of 11mg/day for adults, based on potential impacts on blood levels and neurotoxicity (Manganese - Health Professional Fact Sheet).

Daily intake of manganese for adults according to UK Diet Survey is 4.3mg (mostly from non-alcoholic beverages, cereals and bread). Manganese levels in Scottish bivalves in 2025 averages 1.82mg/kg (highest 3.44mg/kg in Pacific oysters from North Ayrshire).

Manganese 176 results across all species ΣN=1,031 from 56 studies	
Mean	90.8mg/kg
Minimum	0.6mg/kg
25%	7.8mg/kg
Median (50%)	18.4mg/kg
75%	65.9mg/kg
90%	147.4mg/kg
Maximum	2,460.0mg/kg
Minimal risk of excess intake via seaweed	

The manganese content of seaweed is variable. Elevated levels can be detected (4% of the dataset is over 500mg/kg), which skews the mean content (90.8mg/kg; median: 18.4mg/kg). Species differences appear to be less important to manganese concentrations. The three highest levels in the dataset are samples of three disparate species: 2,460mg/kg in Chondrus crispus (Bikker et al., 2020), 1,675mg/kg in Ulva spp (Samarasinghe et al., 2021) and 1,630mg/kg in Fucus vesiculosus (Balina et al., 2016).

Even assuming a high manganese content of 500mg/kg in seaweed, a 5 dry g portion would contain only 2.5mg (i.e. 58% of the UK Diet Survey intake; 23% of the US UL). While levels can be higher than 500mg, these are comparatively infrequent occurrences that are not relevant to chronic dietary exposure. Therefore, it is unlikely that the highest possible manganese levels in seaweed would have any negative impact on health.

Copper

Natural copper levels in soil and rock are relatively low in the UK, apart from isolated locations. Copper concentrations are lower in the Highlands than the Lowlands, but the difference is less marked than other metals. Copper is associated with mineral soils and generally higher in Aberdeenshire and the Central Belt, with some elevated levels in the Western Isles, Skye, and the west coast of Highlands. There are various sources of copper contamination, including roads (worn brake pads and tyres), metal production, corrosion of pipes and fittings and urban runoff (Table 3.3). Importantly, copper is a component of various fungicides and pesticides and can be found in elevated concentrations in slurry and sludge. Similarly, copper is commonly used in marine antifoulant. This means that sheltered estuaries, marinas and harbours may be a source of copper pollution relevant to seaweed.

The daily Reference Intake for UK adults for copper is 1.2mg. This is similar to the ESFA Adequate Intake of 1.6mg for adults. There is no formal UL for copper in the UK, but the EFSA has set a UL in adults of 5mg per day based on liver damage.

According to UK Diet Survey, daily intake of copper for adults is 0.9mg (mostly from cereals and bread). Copper levels in Scottish bivalves in 2025 averaged 4.18mg/kg (highest 15.50mg/kg in Pacific oysters from North Ayrshire).

Copper content of seaweed is variable (interquartile range: 1.4-6.0mg/kg). Although elevated levels can be detected (8% of the dataset is over 20mg/kg), copper concentrations are generally in a similar range to those seen in Scottish bivalves. Species differences appear to be less important to copper concentrations: eight different species make up the top 10% of the dataset.

Copper 199 results across all species ΣN=1,488 from 70 studies	
Mean	5.48mg/kg
Minimum	0.29mg/kg
25%	1.37mg/kg
Median (50%)	2.70mg/kg
75%	6.02mg/kg
90%	13.04mg/kg
Maximum	46.61mg/kg
Minimal risk of excess intake via seaweed	

If taking an elevated copper content of 20mg/kg, a 5 dry gram portion of seaweed would contain only 0.1mg (i.e.11% of the UK Diet Survey intake; 2% of the EFSA UL). It is unlikely that the highest copper levels found in seaweed would have any negative health implications.

Selenium

Selenium is not generally considered a contaminant. Soil levels in the UK are generally low and areas of higher content are in England and Wales. There are few significant sources of selenium contamination (Table 3.3). Selenium was historically used in glass manufacturing and is used in trace amounts in electronics and metal production. One of the main uses in the UK is as a supplement in livestock feed to prevent deficiency. The recommended daily intake in the UK is 60µg for adult women and 75µg for adult men. The upper limit for selenium is the same in the UK and Europe: 300µg per day for adults (0.3mg). This is to protect against chronic selenium toxicity.

Daily intake for adults according to UK diet survey is 77µg of selenium (mostly from non-alcoholic beverages, fish and cereals). Selenium levels in Scottish bivalves in 2025 were relatively consistent across species, averaging 0.35mg/kg (highest 0.45mg/kg in mussels from Sutherland).

The selenium content of seaweed is broadly similar to that seen in Scottish bivalves. Mostly, selenium concentrations are below 1mg/kg (only 14% of the dataset is over 1mg/kg). Several studies have found higher values in different species. Correia et al. (2021) detected selenium at 11.5mg/kg in Saccharina latissima, 8.9mg/kg in Laminaria digitata and 6.3mg/kg in Chondrus crispus. Samarasinghe et al. (2021) measured selenium at 11.1mg/kg in Ulva spp., 3.7mg/kg in Saccharina latissima and 2.5mg/kg in Ascophyllum nodosum. Given the range of seaweeds with results above 1mg/kg, there are no clear species differences with regard to selenium concentrations.

Assuming a high selenium content of 10mg/kg, a 5 dry g portion of seaweed would contain only 50µg (i.e. 60% of the UK Diet Survey intake; 20% of the UL in UK and Europe). It is unlikely any negative health issues could be caused by excess selenium intake from seaweed.

Selenium 93 results across all species ΣN=366 from 28 studies	
Mean	0.81mg/kg
Minimum	0.02mg/kg
25%	0.07mg/kg
Median (50%)	0.14mg/kg
75%	0.42mg/kg
90%	4.50mg/kg
Maximum	11.50mg/kg
Minimal risk of excess intake via seaweed	

Zinc

Zinc levels are less distinctly associated with soil type than other metals. However, zinc levels are lower in the Highlands and more elevated around the Highland Boundary Fault, the Southern Uplands and Strathclyde. Important sources of zinc contamination in the UK include abandoned metal mines and metal processing sites leaching into watercourses. Zinc is a component of tyres and brake pads, leading to roads being a source. Manure and sludge can contain elevated levels. Weathering increases transfer of zinc from galvanised steel into waste water systems (e.g. roof drainage). Overall, there are many potential sources of low level zinc contamination (Table 3.3) but this does not generally cause significant food contamination.

The daily Reference Intake for UK adults for zinc is 7.0mg for adult women and 9.5mg for adult men. The UL for zinc is the same in the UK and Europe – 25mg per day for adults – to protect against reduce copper and iron absorption.

Zinc 209 results across all species ΣN=1,412 from 70 studies	
Mean	40.4mg/kg
Minimum	1.3mg/kg
25%	21.8mg/kg
Median (50%)	32.0mg/kg
75%	50.9mg/kg
90%	73.8mg/kg
Maximum	165mg/kg
Minimal risk of excess intake via seaweed	

The daily intake for UK adults is 7.7mg of zinc (UK Diet Survey), mostly from meat, cereals and bread. Zinc levels in Scottish bivalves in 2025 show variation between species, averaging 25mg/kg in mussels and 220mg/kg in oysters (highest 294mg/kg in European oysters from Eilean Siar).

Zinc levels in seaweed are lower than those in Scottish oysters. Zinc concentrations are mostly below 100mg/kg (only 4% of the dataset is over 100mg/kg) and there are no clear species differences.

Assuming an elevated zinc content of 100mg/kg, a 5 dry g portion of seaweed would contain only 0.5mg (i.e. 6% of the UK Diet Survey intake; 2% of the UL in UK and Europe). Therefore, it is unlikely that the highest zinc levels found in seaweed would have any negative health effects.

Cobalt

Cobalt is found naturally at low levels in bedrock and can be a pollutant from waste consumer goods and metal production (Table 3.3). Cobalt is an essential component of Vitamin B12, but there is no RDI in place in the UK or Europe. It is generally not seen as a contaminant. This is evidenced by the fact that there is no UL established by the EFSA and no legal limit in place. The NOAEL of 23µg per kg body weight per day used by UK EVM is one of the few references available (equivalent to 1.6mg per day).

Cobalt is not included in the UK Diet Survey. However, cobalt is one of the metals in seafood analysed by FSS, averaging 0.04mg/kg in Scottish bivalves in 2025 (highest 0.12mg/kg in surf clams from Fife).

Maximum levels of cobalt in seaweed can exceed 2mg/kg (7% of results are above this level). Fucoid wracks tend to show the highest levels. The only species with mean cobalt concentrations above 1mg/kg are Fucus vesiculosus, Fucus serratus and Ascophyllum nodosum, although Bikker et al. (2020) found an unusually high level of 7mg/kg in Chondrus crispus.

Cobalt 94 results across all species ΣN=776 from 28 studies	
Mean	0.68mg/kg
Minimum	0.01mg/kg
25%	0.16mg/kg
Median (50%)	0.36mg/kg
75%	0.82mg/kg
90%	1.97mg/kg
Maximum	7.00mg/kg
Minimal risk of excess intake via seaweed	

The maximum level found in any sample of Scottish seaweed by Badmus et al. (2021) was 2.63mg/kg in Fucus spiralis. The average level of cobalt detected by Ownsworth et al. (2019) across five species from the Forth Estuary and Firth of Forth was 0.36mg/kg, with a maximum concentration of 1.60mg/kg in a sample of Fucus serratus (these figures align with the Dataset, but the results from this study are not included due to the limited detail).

The concentration of cobalt in seaweed are higher than those seen in Scottish bivalves. However, 5 dry g of seaweed at 2mg/kg is just 10µg intake (<1% of NOAEL level, UK EVM) and so there is minimal risk of ill health from cobalt in edible seaweed.

Iodine

Seaweed is commonly recognised as the richest natural source of iodine. Equally, there is awareness of the variable content in seaweed that presents both nutritional benefits and potential food safety concerns. Understanding iodine concentrations in different types of seaweed is essential for assessing both the nutritional value and potential risks associated with seaweed consumption. This section examines recommended iodine intake levels, variability among relevant seaweed species and the implications for consumer safety.

Iodine in seawater originates mainly from natural weathering of iodine-containing minerals, releasing iodide and iodate ions. Iodine exists primarily in dissolved forms that are readily accessible to marine organisms; seaweeds have evolved efficient uptake mechanisms to absorb these iodine species. This is partly as a by-product of nutrient acquisition and partly for physiological functions. Certain groups, especially brown seaweeds, can accumulate iodine to concentrations far exceeding those in the surrounding water.

Iodine intake and health

Iodine is a key micronutrient required for thyroid hormone synthesis. In turn, iodine regulates an array of physiological processes (e.g. metabolism, growth and neurological development). The recommended daily intake of iodine varies around the world. The UK uses a Recommended Nutrient Intake of 140µg for adults. The advised intake is proportionate to body weight, reducing down to 50µg per day for infants (Table 6.7).

Table 6.7: Recommended Nutrient Intake for iodine in the UK by age group.

Age group	RNI
0-3 months	50µg
4-12 months	60µg
1-3 years	70µg
4-6 years	100µg
7-10 years	110µg
11-14 years	130µg
15+ years	140µg

Historically, deficiency of iodine has been recognised as a major global health problem, leading to neurodevelopmental impairments and goitre. Given the known risks, agencies and regulators have long recommended upper intake levels for iodine (summarised in Table 6.8). The UK guidance of 600µg per day is not a formal level set by a UK body (e.g. Committee on Medical Aspects of Food Policy), instead the UK aligned with European guidance (EFSA, 2006) and has not changed since Brexit. The 600µg limit in place in Europe and the UK is the lowest in the world, together with China (Chinese Nutrition Society, 2023).

Risk assessments by the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 1989) yielded a recommendation of 1,000µg per day; this tends to be the default guidance used worldwide. A similar daily upper level of 1,100µg is advised by agencies in the US (Institute of Medicine, 2001) and Australia & New Zealand (Food Standards Australia New Zealand, 2008). However, higher upper limits are in place in two Asian countries with high rates of seaweed consumption: 2,400µg in South Korea (Ministry of Health and Welfare, 2020) and 3,000µg in Japan (Ministry of Health, Labour and Welfare, 2014). Although there are higher recommended upper intakes around the world, this review is geared around the UK and European limit of 600µg per day.

Table 6.8: Recommended maximum daily intake of iodine in different countries and territories.

Location	Upper Limit	Source
UK	600µg	EFSA (2006)
Europe	600µg	
China	600µg	Chinese Nutrition Society (2023)
WHO (worldwide)	1,000µg	JECFA (1989)
US & Canada	1,100µg	Institute of Medicine (2001).
Australia & New Zealand	1,100µg	Food Standards Australia New Zealand (2008)
South Korea	2,400µg	Ministry of Health and Welfare (2020);
Japan	3,000µg	Ministry of Health, Labour and Welfare (2014)

Daily intake for a UK adult according to National Diet and Nutrition Survey is 126µg of iodine (mostly from milk, dairy products and fish). Although this is close to the recommended intake (Table 6.7), someone avoiding fish, meat and dairy (e.g. a vegan diet) would only consume around 30µg of iodine per day. Urinary iodine concentration (UIC) is a reliable indicator of dietary intake used to assess iodine status at a population level. The National Diet and Nutrition Survey began monitoring UIC in 2013: the most recent report period showed several cohorts were below adequate status and that the median UIC is reducing year-on-year for all cohorts between 2013 and 2023.

Iodine in seaweed

The significance of iodine in seaweed means it is widely included in analytical studies. Levels in seaweed are variable, but it has long been known that levels in seaweed can be elevated to a point of concern for health. The median iodine level across all species and studies in the dataset is 650mg/kg and overall there is a risk of excess iodine intake from edible seaweed. However, the skewed distribution and wide range of results means that further interrogation is necessary (interquartile range = 200-2,674mg/kg; mean = 1,661mg/kg).

The EFSA has identified seaweed as risk for excessive iodine exposure. In 2025, the EFSA issued a draft limit of 1,000mg/kg for all types of seaweed (draft EU limit hereafter). Across all the species in the dataset, 38% of the results exceed the draft EU limit.

Table 6.9a provides an overview of the iodine levels in brown seaweed species. The minority of brown wracks will exceed the draft EU limit (8% of 63 results in the dataset). Elevated levels are possible in Ascophyllum nodosum (max: 1,851mg/kg) and Fucus serratus (max: 1,530mg/kg).

Iodine 247 results across all species ΣN=1,493 from 62 studies	
Mean	**1,661mg/kg**
Minimum	8mg/kg
25%	200mg/kg
Median (50%)	**650mg/kg**
75%	2,674mg/kg
90%	4,643mg/kg
Maximum	**10,000mg/kg[a]**
Risk of excess intake via seaweed	

[a] Excluding one maximum result exceeding 11,000mg/kg due to possible inaccuracy around conversion from wet to dry weight (Schiener et al, 2015)

No other wrack species exceeds the draft EU limit. Himanthalia elongata has an unusually low iodine content for brown seaweed species (median 59mg/kg). The only brown kelp species with a moderate iodine level is Alaria esculenta (median 549mg/kg): all others have elevated concentrations (maximums reach 10,000mg/kg, i.e. iodine is 1% of dry weight). Saccharina latissima is the most widely analysed species and has a median iodine level of 3,124mg/kg (87% of results exceed the draft EU limit). The median iodine content of Laminaria hyperborea Is similar at 3,878mg/kg (all results exceed the draft EU limit). The European species with the highest average iodine concentration is Laminaria digitata: median level is 4,403mg/kg (94% exceed the draft EU limit). There is only one result in the database for Sacchorhiza polyschides (mean 367mg/kg; Cardoso et al., 2023).

Table 6.9a: Detail of iodine levels in the dataset for brown seaweed species featured in four or more studies.

Group	Species	Results in dataset	ΣN	N results above draft EU limit [a] (1,000mg/kg)	Mean	Median	Max[b]
Brown wracks	Ascophyllum nodosum	17	110	4 (24%)	827 mg/kg	670 mg/kg	1,851 mg/kg
	Pelvetia canaliculata	5	17	-	221 mg/kg	210 mg/kg	280 mg/kg
	Fucus spiralis	7	20	-	181 mg/kg	158 mg/kg	232 mg/kg
	Fucus vesiculosus	12	144	-	304 mg/kg	267 mg/kg	830 mg/kg
	Fucus serratus	7	49	1 (11%)	659 mg/kg	440 mg/kg	1,530 mg/kg
	Himanthalia elongata	9	52	-	72 mg/kg	59 mg/kg	230 mg/kg
	All brown wrack species	**63**	**450**	**5 (8%)**	**453 mg/kg**	**300 mg/kg**	**1,851 mg/kg**
Brown kelps	Alaria esculenta	27	163	3 (11%)	595 mg/kg	557 mg/kg	2,400 mg/kg
	Saccharina latissima	68	577	59 (87%)	3,405 mg/kg	3,124 mg/kg	10,000 mg/kg
	Laminaria digitata	16	89	15 (94%)	4,737 mg/kg	4,403 mg/kg	10,000 mg/kg
	Laminaria hyperborea	12	23	12 (100%)	3,847 mg/kg	3,878 mg/kg	11,096 mg/kg
	All brown kelp species	**125**	**853**	**84 (67%)**	**2,963 mg/kg**	**2,648 mg/kg**	**11,096 mg/kg**
All brown seaweed species		**198**	**1,349**	**95 (48%)**	**2,056 mg/kg**	**1,148 mg/kg**	**11,096 mg/kg**

[a] Number of average results (not maximum levels in dataset) above draft iodine proposed for EU (1,000mg/kg); [b] Maximum level across the dataset for species or group.

The iodine concentrations in red seaweed are given in Table 6.9b. Very few results exceed the draft EU limit (8%), with just two in the core species (Mastocarpus stellatus, Nitschke et al. 2018; Chondrus crispus, Lopez-Hortas et al. 2022). Duinker et al. (2020) analysed Norwegian Vertebrata lanosa and clearly determined it has an elevated iodine content (mean: 2,500mg/kg; max: 6,200mg/kg), which is unusual among red seaweed species. The median iodine concentrations in the two most important red seaweed species in Europe are lower (56mg/kg in Porphyra spp; 150mg/kg in Palmaria palmara). There is only one result in the database for Osmundea pinnatifda (single sample of 430mg/kg; Kuepper et al., 2014). Although the average levels in red seaweed are low to moderate, there is a minor risk of elevated levels.

Table 6.9b provides an overview of the iodine concentrations in green seaweed species. Although tested less frequently than other groups, it is clear that iodine levels are generally lower in green seaweed (no results exceed the draft EU limit). The maximum level in the dataset is 300mg/kg (Ulva sp., Ficheux et al., 2023).

Table 6.9b: Detail of iodine levels in the dataset for red and green seaweed species featured in four or more studies.

Group	Species	Results in dataset	ΣN	N results above draft EU limit [a] (1,000mg/kg)	Mean	Median	Max[b]
Red seaweeds	Palmaria palmata	17	131	-	218 mg/kg	150 mg/kg	839 mg/kg
	Chondrus crispus	6	14	1 (17%)	488 mg/kg	278 mg/kg	1,261 mg/kg
	Mastocarpus stellatus	4	13	1 (25%)	558 mg/kg	460 mg/kg	1,107 mg/kg
	Porphyra spp	10	44	-	64 mg/kg	56 mg/kg	205 mg/kg
	All species in group	**39**	**221**	**3 (8%)**	**319 mg/kg**	**150 mg/kg**	**6,200 mg/kg**
Green seaweeds	Ulva lactuca	8	31	-	49 mg/kg	44 mg/kg	290 mg/kg
	Ulva intestinalis	4	17	-	108 mg/kg	111 mg/kg	240 mg/kg
	All species in group	**21**	**109**	**-**	**77 mg/kg**	**63 mg/kg**	**300 mg/kg**

[a] Number of average results (not maximum levels in dataset) above draft iodine proposed for EU (1,000mg/kg); [b] Maximum level across the dataset for species or group.

Maximum and minimum results are not necessarily helpful in understanding the range, given the possibility of extreme outliers. Table 6.10 provides percentile statistics for the species with 10 or more iodine results in the dataset: 50% of the results lie within the 25th-75th percentiles and 80% of the results lie within the 10th-90th percentiles. While mean levels are generally skewed above the median, all species show a very wide range of iodine levels (90th:10th percentile ratios are between 3:1 and 6:1). This pattern should be expected in all species. The natural range of iodine concentrations in seaweed is important for considering both nutritional applications for seaweed and avoidance of overexposure from iodine intake.

Table 6.10: Percentile statistics for iodine levels in the dataset for seaweed species featured in ten or more studies.

Species	Results in dataset	ΣN	Mean	10th percentile	25th percentile	50th percentile (median)	75th percentile	90th percentile
Ascophyllum nodosum	17	110	827 mg/kg	341 mg/kg	632 mg/kg	**670 mg/kg**	980 mg/kg	1,459 mg/kg
Fucus vesiculosus	12	144	304 mg/kg	177 mg/kg	188 mg/kg	**267 mg/kg**	384 mg/kg	498 mg/kg
Alaria esculenta	27	163	595 mg/kg	257 mg/kg	342 mg/kg	**557 mg/kg**	682 mg/kg	1,000 mg/kg
Saccharina latissima	65	577	3,405 mg/kg	943 mg/kg	2,320 mg/kg	**3,124 mg/kg**	4,605 mg/kg	5,712 mg/kg
Laminaria digitata	16	89	4,737 mg/kg	1,983 mg/kg	3,740 mg/kg	**4,480 mg/kg**	5,734 mg/kg	7,384 mg/kg
Palmaria palmata	17	131	218 mg/kg	82 mg/kg	97 mg/kg	**150 mg/kg**	220 mg/kg	428 mg/kg

Even within a single species, it is clear iodine levels can vary widely. This is because seaweed actively accumulates iodine from its surroundings and this uptake is highly sensitive to external conditions and physiology. Carrano et al. (2021) showed that under conditions resulting in oxidative stress (e.g. high temperature, exposure at low water), iodide concentrations in seawater surrounding kelps are elevated. It is likely that kelps release iodide, presumably as an antioxidant. Although this stress could result in higher iodine levels in wild seaweed, this hypothesis is not supported by the dataset. Mean iodine levels in cultivated samples are around 23% higher than wild for Alaria esculenta and around 9% lower for Saccharina latissima.

Seasonal variations in iodine content are well known. Nitschke et al (2018) showed variation in iodine concentration by season in Fucus vesiculosus and Laminaria digitata, generally above average in winter and below average in summer. This pattern was also seen in Fucus serratus by Westby (2018). However, Maribu et al. (2025) demonstrated a clear seasonal pattern in Plasmara palmata, with higher levels in spring/summer and lower levels in autumn/winter. Overall, excess iodine levels are not likely to be controllable through selective harvest seasons (e.g. Wegeberg et al., 2023).

Nitschke & Stengel (2015) demonstrated variation in iodine concentration in different parts of kelp species. Iodine levels were highest in the stipe, then decreasing with distance from the stipe (Table 6.11). However, the fucoid wracks analysed showed no difference between the middle parts and meristematic parts of the fronds. Other studies of kelp sections have found less consistent iodine patterns (e.g. Carrano et al., 2021; Joensson & Nordberg Karlsson, 2024). Overall, it is difficult to consider selective harvesting of frond sections can control iodine content. While Nitschke & Stengel (2015) found lower iodine concentrations in distal sections, the levels were not sufficiently reduced to eliminate concerns over excessive iodine intake (Table 6.11).

Table 6.11: Mean iodine content in different parts of Irish kelp species (N=3; Nitschke & Stengel, 2015).

Species	Holdfast	Stipe	Meristem	Blade
Saccharina latissima	6,130 mg/kg	5,149 mg/kg	3,579 mg/kg	3,341 mg/kg
Laminaria digitata	3,340 mg/kg	10,203 mg/kg	7,097 mg/kg	5,762 mg/kg
Laminaria hyperborea	4,106 mg/kg	8,976 mg/kg	7,828 mg/kg	1,734 mg/kg

Risk from iodine

Methods to reduce iodine have been an active area of research in recent years, primarily to help utilise kelps for food use. Indeed, this research was a primary source of iodine concentrations for this report. Iodine in seaweed is largely water soluble, therefore most reduction methods rely on leaching into water during processing. Examples include:

- Soaking (rehydration in cool water for extended periods, perhaps through multiple changes)
- Blanching (short exposure to hot water)
- Boiling (prolonged exposure to hot water)
- Fermentation (diffusion into the liquid medium, or microbial transformation).

Ultimately, heat-treatments are likely to be the most effective. Recent studies reviewing iodine reduction methods in European species include Trigo et al. (2023), Krook et al. (2024), Sletta et al. (2025), Sund et al. (2025a,b), Kenny et al. (2026).

Although iodine levels are known to be high in many species and processing treatments can reduce content, it is appropriate to consider the overall risk based on concentrations in raw, dried seaweed. Indeed, dried seaweed is almost always washed to some extent, which may cause some degree of iodine loss. It is also important to highlight that most methods of processing or cooking edible seaweed will affect iodine concentrations; manufacturers of food and drink that use dried seaweed should test the final product for iodine.

Iodine in several species of seaweed will generally be 50-100mg/kg (e.g. Himanthalia elongata, Porphyra spp., Ulva lactuca), in which case a 5g dry portion would be an intake of 250-500µg of iodine (i.e. below the 600µg UK/EU upper limit). Even though results for these species can reach 200-300mg/kg, it is unlikely that daily consumption of 5g would lead to chronic overexposure to iodine.

Many species of seaweed have iodine levels around 150-300mg/kg (e.g. Pelvetia canaliculata, Fucus spiralis, Fucus vesiculosus, Palmaria palmata). At this range of concentrations, a 5g dry portion would marginally exceed the 600µg UK/EU upper limit (750µg) and the 1,100µg US/ANZ upper limit (1,500µg). It is possible that regularly consuming 5g of these seaweeds would lead to excess iodine intake.

There are several species with median iodine concentrations near average levels for seaweed (i.e. 400-700mg/kg), but have some results that exceed 1,000mg/kg (e.g. Ascophyllum nodosum, Fucus serratus, Alaria esculenta). Although there is less data available, it appears that some read species also fall into this grouping (Chondrus crispus, Mastocarpus stellatus). Unfortunately, the possibility of elevated levels in these species means that consuming 5 dry grams is more likely to lead to iodine overexposure.

It is clear that iodine levels are elevated in the kelps within the Laminariaceae family. Iodine concentrations in Saccharina latissima, Laminaria digitata and Laminaria hyperborea are generally around 2,000-6,000mg/kg. At this range of concentrations, a only 0.1-0.3g of dred seaweed can be consumed to avoid exceeding the 600µg UK/EU upper limit. Even extending to the 1,100µg US/ANZ upper limit only increases this portion to 0.2-0.6 dry g. Therefore, it can only be concluded that regularly consuming 5g of these seaweeds would lead to excess iodine intake.

Table 6.12 lists key seaweed species by risk category for excess iodine intake. Overall, there is minimal risk for green seaweed, but the risk profile is species dependent for brown seaweeds and green seaweeds.

Table 6.12: Categories for risk of excessive intake of iodine from consuming different seaweed species.

<table>
<tr><th>Category</th><th>Brown seaweeds</th><th>Red seaweeds</th><th>Green seaweed</th></tr>
<tr><td>Minimal risk of excess intake via seaweed</td><td>Himanthalia elongata</td><td>Porphyra spp.</td><td>Ulva lactuca
Ulva intestinalis</td></tr>
<tr><td rowspan="2">Possible risk of excess intake via seaweed</td><td>Pelvetia canaliculata
Fucus spiralis
Fucus vesiculosus
Sacchoriza polyschides*</td><td>Palmaria palmata
Osmundea pinnatifida*</td><td>-</td></tr>
<tr><td rowspan="2">Ascophyllum nodosum
Fucus serratus
Alaria esculenta</td><td rowspan="2">Chondrus crispus
Mastocarpus stellatus</td><td rowspan="2">-</td></tr>
<tr><td rowspan="2">Risk of excess intake via seaweed</td></tr>
<tr><td>Saccharina latissima
Laminaria digitata
Laminaria hyperborea</td><td>Vertebrata lanosa*</td><td>-</td></tr>
</table>

* Indicates species with only one result in the dataset and, therefore, less confident categorisation.

Beneficial trace minerals

Beneficial trace minerals are needed in very small quantities to support health. Indeed, many regulators would not consider all elements in this category to be essential nutrients. Recommended intake levels are often in place, but may not be if daily requirements are easily met through normal dietary intake. It is more likely upper limits will be set, although elements in this category generally have low toxicity; some minerals could be regarded as neutral with regard to human health (e.g. rubidium).

Molybdenum

Molybdenum is widely distributed in nature and soluble forms are ubiquitous in food and water. Certain rock types are likely to result in higher molybdenum levels in surrounding groundwater (e.g. granite), although levels are generally low in Scottish water. Anthropogenic sources include historic or current mining operations, industrial effluents and urban runoff. Molybdenum is used in steel alloys and specialist applications. Combustion of fossil fuels can also lead to atmospheric deposits. Agriculture can be a source due to traces in soil conditioners, fertilisers or sewage sludge.

Molybdenum acts as a cofactor for enzymes linked to different functions. There is limited data on human requirements and deficiency is rare The EFSA state an Adequate Intake of 65µg per day for adults (EFSA,2013). The UK has a similar Nutrient Reference Intake of 50µg per day. The main effect of consuming excess molybdenum is interference with copper absorption. Gout-like symptoms and neurological effects are also possible. The EFSA determined an upper limit of 0.6mg for adults in Europe (EFSA, 2000).

Molybdenum 67 results across all species ΣN=512 from 20 studies	
Mean	0.66mg/kg
Minimum	0.08mg/kg
25%	0.24mg/kg
Median (50%)	0.32mg/kg
75%	0.83mg/kg
90%	1.76mg/kg
Maximum	10.40mg/kg
Minimal risk of excess intake via seaweed	

Higher levels of molybdenum are seen in leafy vegetables, legumes, grains, dairy products and eggs. According to the UK Diet Survey, daily intake for UK adults is just under 100µg per day (mostly from cereals and bread). Molybdenum is not included in Scottish bivalve monitoring.

Molybdenum is often included in elemental analysis of relevant seaweed species. Overall, levels are broadly similar to those seen in terrestrial vegetables. Although there is large variation in molybdenum content, most studies report average levels below 2.0mg/kg (only four results, 6% of the dataset, are above this level). The three studies reporting maximum levels all happen to be analysis of Scottish seaweed: Schiener et al. (2015), Badmus et al. (2021) and Sneddon (2023). For the seven species tested by Badmus et al. (2021), the highest concentrations were all elevated (5.4-10.4mg/kg). In contrast, the maximum concentrations detected by Schiener et al. (2015) and Sneddon (2023) were all below 1.0mg/kg. Comparing species sampled in the same region that appear in both studies, it is notable that the maximum levels reported by Badmus et al. (2021) are all 15-52 times higher than the maximum levels found by Sneddon (2023). This may be an artefact of the analysis or linked to the large number of samples tested by Badmus et al. (2021).

There does not appear to be significant variation between species. There were 15 average results in the dataset above 1.0mg/kg: the concentrations came from analysis of 10 different species. Even at highest concentrations of 10mg/kg detected by Badmus et al. (2021), a 5g portion of dried seaweed would result in the consumption of just 50μg of molybdenum. This matches the UK Nutrient Reference Intake and is around half of the average adult intake in the UK. This would only be 8% of the Upper Limit set by the EFSA. Overall, it is unlikely that consuming seaweed will result in an intake of molybdenum at a level to cause health concerns.

Strontium

Although strontium was named after the village of Strontian on the west coast of Scotland, levels are generally low in Scottish soils compared to the areas in the UK underlain with sandstone and limestone (e.g. County Durham, Somerset). Strontium contamination in the UK is mostly geogenic, although there are minor traces from historic emissions from coal combustion, processing and agriculture (Table 3.3).

There are no recommended daily intakes in place for strontium. This is because it is not considered an essential nutrient with a clear biological requirement. Excessive intake of strontium can affect health by competing with calcium, impacting bone structure, intestinal absorption and kidney function. The EFSA has not drawn a scientific conclusion that sets a safe intake level and does not consider strontium a contaminant requiring such controls. Adequate toxicological data does not exist for strontium. Similarly, the WHO determined that there is insufficient evidence to set an upper intake level for strontium. One of the few agencies to publish an equivalent upper limit is the US EPA, which publish oral Reference Doses (RfDs) as an estimate of daily exposure likely to be without an appreciable risk of deleterious effects. Strontium was added to their IRIS database in 1992, with a RfD of 0.6mg per kg body weight that factored in uncertainty due to the limited data. This is equivalent to a daily intake of 36mg in a 60kg adult.

Strontium is a naturally occurring mineral present in most foods at trace levels. Fresh vegetables can exceed 10mg/kg (e.g. spinach, kale). Strontium is not included in the monitoring of Scottish bivalves. Daily intake for UK adults according to UK diet survey is 1.5mg of strontium (mostly from cereals, bread and non-alcoholic beverages).

There is limited testing of strontium in relevant seaweed species compared to other minerals, but levels are an order of magnitude higher than terrestrial vegetables. There may be variation across species

Strontium Dataset 28 results across all species ΣN=206 from 16 studies	
Mean	626mg/kg
Minimum	17mg/kg
25%	461mg/kg
Median (50%)	658mg/kg
75%	800mg/kg
90%	899mg/kg
Maximum	1,446mg/kg
Minimal risk of excess intake via seaweed	

groups: the results for all green (Ulva intestinalis) and red seaweeds (Palmaria palmata, Osmundea pinnatifida) were all in the lowest 25% quartile. The five highest average levels were in five brown seaweed species (Fucus spiralis, Alaria esculenta, Laminaria digitata, Fucus vesiculosus, Saccharina latissima). Only two results were seen above 1,000mg/kg (7% of the dataset) and it is prudent to assume that seaweed can occasionally contain such high levels. Although a 5 dry gram portion of seaweed at 1,000mg/kg may be a significant increase in the dietary strontium intake of a UK adult (5.0mg v 1.5mg), this would only be 11% of the RfD. Overall, it is unlikely that consuming seaweed will result in an intake of strontium at a level to cause health concerns.

Bromine

Bromine is widely distributed in the environment as bromide (Br^{-1}). Although anthropogenic contamination or introduction is possible, bromide is not generally considered a food safety concern. It naturally occurs in food at trace levels, with Brazil nuts the highest terrestrial source (40-100mg/kg), but is not included in the UK Dietary Survey. Methyl bromide was once applied in the EU as a post-harvest fumigant, but has not been approved for use since 2008.

Brominated compounds are used in flame retardants and have known toxic effects. These are contaminants that can be found in trace levels in fatty foods (e.g. oily fish, meat). Persistent organic pollutant regulations have restricted use and trace levels in food are in general decline. Brominated compounds are treated separately to bromine/bromide (Anthropogenic compounds).

Bromine intake from food is generally unregulated because it is ubiquitous at low levels and is generally not crucial for health. The EFSA was mandated to assess toxicity and food safety concerns of bromide, publishing a report in January 2025. One of the drivers for the assessment was the use of seaweed as an animal feed: a handful of studies had highlighted elevated bromide levels in products that could enter the human food chain (e.g. cow milk and chicken meat). High bromide exposure could interfere with thyroid function, by competing with iodine in hormone formation. In a human study, no effects were observed from daily supplementation at 4mg bromide per kg body weight. However, a higher dosage (9mg per kg body weight per day) increased thyroid hormones and affected the nervous system. The EFSA Scientific Committee established a TDI and ARfD of 0.4mg bromide per kg body weight (28mg per day in a 70kg adult), recommending further research into dietary exposure and more occurrence data for food and feed.

Levels in relevant seaweed species are around an order of magnitude higher than Brazil nuts, although bromine is infrequently tested (only 11 studies in the dataset; interquartile range: 461-981mg/kg). It appears there is variation between species. All five of the bromine levels above 1,000mg/kg were in Saccharina latissima (from Netherlands, Norway and Northern Ireland) measured in five different studies (Schiener et al., 2017; Van Tuinen et al., 2023; Arlov et al., 2024; Nokling-Eide et al., 2024; Sletta et al., 2025). This is compelling evidence that Saccharina latimissa has elevated levels of bromine (mean: 1,319mg/kg, 8 results). Higher levels of bromine are not just seen in brown seaweed, as levels approaching 1,000mg/kg have been detected in red seaweed species (Kuepper et al., 2014; Schiener et al., 2017).

Bromine 28 results across all species ΣN=874 from 11 studies	
Mean	761mg/kg
Minimum	281mg/kg
25%	461mg/kg
Median (50%)	664mg/kg
75%	981mg/kg
90%	1,587mg/kg
Maximum	2,185mg/kg
Possible risk of excess intake via seaweed	

Given the limited available data and high levels seen in multiple studies from different countries, it is prudent to assume that seaweed could contain 2,000mg of bromine per dry kg. Daily intake will be substantially lower than terrestrial foods, but a 5 dry gram portion of seaweed could be 36% of the EFSA ARfD. If Saccharina latissima results are excluded from the dataset, the median and mean levels across the remaining species are both below 600mg/kg: intake of 5 dry grams at this concentration would be just 10% of the EFSA ARfD.

There is a possible risk of excessive intake from seaweed, particularly from consuming Saccharina latissima. However, confidence in this assessment is low given the limited analysis available for review. As the health impacts relate to interference with thyroid function, it is likely that excessive iodine intake – a confidently known and understood risk of seaweed consumption – is of greater concern than elevated bromine intake. Nevertheless, it may be worth monitoring Saccharina latissima given this species appears to have a propensity for higher levels and bromide from seaweed is under review by the EFSA.

Chromium

Chromium generally occurs in two states: trivalent chromium (Cr^{3+}) and hexavalent chromium (in CrO_4^{2-}). Although hexavalent chromium is the more toxic form, typically only total chromium levels are monitored in the environment. The concentration of chromium is generally low and varies widely with rock type. However, it is associated with mineral soils and therefore levels are generally lowest in the Highlands. There are increased levels in the Southern Uplands, Dumfries & Galloway, Mull, Skye and western Sutherland (MacDonald et al., 2005). Generally, trivalent chromium is associated with geogenic sources. Major sources of chromium pollution in the UK include metal production, tanneries, construction materials and wood preservation (Table 3.3).

Chromium is not recognised as an essential nutrient. There are no reference intakes in the UK or Europe, but the US Institute of Medicine set a daily Adequate Intake of 25µg for adult women and 35µg for adult men (Institute of Medicine, 2001). However, there is limited evidence that there is any requirement in the body. There is no maximum dietary intake recommended by any regulator. However, the EFSA issued a risk-based figure for trivalent chromium with regards to food-contact materials: 0.3mg per kg body weight per day (21mg in an adult) on the basis of blood toxicity and thickening of stomach mucosa (EFSA, 2014).

Daily intake in adults according to UK Diet Survey is just 77µg of chromium (mostly from non-alcoholic beverages and cereals). Chromium is included in the monitoring of Scottish bivalves, with an average content of 0.11mg/kg in 2025 (highest level of 0.21mg/kg in mussels from Shetland).

The level of chromium in seaweed is highly variable (interquartile range: 0.50-2.02m/kg). The median level is 0.98mg/kg. Although the mean is skewed by the highest results (2.41mg/kg), only 5% of the results were above 10mg/kg. It is unlikely there is a strong species effect, given the ten highest results were for six different species: Ulva spp. (Olsson et al 2020b; Samarasinghe et al., 2021), Fucus vesiculosus (Balina et al. 2016; Al-Soufi et al. 2025; Pacin et al., 2025), Saccharina latissima (Samarasinghe et al., 2021), Mastocarpus stellatus (Al-Soufi et al., 2025) and Alaria esculenta (Kressig et al., 2021). Olssen et al. (2020b) analysed Ulva intestinalis harvested at seven sites around Sweden, with all samples showing mean levels at least twice as high as those reported for other species (range 15.8-25.2mg/kg). This may be indicative of local pollution, but sampling locations included both open beaches and harbours. Olssen et al (2020b) acknowledge the levels are elevated. A parallel study of a range of Swedish seaweeds detected chromium in Ulva intestinalis at just 0.5mg/kg (Olssen et al., 2020a). Although there are no obvious patterns between species, it is clear that levels can be high.

It is prudent to assume that seaweed could have a chromium content of 25mg per dry kg. A 5 dry gram portion would contain just 125µg of chromium, which would be a significant increase on the average daily intake in the UK. However, it is just 1% of the risk assessment figure used EFSA. Although chromium content in relevant species can be high compared to other foods, it is unlikely that intake from seaweed will be at a level to cause health concerns.

Chromium 99 results across all species ΣN=697 from 39 studies	
Mean	**2.41mg/kg**
Minimum	0.07mg/kg
25%	0.50mg/kg
Median (50%)	**0.98mg/kg**
75%	2.02mg/kg
90%	6.94mg/kg
Maximum	26.3mg/kg
Minimal risk of excess intake via seaweed	

Boron

Boron occurs naturally in the environment and is not generally considered a food safety concern. Geogenic sources are the most important, with boron occurring naturally in sedimentary rocks, marine clays and shales. Boron is highly soluble and is liable to be found in elevated levels in drinking water. Boron is an essential nutrient for plants and can be added to some fertilisers. Many detergents contain boron, which can be transferred to agricultural land through sewage sludge.

According to the EFSA, boron is not proven to be essential for human health and so it is considered a chemical that should be limited. High intake is linked to effects on the male reproductive system through hormone disruption. In 2024, an EFSA panel set a tolerable upper intake level (UL) for boron at 0.16mg per kg body weight per day. This was reaffirmed in an evaluation of boron compounds used as food additives, based on toxicology data (EFSA, 2013). This corresponds to 11.2mg of boron per day for an adult. It is unlikely that total dietary intake regularly exceeds this UL, but boron was not included in the UK Diet Survey. It is found in many foods at over 10mg/kg (e.g. avocados, raisins, almonds).

Boron 12 results across all species ΣN=39 from 6 studies	
Mean	145mg/kg
Minimum	101mg/kg
25%	116mg/kg
Median (50%)	132mg/kg
75%	158mg/kg
90%	199mg/kg
Maximum	254mg/kg
Minimal risk of excess intake via seaweed	

Levels of boron in seaweed are around an order of magnitude higher than terrestrial foods. Unfortunately, boron is a mineral with limited testing on relevant seaweed species: five studies published with samples from France, Norway and Sweden, plus one PhD study on Scottish kelp (Anakastasis, 2011). There is no obvious variation between species and, unlike other minerals, there is not a wide range in the dataset. There was just one result above 200mg/kg.

Given the limited available data, it is prudent to assume that seaweed could contain 200mg of boron per dry kg. A 5 dry gram portion would contain 1mg of boron, which is 9% of the EFSA UL. Although data on boron content in relevant species is limited, it is unlikely that intake of boron from seaweed will be at a level to cause health concerns.

Rubidium

Rubidium is not a significant environmental contaminant in the UK. It occurs naturally as a trace element in many rocks and soils, transferring to groundwater and surface water. There are limited possibilities of anthropogenic contamination, including as a by-product of mining and potential waste from electronics and manufacturing (Table 3.3).

Although rubidium is present at trace levels in the body, it is not generally considered a nutrient. However, it has a low toxicity and is not regarded as an element that can have a negative impact on human health. There are no UIs for rubidium and not even a NOAEL established for humans. It is rarely included in monitoring programmes.

Rubidium is found in a range of food and drink. Anke et al. (2005) investigated rubidium intake in Germany, with the majority of people consuming 1-2mg daily. The study reports vegetables as a food group with higher rubidium levels at 14mg/kg, asparagus had one of the highest levels of 68mg/kg. Unfortunately, rubidium is not included in the UK Diet Survey or Scottish bivalve monitoring.

Rubidium 18 results across all species ΣN=185 from 9 studies	
Mean	20.6mg/kg
Minimum	8.7mg/kg
25%	12.5mg/kg
Median (50%)	19.8mg/kg
75%	27.8mg/kg
90%	34.0mg/kg
Maximum	45.0mg/kg
Minimal risk of excess intake via seaweed	

Average levels of rubidium in seaweed are generally around 20mg/kg, without the extreme ranges seen in some other metals. Although there have been relatively few studies, analysis has covered 11 different species in 5 different countries (including four species in Scotland). There do not appear to be clear species differences, with the highest mean levels found in Swedish Saccharina latissima (mean of 35mg/kg; Kollander et al, 2023) and Ulva intestinalis (mean 34mg/kg; Olsson et al. 2020b).

It is prudent to assume that dried seaweed could contain 50mg of rubidium per kg, which would be equivalent to an intake of 250µg from 5 dry grams. The lack of evidence for toxicity means that there is no reference intake figure, but the levels are comparable to terrestrial foods eaten in greater volume. Furthermore, the relatively high intake from seaweed of 250µg per day would only be 13-25% of the 1-2mg daily intake estimated by Anke et al. (2005). Overall, rubidium levels in seaweed are unlikely to be a health concern.

Vanadium

Vanadium is naturally present in rocks, soil and sediments, with more elevated levels in shales and coal-bearing bedrock. Relevant anthropogenic sources in the UK include burning fossil fuels (especially oil and coal) and metal production (Table 3.3). However, levels are generally low and most pollution is airborne.

Vanadium may be involved in enzyme regulation, but it is not generally considered a nutrient. There is no established upper limit from regulators in the UK and Europe. There are no reports of toxicity from food, although the high doses seen in supplements could cause health issues. The Institute of Medicine in the US has set a Upper Tolerable Limit of 1.8mg per day.

Dietary intake of vanadium is generally low. Vanadium is not included in the UK Diet Survey or Scottish bivalve monitoring. The highest level of vanadium detected in a survey of US foods was 0.15mg/kg (Pennington & Jones, 1987). However, it is possible for certain foods to have higher levels: analysis of turmeric for the FSA in 2022 detected median levels of 1.2mg/kg (max 6.0mg/kg; Fera, 2022). A study of metal in Spanish diets estimated 29µg of vanadium was consumed daily (Bocio et al., 2005). In their analysis of food and drink in Italy, Filippi et al. (2020) detected the highest vanadium levels in chocolate (median: 46.8mg/kg) and median total intake of 10.4µg per day (mostly from vegetables and cereals).

Vanadium 13 results across all species ΣN=97 from 7 studies	
Mean	1.39mg/kg
Minimum	0.29mg/kg
25%	1.25mg/kg
Median (50%)	1.34mg/kg
75%	1.63mg/kg
90%	1.74mg/kg
Maximum	3.04mg/kg
Minimal risk of excess intake via seaweed	

There have been relatively few studies of vanadium in seaweed. Although there have been none in the UK, analysis has covered 10 different species in 4 different countries. Vanadium levels in seaweed are generally around 1.5mg/kg (interquartile range: 1.25-1.63mg/kg). The highest level in the dataset was in French Ascophyllum nodosum (mean of 3.0mg/kg; Barrat et al., 2024).

Given the limited available data, it is prudent to assume that seaweed could contain vanadium at levels of 3mg per dry kg. A 5 dry gram portion would contain 15µg of vanadium. This amount of vanadium is a significant proportion of estimated daily intake in Italy (Filippi et al., 2020) and Spain (Bocio et al., 2005), but is less than 1% of the upper limit in the US. Despite limited data, it is unlikely that intake of vanadium from seaweed will be at a level to cause health concerns.

Lithium

Lithium compounds are widely distributed in nature and are easily absorbed by plants. As a metal of increasing interest, lithium mining may become a relevant source of contamination in the UK. Most lithium deposits are in Cornwall, but there are some in Aberdeenshire. Lithium-ion batteries in waste consumer goods can be a risk if not properly disposed of or damaged and traces of lithium can be found in supplied water (Table 3.3). However, the risk of contamination of food is minimal.

Lithium is used as a treatment for bipolar disorder and so toxicological studies are linked to treated patients. The main negative health impact of excess lithium relates to kidney function, but thyroid issues are also possible. Lithium-induced toxicity in humans is complicated and poorly understood. There is little information available regarding upper limits for lithium intake. The EFSA has not established dietary reference values or tolerable ULs for lithium. The EPA in the US provided a provisional reference dose for the non-cancer assessment of daily exposure from lithium of 2µg per kg body weight, equivalent to 140µg daily intake for an adult.

Unfortunately, lithium is not included in the UK Diet Survey or Scottish bivalve monitoring. Iordache et al. (2024) analysed lithium content in food and drink marketed in Romania, finding the highest mean levels in leafy vegetables (9.4mg/kg) and red wine (17.9mg/kg). When converting to estimated daily intake, fewer than 1% of the hundreds of samples tested exceeded the provisional reference dose issued by the EPA.

Lithium 17 results across all species ΣN=158 from 8 studies	
Mean	1.36mg/kg
Minimum	0.36mg/kg
25%	0.51mg/kg
Median (50%)	0.94mg/kg
75%	1.76mg/kg
90%	2.90mg/kg
Maximum	5.18mg/kg
Minimal risk of excess intake via seaweed	

Levels of lithium in seaweed are generally around 1mg/kg, without the extreme ranges seen in some other minerals. Although there have been relatively few studies, testing has covered 11 different species in 6 different countries. The highest levels were found in Scotland, in Saccharina latissima (single result of 5.2mg/kg; Anakastasis, 2011) and Osmundea pinnatifida (mean 2.9mg/kg; Biancacci et al., 2022). Given there may be a tendency for higher levels of lithium in Scottish seawater, it is appropriate to assume that dried seaweed could contain 5mg per kg. This would be equivalent to a lithium intake of 25µg from seaweed, which would be 18% of the provisional reference dose issued by the EPA. It is unlikely that intake of lithium from seaweed could cause health concerns in humans, especially as the concentrations are lower or comparable to terrestrial foods eaten in greater volume.

Characterised toxic trace elements

Many elements are not required in the body to support health. Non-essential elements that can cause adverse health effects are considered toxic. Some may only be toxic if ingested in excessive quantities, but many are damaging to health even at trace amounts. The toxicity of many elements is well understood and they are routinely included in monitoring programmes, which provides a significant set of seaweed data for interrogation. It is likely tolerable intake limits will be in place; daily limits are often used, but longer timescales are often applied for contaminants liable to accumulate in the body over time (e.g. weekly). Tolerable limits can sometimes be withdrawn by authorities if there is sufficient evidence to indicate intake should be completely avoided.

Nickel

The concentration of nickel in soil varies according to rock type. The mineral soils of the Lowlands and Aberdeenshire exhibit higher levels than the organic soils of the Highlands. However, there are areas with elevated levels in the Inner Hebrides due to the nature of the soil composition. Mull, Skye and western Sutherland show higher concentrations in stream sediments (MacDonald et al., 2005). Elevated concentrations around Glasgow and Edinburgh are likely connected to anthropogenic contamination. Pollution sources in the UK include metal production and fossil fuel combustion (Table 3.3). Nickel is also found in brakes and tyres, which leads to trace runoff from roads. Contamination will be more likely in industrial areas and near power stations and ports.

Nickel may possibly help with enzyme function and metabolism in the body. However, normal dietary intake will provide more than enough for any putative biological roles and so nickel is regarded as toxic. People can exhibit a sensitivity to nickel. Otherwise, chronic dietary exposure could create digestive problems and effects on the liver and kidneys. The EFSA assessed nickel exposure risk and issued a tolerable daily intake of 13µg of nickel per kg body weight in 2025. High intake is linked to effects on the male reproductive system through hormone disruption. In 2024, an EFSA panel set a tolerable upper intake level (TUI) for nickel at 0.16mg per kg body weight per day. This is equivalent to 0.91mg in an adult and comparable to the TUI set by the National Academy of Medicine (1.0mg per day).

Daily nickel intake for adults according to UK Diet Survey is 0.13mg (mostly from non-alcoholic beverages and cereals). Nickel averages 0.11mg/kg in Scottish bivalves (the highest level was in Fife surf clams: 0.26mg/kg). Levels tend to be higher in plant-based foods. A study on nickel by the EFSA (2020) analysed over 48,000 items. It included 516 items of seaweed and products containing seaweed (e.g. seaweed pasta), noting that levels (mean: 2.0mg/kg) were higher than many other vegetables. However, mean nickel levels were higher in dried legumes (3.1mg/kg), tea / herbs for infusion (4.2mg/kg) and cocoa / cocoa products (9.0mg/kg). For dried seaweed, the maximum levels were found in kombu (29.6 mg/kg) and laver (27.3 mg/kg).

The evidence base for nickel in food led to the introduction of maximum levels in Europe effective for many food categories in July 2025, with expansion to cereals in 2026 (Table 6.13). The limits in place for seaweed are higher than any other food product, reflecting the relatively infrequent consumption and small portion size. For wakame seaweed – presumed to be Undaria pinnatifida invasive from the Pacific – the limit for nickel is 40.0mg/kg (3.6.8.2, amendment to Regulation, EU, 2023/915); this is reduced to 30.0mg/kg in all other species of seaweed (3.6.8.1).

Nickel is a metal widely included in seaweed analysis. Levels in seaweed are variable, but the average levels in the dataset broadly correspond with those detected in seaweed by the EFSA (2020). However, there were no levels near either the EU maximum limit or the highest concentrations in dried seaweed samples (i.e. 30.0mg/kg). Only 6% of results were above 10.0mg/kg.

Table 6.13: Maximum nickel limits for selected foods, implemented in Europe in 2025 and 2026

Food	Maximum limit for nickel
Walnuts, cashews	10.0mg/kg
Brassica vegetables	0.5mg/kg
Peanuts	12.0mg/kg
Oats	5.0mg/kg
Cocoa powder	15.0mg/kg
Durum wheat	1.5 mg/kg
Wakame seaweed	40.0mg/kg
Other seaweeds	30.0mg/kg

Table 6.14: Average and maximum nickel content in seaweed species with at least four studies in the dataset.

	Studies in the dataset			Nickel content	
Species	Number	Unique countries	Aggregated number of samples	Mean[a]	Maximum[b]
Fucus serratus	4	4	84	8.05mg/kg	18.50 mg/kg
Fucus spiralis	7	4	50	4.46mg/kg	8.13 mg/kg
Fucus vesiculosus	22	7	357	4.45mg/kg	11.60 mg/kg
Palmaria palmata	5	4	34	4.44 mg/kg	8.65 mg/kg
Alaria esculenta	9	4	80	1.65 mg/kg	10.74 mg/kg
Laminaria digitata	4	2	42	1.51 mg/kg	4.34 mg/kg
Ascophyllum nodosum	6	5	34	1.20 mg/kg	1.60 mg/kg
Saccharina latissima	18	7	112	0.62 mg/kg	4.87 mg/kg

[a] Mean of median, mean or single results reported in studies; [b] Maximum of median, mean or single results reported in studies, or the maximum level where reported and when higher than the median, mean or single results.

Nickel 90 results across all species ΣN=975 from 30 studies	
Mean	3.07mg/kg
Minimum	0.13mg/kg
25%	0.81mg/kg
Median (50%)	1.77mg/kg
75%	4.24mg/kg
90%	7.84mg/kg
Maximum	18.50mg/kg
Minimal risk of excess intake via seaweed	

Average and maximum nickel content in species with an acceptable number of results in the dataset are given in Table 6.14. There appears to be some differences between species, with the highest mean levels seen in Fucus species (Fucus serratus: 8.05mg/kg; Fucus spiralis: 4.46mg/kg; Fucus vesiculosus: 4.45mg/kg). Although Alaria esculenta is related to the Asian wakame that has specific EU limits, there appears to be no obvious risk of elevated nickel content in this species (maximum: 10.74mg/kg).

Assuming a worst case content of 20mg of nickel per kg of dried seaweed, a 5g portion would contain 0.1mg. This would be a substantial increase on the average adult intake in the UK, but only 11% of the 0.91mg TUI set by EFSA. Even seaweed at the 40mg limit for wakame (Table 6.13) would only be 22% of the TUI. Therefore, it is unlikely that intake of nickel from seaweed could cause health concerns.

Aluminium

Aluminium is one of the most common elements in the Earth's crust. Aluminium is associated with mineral soils. Levels are generally lowest in the organic soils of the Highlands, with levels around four times higher in the Southern Uplands, Inner Hebrides and Aberdeenshire. Aluminium is more likely to dissolve into water in acidic conditions; natural aluminium levels will be elevated in aquifers around Scotland where there are peat-rich soils. Analysis of groundwater around Scotland found that the highest levels were in the granites of Dumfries & Galloway, volcanic rocks of Skye and the gneiss of Lewis (MacDonald & Ó Dochartaigh, 2005). Macdonald et al. (2005) mapped aluminium levels in groundwater, demonstrating that most of Scotland is at risk. Lower levels of aluminium are only seen in Central Scotland, Moray Firth, Caithness and Orkney.

There is no known biological function for aluminium in the human body. Only a small proportion of ingested aluminium is absorbed during digestion, although it can persist in the body. Most aluminium is excreted by the kidneys, but chronic exposure can have effects on bone health, neurology, iron metabolism and kidney function. The Tolerable Weekly Intake for aluminium used by the EFSA is 1mg per kg body weight, which is equivalent to 10mg per day for an adult.

The primary source of exposure for people is through dietary intake. Trace levels of aluminium are commonly found in food (e.g. cereals: up to 10mg/kg) and certain foods can have elevated levels (e.g. cocoa powder: up to 100mg/kg). Aluminium exposure can be elevated through transfer from packaging (e.g. foil) and additives (e.g. baking powder). Aluminium content is not part of Scottish bivalve monitoring. Daily intake for an adult according to the UK Diet Survey is 2.9mg (almost exclusively from non-alcoholic beverages, cereals and bread): this is 29% of the Tolerable Intake.

Aluminium levels in seaweed show considerable variation (interquartile range: 25.2-356.5mg/kg). The metal is frequently included in seaweed contamination analysis (dataset comprises results for 16 species across 10 countries). The average concentration is skewed by a small number of elevated levels (median: 120mg/kg; mean: 442mg/kg) and 13% of results are above 1,000mg/kg. The highest levels are all from seaweed harvested in Scotland and Northern Ireland. Table 6.15 summarises the concentrations of aluminium in seaweed from the countries with the most results in the dataset: average levels in Scotland are roughly double those in Spain (the country with the next highest levels). One of the few species consistently tested across Europe is Saccharina latissima. Scottish Saccharina latissima has considerably higher levels of aluminium than the same species from Sweden or Norway (Table 6.15). This is indicative of a particular issue in Scotland regarding aluminium in seaweed.

Aluminium 63 results across all species ΣN=522 from 27 studies	
Mean	441.7mg/kg
Minimum	1.48mg/kg
25%	25.2mg/kg
Median (50%)	120.0mg/kg
75%	356.5mg/kg
90%	787.1mg/kg
Maximum	6,110mg/kg
Possible risk of excess intake via seaweed	

Table 6.15: Aluminium concentrations in relevant seaweed species in countries with eight or more results in the dataset, plus levels for Saccharina latissima by country where reported.

		Spain	Sweden	Norway	Scotland
All species	**Results in dataset**	9	11	12	8
	Number of species	4	8	6	5
	ΣN	208	24	95	65
	Mean	215.9mg/kg	101.5mg/kg	114.6mg/kg	550.2mg/kg
	Minimum	15.2mg/kg	9.5mg/kg	1.5mg/kg	57.5mg/kg
	Median (50%)	136.5mg/kg	12.5mg/kg	69.5mg/kg	235.5mg/kg
	Maximum	606.8mg/kg	413.0mg/kg	340.0mg/kg	1,408.0mg/kg
Saccharina latissima only	**ΣN**	-	10	29	10
	Mean	-	278.1mg/kg	42.4mg/kg	1,101.7mg/kg
	Max	-	413.0mg/kg	76.0mg/kg	1,877.0mg/kg

Schiener et al. (2015) analysed the seasonal composition of kelp species wild harvested at Clachan Sound, near Oban on the west coast of Scotland. All species exhibited a wide variation in aluminium content, but Saccharina latissima is distinctly higher (reaching 1,877mg/kg; Table

6.16). This is aligned with the aluminium content measured by Anakastasis (2011) of duplicate samples of Saccharina latissima collected near Oban (1,402mg/kg). Although Alaria esculenta results were given by Schiener et al. (2015) for three samples, they are excluded from the dataset as they match the Saccharina latissima results for the corresponding months. In a separate study, Schiener et al. (2017) found even higher levels in samples from Northern Ireland: 6,110mg/kg in Saccharina latissima and 5,270mg/kg in Palmaria palmata.

Table 6.16: Aluminium levels in seaweed species harvested in Scotland.

Species	N	Mean	Min	Median (50%)	Max	Number of results >1,000mg/kg	Source
Laminaria digitata	8	57.5 mg/kg	8.0 mg/kg	60.0 mg/kg	121.0 mg/kg	-	Schiener et al. (2015)
Laminaria hyperborea	8	159.8 mg/kg	2.0 mg/kg	69.0 mg/kg	159.8 mg/kg	-	Schiener et al. (2015)
Saccharina latissima	8	702.9 mg/kg	13.0 mg/kg	592.0 mg/kg	1,877.0 mg/kg	2	Schiener et al. (2015)
Osmundea pinnatifida	12	1,408.0 mg/kg	527.0 mg/kg	1267.4 mg/kg	3,245.6 mg/kg	6	Biancacci et al. (2022)

Biancacci et al. (2022) considered the seasonal variation of the composition of Osmundea pinnatifida, also wild harvested near Oban. Aluminium was found in the highest concentration of all elements tested. The mean level was 1,408mg/kg (ranging from 527 to 3,246mg/kg). Biancacci et al. (2022) noted that aluminium concentrations were correlated with salinity and, therefore, freshwater input from surrounding land. The collection site is surrounded by granitic mountains and peatland, which is a setting where higher transfer of terrestrial aluminium is possible.

It seems likely that seaweed in Scotland has an elevated aluminium content. However, the results for aluminium in Scotland are for seaweed harvested from the Oban area and, as noted by Biancacci et al. (2022), this may be connected to local geogenic sources. Studies have found that aluminium levels in seaweed are positively correlated with iron content (e.g. Wegeberg et al., 2023; Barrat et al., 2024). Half of the highest 10% of iron concentrations in the dataset are Scottish seaweed. Sneddon (2023) analysed seaweed from one supplier in different areas of Scotland and found markedly different median iron levels in Saccharina latissima: 23mg/kg in wild samples from Caithness in the north and 872mg/kg in farmed samples from near Oban in the west. Therefore, it is reasonable to assume that aluminium may not be universally high across all regions in Scotland. The highest mean aluminium levels in the dataset were detected by Schiener et al. (2017) on three species harvested in Strangford Lough in Northern Ireland: 2,300mg/kg in Ascophyllum nodosum, 5,270mg/kg in Palmaria palmata, 6,110mg/kg in Saccharina latissima.

Vazquez-Arias et al. (2025) carried out transplantation of Fucus vesiculosus in Spain, determining that the levels of aluminium represented a bioconcentration factor of millions compared to the surrounding seawater. Aluminium transferred from terrestrial sources can be readily absorbed by seaweed. Aluminium can be added to sediment to bind phosphorous and improve water quality. Levels in Fucus vesiculosus were monitored by Kumblad et al. (2024) following aluminium water treatment in Sweden. Kumblad et al. (2024) found levels of aluminium were around 1,750-2,000mg/kg in the seaweed in 2014, compared to around 250-500mg/kg at a reference site. Concentrations fell over the following years, with all samples at both sites below around 500mg in 2018. Nevertheless, the elevated levels seen in 2014 demonstrate the capacity of seaweed to absorb large amounts of aluminium.

It is clear that the concentrations of aluminium in seaweed can exceed 1,000mg/kg, which is a substantially higher level than is seen in other foods. Although there are only 8 average results above 1,000mg/kg in the dataset, many studies have shown maximum levels can exceed this threshold (e.g. Schiener et al., 2015; Schiener et al., 2017; Biancacci et al., 2022). However, the only study to have found mean levels over 1,500mg/kg is Schiener et al. (2017), which were from three species harvested in one location in Northern Ireland. Consuming a 5g portion of dried seaweed containing 1,500mg of aluminium per kg means intake of 7.5mg: this exceeds the daily intake for an adult (UK Diet Survey) and is 75% of the EFSA tolerable limit. Allowing for exposure to aluminium through other dietary sources, 1,500mg/kg is a reasonable figure to use as a threshold for a level of aluminium in seaweed that could lead to excessive intake.

In their long-term analysis of Spanish Fucus spp, Pacin et al. (2025) found median concentrations where decreasing for many toxic metals (e.g. chromium, nickel, cadmium, mercury), but increasing for aluminium. Therefore, aluminium may become a more significant element for seaweed food safety in the near future.

Cadmium

Cadmium is found naturally at low levels, although rarely as its own mineral and more commonly associated with zinc ores. Volcanic activity can distribute cadmium more widely. Groundwater may have moderately higher cadmium concentrations in certain locations around Scotland, such as Dumfries & Galloway, Arran, Clyde Valley, Forth Estuary and the Ardnamurchan peninsula (Macdonald et al., 2005). However, elevated cadmium levels are usually connected to human activity. Cadmium is more available in acidic soils and more likely to be transferred in water systems and absorbed by plants via transport systems intend for essential minerals (e.g. zinc, iron).

Historic mining activity can result in localised elevated cadmium levels. Processing of non-ferrous metals continues to be a source of cadmium pollution (e.g. scrap metal). Industrial scale combustion of fossil fuels is also a contributor to environmental cadmium pollution in the UK, but this has reduced with the phase-out of coal. Cadmium can be found in many consumer products (e.g. batteries, electronics) and can be released into the atmosphere through incineration. Cadmium is often a contaminant in phosphate fertilisers, which can lead to elevated soil levels in agricultural fields. Generally, most rural soils in the UK will have a cadmium content under 1mg/kg. In contrast, cadmium levels will be much higher in former mining areas and industrial land (brownfield sites). The Macaulay Land Use Research Institute carried out soil measurements in 1990, finding increasing cadmium levels from north to south (North Scotland: 0.5mg/kg; South Scotland: 1.3mg/kg).

Table 6.17: Maximum cadmium limits for selected foods in Europe (Regulation (EC) No 1881/2006; wet weight).

Food	Maximum limit for cadmium
Most leafy vegetables	0.10mg/kg
Salt	0.50mg/kg
Cocoa powder	0.60mg/kg
Crustaceans	0.50mg/kg
Bivalves	1.00mg/kg
Cephalopods	1.00mg/kg
Muscle meat of lower-trophic fish species	0.05mg/kg
Muscle meat of higher-trophic fish species	0.25mg/kg
Food supplements	1.00mg/kg
Food supplements containing mostly dried seaweed or products derived from seaweed	**3.00mg/kg**

Unlike other metals like arsenic and mercury, there is less diverse speciation of cadmium and more consistent toxicity. In food, cadmium is almost entirely present in inorganic forms (Cd^{2+}) bound to sulphur-containing proteins (e.g. enzymes, metallothioneins) and plant cell wall structures (e.g. cellulose, alginate). Cadmium has no known biological role. Chronic exposure leads to accumulation in the body, resulting in damaged kidney function, bone health problems and increased cancer risk. The EFSA reduced the tolerable weekly intake for cadmium down to 2.5µg per kg of body weight in 2009, based on indicators of kidney function. This is equivalent to 25µg per day for an adult.

There are cadmium limits in Europe for most foods (Table 6.17). Currently, there are no specific regulations stipulating maximum cadmium levels in seaweed sold as food or as an ingredient in foodstuffs. However, Regulation (EC) No 1881/2006 provides for maximum cadmium levels of 3.0mg/kg in food supplements consisting exclusively or mainly dried seaweed or products derived from seaweed (this is higher than the 1.0mg/kg limit in place for other food supplements). infants and children (Regulation (EC) No 2023/915).

The French national standard for seaweed has a longstanding cadmium limit of 0.5mg per dry kg (ANSES). When comparing to the European limits for seafood (Table 6.17), the French threshold matches the limit for crustaceans and is lower than the limits for bivalves and cephalopods. The draft limits for cadmium proposed for edible seaweed in Europe are similar to the current limit for seaweed-based food supplements, with the lowest limit set at 3.0mg/kg (Table 6.18).

Table 6.18: Draft cadmium limits for seaweed in Europe as an amendment to Regulation (EC) No 2023/915 proposed in December 2025 (dry weight, as placed on the market).

Category	Maximum limit for cadmium
Brown seaweed	3.00mg/kg
Green seaweed	4.00mg/kg
Red seaweed	4.00mg/kg

The majority of cadmium exposure comes from the diet. Daily intake for adults in the UK is 13µg (UK Diet Survey), mostly from non-alcoholic beverages, cereals, bread and potatoes. The highest cadmium level seen in recent seafood monitoring by the UK Food Agencies (Table 6.19) is 0.52mg/kg (in oysters from Barra in the Outer Hebrides). The mean levels of cadmium are all below 0.10mg/kg for other seafood monitored in the UK. All seafood samples from England, Wales, Northern Ireland and Scotland were below the European limits for cadmium in seafood (Table 6.17).

Table 6.19: Cadmium levels detected in recent UK Food Agency seafood surveys.

	England & Wales [a]			Northern Ireland [b]		Scotland [c]
	Fish	Crustaceans	Cephalopods	Fish	Crustaceans	Bivalves
Number of samples tested	107	31	13	35	11	9
Proportion of samples above LOQ[d]	54% (53)	90% (28)	77% (10)	34% (12)	100% (11)	100% (9)
Mean level detected	0.014mg/kg	0.017mg/kg	0.013mg/kg	0.007mg/kg	0.092mg/kg	0.21mg/kg
Maximum level detected	0.180mg/kg (Mackerel, SW England)	0.157mg/kg (Crab, SW England)	0.023mg/kg (Cuttlefish, SW England)	0.026mg/kg (Mackerel, Irish Sea)	0.310mg/kg (Langoustine, Irish Sea)	0.52mg/kg (European oysters, Barra)

[a] Fera Science for Food Standards Agency, 2025a; [b] Fera Science for Food Standards Agency Northern Ireland, 2025b; [c] Fera Science for Food Standards Scotland, 2025; [d] Limit of Quantification.

Cadmium 281 results across all species ΣN=2,397 from 79 studies	
Mean	**0.85mg/kg**
Minimum	0.01mg/kg
25%	0.21mg/kg
Median (50%)	**0.59mg/kg**
75%	1.20mg/kg
90%	2.02mg/kg
Maximum	5.29mg/kg
Possible risk of excess intake via seaweed	

Cadmium is widely recognised as a contaminant and so it is one of the most commonly tested metals in analysis of European seaweed (dataset comprises results for 24 species across 15 countries). The average concentration (median: 0.59mg/kg; mean: 0.85mg/kg) is higher than the levels of cadmium seen in other seafood (Table 6.19), but there are very few elevated levels (96% of results are below 3.00mg/kg).

Alaria esculenta may have a greater affinity for cadmium compared to other species; the highest results in the dataset are all for Alaria esculenta (Koester, 2023; Wegeberg et al., 2023). The average level is Alaria esculenta is higher than Saccharina latissima (mean 1.86mg/kg vs mean 0.96mg/kg), which are two species often analysed together in studies. This pattern can be seen in some countries (e.g. Norway, France), but not in others (e.g. Scotland, Greenland).

The range of cadmium levels in Scottish seaweed is similar to other countries (e.g. Ireland, Spain), higher than some (e.g. France, Sweden, Norway) and lower than others (e.g. Greenland, Iceland). Unlike some other contaminants, there are no outliers with highly elevated cadmium levels (Table 6.20): the maximum result in the dataset is 5.29mg/kg in wild Alaria esculenta sampled in Greenland in 2016 (Wegeberg et al., 2023). There are 16 studies reporting single, average or maximum results over 3.00mg/kg; they are from five countries that are all in northern Europe (Scotland, Norway, Iceland, Greenland, Faroes) and cover nine different species (6 brown seaweeds, 3 red seaweeds). This indicates that may be more variation between locations than species.

Table 6.20: Cadmium concentrations in relevant seaweed species in countries with eight or more results in the dataset.

	Ireland	Portugal	Ice-land	Green-land	France	Sweden	Spain	Scotland	Norway
Results in dataset	8	9	11	13	15	23	25	27	86
Number of species	5	5	8	5	10	11	11	13	23
ΣN	28	21	31	191	314	42	323	435	726
Mean	0.69 mg/kg	0.58 mg/kg	1.61 mg/kg	1.67 mg/kg	0.64 mg/kg	0.41 mg/kg	0.75 mg/kg	0.95 mg/kg	0.80 mg/kg
Minimum	0.13 mg/kg	0.15 mg/kg	0.11 mg/kg	0.29 mg/kg	0.05 mg/kg	0.01 mg/kg	0.01 mg/kg	0.05 mg/kg	0.03 mg/kg
Median (50%)	0.74 mg/kg	0.35 mg/kg	1.58 mg/kg	1.32 mg/kg	0.29 mg/kg	0.20 mg/kg	0.71 mg/kg	0.72 mg/kg	0.46 mg/kg
Maximum	1.60 mg/kg	1.65 mg/kg	3.02 mg/kg	5.29 mg/kg	2.01 mg/kg	2.10 mg/kg	2.64 mg/kg	3.21 mg/kg	5.00 mg/kg

Consuming 5 dry grams of seaweed at 3.00mg/kg (i.e. the current limit for food supplements containing seaweed and the draft limit proposed for Europe for brown seaweed) would result in intake of 15µg of cadmium. This is slightly more than the current average adult intake (UK Diet Survey) and 60% of the tolerable daily intake (EFSA, 2009). Given the European legislation is working to 3.00mg/kg, it is appropriate to use this limit in the UK. There are just two studies on Scottish species that have detected cadmium above this limit: a median of 3.08mg/kg in Laminaria digitata (Anakastasis, 2011) and a maximum of 3.21mg/kg in samples of Himanthalia elongata (Sneddon, 2023). Although there may be occasional samples that breach the 3.00mg/kg limit, these would likely fall into under occasional exceedances and not a food safety concern. It is possible Scottish seaweed can contain cadmium at levels that would result in overexposure. However, average levels are mostly at concentrations where risk is minimal. Nevertheless, cadmium should be included in monitoring programmes given it is a fully characterised toxic element with legal limits in place.

It is also worth noting that there is a maximum limit in place for feed materials of vegetable origin: 1mg/kg for cadmium in feed with a moisture content of 12% (Directive 2002/32/EC). This is more problematic, with 31% of average levels in the dataset exceeding this limit. Most feed applications use Ascophyllum nodosum, which has a mean level of 0.63mg/kg in the dataset. The level in Scotland may be lower still given Sneddon (2023) found a mean cadmium concentration of 0.23mg/kg in Ascophyllum nodosum.

Mercury

Mercury naturally occurs in rocks and soils in small quantities and, occasionally, in mineral form. Localised mineralised mercury is sometimes seen in Wales, Derbyshire and the North Pennines. Volcanic activity can also be a natural source of mercury contamination. Historically, the most important anthropogenic input of mercury to the environment in the UK was coal burning. Emissions have reduced significantly as coal is phased out, but legacy contamination is still found in soil and sediment. Metal production can also cause mercury contamination. Mercury is also found in consumer goods (e.g. fluorescent lamps). Overall, mercury pollution is limited in the UK and the main concerns are historic contamination and long-range atmospheric transport.

Mercury is one of the most toxic metals because it binds strongly to proteins. Mercury is transformed by biochemical and biological reactions into more toxic organic compounds:

- Elemental mercury is poorly absorbed if swallowed, but inhaled vapour causes neurotoxicity.
- Inorganic mercury (e.g. mercuric chloride) has toxic effects, causing gastrointestinal problems and kidney failure.
- Organic mercury, especially methylmercury, is the most toxic form as it is easily absorbed and bioaccumulates. Severe neurotoxic effects are possible from low level chronic exposure, especially in children.

Methylmercury is by far the most common form of organic mercury in the food chain. The EFSA Scientific Opinion published in 2012 considered levels of mercury in food samples sourced across Europe (mostly between 2004 and 2010). It was clear that fish and seafood was the most important food group for mercury occurrence. Indeed, this was the only category for which methylmercury data was available for analysis. Mercury in fish muscle was generally found to be 80-100% methylmercury. For other seafood, methylmercury typically comprises 50-80% of the total.

Almost exclusively, only total mercury is measured in seaweed contamination studies. Harding et al. (2018) included two species of

Table 6.21: Median levels of total mercury and methylmercury detected in Canadian seafood, with all figures reported as wet weight (Harding et al., 2018).

Species	N	Methyl-mercury	Total mercury	Proportion as methyl-mercury
Ascophyllum nodosum	**3**	**0.2µg/kg**	**11.8µg/kg**	**2%**
Fucus vesiculosus	**3**	**0.2µg/kg**	**6.2µg/kg**	**3%**
Blue mussel	12	5.1µg/kg	20.1µg/kg	25%
American lobster	9	24.1µg/kg	33.5µg/kg	72%
Atlantic cod	19	26.0µg/kg	28.0µg/kg	93%
Spiny dogfish	16	79.9µg/kg	103.2µg/kg	77%
Swordfish	11	628µg/kg	1,192µg/kg	53%

brown wrack in their broad sampling of plankton and seafood in Nova Scotia, Canada. The results showed there were similar proportions of methylmercury in fish, molluscs and crustaceans to those reported by the EFSA (selected median levels included in Table KYKHG). However, the total mercury levels in seaweed were lower than other seafood and comprised only 2-3% methylmercury. This aligns with the known biomagnification of mercury levels up the food chain.

The EFSA Scientific Opinion (2012) used provisional tolerable weekly intakes established by the Joint FAO/WHO Expert Committee on Food Additives: 1.6µg/kg body weight for the more toxic methylmercury and 4.0µg/kg body weight for inorganic mercury (expressed as total mercury). Given the levels of methylmercury are low in seaweed, it is reasonable to assume a provisional tolerable weekly intake of 4.0µg/kg body weight (equivalent to 40µg per day for an adult) for mercury in seaweed.

Daily intake of mercury for adults according to UK Diet Survey is 3µg, primarily from fish. This is broadly similar to the intake levels stated by the EFSA (2012). The known risks of mercury in seafood means that levels are routinely tested in the UK. Levels of mercury in seafood are monitored around the UK (Table 6.22).

Table 6.22: Mercury levels detected in recent UK Food Agency seafood surveys.

	England & Wales [a]			Northern Ireland [b]		Scotland [c]
	Fish	Crustaceans	Cephalopods	Fish	Crustaceans	Bivalves
Number of samples tested	108	31	13	35	11	9
Proportion of samples above LOQ[d]	100% (108)	100% (31)	85% (11)	97% (34)	100% (11)	100% (9)
Mean level detected	0.128mg/kg	0.168mg/kg	0.056mg/kg	0.094mg/kg	0.216mg/kg	0.01mg/kg
Maximum level detected	0.870mg/kg (Sea bass, SE England)	0.400mg/kg (Lobster, Wales)	0.080mg/kg (Cuttlefish, SW England)	0.360mg/kg (Haddock, Irish Sea)	0.680mg/kg (Langoustine, Irish Sea)	0.03mg/kg (Pacific oysters, Colonsay)

[a] Fera Science for Food Standards Agency, 2025a; [b] Fera Science for Food Standards Agency Northern Ireland, 2025b; [c] Fera Science for Food Standards Scotland, 2025; [d] Limit of Quantification.

The EU sets legally binding maximum levels (MLs) for mercury in various foods to protect public health (Regulation (EC) No 2023/915 and amendments), expressed in mercury per fresh kg of food (wet weight). The primary focus is on seafood, with the limits ranging from 0.30mg/kg to 0.50mg/kg with trophic level (Table 6.23). The only other stated limits are for salt and food supplements, which are both 0.10mg/kg. Although seaweed is not listed, it is reasonable to apply a limit of 0.10mg/kg given the common, long-standing use in food supplements. This matches the French national standard for seaweed that included a limit of 0.10mg of mercury per dry kg (ANSES). Hereafter, this 0.10mg/kg is referred to as the France/EU limit. Eating 5 dry grams of seaweed at the France/EU limit would result in intake of 0.5µg of mercury: 17% of the average adult daily intake (UK Diet Survey) and just 1% of the provisional tolerable intake used by the EFSA in 2012 (40µg per day for an adult). Regulation (EC) 396/2005 listed maximum residue levels of mercury compounds used in pesticides, including 0.01mg/kg for algae and prokaryotes (the default low level). As pesticides with mercury have been phased out, there is little risk of contamination via agricultural applications. Regulation (EU) 2018/73 amended, added and clarified limits for residues in a range of products. Although there was no change to algae, it is not appropriate to apply the 0.01mg/kg limit to seaweed given the target for the legislation is pesticide residues.

Table 6.23: Maximum mercury limits for selected foods in Europe (Regulation (EC) No 2023/915 and amendments; wet weight).

Food	Maximum limit for mercury
Salt	0.10mg/kg
Food supplements	**0.10mg/kg**
Marine gastropods	0.30mg/kg
Cephalopods	0.30mg/kg
Crustaceans	0.50mg/kg
Bivalves	0.50mg/kg
Lower-trophic fish species listed (e.g. sole, pollock, salmon)	0.30mg/kg
Fishery products and muscle meat of fish not specifically listed	0.50mg/kg
Higher-trophic fish species listed (e.g. tuna, halibut, swordfish)	1.00mg/kg

Mercury is commonly included in elemental analysis of seaweed, featuring in 38 studies testing 20 species from 13 different countries. Mercury levels in seaweed are very low: there are only a handful of average results in the dataset over France/EU limit of 0.10mg/kg (97% of the dataset is under this level). The mean level is 0.03mg/kg, which is aligned with the mean levels of mercury in UK seafood (Table 6.22).

Mercury 137 results across all species ΣN=1,094 from 38 studies	
Mean	0.026mg/kg
Minimum	0.003mg/kg
25%	0.006mg/kg
Median (50%)	0.016mg/kg
75%	0.030mg/kg
90%	0.050mg/kg
Maximum	2.80mg/kg
Minimal risk of excess intake via seaweed	

There are seven species for which there are five of more results for mercury (Table 6.24). It is important to note that mean levels of mercury are skewed by outliers with higher concentration. For the three species with the highest average levels, all are skewed by results in samples harvested in 2013: Fucus serratus at 0.30mg/kg (Westby, 2018), Fucus spiralis at 0.16mg/kg (Cabrita et al., 2016), Saccharina latissima at 0.12mg/kg (Cabrita et al., 2016). All these levels are below the maximum levels in UK seafood (Table 6.22). When considering the dataset for mercury, 2013 appears to be unusually high: the average across six studies in 2013 is 0.12mg/kg and the averages for all other years are below 0.03mg/kg. This may be an indication of declining levels of mercury in seaweed, but it is beyond the scope of this review to reach conclusions on long term trends. Roleda et al. (2019) appear to have detected the highest levels of mercury, in wild Norwegian seaweed harvested in 2015, with maximum concentrations in samples of 0.31mg/kg in Palmaria palmata and 0.26mg/kg in Alaria esculenta.

Table 6.24: Detail of mercury levels in the dataset for species featured in five or more studies.

Species	Results	ΣN	Mean	Average results >0.10 mg/kg	25%	Median (50%)	75%	90%	Max
Fucus serratus	5	28	0.080 mg/kg	1	0.003 mg/kg	0.009 mg/kg	0.085 mg/kg	0.214 mg/kg	0.300 mg/kg
Fucus spiralis	6	27	0.039 mg/kg	1	0.009 mg/kg	0.020 mg/kg	0.026 mg/kg	0.094 mg/kg	0.161 mg/kg
Saccharina latissima	35	210	0.028 mg/kg	1	0.013 mg/kg	0.019 mg/kg	0.028 mg/kg	0.047 mg/kg	0.117 mg/kg
Palmaria palmata	10	70	0.028 mg/kg	-	0.004 mg/kg	0.030 mg/kg	0.051 mg/kg	0.076 mg/kg	0.314 mg/kg[a]
Alaria esculenta	10	75	0.019 mg/kg	-	0.005 mg/kg	0.008 mg/kg	0.023 mg/kg	0.041 mg/kg	0.258 mg/kg[a]
Fucus vesiculosus	17	334	0.021 mg/kg	-	0.008 mg/kg	0.014 mg/kg	0.029 mg/kg	0.049 mg/kg	0.071 mg/kg
Ascophyllum nodosum	9	54	0.017 mg/kg	-	0.015 mg/kg	0.020 mg/kg	0.023 mg/kg	0.025 mg/kg	0.033 mg/kg[b]

[a] Roleda et al. (2019); [b] Duinker et al. (2020).

Ficheux et al. (2023) analysed a variety of species harvested in Brittany, France. Although the level of mercury in the majority of samples was below the limit of quantification (57%), this study detected some of the highest levels of mercury in the dataset and warrants further interrogation. As shown in Table 6.25, only four samples had levels of mercury above 0.10mg/kg. The highest level detected was 1.00mg/kg (Ulva sp.).

Ervik (2019) summarised the analysis of metals in 48 samples of Norwegian Laminaria hyperborea over 2015-2017. The median level was reported at 0.08mg/kg, which places it in the top 10% of the dataset. However, the maximum level detected was 2.80mg/kg: the highest maximum level in the dataset. Ervik (2019) is the only study of Laminaria hyperborea in the dataset and so it is difficult to determine if this species is prone to elevated mercury levels. Nevertheless, studies analysing multiple species have concluded that mercury concentrations do not vary between tested seaweeds (e.g. Roleda et al., 2019). Although the level detected by Ervik (2019) is higher than the EU limit for predatory fish, consuming 5 dry grams of Laminaria hyperborea at 2.80mg/kg would result in intake of just 14μg of mercury. This is 35% of provisional tolerable intake (EFSA, 2012) and so it is very unlikely that even the maximum levels in the dataset would be high enough to cause health issues. Nevertheless, mercury would be worth including in ongoing monitoring given it is a fully characterised toxic element with legal limits in place.

Table 6.25: Mercury levels detected in French seaweed (Ficheux et al., 2023).

Species	N	N samples below LOQ[a]	N samples above 0.10mg/kg[b]	Mean	Median	Max
Fucus sp.	25	16	-	0.03mg/kg	0.01mg/kg	0.10mg/kg
Himanthalia elongata	14	10	-	0.01mg/kg	0.02mg/kg	0.03mg/kg
Palmaria palmata	38	30	1	0.07mg/kg	0.10mg/kg	0.13mg/kg
Porphyra sp.	12	4	-	0.04mg/kg	0.03mg/kg	0.10mg/kg
Saccharina latissima	18	8	1	0.04mg/kg	0.03mg/kg	0.17mg/kg
Ulva sp.	32	11	2	0.07mg/kg	0.04mg/kg	1.00mg/kg
All samples	**139**	**79**	**4**			

[a] Limit of Quantification; [b] Limit set in France (ANSES).

There are a few conclusions to draw on mercury levels in relevant seaweed species:

- Mercury levels in seaweed are generally low, often less than other seafood.
- Mercury levels are less than the France/EU limit of 0.10mg/kg.
- Several studies have detected higher levels mercury in samples, but average levels are rarely above the France/EU limit.
- Studies analysing multiple species have concluded that mercury concentrations do not vary between tested seaweeds (e.g. Roleda et al., 2019).

It is appropriate to use the France/EU limit for mercury of 0.10mg/kg, given the application of seaweed for food supplements. Mercury levels above this limit are possible, but unlikely to be indicative of contamination that would cause health issues. Mercury is not mentioned in the proposed changes to Annex I to Regulation (EU) 2023/915 issued in December 2025.

Lead

Lead levels in streams and soil are generally low in Scotland. However, they can be higher in the Grampians, Arran, Dumfries & Galloway and the Southern Uplands. There are also elevated concentrations around Glasgow and Edinburgh. The Macaulay Land Use Research Institute carried out soil measurements in 1990, finding low average lead levels in North Scotland (29mg/kg) and the highest in central Scotland (180mg/kg). Unlike other metals, lead is less associated with underlying geology and can be found in organic soils in areas prone to anthropogenic contamination. The many disused metal mines around the UK can continue to leach lead into soil and groundwater. There were once many domestic uses for lead, including paint and plumbing. Older properties can still contain lead, with an increased likelihood in larger urban areas. Particulates from leaded petrol can still be found near busy roads and industrial areas. Lead is found in electronics, batteries and other consumer goods. Lead can also be found in rural aquatic ecosystems from discarded ammunition and fishing tackle. However, rural areas will generally be lower than urban areas due to man-made sources.

Table 6.26: Maximum lead limits for selected foods in Europe (Regulation (EC) No 2023/915 and amendments; wet weight).

Food	Maximum limit for lead
Vegetables	0.1-0.3mg/kg
Dried spices	0.6-2.0mg/kg
Salts	1.0-2.0mg/kg
Fish (muscle meat) & Cephalopods	0.3mg/kg
Crustaceans	0.5mg/kg
Bivalve molluscs	1.5mg/kg
Food supplements	3.0mg/kg

There are no tolerable upper intake levels for lead, because it is known to be toxic at very low levels and there is no clear threshold below which health effects do not occur. The EFSA has stated that an upper limit cannot be established and that exposure to lead should be as low as reasonably achievable. The EFSA used the provisional tolerable weekly intake (PTWI) set by the WHO of 25µg lead per kg body weight (equivalent to 250µg per day for an adult). However, reappraisal by the ESFA in 2010 lead to withdrawal of the PTWI. Using a Benchmark Dose Lower Confidence Limit (BMDL) approach, the lowest BMDL applied was 0.5µg of lead per kg body weight per day (for a 1% extra risk of developmental neurotoxicity). Conservatively applying this to an adult, the recommended maximum intake could be as low as 35µg daily for an adult. However, it is important to underscore the EFSA stated that there is no safe level.

There are limits in place for the majority of foodstuffs, under Regulation (EC) No 2023/915 and amendments. Limits are generally under 1.0mg/kg, with higher thresholds in place for salt, certain spices and bivalves (Table 6.26). At present, there is no specific limit in place for seaweed sold as food. However, the use of seaweed in food supplements means it is reasonable to apply a limit of 3.0mg/kg as placed on the market (i.e. dry weight). However, the French national standard for seaweed included a higher limit of 5.0mg of lead per dry kg (ANSES). It is important to note that there are lower limits in place for products intended for infants and children (Regulation (EC) No 2023/915). The draft maximum limits for lead proposed for seaweed in Europe vary by group, with the lowest limit set at 0.5mg/kg (Table 6.27). The proposed limits are substantially lower than the French limit for lead (5.0mg/kg). However, they reflect the precautionary approach to minimise dietary lead exposure.

Table 6.27: Draft lead limits for seaweed in Europe as an amendment to Regulation (EC) No 2023/915 proposed in December 2025 (dry weight, as placed on the market).

Category	Maximum limit for lead
Brown seaweed	1.5mg/kg
Green seaweed	2.0mg/kg
Red seaweed (except Porphyra species)	2.0mg/kg
Porphyra species (nori, laver)	0.5mg/kg

Daily intake for UK adult according to UK diet survey is 8µg of lead (mostly from non-alcoholic beverages, alcoholic beverages and green vegetables). The highest lead level seen in recent seafood monitoring by the UK Food Agencies is 0.15mg/kg (in mussels from Shetland). Table 6.28 provides the most recent results for lead in seafood from England, Wales, Northern Ireland and Scotland. All of the 206 samples were under the EU limits stated in Table 6.26.

Table 6.28: Leads levels detected in recent UK Food Agency seafood surveys.

	England & Wales [a]			Northern Ireland [b]		Scotland [c]
	Fish	Crustaceans	Cephalopods	Fish	Crustaceans	Bivalves
Number of samples tested	108	31	13	35	11	9
Proportion of samples >LOQ [d]	40% (43)	90% (28)	77% (10)	0%	45% (5)	100% (9)
Mean level detected	0.008mg/kg	0.017mg/kg	0.009mg/kg	All <0.020 mg/kg d	0.032mg/kg	0.09mg/kg
Maximum level detected	0.034mg/kg (Sardines, SW England)	0.050mg/kg (Crab, NE England)	0.013mg/kg (Cuttlefish, SW England)		0.070mg/kg (Langoustine, Irish Sea)	0.15mg/kg (Mussels, Shetland)

[a] Fera Science for Food Standards Agency, 2025a; [b] Fera Science for Food Standards Agency Northern Ireland, 2025b; [c] Fera Science for Food Standards Scotland, 2025; [d] Limit of Quantification.

Lead is frequently analysed in seaweed. The dataset includes 244 studies from 15 different countries, with all of the relevant seaweed species covered. Lead concentrations are generally low. The median level covering all species is 0.33mg/kg, which is broadly similar to levels seen in Scottish bivalves (Table 6.28). Across the dataset, 90% of the average results for lead are below 1.44mg/kg and only 4% of results are above 3.00mg/kg (the European limit for food supplements). However, lead levels can occasionally reach much higher levels.

Lead 244 results across all species ΣN=1,751 from 71 studies	
Mean	0.75mg/kg
Minimum	0.01mg/kg
25%	0.16mg/kg
Median (50%)	0.33mg/kg
75%	0.83mg/kg
90%	1.44mg/kg
Maximum	13.40mg/kg
Possible risk of excess intake via seaweed	

Studies have compared seaweed harvested from unpolluted seas with seaweed harvested from areas identified as vulnerable to pollution or runoff. There is evidence that lead is higher in seaweed sampled from polluted water in Fucus vesiculosus from Spain (Garcia-Seoane et al., 2020a&b) and Saccharina latissima from Norway (Niedzwiedz et al., 2024). It is clear that there are some elevated outliers in the dataset. For example, a single result for Fucus vesiculosus from Latvia at 11.00mg/kg (Balina et al., 2016). This likely relates to local pollution or conditions in the Baltic when the samples were harvested in 2015. The maximum level detected by Sa Montiero et al. (2019) in Danish Fucus vesiculosus was 9.60mg/kg. Kressig (2021) found lead in Alaria esculenta from Greenland reached 7.93mg/kg. However, it appears that higher levels of lead may be more likely in Ulva species. Ficheux et al. (2023) analysed contaminant concentrations in a range of species harvested in France (Table 6.29). Ulva species were the only group that had samples above the 5.00mg/kg limit for lead in France (10%). The maximum concentration of lead in Ulva species was 13.40mg/kg, which is significantly higher than the highest levels in most other species. In addition, elevated levels were detected by Olsson et al. (2020b) in Swedish Ulva intestinalis (maximum 5.40mg/kg) and by Duinker et al. (2020) in Norwegian Ulva lactuca (maximum 5.70mg/kg).

Table 6.29: Lead levels detected in French seaweed (Ficheux et al., 2023; upper bound).

Species	N	N samples below LOQ[a]	N samples above 5.00mg/kg[b]	Mean	Median	Max
Fucus sp.	27	8	-	0.95mg/kg	0.65mg/kg	1.40mg/kg
Himanthalia elongata	18	9	-	1.30mg/kg	0.99mg/kg	3.60mg/kg
Palmaria palmata	33	26	-	1.06mg/kg	1.01mg/kg	3.20mg/kg
Porphyra sp.	5	3	-	0.88mg/kg	1.00mg/kg	1.14mg/kg
Saccharina latissima	18	9	-	0.99mg/kg	1.10mg/kg	2.00mg/kg
Ulva sp.	40	5	4	2.49mg/kg	1.79mg/kg	13.40mg/kg
All samples	**141**	**60**	**4**			

[a] Limit of Quantification; [b] Limit set in France (ANSES).

While it may appear that Ulva species have an affinity for lead, it is challenging to discern any particular species effects given that these varieties of seaweed are often harvested in areas with freshwater influence and, therefore, exposure to terrestrial runoff. Indeed, the fact that high levels are seen in other seaweeds is evidence that lead contamination is not unique to Ulva species.

The details of the lead concentrations for species included in at least four studies are given in Table 6.30. When considering the average results reported (not the maximum concentrations), very few species are above the current and proposed limits for lead in Europe (Table 6.30). The mean levels of lead in Fucus spiralis sampled in England by Oaten et al. (2017) range between 1.29mg/kg and 1.87mg/kg, with three results exceeding the 1.5mg/kg limit proposed in Europe. However, mean and median concentrations in Fucus spiralis are 0.92mg/kg and 0.90mg/kg, respectively. It is unlikely there is an issue with this species. A mean level of 3.2mg/kg was detected in Scottish Osmundea pinnatifida by Biancacci et al. (2022), which would exceed both the current and draft European limits. Lead levels in Porphyra species appear to be lower than other red seaweeds. This is reflected in the lower draft European limit of 0.5mg/kg, although there are a few studies in the dataset that have reported average concentrations of lead marginally above the draft limit (0.88mg/kg by Biancarosa et al., 2018; 0.85mg/kg by Duinker et al., 2020; 0.58mg/kg by Ficheux et al., 2023).

Eating 5 dry grams of seaweed at 3mg/kg would result in intake of 15µg of lead. This is approximately double the average adult daily intake (UK Diet Survey). Using the lowest BMDL applied by the EFSA in 2010, 15µg of lead would be 43% of the 35µg maximum for an adult (although it is important to acknowledge that the EFSA no longer provide any recommended limit).

Table 6.30: Detail of lead levels in the dataset for species featured in four or more studies.

Group	Species	Results in dataset	ΣN	N above 3.00 mg/kg[a]	N above Draft EU limit[b]	Mean	Median	Max[c]
Brown seaweeds	Ascophyllum nodosum	17	122	-	1	0.33 mg/kg	0.11 mg/kg	4.40 mg/kg
	Pelvetia canaliculata	4	14	-	-	0.30 mg/kg	0.31 mg/kg	0.41 mg/kg
	Fucus spiralis	10	33	-	3	0.92 mg/kg	0.90 mg/kg	2.30 mg/kg
	Fucus vesiculosus	25	338	1	2	0.87 mg/kg	0.38 mg/kg	11.00 mg/kg
	Fucus serratus	8	50	1	1	1.16 mg/kg	0.45 mg/kg	6.60 mg/kg
	Himanthalia elongata	6	40	-	-	0.31 mg/kg	0.12 mg/kg	3.60 mg/kg
	Laminaria digitata	6	52	-	-	0.27 mg/kg	0.17 mg/kg	1.00 mg/kg
	Saccharina latissima	54	336	1	2	0.49 mg/kg	0.22 mg/kg	6.20 mg/kg
	Alaria esculenta	24	160	-	-	0.42 mg/kg	0.32 mg/kg	7.93 mg/kg
	All species in group	170	1,368	3	11	0.58 mg/kg	0.20 mg/kg	11.00 mg/kg
Red seaweeds	Chondrus crispus	7	13	1	1	1.26 mg/kg	0.35 mg/kg	6.60 mg/kg
	Palmaria palmata	28	133	2	2	0.99 mg/kg	0.73 mg/kg	7.20 mg/kg
	Porphyra spp	10	37	-	3	0.38 mg/kg	0.33 mg/kg	1.70 mg/kg
	All species in group	50	271	4	7	0.94 mg/kg	0.56 mg/kg	7.20 mg/kg
Green seaweeds	Ulva spp	17	90	1	3	0.98 mg/kg	0.62 mg/kg	13.40 mg/kg
	All species in group	24	104	3	5	1.60 mg/kg	0.87 mg/kg	13.40 mg/kg

[a] Number of average results (not maximum levels in dataset) above lead limits for food supplements in Regulation (EC) No 2023/915 and amendments; [b] Number of average results (not maximum levels in dataset) above draft lead limits in Europe proposed in December 2025 (brown seaweed: 1.5mg/kg, green seaweed: 2.0mg/kg, Porphyra species: 0.5mg/kg, other red species: 2.0mg/kg); [c] Maximum level across the dataset for species or group.

A maximum limit of 3.0mg/kg seems reasonable given median levels are around 0.1-0.9mg/kg depending on species and very few results in the dataset exceed this level (Table 6.30). According to the results in the dataset, there is no species with a median lead concentration that would exceed the proposed limits in Europe of 0.5-2.0mg/kg (Table 6.27). Consuming 5 dry grams of Porphyra seaweed with a content of 0.5mg/kg would mean intake of 2.5µg of lead (32% of average adult daily lead consumption in the UK). However, this reduced limit may be disproportionate given the relatively small portions of seaweed consumed; the maximum limit for bivalves in Europe is 1.5mg/kg (Table 6.26), which are likely to be eaten in larger volumes than seaweed.

Lead levels are generally low in the dataset, but it is certainly possible to detect concentrations in European edible seaweed species that could be indicative of a contamination issue. Lead should be included in ongoing monitoring, with testing frequency determined by local risks and target species.

Arsenic

Arsenic can bond with sulphide minerals, which are typically associated in Scotland with acidic igneous rocks like granite and mineral soils. Macdonald et al. (2005) mapped arsenic levels in groundwater, highlighting a risk of elevated concentrations in Dumfries & Galloway, Central Scotland (broadly Argyll across to Angus), Moray Firth, Caithness, Orkney and Shetland. Generally, there are lower levels in the Highlands and the Southern Uplands. Key anthropogenic sources include coal combustion, metal processing and waste streams from industries such as textiles and glassware (Table 3.3). Arsenic was historically used in wood preservers and pesticides, which may persist in soil. Mining can also exposure arsenic-rich minerals to weathering, but this is less of a concern in Scotland.

Arsenic usually exists in water in two oxidation states – trivalent arsenic (As^{3+}) or pentavalent arsenic (As^{5+}) – and environmental conditions influence the principal species (Table 6.31). Pentavalent arsenic is more dominant in oxygenated seawater and trivalent arsenic is more dominant in acidic groundwater. Arsenic levels in seawater are affected by freshwater input, weathering and sedimentation. Both valencies of arsenic will form inorganic compounds (without carbon) and organic compounds (including carbon).

The toxicity of arsenic varies considerably depending on the form (Table 6.31). Inorganic arsenic is more toxic because it is highly reactive and directly absorbed. Carbon-bound organic arsenic is more stable and mostly non-toxic. Pentavalent arsenic has a lower toxicity as it is less well absorbed. Trivalent arsenic has a stronger affinity to proteins, making it more easily absorbed. Methylated trivalent arsenicals include monomethylarsonious acid (MMA^{3+}) and dimethylarsonious acid (DMA^{3+}). These are metabolic intermediates, produced during metabolism of inorganic arsenic in the liver. Although they are highly toxic, methylated trivalent arsenicals tend to be short lived and are excreted via the kidneys. The equivalent organic compounds of pentavalent arsenic (commonly abbreviated to MMA, DMA) are more stable and have low toxicity. Arsenobetaine is a small, stable organic compound of pentavalent arsenic that is rapidly excreted via the kidneys unchanged. Arsenosugars and arsenolipids are larger, more complex organic compounds of pentavalent arsenic that are metabolised by humans to dimethylarsinate. Predominant arsenosugars found in seaweed include compounds of glycerol, sulphate and phosphate.

Table 6.31: Speciation of arsenic under different environmental conditions.

Species of Arsenic	Typical environmental conditions	Dominant compound names	Toxicity
As^{3+} As(III) Trivalent	Reducing (more common in anoxic sediments and acidic groundwaer)	Inorganic: Arsenite (arsenious acid) and often reported as As(III))	High (disrupts cellular processes and binds to enzymes)
		Organic[a]: monomethylarsonious acid (MMA^{3+}), dimethylarsonious acid (DMA^{3+})	
As^{5+} As(V) Pentavalent	Oxidising (dominant species in seawater as it is oxygen rich and mildly alkaline)	Inorganic: Arsenate (arsenic acid) and often reported as As(V))	Medium (interferes with cellular energy processes)
		Organic: monomethylarsonic acid (MMA), dimethylarsinic acid (DMA), arsenobetaine, arsenosugars	Low (stable and mostly excreted unchanged)

[a] Methylated trivalent arsenicals are short-lived chemical intermediates in human metabolism of inorganic arsenic

The EFSA published a scientific opinion on the toxicity of arsenic from dietary intake in 2009. It acknowledges organic arsenic compounds have low toxicity (aligning with Table 6.31), judging that they did not warrant inclusion in the assessment. The FAO/WHO established a provisional tolerable weekly intake of 15µg of inorganic arsenic per kg body weight, but the EFSA stated in 2009 it was no longer appropriate for a genotoxic and carcinogenic elements with no safe threshold (it then was withdrawn by FAO/WHO in 2010). In place of tolerable intake levels, the EFSA instead considered reference points for a 1% excess risk of health impacts from inorganic arsenic intake (Table 43 in EFSA, 2009). They ranged between 0.34µg per kg BW per day (for risk of lung cancer) and 7.5µg per kg BW per day (for risk of bladder cancer), which the EFSA rounded to a range of 0.3-8.0µg per kg BW per day to create a single reference point for risk characterisation. This corresponds to 0.021-0.560mg of inorganic arsenic per day for an adult.

The EFSA assessment in 2009 estimated that an adult consumer of algae as food will have a daily intake of 0.282mg of inorganic arsenic (4.03µg per kg body weight; 70kg; Tables 31 & 32; EFSA, 2009; EFSA Journal 2009 7(10): 1351). It used a baseline scenario of an adult having a daily exposure equivalent to 0.030mg of inorganic arsenic from food (0.43µg per kg body weight), but an extreme assumption where 10g of dried seaweed is consumed and 70% of total arsenic is in inorganic form (i.e. the inorganic arsenic level in the seaweed is 21.6mg/kg). Under this scenario, 89% of inorganic arsenic dietary intake in an algae consumer would derive from seaweed. While this points towards a high risk from seaweed, it is contingent on consumption of seaweed species with an unusually elevated inorganic arsenic content.

Firstly, this review will focus on the total arsenic content of relevant seaweed species. Arsenic is typically reported as the total content, even though the varying toxicity of the different forms is widely known and the food limits in place under Regulation (EC) No 2023/915 are for inorganic arsenic (Table 6.37). Total arsenic measurements are cheaper, faster and more reproducible across different laboratories. Speciation of arsenic content requires more complex analytical techniques (e.g. HPLC-ICP-MS) that are more expensive and harder to standardise. This review will return to consider speciation of arsenic, with particular focus on inorganic forms. There are no limits on total arsenic in human food. However, Directive 2002/32/EC and amendments includes limits seaweed used as animal feed (Table 6.32). Essentially, the limits are 10mg/kg for pet food and 40mg/kg for feed for livestock. There is less likelihood of breaching the 10mg/kg for pet food given seaweed would always be just one ingredient of many. In addition, authorities can compel companies to demonstrate that the inorganic arsenic content is below 2mg/kg.

Table 6.32: Limits for total arsenic content for seaweed used in animal feed in Europe (Directive 2002/32/EC; dry weight, relative to a feed with a 12% moisture content; seaweed meal and feed materials derived from seaweed).

Category	Maximum limit for total arsenic[a]
Feed materials (i.e. livestock)	40mg/kg
Complete feed for pet animals	10mg/kg
Complementary feed for pet animals	10mg/kg

[a] Upon request, products must be demonstrated to have an inorganic arsenic content lower than 2mg/kg.

Most of the arsenic in consumed in the diet comes from organic arsenicals in seafood, which are excreted unchanged in urine and do not accumulate or cause toxicity. This was shown in the UK Dietary Survey, where almost all of the 70μg of total arsenic consumed in the average daily diet comes from fish (88%). The highest total arsenic level seen in recent seafood monitoring by the UK Food Agencies is 38.2mg/kg (in crab from Wales). Table 6.33 provides the most recent results for total arsenic in UK seafood. There were detections of arsenic in all 161 samples tested (arsenic is not part of testing in Northern Ireland).

Table 6.33: Total arsenic levels detected in recent UK Food Agency seafood surveys.

	England & Wales [a]			Scotland [b]
	Fish	Crustaceans	Cephalopods	Bivalves
Number of samples tested	108	31	13	9
Proportion of samples >LOQ [c]	100%	100%	100%	100%
Mean level detected	4.8mg/kg	18.4mg/kg	11.7mg/kg	2.0mg/kg
Maximum level detected	33.2mg/kg (Skates & Rays, SW England	38.2mg/kg (Crab, Wales)	17.6mg/kg (Cuttlefish, SW England)	2.54 mg/kg (Pacific oysters, Wester Ross)

[a] Fera Science for Food Standards Agency, 2025a; [b] Fera Science for Food Standards Scotland, 2025; [c] Limit of Quantification.

Total arsenic is typically included in elemental analysis of seaweed, with the dataset featuring 79 studies from 16 different countries. All of the relevant seaweed species are included in the dataset. The total arsenic level in seaweed (median 44.3mg/kg; mean 46.9mg/kg) is higher than the levels seen in UK seafood (Table 6.33). However, it is clear that there is considerable variation between species (Table 6.34). Levels are lowest in green seaweeds (mean 7.8mg/kg). Red seaweeds have a marginally increased content of total arsenic (mean 14.0mg/kg), with Porphyra species showing higher levels (mean 30.2mg/kg). Very few levels exceed the 40mg/kg animal feed limit in Europe in these two groups (2 4% of red seaweed results; 9% of green seaweed results) and, generally, concentrations in these two groups are broadly similar to UK seafood (Table 6.33). However, the levels in brown seaweed are significantly higher (mean 58.9mg/kg) and the majority of total arsenic results exceed the 40mg/kg animal feed limit (69%). Concentrations in kelp species (mean 70.7mg/kg; 89% exceeding 40mg/kg) are higher than those in wrack species (mean 39.5mg/kg; 36% exceeding 40mg/kg). It is clear that total arsenic levels can be much higher in brown seaweed, with maximum reported levels exceeding 100mg/kg in four species (Ascophyllum nodosum, Fucus vesiculosus, Alaria esculenta, Laminaria hyperborea) and 200mg/kg in two species (Laminaria digitata, Saccharina latissima).

Total Arsenic 281 results across all species ΣN=1,555 from 79 studies	
Mean	46.9mg/kg
Minimum	2.5mg/kg
25%	20.7mg/kg
Median (50%)	44.3mg/kg
75%	66.0mg/kg
90%	89.6mg/kg
Maximum	214.0mg/kg

The level of total arsenic in Scottish seaweed is higher than seaweed from many other countries around Europe, but less than Iceland and Ireland (Table 6.35). This is seen across all species and also in Saccharina latissima, which is the species with the largest number of results in the dataset (Table 6.34). Indeed, the mean concentration of total arsenic in Icelandic Saccharina latissima exceeds 100mg/kg. This indicates local geology will influence total arsenic concentrations. Given elevated levels are seen in brown kelp species, it is also worth noting that Scotland has a relatively high proportion of results from brown kelps (52%; Table 6.35) and this may account for the slightly higher total arsenic levels. Higher concentrations of total arsenic are seen in in winter months in kelp species (e.g. Petursdottir et al. 2019; Sim et al., 2023).

It is possible for total arsenic levels to reach 200mg/kg in edible seaweed. At this concentration, a 5g portion of dried seaweed would be an intake of 1mg. Although this is approximately 14 times the current average daily intake (UK Diet Survey), it is clear that total arsenic is of limited relevance for human toxicity and further speciation is required. For practical purposes, almost all brown seaweed species can have a total arsenic content above 40mg/kg (animal feed limit). Only a few species have mean levels below this limit (Fucus spiralis, Himanthalia elongata, Pelvetia canaliculata, Undaria pinnatifida).

Table 6.34: Detail of total arsenic levels in the dataset for seaweed species featured in four or more studies.

Group	Species	Results in dataset	ΣN	N results above 40.0 mg/kg[a]	Mean	Median	Max[b]
Brown seaweeds	Ascophyllum nodosum	25	130	8	42.5 mg/kg	33.0 mg/kg	113.0 mg/kg
	Fucus spiralis	12	48	2	27.7 mg/kg	25.8 mg/kg	44.0 mg/kg
	Fucus vesiculosus	30	385	16	48.9 mg/kg	44.7 mg/kg	120.0 mg/kg
	Fucus serratus	7	35	4	41.6 mg/kg	42.4 mg/kg	67.0 mg/kg
	Himanthalia elongata	8	30	2	31.3 mg/kg	31.7 mg/kg	55.3 mg/kg
	Laminaria digitata	30	40	107	92.7 mg/kg	85.9 mg/kg	210.0 mg/kg
	Laminaria hyperborea	4	17	4	88.74 mg/kg	85.8 mg/kg	120.5 mg/kg
	Saccharina latissima	58	330	52	70.2 mg/kg	68.5 mg/kg	214.0 mg/kg
	Alaria esculenta	23	130	21	58.6 mg/kg	53.1 mg/kg	116.0 mg/kg
	All species in group	211	1,286	146	58.9 mg/kg	53.1 mg/kg	214.0 mg/kg
Red seaweeds	Chondrus crispus	7	14	-	14.1 mg/kg	13.2 mg/kg	24.0 mg/kg
	Palmaria palmata	35	112	-	8.3 mg/kg	8.0 mg/kg	22.0 mg/kg
	Porphyra spp	10	28	2	30.2 mg/kg	28.3 mg/kg	55.0 mg/kg
	All species in group	56	231	2	13.9 mg/kg	11.3 mg/kg	55.0 mg/kg
Green seaweeds	Ulva lactuca	10	21	-	5.1 mg/kg	5.4 mg/kg	11.6 mg/kg
	All species in group	17	49	1	7.8 mg/kg	5.8 mg/kg	51.0 mg/kg

[a] Number of average results (not maximum levels in dataset) above total arsenic limit for seaweed used as animal feed in Directive 2002/32/EC and amendments; [b] Maximum level across the dataset for species or group.

Table 6.35: Total arsenic concentrations in relevant seaweed species in countries with 14 or more results in the dataset, plus levels for Saccharina latissima by country where reported.

		Ireland	Sweden	Scotland	Spain	Iceland	Norway
All species	Results in dataset	21	19	33	34	43	66
	Number of species	7	9	13	12	8	16
	Results in dataset from brown kelps	9 (43%)	10 (53%)	17 (52%)	9 (26%)	26 (60%)	31 (47%)
	ΣN	77	44	202	342	125	300
	Mean	57.3 mg/kg	41.1 mg/kg	54.7 mg/kg	42.3 mg/kg	71.7 mg/kg	38.5 mg/kg
	Minimum	5.7 mg/kg	3.7 mg/kg	3.4 mg/kg	3.1 mg/kg	2.5 mg/kg	4.5 mg/kg
	Median (50%)	63.0 mg/kg	38.3 mg/kg	46.3 mg/kg	44.3 mg/kg	63.0 mg/kg	45.0 mg/kg
	Maximum	105.0 mg/kg	100.0 mg/kg	149.5 mg/kg	120.0 mg/kg	214.0 mg/kg	120.0 mg/kg
Saccharina latissima only	ΣN	3	28	14	6	25	161
	Mean	105.0 mg/kg	60.8 mg/kg	67.8 mg/kg	79.2 mg/kg	105.5 mg/kg	61.2 mg/kg
	Max	105.0 mg/kg	100.0 mg/kg	88.0 mg/kg	89.4 mg/kg	214.0 mg/kg	120.0 mg/kg

Speciation of arsenic in seaweed

In the EFSA scientific opinion published in 2009, only inorganic arsenic is considered in the toxicity assessment. This is a reasonable approach given the lower toxicity of organic arsenic compounds (Table 6.31). However, it is likely arsenosugars (common in seaweed) are more toxic than arsenobetaine (common in other seafood) and it is worthwhile considering the content of different arsenic species in seaweed.

Arsenobetaine is a naturally occurring organic arsenic compound that is chemically stable and rapidly excreted. It is known as the primary arsenic form in seafood, but arsenobetaine is only present at seaweed in trace levels. Yu et al. (2024) found a mean arsenobetaine level of 0.4% of total arsenic. Similarly, Al Souti et al. (2025) detected arsenobetaine at a mean level of 0.2% of total arsenic. Overall, arsenobetaine is essentially irrelevant for seaweed given both toxicity and content are minimal.

Organic arsenosugars accumulate in seaweed tissue after conversion from absorbed inorganic arsenic. Arsenosugars are likely a by-product of normal biological activity and not generated through arsenic detoxification (Sim et al., 2023). Arsenosugars have a lower toxicity as they are metabolised after ingestion and quickly excreted. They can be the most common arsenical compounds in seaweed. The mean proportion of arsenosugars across all species studied by Al Soufi et al. (2025) was 55% of total arsenic, which is similar to the proportion (mean: 60% of total arsenic) for European species analysed by Yu et al. (2024). Raab et al. (2025) found a higher contribution from arsenosugars in Laminaria hyperborea (75% of total arsenic) than Laminaria digitata (31% of total arsenic).

Arsenosugars share a common structural core but differ in the chemical group attached to the sugar moiety. Petursdottir et al. (2019) showed that sulfonate arsenosugar (AsSug-SO_3) is the dominant form in both Alaria esculenta and Saccharina latissima. Al Soufi et al. (2025) also found sulfonate arsenosugar was the leading form in Fucus vesiculosus, with glycerol arsenosugar (AsSug-Gly) dominant in Himanthalia elongata and phosphate arsenosugar (AsSug-PO_4) dominant in Porphyra spp.

The analysis by Al Souti et al. (2025) indicates that the levels of most arsenical species are consistent across the different varieties of species studied, with arsenosugars the notable exception. Samples of Ulva spp had the lowest total arsenic content of the seven Spanish seaweeds tested (mean: 4.1mg/kg) and similar mean levels of the other arsenic species, with the exception of arsenosugars (1.4mg/kg in Ulva spp; ranging from 7.6mg/kg in Mastocarpus stellatus to 49.9mg/kg in Saccharina latissima). A similar pattern was seen in European seaweed tested by Yu et al. (2024): Spanish Ulva spp had the lowest content of both total arsenic (mean: 3.1mg/kg) and arsenosugars (mean: 0.4mg/kg) but not the lowest levels of other arsenic species. Therefore, arsenosugars may be the primary contributor to varying total arsenic levels between species of seaweed.

Arsenolipids are fat soluble organic arsenic compounds that are less well studied in seaweed. Petursdottir et al. (2019) carried out comprehensive analysis on Icelandic Alaria esculenta and Saccharina latissima. The mean content of arsenolipids across the different fractions was 7.4mg/kg in both species, with a maximum level of 12.4mg/kg (in the holdfast of Alaria esculenta) and arsenolipids between 4% and 12% of total arsenic content. Arsenolipids are also found in fish (e.g. tuna; Stiboller et al., 2019) and are considered more toxic than other organic arsenic compounds.

Improvements to analytical methods have resulted in DMA and MMA being analysed in a range of seaweed species in recent years. In the majority of analyses, DMA is found in higher levels than MMA (Jonsson and Karlssen, 2023; Yu et al., 2024; Sim et al., 2024a; Al Souti et al., 2025). However, this is not consistent across all seaweed species. Generally, the sum of DMA and MMA in seaweed is low (Table 6.36). Yu et al. (2024) included Laminaria ochroleuca in their analysis of European and Asian seaweed. The sums of DMA and MMA were markedly different in the two samples from Spain: 0.6mg/kg and 5.9mg/kg. Al Soufi et al. (2025) also included Spanish Laminaria ochroleuca in their study, determining the sum of DMA and MMA to be 0.9mg/kg. It is possible that the elevated result for one sample in Yu et al. (2024) is an error, given text description of the DMA levels and species identification issues in other samples. Excluding this single elevated result for Laminaria ochroleuca, it appears that Saccharina latissima has the highest levels of DMA and MMA (sum 2.5mg/kg in Jonsson and Karlssen, 2023; sum 2.2mg/kg in Sim et al., 2024a).

Speciation of arsenic in seaweed will depend on the analytical technique used (e.g. Sim et al., 2024a). Certain compounds will be more likely to co-elute during extraction; studies typically report extraction efficiency to record that concentrations could not be determined for all arsenic species. It is important to note that there is insufficient data to warrant limits on organic arsenic compounds in seaweed. However, scientific knowledge is increasing and limits may be put in place on species of arsenic in the future if there is evidence of negative health effects.

Table 6.36: Levels of the organic arsenic compounds DMA and MMA detected in studies of European seaweed

			Sum of DMA and MMA		Sum of DMA and MMA as proportion of total arsenic	
Study	**Countries**	**Number of species[a]**	**Mean**	**Range across species**	**Mean**	**Range**
Yu et al. (2024)	Spain, Ireland	7	0.9 mg/kg	0.1-5.9 mg/kg	2.7%	0.4-11.6%
Jonsson & Karlssen (2024)	Norway, Ireland, Sweden	4	1.6 mg/kg	0.4-2.5 mg/kg	3.1%	1.9-7.2%
Sim et al. (2024a)	Iceland	6	0.9 mg/kg	0.2-2.2 mg/kg	1.5%	0.7-2.8%
Al Souti et al. (2025)	Spain	7	1.1 mg/kg	0.7-1.3 mg/kg	1.9%	1.7-4.7%[b]

[a] European species only; [b] Excluding Ulva spp as low total arsenic level skews contribution by DMA and MMA.

Inorganic arsenic

Inorganic arsenic is recognised as the most toxic form. It is increasingly analysed and reported. There can be inconsistency in how studies convert speciated arsenic compounds into an inorganic arsenic level, in addition to different analytical methodologies. UKAS accredited tests use HPLC coupled with ICP-MS to quantify trivalent arsenic and pentavalent arsenic down to 0.01mg/kg. This aligns with the EU limits, which state that inorganic arsenic is the sum of trivalent arsenic and pentavalent arsenic (Regulation (EC) No 2023/915).

The first European limits for inorganic arsenic in food were introduced for rise in 2016. In November 2023, the EFSA concluded that chronic dietary intake of inorganic arsenic was associated with adverse health outcomes and it was appropriate to establish limits for seafood. Commission Regulation (EU) 2025/1891 became law in September 2025, amending Regulation (EC) No 2023/915. The current limits for seafood and selected products are given in Table 6.37. Some limits are markedly low (e.g. 0.05mg/kg in cephalopods), but there is a comparatively high limit for langoustine of 1.50mg/kg. In contrast to metals like cadmium, lead and mercury, there are no limits on inorganic arsenic content in food supplements in Europe. However, the United States Pharmacopeia is a widely used voluntary standard: it provides a component limit of 1.5mg/kg for inorganic arsenic.

The French national standard for seaweed includes a limit for inorganic arsenic of 3.0mg per dry kg (ANSES), which is double the highest limit in place for seafood in Europe (Table 6.37). The draft maximum limits for inorganic arsenic proposed for seaweed in Europe are 0.5mg for red seaweed species and 1.0mg for brown and green species (Table 6.38). These limits are substantially lower than the French standard and are comparable to the limits in place for seafood (Table 6.37).

According to the UK Diet Survey, daily intake of inorganic arsenic for adults is 16µg – mostly from non-alcoholic beverages, cereals, potatoes and other vegetables. This is equivalent to 23% of the daily intake of total arsenic.

Table 6.37: Maximum inorganic arsenic limits for selected foods in Europe (Regulation (EC) No 2023/915 and amendments; wet weight).

Food	Maximum limit for inorganic arsenic
Fruit juices	0.02mg/kg
Parboiled rice, husked rice and rice flour	0.25mg/kg
Salt	0.50mg/kg
Cephalopods	0.05mg/kg
Bivalve species other than those listed	0.50mg/kg
Scallops	0.10mg/kg
Crustaceans species other than those listed	0.20mg/kg
Crab and crab-like crustaceans	0.10mg/kg
Langoustine and rock lobster	1.50mg/kg
Fish species other than those listed	0.10mg/kg
Higher-trophic fish species listed (e.g. monkfish, haddock, herring)	0.50mg/kg

The maximum level of inorganic arsenic detected in recent seafood monitoring by the UK Food Agencies is 0.011mg/kg (in lobster from NE England). Table 6.39 provides the most recent results for inorganic arsenic in seafood from England & Wales (only total arsenic is reported in Northern Ireland and Scotland). All of the 76 samples were under the EU limits stated in Table 6.37. This aligns with wider research into inorganic arsenic levels in seafood. A study of Scandanavian fish (Larssen et al., 2005) that detected total arsenic at mean levels between 0.55mg/kg (wild Swedish salmon) and 7.80mg/kg (wild plaice from the Skaggerak) found low levels of inorganic arsenic. Indeed, inorganic arsenic concentrations were usually below the level of quantification and, when present, generally under 1% of the total concentration.

Table 6.38: Draft inorganic arsenic limits for seaweed in Europe as an amendment to Regulation (EC) No 2023/915 proposed in December 2025 (dry weight, as placed on the market).

Category	Draft maximum limit for inorganic arsenic
Red seaweed	0.5mg/kg
Green seaweed	1.0mg/kg
Brown seaweed	1.0mg/kg

Table 6.39: Total inorganic arsenic levels detected in the FSA seafood survey 2025 in England and Wales (Fera Science, 2025a).

	Fish	Crustaceans	Cephalopods
Number of samples tested	52	14	10
Proportion of samples with detection	6% (3)	29% (4)	-
Maximum level detected	0.010mg/kg (Sardines, SW England)	0.011mg/kg (Lobster, NE England)	-

Inorganic arsenic is less frequently included in seaweed analysis than total arsenic (approximately 1:3 ratio). The dataset includes 25 studies from 10 different countries covering 16 relevant seaweed species. The inorganic arsenic level in seaweed (median 0.21mg/kg; interquartile range: 0.10-0.45mg/kg) is higher than the levels seen in UK seafood (Table 6.39). Given the clear variation in total arsenic concentration between species (Table 6.34), it is important to consider inorganic arsenic by species. Unlike total arsenic, there are no strong patterns regarding inorganic arsenic levels in the different seaweed groups. High concentrations can occasionally be detected in some species, which skews the mean level (0.60mg/kg). However, it is important to stress that these conclusions apply only when Laminaria digitata is excluded from the dataset as the elevated inorganic arsenic levels of this species are recognised in the scientific literature.

Inorganic Arsenic 101 results across all species[a] ΣN=630 from 25 studies	
Mean	0.60mg/kg
Minimum	0.01mg/kg
25%	0.10mg/kg
Median (50%)	0.21mg/kg
75%	0.45mg/kg
90%	0.88mg/kg
Maximum	49.50mg/kg
Possible risk of excess intake via seaweed	

[a] Excluding Laminaria digitata

Table 6.40 provides inorganic arsenic levels for species featured in five or more studies in the dataset. Red seaweeds generally have the lowest levels (mean 0.32mg/kg). Species of Porphyra have the lowest inorganic arsenic content, but Ficheux et al. (2023) detected levels exceeding the proposed 0.5mg/kg European limit (Table 6.38), with a mean content of 0.62mg/kg and a maximum of 1.81mg/kg. Palmaria palmata tends to be higher. Yu et al. (2025) found mean levels above the European limit in Palmaria palmata from Spain (0.64mg/kg) and Ireland (1.60mg/kg). Stedt et al. (2025) detected a mean level of 0.64mg/kg in Norwegian Palmaria palmata.

Green seaweeds have a similar inorganic arsenic content as red species. All of the studies of green seaweed in the dataset have detected inorganic arsenic at mean concentrations below the proposed 1.0mg/kg European limit (Table 6.38), although Ficheux et al. (2023) reported a maximum content of 2.3mg/kg in a species of Ulva from France. Samarasinghe et al. (2021) detected elevated levels of inorganic arsenic in an Ulva species harvested in Denmark, but only in one of the two samples taken from different locations and in months. Given the implications for the risk profile of Ulva species, it is helpful to further interrogate the data presented by Samarasinghe et al. (2021). The inorganic arsenic level in a sample collected in June 2018 in Mariager Fjord was moderate (0.65mg/kg), whereas a much higher level was detected in a sample taken in August 2018 in Skive Fjord (8.30mg/kg). The authors acknowledge the elevated level in the August sample is an issue, but consider the difference to linked to harvest season. However, the variation may relate to the locality. It is around 35km from the western extent of the Mariager Fjord to the open sea of the Kattegat, but Skive Fjord is approximately 100km inland from the open North Sea. This may create comparatively higher contamination risks in Skive Fjord that make this sample less comparable to other locations. Indeed, this possibility is evidenced by the fact that levels of nickel, barium, cobalt, zinc, manganese, copper were all at least twice as high in the Skive Fjord sample. Therefore, only the levels of total arsenic and inorganic arsenic measured in the Ulva sample from Skive Fjord are included in the dataset.

Table 6.40: Detail of inorganic arsenic levels in the dataset for species featured in five or more studies.

Group	Species	Results in dataset	ΣN	N results above proposed EU limit (0.5mg/kg or 1.0mg/kg)[a]	Mean	Median	Max[b]
Brown seaweeds	Ascophyllum nodosum	7	43	-	0.22 mg/kg	0.11 mg/kg	1.21 mg/kg
	Fucus vesiculosus	6	35	-	0.20 mg/kg	0.21 mg/kg	0.35 mg/kg
	Himanthalia elongata	5	35	1	0.89 mg/kg	0.21 mg/kg	3.75 mg/kg
	Saccharina latissima	22	169	4 (18%)	0.99 mg/kg	0.22 mg/kg	49.50 mg/kg
	Alaria esculenta	8	48	1 (13%)	0.93 mg/kg	0.55 mg/kg	4.19 mg/kg
	Laminaria digitata	17	105	15 (88%)	24.85 mg/kg	23.5 mg/kg	87.00 mg/kg
	All species in group[c]	**63**	**398**	**7 (11%)**	**0.66 mg/kg**	**0.19 mg/kg**	**9.69 mg/kg**
Red seaweeds	Palmaria palmata	8	87	3 (38%)	0.52 mg/kg	0.39 mg/kg	1.60 mg/kg
	Porphyra spp	9	34	1 (11%)	0.22 mg/kg	0.09 mg/kg	1.81 mg/kg
	All species in group	**23**	**152**	**4 (17%)**	**0.32 mg/kg**	**0.24 mg/kg**	**1.80 mg/kg**
Green seaweeds	Ulva lactuca	5	22	-	0.32 mg/kg	0.27 mg/kg	0.58 mg/kg
	All species in group	**15**	**80**	**1 (7%)**	**0.81 mg/kg**	**0.21 mg/kg**	**8.30 mg/kg**

[a] Number of average results (not maximum levels in dataset) above draft inorganic arsenic limit proposed for EU for red seaweed (0.5mg/kg) and brown and green seaweed (1.0mg/kg) as summarised in Table 6.38; [b] Maximum level across the dataset for species or group; [c] Figures for brown seaweed exclude Laminaria digitata.

There appears to little risk of elevated inorganic arsenic in fucoid wracks (i.e. Ascophyllum nodosum, Pelvetia canaliculata, Fucus species); average results are below the proposed 1.0mg/kg European limit (Table 6.38). There may be an exception for inorganic arsenic in Himanthalia elongata. Four studies all found low levels in samples from Norway (Biancarosa et al., 2018; Duinker et al., 2020), France (Ficheux et al. 2023) and Spain (Al-Soufi et al., 2025), with the highest mean concentration at 0.43mg/kg (Al-Soufi et al., 2025). However, Yu et al. (2024) detected a mean content of inorganic arsenic at 3.75mg/kg in Spanish Himanthalia elongata, which suggests it is a species capable of elevated levels.

Higher levels of inorganic arsenic are possible in kelp species. Although Alaria esculenta generally has low levels (median: 0.55mg/kg), a high mean level of 4.19mg/kg was detected in a sample from Ireland by Joensson & Nordberg Karlsson (2024). Saccharina latissima also typically has lower levels (median: 0.22mg/kg). However, several studies have found inorganic arsenic at concentrations above the proposed 1.0mg/kg European limit. Two single measurements of 1.92mg/kg and 3.67mg/kg were reported by Dahlstedt et al. (2026) in Saccharina latissima harvested in different months. Comparing Saccharina latissima harvested in different countries, Joensson & Nordberg Karlsson (2024) detected an elevated level of inorganic arsenic in wild harvested material sourced from Ireland (mean 9.69mg/kg). This was remarkably higher than the mean levels found in Saccharina latissima cultivated in Sweden (0.21mg/kg) and Norway (0.19mg/kg). This is noteworthy given the elevated content seen in Irish Alaria esculenta (mean 4.19mg/kg); the authors acknowledge both the evident disparity in inorganic arsenic between species and also the unknown cause for the geographic variation. In their dataset of 39 samples of French Saccharina latissima, Ficheux et al. (2023) found a median level of inorganic arsenic similar to others in the dataset (0.20mg/kg). The statistics presented indicate several samples were over the proposed 1.0mg/kg European limit, with one result at 49.50mg/kg skewing the mean to 2.08mg/kg. This level of 49.50mg/kg is remarkably high, far exceeding the . The findings of Ficheux et al. (2023) and Joensson & Nordberg Karlsson (2024) demonstrate that high levels of inorganic arsenic are possible in Saccharina latissima, even though the majority of the results are below the proposed 1.0mg/kg European limit.

Laminaria digitata

Laminaria digitata is a seaweed with consistently high levels of inorganic arsenic. Table 6.41 provides a summary of the levels found in studies across Europe. It is rare that inorganic arsenic is not detected at concentrations over the proposed 1.0mg/kg European limit. In a study of analytical methods, Marschner et al. (2019) detected inorganic arsenic in Laminaria digitata gathered at four sites on the east coast of Aberdeenshire. Two samples had elevated mean levels (9.1mg/kg, 12.0mg/kg), whereas two samples were low (0.39mg/kg, 0.66mg/kg): these are the two only results for Laminaria digitata in the dataset below the proposed 1.0mg/kg European limit.

Biancarosa et al. (2018) found a mean level of 1.10mg/kg in Norwegian Laminaria digitata, but the larger study by the Duinker et al. (2020) found a mean level of 24.0mg/kg (max: 79.0mg/kg). Ronan et al. (2017) analysed inorganic arsenic in Irish Laminaria digitata, with the mean level ranging from 23.0mg/kg in the young blade to 44.0mg/kg in the distal blade. The highest level

Table 6.41: Inorganic arsenic concentrations measured in Laminaria digitata in the dataset (only including concentrations in harvestable sections of thallus, excluding meristem and stipe).

	Iceland	Ireland	Norway	Scotland
Studies in dataset	Sim et al. (2024a)	Ronan et al. (2017)	Biancarosa et al., (2018) Duinket et al. (2020)	Marschner et al. (2019) Ownsworth et al. (2019) Ender et al. (2019) Raab et al. (2025)
ΣN	3	20	42	27
Average level(s)	54.0 mg/kg	23.0-44.0 mg/kg	1.1mg/kg 24.0mg/kg	0.4-12.0mg/kg 25.0mg/kg[a] 62.0mg/kg 61.6mg/kg
Maximum level in any sample	-	87.0mg/kg	79.0mg/kg	66.9mg/kg

[a] Median level stated for Ownsworth et al. (2019), all others mean level.

in any fraction of Laminaria digitata sampled by Ronan et al. (2017) was 87.0mg/kg, whereas the maximum level in Ascophyllum nodosum was 0.7mg/kg. Sim et al. (2024a) found a mean level of 54.0mg/kg in Laminaria digitata from Iceland. Numerous studies have been published on Scottish inorganic arsenic, likely because of the interests of the research group at Aberdeen University. Ownsworth et al. (2019) analysed arsenic in Fucus vesiculosus and Laminaria digitata harvested in the Forth Estuary and Firth of Forth, finding clear differences between the two species. Ownsworth et al. (2019) reported a median level of 25.0mg/kg in Laminaria digitata from the Firth of Forth, with a maximum of 66.9mg/kg (maximum level in Fucus vesiculosus was 0.2mg/kg). Ender et al. (2019) and Raab et al. (2025) both analysed Laminaria digitata from Aberdeenshire, reporting mean content of 62.0mg/kg and 61.7mg/kg respectively. Although there is limited data on inorganic arsenic from different European countries, it is unlikely that there is a geographic effect. The average levels in Scotland can be both high (Ender et al., 2019; Raab et al., 2025) and low (Marschner et al., 2019), with the highest maximum levels reported in other countries (Ronan et al., 2017; Duinker et al., 2020). Also, inorganic arsenic levels can vary within samples of Laminaria digitata collected over short distances (Marschner et al., 2019). The results presented in Table 6.41 do not indicate that inorganic arsenic levels are higher in Scotland than other countries.

There is clear evidence in Europe that a high proportion of the arsenic in Laminaria digitata is present in inorganic form, which is unusual amongst the relevant seaweed species. This pattern has also been seen in the same species harvested across the Atlantic. For example, nine of the relevant seaweed species were tested in New England by Taylor & Jackson (2016) and the mean level of inorganic arsenic in Laminaria digitata was 8.3mg/kg (the next highest was Ulva lactuca at 0.13mg/kg).

Key conclusions for inorganic arsenic in Laminaria digitata:

- Inorganic arsenic levels can vary within samples of Laminaria digitata collected over short distances (Marschner et al., 2019).
- It is unique to the species not local environmental factors, with multiple studies finding lower levels in species tested alongside Laminaria digitata (e.g. Ascophyllum nodosum, Ronan et al., 2017; Fucus vesiculosus, Ownsworth et al. 2019; Laminaria hyperborea, Raab et al., 2025).
- Levels are typically higher in younger parts of the plant (Ronan et al., 2017; Sim et al., 2024a) and so there is no opportunity to manage inorganic arsenic level in the end product by careful, selective harvesting.
- Detection of a lower level may be an artefact linked to the extraction method. Feldmann et al. (2000) did not detect inorganic arsenic no detection in Laminaria digitata, with a comment in a paper from the same authorship group that the extraction method may have caused coelution of the inorganic arsenic with arsenosugars (Ronan et al., 2017).

Sargassaceae family species

Many species in the Sargassaceae family include ecologically and commercially important seaweeds. The Sargassaceae family is a diverse group that includes the genus Sargassum and a range of species found in Scottish waters (e.g. Ericaria selaginoides, Bifurcaria bifurcata, Gongolaria baccata). It is well known that many Sargassaceae species retain arsenic in inorganic form.

Sargassum fusiforme (formerly Hizikia fusiforme) is commonly known as hijiki (sometimes hiziki). It is an edible brown seaweed traditionally consumed in East Asian cuisine. Research into the arsenic levels in Sargassum fusiforme intensified in the 1990s with improved speciation techniques that confirmed significant proportions were inorganic forms. Government food safety agencies began to issue official risk communications on this species. The Canadian Food Inspection Agency first advised consumers to avoid consumption in 2001. The UK Food Standards Agency (FSA) advised against eating this species in 2004, following a survey that showed Sargassum fusiforme was the only species tested to contain a significant level of inorganic arsenic. The statement by the FSA led to agencies in other countries issuing similar advice on Sargassum fusiforme in the following year (e.g. Food Standards Australia New Zealand, Food Safety Authority of Ireland, Hong Kong Centre for Food Safety). The overseas advisory positions on imported seaweed led the Japanese Government to take a position on consumption of Sargassum fusiforme. The Health, Labor and Welfare Ministry issued a statement the same week as the UK Food Standards Agency announcement, asserting that Sargassum fusiforme was safe to eat in small quantities as part of a balanced diet (The Japan Times). This was likely a protective position given the traditional culinary application and relavitely infrequent consumption. Research in Japan has indicated there are health impacts from consuming Sargassum fusiforme. For example, the dietary exposure study by Mise et al. (2019) found consumption elevates levels of inorganic arsenic intake in Japanese children and pregnant women.

The inorganic arsenic levels in Sargassum fusiforme are now well characterised. A recent study by Huang et al. (2020) analysed arsenic levels in Sargassum fusiforme from China and Korea.

The range in mean inorganic arsenic levels in different months were 40.3-58.0mg/kg (Chinese seaweed; 69-86% of total arsenic) and 24.2-45.4mg/kg (Korean seaweed; 69-99%). This aligns with the results from European researchers (e.g. 59.0mg/kg in single sample tested by Duinker et al., 2000). There has been considerable research effort into how processing can reduce inorganic arsenic content in Sargassum fusiforme. Park et al. (2018) detected only inorganic pentavalent arsenic and organic arsenobetaine in their speciation of Korean Sargassum fusiforme. Levels of both arsenic species were significantly reduced when boiled for five minutes, with inorganic arsenic reducing by 80%. However, the extremely elevated concentration in the raw material meant the treated seaweed still had a level of 21.5mg/kg. In addition, Park et al. (2018) showed the leaves have a higher arsenic content than the stalk; the heat treated leaves had an inorganic arsenic concentration of 44.4mg/kg after heat treatment. Jonssen & Karlsson (2024) demonstrated that processing reduced inorganic arsenic content of Saccharina latissima from Sweden (high pressure pasteurisation: -63%; soaking in water: -86%; blanching: -86%). However, this was from a comparatively low initial mean concentration of 0.21mg/kg. Although basic processing methods relevant to domestic kitchens lessen inorganic arsenic levels, it appears unlikely that elevated levels in raw material can be sufficiently reduced to eliminate health risks from chronic consumption.

Sargassum muticum is another species of the Sargassaceae family native to the northwest Pacific, but is has spread across most of the northeast Atlantic European coastline (commonly known as Japanese wireweed). It grows rapidly into dense canopies, competing with native species (e.g. Fucus spp, Laminaria spp). Although there are studies measuring arsenic levels in European samples of Sargassum muticum, most papers report total arsenic without speciation. Balboa et al. (2015) reported inorganic arsenic in Sargassum muticum collected from northern Spain, but did quantify concentrations. Duinker et al. (2000) found levels of inorganic arsenic in Sargassum muticum ranged between 48 and 68mg/kg, which aligns with the elevated concentrations seen in Sargassum fusiforme. The implications of high inorganic arsenic levels should be considered in commercial applications for Sargassum muticum in Europe, but it is unlikely the elevated levels are a risk in Scotland.

In the report by Duinker et al. (2020) summarising testing for the Norwegian Food Safety Authority, inorganic arsenic levels were measured in several seaweed species in the Sargassaceae family (Table 6.42). This direct comparison demonstrates elevated concentrations are found in European Sargassaceae species. Halidrys siliquosa is known as sea oak and is commonly found in northwest Europe and Duinker et al. (2000) found levels of inorganic arsenic reached 42.0mg/kg. Composition of Halidrys siliquosa is less widely studied than other species; it is likely that the Norwegian Food Safety Authority data included the 2.4mg/kg mean concentration detected by Biancarosa et al. (2018). The Asian species Eisenia bicyclis is commonly known as arame but sometimes referred to as sea oak. However, it is a species in the Laminariaceae family unrelated to Halidrys siliquosa. It does not share the inorganic arsenic issue; Duinker et al. (2020) detected a level of 0.02mg/kg in the single sample they analysed.

Table 6.42: Species with the highest levels of inorganic arsenic in testing for the Norwegian Food Safety Authority (Duinker et al., 2020).

Family	Species	Description	N	Inorganic arsenic level		
				Mean	**Median**	**Range**
Sargassaceae	Sargassum fusiforme	Hijiki – culinary seaweed imported from Asia	1	59.0 mg/kg		-
	Sargassum muticum	Wireweed - invasive species to Europe	4	54.0 mg/kg	51.0 mg/kg	48.0-68.0 mg/kg
	Halidrys siliquosa	Sea oak – native to Europe	8	12.0 mg/kg	7.6 mg/kg	2.4-42.0 mg/kg
Laminariaceae	Laminaria digitata	Oar weed – native to Europe (relevant seaweed species)	40	24.0 mg/kg	21.0 mg/kg	<0.1-79.0 mg/kg
	Saccharina latissima[a]	Sugar kelp – native to Europe (relevant seaweed species)	77	0.2 mg/kg	0.2 mg/kg	<0.1-0.67[b] mg/kg

[a] Next highest mean level of inorganic arsenic in species included in the study from more than two samples; [b] Maximum level detected in any sample of all other species was 2.7mg/kg (Alaria esculenta).

Following the research by Duinker et al. (2020), the Norwegian Food Safety Authority advised consumers to avoid products from Laminaria digitata because of high inorganic arsenic levels. This appears to be the first example of a national authority making a statement on Laminaria digitata equivalent to the many international recommendations on the inorganic arsenic hazard in Sargassum fusiforme.

Estimating inorganic arsenic content

In an assessment by the EFSA in 2014, inorganic arsenic levels were estimated in seaweed by a proportion of total arsenic. Sargassum fusiforme (hijiki) was acknowledged as a risk for inorganic arsenic and repeatedly referenced as unusually high. However, inorganic arsenic levels for other species of seaweed were estimated based on 1% of the total arsenic content. The assessment mentions Laminaria species, but there would have been less awareness of the speciation of arsenic in Laminaria digitata at time of publication. The estimation of inorganic arsenic from total arsenic is acknowledged as an inherent uncertainty.

Applying a percentage conversion of total arsenic to inorganic arsenic is not recommended. Table 6.43 summarises the proportion of total arsenic as inorganic arsenic in different species, utilising only studies in the dataset where ratios could be reliably calculated (i.e. both total and inorganic arsenic measured in the same sample). Laminaria digitata is a species with an elevated total arsenic content and it also has a high proportion of inorganic arsenic (mean: 31% of total). Other species of brown seaweed have a mean inorganic arsenic ratio near 1%, although some samples in the dataset reached 7-9% (e.g. Himanthalia elongata, Alaria esculenta, Saccharina latissima). Although some red and green species show higher mean inorganic arsenic ratios (e.g. 7% in Palmaria palmata; 8% in Ulva lactuca), the inorganic arsenic concentrations are low in these species (Table 6.40, Table 6.43). This demonstrates the important of direct measurement of inorganic arsenic in seaweed and the improved analytical speciation techniques should be utilised for any food safety risk assessments.

Table 6.43: Proportion of total arsenic as inorganic arsenic for species featured in four or more studies in the dataset.

		Studies in dataset with calculable proportions[a]		Level of inorganic arsenic		Inorganic arsenic as proportion of total arsenic	
Group	**Species**	**Results**	**ΣN**	**Mean**	**Max**	**Mean**	**Max**
Brown seaweeds	Ascophyllum nodosum	7	19	0.24 mg/kg	0.88 mg/kg	0.6%	2.8%
	Fucus vesiculosus	5	12	0.21 mg/kg	0.35 mg/kg	0.4%	0.6%
	Himanthalia elongata	4	31	1.11 mg/kg	3.75 mg/kg	2.2%	7.3%
	Saccharina latissima	19	90	0.92 mg/kg	9.69 mg/kg	1.1%	9.2%
	Alaria esculenta	4	11	1.45 mg/kg	4.19 mg/kg	1.9%	7.2%
	Laminaria digitata	**11**	**46**	**31.94 mg/kg**	**62.00 mg/kg**	**31.3%**	**57.1%**
	All other species in group[b]	**48**	**203**	**0.71 mg/kg**	**9.69 mg/kg**	**1.2%**	**9.2%**
Red seaweeds	Palmaria palmata	7	64	0.56 mg/kg	1.60 mg/kg	7.0%	20.1%
	Porphyra spp	10	28	0.26 mg/kg	0.62 mg/kg	0.7%	1.6%
	All species in group	51	221	0.37 mg/kg	1.60 mg/kg	3.1%	20.1%
Green seaweeds	Ulva lactuca	9	17	0.36 mg/kg	0.58 mg/kg	8.5%	18.7%
	All species in group	15	42	1.29 mg/kg	8.30 mg/kg[b]	15.3%	71.6%[c]

[a] Studies from the dataset are only included in Table 6.43 if both total and inorganic arsenic were measured in the same sample; [b] Laminaria digitata excluded from brown seaweed statistics as the species has elevated levels; [c] Outlier for one of two samples of Danish Ulva sp. analysed Samarasinghe et al. (2021).

Limits on inorganic arsenic in seaweed

The proposal to introduce regulations on inorganic arsenic for seaweed in Europe (as an amendment to Regulation (EC) No 2023/915) would be the first limit on seaweed pertinent to the UK. Some producers in Scotland have recognised the risk of inorganic arsenic and – without a legal limit in place for seaweed or a suitable proxy – used the 3.0mg/kg limit in the French national standard for seaweed. The introduction of limits for seafood in EU law in September 2025 provides a benchmark of more relevance to seaweed. The highest limit for seafood is 1.5mg/kg (langoustine, Table 6.37), which is half the limit for seaweed in France. This divergence appears reasonable given seafood is consumed in greater quantities than seaweed. Indeed, Ficheaux et al. (2023) incorporated their analysis of inorganic arsenic in French seaweed into a dietary risk exposure assessment and suggested that the 3mg/kg limit in France could be increased to 10mg/kg. In New Zealand, Sargassum fusiforme (hijiki) is classified as a 'risk food' and all consignments are inspected and tested for inorganic arsenic. Any batches that do not meet the limit of 1mg/kg cannot be imported.

The proposed maximum limits for inorganic arsenic in European seaweed are 0.5mg/kg for red species and 1.0mg/kg for brown and green species (Table 6.38). These limits are a significant reduction on the longstanding French standard. With the exception of Laminaria digitata, all of the species featured in five or more studies have a median inorganic arsenic content within the proposed European limits (Table 6.40). Unfortunately, the dataset includes species that have a proportion of results exceeding the proposed European 1.0mg/kg limit for brown and green seaweed (18% for Saccharina latissima, 13% for Alaria esculenta) and the 0.5mg/kg limit for red seaweed (38% for Palmaria palmata, 11% for Porphyra spp). In contrast, 88% of the results for Laminaria digitata proposed exceed the European 1.0mg/kg limit.If the French limit of 3.0mg/kg was applied across Europe, only four results in the dataset would exceed the standard (4% of results): Saccharina latissima from Sweden (Dahlstedt et al., 2026), Saccharina latissima from Ireland (Joensson & Nordberg Karlsson, 2024), Alaria esculenta from Ireland (Joensson & Nordberg Karlsson, 2024) and Himanthalia elongata from Spain (Yu et al., 2024). It is important to emphasise this excludes the likely outlier for a sample of Danish Ulva spp (Samarasinghe et al., 2021) and Laminaria digitata (82% of results in the dataset are over 3.0mg/kg).

Consuming 5 dry g of seaweed with a 3.0mg/kg inorganic arsenic content would result in an intake of 15µg. This is nearly equivalent to the daily intake of inorganic arsenic for a UK adult (UK Dietary Survey). Although there is a need to reduce intake of inorganic arsenic – especially in vulnerable cohorts such as pregnant women and children – a limit of 3.0mg/kg is an appropriate threshold. By and large, the 3.0mg/kg threshold minimises risk to health from dietary exposure while avoiding burdensome restrictions on seaweed producers. It is possible that higher concentrations will be detected in many edible seaweed species. However, this would fall generally under the category of low frequency exceedance and less likely to indicate a contamination issue.

It is necessary to reiterate that Laminaria digitata has high inorganic arsenic levels, uniquely amongst the relevant seaweed species considered in this review. Therefore, it is reasonable to align Laminaria digitata with the numerous recommendations on the inorganic arsenic hazard known in Sargassum fusiforme (as the Norwegian Food Safety Authority advised following the research by Duinker et al., 2020).

In conclusion, there is a risk of overexposure of inorganic arsenic from Laminaria digitata and a possible risk of excess intake from other species of seaweed. Producers should test levels routinely and not rely on conversion from total arsenic.

Other toxic trace elements

While there are many elements known to be toxic, the risk profile is less well characterised for some. This may mean that fewer tolerable upper limits are published, often because authorities do not have sufficient information to reach firm conclusions. The nature of analytical chemistry means many studies of seaweed composition yield concentrations for a broad sweep of elements. However, infrequent inclusion makes it difficult to apply risks profiles. This section groups together elements with fewer results in the dataset.

Barium

Barium is naturally present in rocks and exhibits a wide range in concentrations around the UK. The highest levels are associated with various orefields in England. However, moderate to high levels are seen in localised areas of Scotland, which is known as a region with igneous and metamorphic rocks containing high concentrations of barium. There is wide variation within small localities according to underlying bedrock: Skye has some of the lowest and highest concentrations in Scotland. Macdonald et al. (2005) mapped areas with elevated barium levels in groundwater, which highlighted Central Scotland, the Moray Firth, Caithness, Orkney and northern Argyll as areas of risk. Anthropogenic barium contamination is not as important, although there may be some relevant historic mining and industrial applications. It is used to manufacture various consumer goods, which means landfill leachate can contain barium. A possible source for the marine environment is barium sulphate used in oil and gas drilling.

There is no nutritional requirement for barium in humans. Barium sulphate is insoluble and is used in medical imaging. However, soluble barium compounds are toxic. Chronic barium exposure can lead to effects on bones and the kidneys. There are no tolerable intakes in place in Europe, but the US EPA has set an oral Reference Dose of 0.2mg of barium per kg body weight per day (equivalent to 14mg per day for an adult).

Barium 38 results across all species ΣN=245 from 20 studies	
Mean	17.3mg/kg
Minimum	0.1mg/kg
25%	8.4mg/kg
Median (50%)	12.9mg/kg
75%	16.3mg/kg
90%	27.4mg/kg
Maximum	117.8mg/kg
Minimal risk of excess intake via seaweed	

Barium is not part of monitoring in Scottish bivalves but it is in the UK Diet Survey. Daily intake for UK adults is 0.48mg of barium (mostly from non-alcoholic beverages, cereals and bread). This is lower than the median dietary intake is 0.84mg per day calculated by Filippini et al. (2020) in Italy.

Barium has been included in a reasonable number of studies, covering 8 countries and 11 relevant seaweed species. Levels in seaweed are variable, but median levels are 12mg/kg and only 5% of results were above 50mg/kg. The highest level in the dataset is 118mg/kg in Fucus vesiculosus, collected in the Baltic by the German Environmental Specimen Bank for monitoring long-term contamination tends. The analysis of Scottish kelps by Schiener et al. (2015) found lower maximum levels of barium (Saccharina latissima: 22mg/kg; Laminaria digitata: 11mg/kg; Laminaria hyperborea: 10mg/kg).

Using the maximum level of 118mg/kg, a 5 dry g portion of seaweed would result in 0.59mg of barium being consumed. This is more than the adult dietary intake in the UK, but lower than the equivalent in Italy. It is also just 4% of the US EPA Reference Dose. Therefore, it is unlikely that barium from seaweed will cause health concerns.

Titanium

Titanium is naturally abundant in rocks, especially older crystalline rocks (e.g. gneiss). The mineral forms found in the UK have a high chemical resistance that leads to accumulation in older, acidic, upland soils. Rivers transport titanium into the marine environment, but the low solubility of mineral forms means natural sources of titanium are low in seawater. Anthropogenic titanium contamination comes from wastewater treatment discharges, industrial sites, waster consumer products and urban runoff (Table 3.3). Titanium dioxide is commonly used in cosmetics, paint, toothpaste and sunscreen.

There is no requirement for titanium in the body. As metallic and ionic titanium is inert, insoluble and not bioavailable, the risk of toxicity from oral intake is very low. There is no Tolerable Daily Intake for elemental titanium in Europe or Reference Dose in the US. Titanium dioxide was used as a food additive in Europe and the UK (E171). In 2021, the EFSA determined that no safe level could be established due to uncertainty around toxicity. Titanium dioxide has been banned in the EU and UK as a food additive since 2022. This conclusion is specific to titanium dioxide, but the ESFA panel concluded that adverse health effects in rats were seen at daily intake of 1,000mg per kg body weight.

Titanium is found in trace quantities in food, mostly from residual soil particles. Titanium is not monitored in Scottish bivalves and it is not in the UK Diet Survey. Filippini et al. (2020) included titanium in their analysis of metal intake in Italy. Products with higher titanium levels include chocolate (median: 3.3mg/kg), white meat (median: 2.0mg/kg) and nuts and seeds (median: 1.6mg/kg). Overall median daily dietary intake is 0.88mg per day, mainly from milk, dairy, meat and cereals.

Titanium 10 results across all species ΣN=89 from 8 studies	
Mean	28.5mg/kg
Minimum	0.9mg/kg
25%	8.8mg/kg
Median (50%)	12.5mg/kg
75%	40.8mg/kg
90%	47.4mg/kg
Maximum	160.0mg/kg
Minimal risk of excess intake via seaweed	

Unfortunately, there is limited analysis of titanium levels in seaweed (10 studies covering 6 species in 4 countries). There is a median concentration of 12.5mg/kg in in the dataset, but a wide range of levels. The highest concentrations were detected in a study of Scottish kelps by Schiener et al. (2015). Laminaria digitata, Laminaria hyperborea and Saccharina latissima were harvested from the wild near Oban. All species showed broadly similar ranges of titanium (Table 6.44), with the highest single sample at 160mg/kg (Saccharina latissima harvested in August 2010). Consuming 5 dry grams of dried seaweed at this concentration would result in intake of 0.8mg of titanium. This is broadly similar to the daily dietary intake estimated by Filippini et al. (2020).

Table 6.44: Titanium levels in species of Scottish kelp analysed by Schiener et al. (2015).

	Sampling		Titanium content		
Species	Number	Months tested	Minimum	Median	Maximum
Laminaria digitata	8	7	39mg/kg	47mg/kg	53mg/kg
Laminaria hyperborea	8	7	0mg/kg	60mg/kg	106mg/kg
Saccharina latissima	8	7	3mg/kg	94mg/kg	160mg/kg

Titanium levels in relevant seaweed species are elevated compared to terrestrial foods and the highest contents detected are in Scottish kelps. However, the small portion size and minimal evidence of toxicity means that there is no practical risk of excessive titanium intake.

Silver

Silver is generally only naturally present in rocks and soils in low concentrations. There are some mineralised areas in the UK, including Cornwall, Devon, Wales and the Pennines. Most of Scotland does not have elevated silver, although the Southern Uplands is somewhere where silver occurred with lead-zinc mineralisation and so can be found in historic mining areas. The risk of contamination is driven by anthropogenic sources of silver (Table 3.3). The primary source is wastewater and sewage effluent containing traces of silver used in cosmetics, cleaning products and textiles. Silver can also be washed off surfaces and into urban runoff. There are also historic sources from metal production and chemical manufacturing.

There is no biological role for silver in the human body and no regulator considers it a nutrient. Generally, silver is poorly absorbed but tends to bind to proteins and accumulate in tissues. The EFSA cannot confirm a safe intake level for silver as a food colour (E174) due to limited scientific data (EFSA, 2025). However, this was partly driven by use of nano-silver particles (1-100nm). The US EPA has set a daily Reference Dose for silver of 5µg per kg body weight, equivalent to 0.35mg per day.

Silver is not included in UK Diet Survey, but it is part of bivalve monitoring in Scotland. Although silver concentrations are low in mussels (max: <0.01mg/kg), levels are higher in oysters (mean: 0.69mg/kg; max: 0.97mg/kg). Filippini et al. (2020) included silver in their study of metal intake in Italy. Assessing a range of food and drink, silver was below limit of detection in 49% of 908 samples tested. Foods with higher silver levels include crustaceans and molluscs (median: 4.8µg/kg) and mushrooms (median: 4.6µg/kg). Overall estimated daily dietary intake is 0.9mg per day, mainly from cereals and fresh fruit.

Silver 19 results across all species ΣN=66 from 8 studies	
Mean	2.15mg/kg
Minimum	0.01mg/kg
25%	0.02mg/kg
Median (50%)	0.04mg/kg
75%	0.11mg/kg
90%	0.21mg/kg
Maximum	32.0mg/kg[a]
Minimal risk of excess intake via seaweed	

[a] Outlier for Ulva intestinalis that may be a unit error in the published data

Relatively few studies have analysed silver in seaweed (8 studies covering 5 species in 5 countries), but levels are generally very low. The median concentration in the dataset is just 0.05mg/kg and just 13% of results are above 0.2mg/kg (i.e. below the level of silver seen in Scottish oysters). However, Olssen et al. (2020b) harvested Ulva intestinalis at seven sites around Sweden and detected silver at consistently high levels (range 29.7-32.0mg/kg). This is the only study in the dataset to test Ulva intestinalis and the elevated concentrations are around one thousand times larger than the median result in the dataset. Therefore, Ulva intestinalis may have a tendency to absorb silver or there could be a fault in the data (e.g. unit reporting error of ppm instead of ppb). The next highest level of silver in the dataset is 0.24mg/kg in English Fucus spiralis (Oaten et al., 2017). The average level of silver detected by Ownsworth et al. (2019) across five species sampled in the Forth Estuary and Firth of Forth was 0.07mg/kg, with a maximum concentration of 0.20mg/kg in a sample of Ascophyllum nodosum (these figures align with the dataset, but the results from this study are not included as there is insufficient detail to justify inclusion).

Assuming an extreme case of 30mg/kg, a 5 dry gram portion would contain 150µg of silver. This is likely to be a significant increase in the overall dietary intake and 43% of the daily Reference Dose set by the US EPA. However, if taking the next highest level seen of 0.24mg/kg, a 5 dry gram portion would be just 0.3% of the US EPA Reference Dose. Although data is limited, it is unlikely that intake of silver from seaweed will be sufficiently high to cause health concerns. Anyone working with Ulva intestinalis should conduct further research and, if warranted, carry out independent analysis to better characterise the risk of elevated silver levels.

Tin

Tin occurs naturally in soil and rocks across the UK at low levels. However, the only region with naturally elevated tin levels is Cornwall. Historic mining and mineral processing has left a legacy of localised tin contamination (e.g. around Camborne and Redruth). Other anthropogenic sources of tin contamination include combustion of fossil fuels and leaching from waste consumer goods in landfill (Table 3.3). Tin was once a widely used antifoulant in the form of tributyl-tin (TBT), which has a much higher toxicity than inorganic tins used in food canning. Indeed, Oaten et al. (2017) connected seasonal variations in tin concentrations in seaweed with removal of old antifoulant paint during winter. A ban has been in place for TBT antifoulants since 2008 and this is no longer a major source.

No biological requirement for tin has been demonstrated in humans. The EFSA has no established tolerable daily intake for tin in food. Inorganic tin is poorly absorbed in the body and has a relatively low toxicity. Organotins are persistent – such as TBT – are more likely to be absorbed, causing endocrine disruption and immunotoxicity. The US EPA has published a provisional oral Reference Dose for inorganic tin of 0.6mg per kg body weight per day. This is equivalent to a daily intake of 42mg in a 70kg adult. There is also a packaging migration limit in Europe of 100mg of tin per kg of food.

Tin is not monitored in Scottish bivalves but it is in the UK Diet Survey; daily intake for UK adult is 1.6mg. The primary source is canned vegetables, due to the migration of tin from metal food containers.

Unfortunately, there is limited analysis of tin levels in seaweed (6 studies covering 5 species in 5 countries). It is possible that extending the selection criteria back ten or twenty years would yield more results. However, this would likely link to environmental monitoring of tin linked to TBT, which less concerning currently. There is a median level of 0.03mg/kg in in the dataset, but without a wide range of concentrations in contrast to many other metals. Tin was included in the analysis of 17 samples of Norwegian Saccharina latissima by Niedzwiedz et al. (2024): the maximum level detected was 0.31mg/kg.

Tin 11 results across all species ΣN=40 from 6 studies	
Mean	0.08mg/kg
Minimum	0.01mg/kg
25%	0.02mg/kg
Median (50%)	0.03mg/kg
75%	0.16mg/kg
90%	0.22mg/kg
Maximum	0.31mg/kg
Minimal risk of excess intake via seaweed	

Unusually, France implemented a national standard for seaweed that included a limit of 5mg of tin per dry kg. They were defined by what is now known as the French Agency for Food, Environmental and Occupational Health & Safety (ANSES). The 5mg/kg limit was selected to provide a large safety margin to consumers rather than specific toxicological concerns. There appears to be minimal risk of tin content in seaweed exceeding the French national standard.

Consuming 5 dry grams of dried seaweed at a concentration of 0.31mg/kg (i.e. the maximum detected by Niedzwiedz et al., 2024) would result in intake of just 2µg of tin. This minute intake is <0.1% of the tin consumed in the UK adult diet and <0.01% of the US EPA Reference Dose. Although there are fewer results in the dataset than most of the other characterised toxic trace elements, the levels of tin in seaweed are likely to be low when material is sourced from clean locations. Overall, there is minimal risk of overexposure to tin via edible seaweed.

Thallium

Thallium is found in ores of metals (e.g. lead, zinc, copper) and is readily mobilised during weathering. Areas of the UK with relatively higher areas include the Lake District, Pennines, Peak District, North Wales, Southwest England. Key anthropogenic sources are coal combustion and metal processing (Table 3.3). Traces of thallium are found in the materials used in cement and some electronics. The toxicity of thallium relates to competition with potassium. It is easily absorbed in the body and interferes with cellular processes. Chronic exposure can lead to neurological effects, hair loss and gastrointestinal symptoms.

Although the EFSA has included thallium in some recent assessments of trace elements, there is no determination of safe intake level due to apparent data gaps. Analysis of teas by the EFSA (EFSA, 2022) referred to the provisional Reference Dose values for thallium derived by the US EPA for hair loss: 10ng per kg body weight per day (i.e. 0.7µg for an adult). However, the daily intake for a UK adult (UK Diet Survey) is 6µg of thallium (mostly from non-alcoholic beverages) and so it is unlikely that the US EPA provisional reference dose is relevant. A study on dietary intake in New Zealand (Pearson & Ashmore, 2020) used a WHO (1996) reference of 0.18ng of thallium per kg body weight, which corresponds to 12.6µg per day. This is a more reasonable level to use given it is approximately double to average UK adult intake.

There is limited data regarding thallium concentration in food; thallium is not included in the monitoring of Scottish bivalves. However, Kim et al. (2021) measured the levels of thallium in a broad range of food and beverage products in South Korea: 98% of samples were below 0.01mg/kg. Similarly, analysis of products to assess dietary intake in New Zealand determined that 87% of samples were below 0.01mg/kg (Pearson & Ashmore, 2020).

Thallium is very rarely tested in relevant seaweed species. There are only four studies in the dataset that include thallium, covering only three species originating from Germany and Sweden. The median level of thallium is just 0.01mg/kg, but the mean level is heavily skewed by a study in the dataset with an elevated concentration. Thallium is part of the monitoring programme on Fucus vesiculosus run by the German Environmental Specimen Bank, with 0.011mg/kg the maximum level found in 2025. Jonssen & Nordberg Karlson (2023) reported a mean level of 0.006mg/kg in Saccharina latissima from Sweden. Kollander et al. (2023) detected a maximum concentration of 0.040mg/kg in wild Swedish Ulva intestinalis. However, Olsson et al. (2020b) found significantly higher levels in Ulva intestinalis harvested in Sweden. The mean level across seven different sites was 8.91mg/kg, with a maximum concentration of 13.20mg/kg. This is significantly higher than the levels in foods reported by Kim et al. (2023), but it may be a unit reporting error (i.e. mg in place of µg).

Thallium 6 results across all species ΣN=31 from 4 studies	
Mean	1.49mg/kg
Minimum	<0.01mg/kg
Median (50%)	0.01mg/kg
Maximum	13.20mg/kg[a]
Minimal risk of excess intake via seaweed	

[a] Outlier for Ulva intestinalis that may be a unit error in the published data

There are some relevant results from studies not included in the dataset. A study in Southwest England investigated thallium presence in sediments, deposit feeding invertebrates and Fucus species (Turner et al., 2013; excluded from dataset due to publication date). Thallium levels were around 0.03mg/kg in seaweed, with bioenrichment as high as 170 times seawater levels. Parus & Karbowska (2020) measured thallium in a species of Ulva from Bulgaria, finding a mean level of 2.12mg/kg and a maximum level of 2.49mg/kg. This study was excluded from dataset as the Black Sea coast is unlikely to be representative of Scottish seas, but the concentrations are similar to those reported by Olsson et al.(2020b) for Ulva intestinalis. In their analysis of trace elements in contaminated areas of the Mediterranean seaweed, Squadrone et al. (2018a,b) found a maximum level of thallium of 0.16mg/kg (in a species of green seaweed).

When Kim et al. (2021) measured the levels of thallium in South Korean food and drink, their analysis included three species of seaweed. The maximum concentrations in the seaweed samples analysed was 0.013mg/kg (fresh Undaria pinnatifida), which would be approximately 0.10mg of thallium per dry kg. The level in fresh seaweed was comparable to the maximum levels measured by et al. (2021) in sweet potato (0.013mg/kg), lettuce (0.014mg/kg), cabbage (0.016mg/kg). Kim et al. (2021) raised no concerns at the levels detected.

A concentration of thallium in seaweed at 0.1mg/kg corresponds to intake of 0.5µg from a 5 dry g portion. This is a low intake of thallium (9% of current dietary intake; 4% of the limit used by Pearson & Ashmore, 2020) and it is unlikely consuming seaweed could cause health issues related to chronic thallium exposure. However, the reported higher levels of thallium in Ulva species (Ollson et al., 2020b; Parus & Karbowska, 2020) are a concern. Consuming 5 dry g of Ulva intestinalis at the maximum concentration of 13.20mg/kg detected by Olsson et al. (2020b) would be over five times the limit for thallium used in the New Zealand study by Pearson & Ashmore (2020). Therefore, anyone working with Ulva species should carry out independent analysis to characterise the risk of thallium in their end product. Continued research into the toxicity of thallium may also provide more insight into levels that could lead to health concerns (i.e. implementation of a tolerable upper limit by the EFSA).

Bismuth

Natural bismuth contamination in the UK is rare as it generally is only found in rocks at trace levels. Areas with moderate levels are all in England (e.g. Cornwall, Devon, Lake District, Peak District). Anthropogenic sources are linked to combustion of coal and oil, metal production and waste incineration (Table 3.3). Bismuth also is used in small amounts in pharmaceuticals, cosmetics and pigments.

Daily intake in adults according to UK Diet Survey is just 4µg of bismuth (mostly from dairy products and non-alcoholic beverages). The food group with the highest level of bismuth is dairy products (reaching 6µg/kg), but many food and drink products are under 1µg/kg. Bismuth is not included in the monitoring of Scottish bivalves. The trace level of bismuth in food means that it is not considered an element that requires dietary risk assessment and, therefore, no tolerable intake or reference dose is available. Much higher levels can be safely consumed in the form of medicines (i.e. milligrams of bismuth daily).

Bismuth 3 results across all species ΣN=25 from 2 studies	
Minimum	<0.01mg/kg
Median	0.01mg/kg
Maximum	0.02mg/kg
Minimal risk of excess intake via seaweed	

Bismuth is very rarely tested in relevant seaweed species. Kollander et al. (2023) detected 6µg of bismuth per kg of farmed Swedish Saccharina latissima. Bismuth was included in the analysis of 22 samples of Norwegian Saccharina latissima by Niedzwiedz et al. (2024): the maximum level detected was 18µg/kg (in an area by terrestrial runoff).

Assuming a concentration of bismuth in seaweed at 0.1mg/kg in seaweed, a 5 dry g portion would be 0.5µg. This is a negligible amount of bismuth (13% of current dietary intake) and it is unlikely consuming seaweed could cause health concerns.

Beryllium

Beryllium is rarely found in nature. It binds to other minerals in the soil and so does not tend to accumulate in plants. Levels in seawater are also generally very low. There are some rock types that contain enough beryllium to result in detectable levels in groundwater, but these are not a pollution concern. Anthropogenic sources of beryllium include fossil fuel combustion and waste incineration (Table 3.3). Almost all human exposure to beryllium is from occupational settings. Excessive oral intake of beryllium can have gastrointestinal health impacts, but dust inhalation is far more hazardous.

The EFSA has not assessed a safe intake level for beryllium, largely because it is rarely found in the environment. Adequate toxicological data does not exist for beryllium. Similarly, the WHO determined that there is insufficient evidence to set an upper intake level for beryllium. The US EPA published in 1987 an oral Reference Dose (RfD) for beryllium: 2µg per kg body weight. This is equivalent to a daily intake of 0.14mg in a 70kg adult.

Beryllium is not included in the UK Diet Survey and not measured in Scottish bivalves. In Italy, Filippino et al. (2020) found the highest median levels of beryllium in chocolate (0.51µg/kg) and legumes (0.34µg/kg), with median daily intake of 0.24µg (mostly from vegetables, cereals and beverages).

There are few reported concentrations of beryllium in relevant seaweed species, but levels are generally low (median: 0.01mg/kg). Biancacci et al. (2012) included beryllium in their analysis of seasonal variation in Scottish Osmundea pinnatifida. While the reported maximum level was 77.4mg per kg, review with the authors determined that the level measured was 77.4µg per kg. Squadrone et al. (2018a,b) carried out comprehensive analysis of trace elements in seaweed in the Mediterranean, including areas with pollution concern. The maximum level of beryllium detected was 0.70mg/kg, in a brown seaweed (highest in green seaweeds: 0.55mg/kg; highest in red seaweeds: 0.19mg/kg). The results were not included in the literature review because none of the 14 species are relevant to commercial seaweed in Scottish waters, but they demonstrate that seaweed can contain elevated levels of beryllium in contaminated seas.

Beryllium 4 results across all species ΣN=88 from 4 studies	
Minimum	<0.01mg/kg
Median	0.01mg/kg
Maximum	0.08mg/kg
Minimal risk of excess intake via seaweed	

Even assuming a high concentration of beryllium at 0.5mg/kg in seaweed, a 5 dry g portion would be 2.5µg. This is likely to be more than the current dietary intake, but it is 2% of the Reference Dose issued by the US EPA. Therefore, it is unlikely that consuming seaweed will result in an intake of beryllium at a level to cause health concerns.

Antimony

Antimony is one of the pnictogen or Group 15 elements, along with arsenic and bismuth. Antimony is rarely found in naturally occurring deposits in the UK, although some minor deposits are seen in Dumfries and Galloway. The metal has a wide range of applications (e.g. pigments, medicines), but the main uses are flame retardants and formation of alloys with unique properties (e.g. in lead-acid batteries). Sources of contamination include roads (from brake wear), metal production and incineration (Table 3.3). Food safety concerns generally relate to migration of antimony from food-contact materials, especially polyethylene terephthalate (PET) plastics used for liquids. Antimony is used as a catalyst during manufacturing, with traces remaining in the finished PET polymer that can leach back into the product.

Health concerns from dietary antimony focus on chronic, cumulative exposure rather than acute toxicity. Higher exposures have been associated with gastrointestinal irritation and systemic effects in animal studies, and antimony trioxide is classified as a possible human carcinogen by some agencies. The tolerable daily intake proposed by the WHO is 6µg antimony per kilogram of body weight, approximately 0.42mg per day for an adult.

Regulatory limits are designed to minimize health risk. For example, EU and U.S. drinking-water standards typically set limits near 5–6 µg/L of antimony, and specific migration limits for food contact materials (e.g., PET) are often around 40 µg/kg food. Typical everyday exposures from bottled beverages are far below these limits and well under established tolerable daily intake values, but factors like storage at high temperatures, extended durations, or poor packaging quality can increase migration.

Daily intake for UK adult according to UK diet survey is 2µg of antimony (mostly from non-alcoholic beverages, condiments, alcoholic beverages and cereals). This is comparable to the 3µg daily intake in Italy estimated by Filippini et al. (2020). Upper bound concentrations of antimony in UK food are low (e.g. 1µg/kg in fruit and vegetables; 3µg/kg in cereal and meat products; 5µg/kg in bread).

Antimony is rarely tested in the relevant seaweed species (detected in 3 studies in 2 species across 3 countries). The most comprehensive analysis is by Niedzwiedz et al. (2024) on 51 samples of Norwegian Saccharina latissima. Maximum levels reached 13µg/kg in a control area, 40µg/kg by glacial runoff and 112µg/kg by terrestrial runoff.

Assuming antimony concentrations can reach 0.1mg/kg in seaweed, a 5 dry g portion would be 0.5µg (25% of current intake in the UK; 0.1% of the Tolerable Daily Intake proposed by the WHO). Therefore, there is no practical risk of excessive antimony intake from seaweed.

Antimony 4 results across all species ΣN=72 from 3 studies	
Minimum	0.01mg/kg
Median	0.02mg/kg
Maximum	0.11mg/kg
Minimal risk of excess intake via seaweed	

Uranium

Uranium is best known for its role in the nuclear industry. However, naturally occurring uranium-238 has low radioactivity and must be enriched once imported into the UK. These contamination risks are heavily regulated and falls under assessment of radionuclides for the purposes of this review. Uranium can be found in trace concentrations in rocks and soils in the UK. Granitic and igneous rocks are the most important natural source; uranium is more likely to be detected in Cornwall, Devon and Aberdeenshire. There are limited sources of contamination in the UK (Table 3.3). Phosphate rocks contain traces of uranium, which means that uranium can sometimes be found in effluents and wastes from fertiliser and chemical works. Uranium mining in the UK has never been at a large scale, with limited small-scale historic production in Cornwall. Uranium can be found in coal, with combustion releasing uranium into the environment.

Health concerns from naturally occurring uranium are linked to its behaviour in soluble form as a heavy metal, but is considered less toxic than cadmium, mercury and lead. Ingested uranium will accumulate in the kidneys, leading to damage. The tolerable daily intake established by the WHO is 0.6μg uranium per kilogram of body weight in relation to effects on kidney function. This was endorsed by the EFSA in 2009 and is equivalent to intake of 0.042mg per day for an adult.

Uranium is not included in the UK Diet Survey. Filippini et al. (2020) estimated daily intake of uranium in Italy is 0.8μg, with median levels in food and drink generally low (e.g. 0.8μg/kg in fish and seafood, 0.5μg/kg in cereals).

Uranium 4 results across all species ΣN=69 from 4 studies	
Minimum	0.06mg/kg
Median	0.16mg/kg
Maximum	0.34mg/kg
Minimal risk of excess intake via seaweed	

Uranium is more commonly tested in radionuclide assessment of seaweed, but there are a handful of studies measuring concentrations in the relevant seaweed species (dataset includes 4 studies in 3 species across 3 countries). The highest mean concentration of uranium was detected in French Ascophyllum nodosum by Barrat et al. (2024): 0.34mg/kg. The average level of uranium across five species tested in the Forth Estuary and Firth of Forth by Ownsworth et al. (2019) was 0.38mg/kg, with a maximum concentration of 0.81mg/kg in a sample of Fucus vesiculosus (this study is not included in the dataset as the paper does not supply sufficient detail to warrant inclusion).

Given the limitations of the dataset, it is helpful to consider the research carried out by Sim et al. (2024). Their analysis of Icelandic seaweed included many relevant species, but the results were presented by groups. The maximum level of uranium detected in any sample was 1.9mg/kg (in an unspecified brown seaweed). In their analysis of trace elements in contaminated areas of the Mediterranean seaweed, the highest level of uranium found by Squadrone et al. (2018a,b) was 5.3mg/kg (in a species of brown seaweed).

It is evident that uranium levels can be higher in seaweed than other foods. At a concentration of 5mg/kg in seaweed, a 5 dry g portion would result in intake of 25μg of uranium. This would be 60% of the Tolerable Daily Intake (WHO, EFSA). However, this level is an order of magnitude higher than the maximum level in the dataset. Overall, it is unlikely that seaweed consumption could lead to excessive intake of uranium. However, it is important to caveat this characterisation with the uncertainty caused by the limited testing.

Rare earth elements

The nature of contaminant testing means a wide array of elements are detected in seaweed at trace levels. Rare earth elements (REEs) are a group of 17 metals with similar characteristics (e.g. neodymium, cerium, europium, lanthanum, scandium, yttrium). Seaweed is known to accumulate REEs at concentrations much higher than seawater, which makes seaweed a useful indicator of these trace elements. Other sets include platinum group elements (PGEs; e.g. platinum, iridium, osmium, ruthenium, rhodium, palladium) and actinides (e.g. actinium, thorium, protactinium). There are few such elements with characterised toxicological risks.

Kollander et al. (2023) tested three species of seaweed as part of a wider set of foods in Sweden, detecting 74 different elements. Barrat et al. (2024) included REEs in their analysis of Ascophyllum nodosum in France, finding a positive correlation with abundance of iron. Niedzwiedz et al. (2024) detected a variety of trace elements in their analysis of Saccharina latissima in Svalbard, Norway. Many of the rarer elements are found at very low levels in seaweed (i.e. <0.01mg/kg). Studies often omit such elements from analysis as they are below the limit of detection (e.g. hafnium, tantalum and ruthenium by Wegeburg et al., 2023). One of the few studies to detect rarer elements at levels above 1mg/kg is Olsson et al. (2020b), where Ulva intestinalis was sampled around Sweden. Barrat et al. (2024) demonstrated that REEs were higher upstream in a French estuary and so it is likely that accumulation corresponds to local pollution. The capacity of seaweed to absorb trace elements has led to proposals to use seaweed-based technologies to treat toxic waste water (e.g. Viana et al., 2024).

Generally, it is unlikely that rare elements such as REEs and PGEs represent a food safety issue in seaweed. The toxicity of most rare elements is unclear. However, this is an expanding area of research that must be kept under review.

7. ANTHROPOGENIC COMPOUNDS

In the marine environment, a range of anthropogenic contaminants arise from agricultural, industrial and urban activities across coastal catchments. Substances such as pesticides and polychlorinated biphenyls enter coastal waters via rivers, wastewater treatment works, run-off and atmospheric deposition. Many of these compounds are persistent and hydrophobic. This can lead to accumulation in marine sediments and uptake by biota. Harmful compounds can also be inadvertently generated during processing (e.g. glycidyl fatty acid esters). There are also anthropogenic contaminants that can originate from both environmental sources and material processing (e.g. polycyclic aromatic hydrocarbons).

Halogenated POPs

Halogenated persistent organic pollutants (POPs) are a group of long-lasting environmental contaminants that have attracted increasing attention due to their bioaccumulation potential Their toxicological profiles raise concerns for long-term health effects.

Dioxins and PCBs

Dioxins and polychlorinated biphenyls (PCBs) are persistent organic pollutants that can accumulate in the food chain and pose potential health risks to humans. Their lipophilic nature means they persist in fatty tissues These compounds are highly stable and resist environmental degradation, meaning they can remain in ecosystems for long periods.

Generally, dioxins and PCBs are primarily ingested through animal-based foods such as meat, dairy, fish and seafood. Because they accumulate in fatty tissues, foods with higher fat content tend to have higher concentrations. Long-term exposure, even at low levels, has been associated with a range of adverse health effects (e.g. disruption of the endocrine system, impaired immune function, increased cancer risk).

Dioxins are mainly by-products of industrial processes and combustion; they are not intentionally produced. Key contributors include waste incineration, household fuel burning, fossil fuel combustion and metal production. These processes release dioxins into the atmosphere, which then deposit onto land and water surfaces and are washed into rivers and coastal seas. PCBs were widely used in the UK until bans in the 1980s (e.g. electrical equipment, lubricants, building materials). Unfortunately, they persist in old infrastructure, landfills and contaminated soil. Dioxins include polychlorinated dibenzo-p-dioxins (PCDDs).

Importantly, dioxins and PCBs are hydrophobic and bind to particles. They accumulate in sediments, which then act as long-term reservoirs. Disturbance – either naturally during storms or during human activity like dredging – can remobilise these pollutants into the water column. In UK coastal areas, it is important to pay attention to nearby shipyards, waste disposal sites and industrial activity.

In most cases, the risk of dioxin and PCB contamination in seaweed will be low. This is partly because seaweed absorbs pollutants directly from water. Seaweed contaminated with sand may be more at risk given potential for dioxins and PCBs to persist in sediment. Furthermore, the fat content of seaweed is low and this restricts accumulation of fat-soluble compounds like dioxins and PCBs.

Table 7.1: Maximum values for feed materials of plant origin in Europe (relative to feed with a moisture content of 12%).

Category	Maximum limit for feed
Sum of dioxins	0.75ng/kg
Sum of dioxins and dioxin-like PCBs	1.25ng/kg
Sum of non-dioxin-like PCBs	10μg/kg

The main concerns for dioxin and PCB exposure are meat, seafood and oils. The EU sets maximum levels (MLs) to protect public health, but they are almost exclusively for animal products (Regulation No 2023/915 and amendments; 4.1). Specificallly, they are for i) the sum of dioxins, ii) sum of dioxins and dioxin-like PCBs and iii) sum of non-dioxin-like PCBs per gram of fat. There are MLs in place for animal feed in the EU (Directive 2002/32/EC; Table 7.1).

Seaweed is rarely included in monitoring programs. One of the few studies to assess the content of dioxins and PCBs in a relevant seaweed species is Hahn et al. (2022), where Fucus spiralis from three sites on the Pacific coast were analysed. Samples contained a sum of 40 PCBs at a median concentrations of 4-14μg/kg dry weight (depending on approach to calculation) and a sum of PCDDs/furans at a median concentration of 0.4ng/kg dry weight. Hahn et al. (2022) attempted to compare levels with others published in the literature, but there were few relevant studies available. Banach et al. (2020) included dioxins and PCBs in their review of food safety in European seaweed, concluding that there was limited data available for assessment.

Brominated flame retardants

Brominated flame retardants (BFRs) are persistent, bioaccumulative chemicals with a similar risk profile to dioxins and PCBs. Historically, BFRs were added to various consumer products to reduce flammability (e.g. textiles, electronics). Examples include polybrominated diphenyl ethers (PBDEs), traces of which are released from wastewater systems and contaminated urban environments.

Again, Hahn et al. (2022) is a rare study to include assessment of BFRs. Samples of Fucus spiralis contained a sum of PBDEs at a median concentration of 1.9μg/kg dry weight. However, seaweed is known to metabolise halogens and naturally generate organobromines. Leri et al. (2019) quantified organobromine compounds in Scottish seaweed and postulated the vast majority were of natural origin. In their assessment of food safety hazards in European seaweed, Banach et al. (2020) concluded that there was limited data to assess BFRs.

Perfluoroalkyl substances

Per- and polyfluoroalkyl substances (PFAS) are a group of thousands of persistent chemicals that can accumulate in the environment and enter the food chain. In seafood, PFAS are a cause for concern due to accumulation in aquatic ecosystems and concentration in biota over time.

Regular consumption of PFAS-contaminated food is associated with increased cholesterol levels, reduced immune system effectiveness and disruptions to hormone function. There is also evidence linking long-term exposure to a higher risk of cancer and developmental issues. The strong chemical bonds in PFAS mean they break down very slowly. They can remain in both the environment and the human body for years. Even low dietary intake can contribute to these adverse health outcomes. Food packaging and cookware coatings are also relevant sources. Watercourses can also be contaminated from industrial discharges, the use of fire-fighting foam (e.g. at airports) and the application of sewage sludge to land.

The EU sets maximum levels for PFAS to protect public health, but they only cover animal products (Regulation No 2023/915 and amendments; 4.2). Limits are stated for perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA) and perfluorohexane sulfonic acid (PFHxS), plus the sum of PFOS, PFOA, PFNA and PFHxS. Although there are no limits specified for seaweed, there are limits seafood (bivalves and crustaceans: 5μg/kg for sum of the four PFAS; wet weight basis).

Seaweed has the potential to accumulate PFAS, although there has been limited research to date. Ford & Ginley (2024) sampled Fucus vesiculosus by a discharge pipe for water treatment works on the south coast of England. Four different PFAS compounds were detected at quantifiable levels (highest average at 7.0μg/kg). In their analysis of samples from the German Environmental Specimen Bank, Kotthoff et al. (2020) found the sum of PFAS in Fucus vesiculosus 3.5μg/kg. Suther (2024) included PFAS in an analysis of seaweed from the Salish Sea on the Pacific coast of the US. Seventeen different PFAS compounds were detected. The only samples with quantifiable PFOA and PFOS were all Ulva species.

As global consumption of seaweed increases, improved monitoring, regulation and risk assessment of PFAS contamination in marine food systems will become increasingly important. Horizon scanning is critical for identifying emerging PFAS contamination risks in seaweed.

Polycyclic aromatic hydrocarbons

Seaweed is susceptible to contamination by polycyclic aromatic hydrocarbons (PAHs). PAHs are considered non-alkylated if they consist only of fused aromatic rings without side chains. Alkylated PAHs have one or more side chains. Non-alkylated PAHs are the parent structures most often specified in regulations. Table 7.2 summaries the two categories of PAHs, which have different sources and characteristics relevant to seaweed contamination. Non-alkylated PAHs originate primarily from incomplete combustion of organic material (e.g. fossil fuels, wood), whereas alkylated PAHs come from petroleum-related sources (e.g. fuel spills, shipping activity, urban runoff, industrial discharges). It is possible to find elevated levels of PAHs in coastal and nearshore environments, particularly those adjacent to ports, sewage outfalls, rivers and urban areas. PAHs do not generally biomagnify to the same extent as some persistent organic pollutants. Instead, they are indicative of local pollution.

Seaweeds can absorb PAHs dissolved in seawater and via particulate matter adhering to their surfaces. Contamination risk is highest in seaweed collected from industrialised or urban coastal areas, whereas seaweed from less impacted shoreline typically contain much lower PAH levels. Although PAHs are frequently tested in seafood, analysis of PAHs in seaweed is less common.

A minor spill of marine fuel oil occurred off the west coast of Sweden in April 2022. The spilled oil was difficult to recover, ultimately depositing on coastline along the archipelago outside Gothenburg. Seaweed – Fucus serratus and Fucus vesiculosus – was sampled at nearby locations 19 days after the spill and analysed for PAH content by Pålsson et al. (2024). An extensive range of compounds was analysed to cover the variety of hazardous substances present in oil. Concentrations of non-alkylated PAHs in seaweed from a heavily affected site were high (benzo[a]pyrene: 660µg/kg wet weight; fluoranthene: 400µg/kg wet weight). Levels of alkylated PAHs were approximately three times higher. All the levels in seaweed were an order of magnitude higher than those in oysters at the same site. All concentrations were low or zero in seaweed harvested from less affected coastline.

Table 7.2: Comparison of non-alkylated PAHs and alkylated PAHs, with relevance to seaweed

	Non-alkylated PAHs	Alkylated PAHs
Primary source	Incomplete combustion of organic material (vehicle exhaust, fuel burning, wildfires)	Crude oil and petroleum products (diesel spills, harbour activity)
Characteristics	More water soluble, quicker degradation	More hydrophobic, persisting longer
Examples	Napthalene, Phenanthrene, Benzo[a]anthracene, Benzo[b]fluoranthene Benzo[a]pyrene, Chrysene	1-Methylphenanthrene, Dimethylfluorenes, C2-Dibenzothiophenes Methylchrysene
Regulatory focus	High	Low
Relevance to seaweed	Medium	High

Knøfler et al. (2024) analysed the PAH content of unspecified species of Fucus in the Faroes. The highest levels were found in seaweed from Tórshavn harbour: total non-alkylated PAH levels were 170µg/kg wet weight (phenanthrene at 94µg/kg, pyrene at 47µg/kg, fluorene at 23µg/kg) and total alkylated PAH levels were 1,900µg/kg (alkyl naphtalene, C1-C4 at 980µg/kg; alkyl phenanthrene, C1-C4 at 490µg/kg; alkyl fluorene, C1-C4 at 360µg/kg). In contrast, barely any PAHs were detected at the unpolluted reference site at Kirkjubøur.

Soares et al. (2021) analysed PAHs in seaweeds from northern Portugal, including Ascophyllum nodosum, Fucus vesiculosus, Fucus spiralis, Chondrus crispus, Porphrya spp. and Ulva spp. Levels were generally low, with no detected level for 78% of combinations of seaweed and PAH. Seven different PAHs were detected (pyrene, benzo[a]pyrene. acenaphthene, naphthalene, fluorene, phenanthrene, c + Benzo[j]fluoranthene). However, the highest level for any combination of seaweed and PAH was just 2.9µg/kg dry weight (pyrene in wild Porphyra spp.). Soares et al. (2021) noted the relatively remote location of the sample sites.

It is clear that PAHs can be detected in seaweed suspected to be contaminated, whereas there is near-absence in unpolluted locations. Levels of alkylated PAHs associated with contaminated seaweed are substantially higher than non-alkylated PAHs. However, it is important to note that regulation around PAH levels is linked to incomplete combustion of organic matter during grilling or smoking of food products. The EU sets maximum levels for PAHs in various foods to protect public health (Regulation No 2023/915 and amendments) under process contaminants (5.1). These limits are only for non-alkylated PAHs (i.e. products of combustion, not petrogenic contamination). Limits are stated for benzo[a]pyrene and the sum of 4 non-alkylated PAHs (benzo[a]pyrene, chrysene, benzo[b]fluoranthene, benzo(a) anthracene). There are no limits specified for seaweed, although there are relevant limits for food supplements containing botanicals and powders of plant origin for beverages (both 10 & 50µg/kg). Parallel products include dried herbs and dried species (both 10 & 50µg/kg), which are higher than the specified limits in place for other foods (e.g. oil, smoked meat and fish, bivalve molluscs and cocoa).

Banach et al. (2020) include PAHs in their food safety assessment food safety and concluded studies showed concentrations in seaweed not of concern for human health. More recent analysis of seaweed shows that levels of PAHs will likely be below regulated limits in areas with low contamination risk. However, levels may be above regulated limits if seaweed is harvested from polluted coastline. This underscores the importance of harvest area selection and routine monitoring. Overall, the risk of PAH contamination in seaweed is site specific but likely to be minimal if harvesting in a low risk area.

Other contaminants

3-monochloropropane-1,2-diol (3-MCPD)

3-monochloropropane-1,2-diol (3-MCPD) is a small chlorinated organic compound (C3H7ClO2), existing as free 3-MCPD or 3-MCPD fatty acid esters. Health concerns of acute exposure include kidney damage and male fertility. It is not intentionally added to food. Instead, 3-MCPD is formed when fats and oils are heated in the presence of chloride ions. Refined vegetable oils and processed goods using vegetable oils are at risk of containing 3-MCPD (e.g. margarine, baked goods). Soy sauce carries a 3-MCPD risk because some manufacturing methods combine acid hydrolysis, salt, fat and heat.

There are no relevant limits in place in Regulation No 2023/915 and amendments for 3-MCPD in seaweed. The production process of soy sauce means that there is a limit in place (5.2). Limits exist for levels of 3-MCPD (the sum of 3-MCPD and 3-MCPD fatty acid esters) in vegetable oils (5.3). This includes a limit of 2,500µg/kg for oils of marine origin (5.3.1.2).

There is no apparent testing of 3-MCPD in seaweed. Beeken et al. (2022) anlaysed MCPD esters in purchased food supplements made using oils derived from fish, krill and microalgae. All levels in the algal oils were substantially lower than the fish oil and not of concern for human health. While processed seaweed-derived oil could theoretically contain 3-MCPD, lipid levels in Scottish species are under 10% of dry weight (Badmus et al., 2022). Therefore, it is unlikely that 3-MCPD is a relevant contaminant for seaweed.

Glycidyl fatty acid esters

Glycidyl fatty acid esters (GEs) are a class of process contaminants similar to 3-MCPD esters, in that they are formed when fats and oils are heated at high temperature. GEs are esters formed between glycidol and fatty acids, with the chemical formula dependent on the nature of the fatty acid chain. In the human body they can release glycidol, a compound considered genotoxic.

Refined vegetable and processed goods are the products at highest risk of containing GEs, but marine oils are also at risk. There is a limit in Regulation No 2023/915 and amendments for 3-MCPD in place for vegetable oils and fats, fish oils and oils from other marine organisms of 1,000µg/kg (5.4.1).

Beeken et al. (2022) included GEs in their analysis of marine oil food supplements. As for 3-MCPD, levels of GEs in food supplements made using oils derived from microalgae were lower than those from fish oil. Overall, it is unlikely that GEs are a relevant contaminant for seaweed.

Nitrates and nitrites

Concerns about nitrate contamination in food relate to the convertion in the body to nitrite, which in turn can result in negative health impacts (e.g. oxygen transport in the blood, formation of potentially carcinogenic substances). In the EU, nitrate is already regulated under Regulation (EU) 2023/915 in certain high-risk foods (e.g. leafy vegetables). These limits reflect the fact that plants can accumulate nitrate from soil and fertilisers.

Seaweeds absorb dissolved nitrogen compounds from marine environments, particularly in areas affected by agricultural runoff or wastewater discharge. Casas-Agustench et al. (2024) measured nitrate and nitrite in commercial seaweed products available in the UK (originating from Scotland, England, Northern Ireland, Ireland, Spain and Japan). The nature of the study makes it difficult to draw strong conclusions on species variation, but the mean level of nitrates in Japanese nori was 17,191mg/kg. Mean levels of nitrates were lower in European seaweed (57-4,475mg/kg). The consumption of 5g of dried seaweed from Europe would be 0.1-6.1% of acceptable daily intake (259mg/day for a 70kg adult). Nitrite levels were lower (maximum mean level of 3.6mg/kg), with 5g at most 0.4% of acceptable daily intake (4.9mg/day for a 70kg adult).

Nitrate levels in seaweed can vary depending on harvesting location and environmental conditions. However, controls implement to limit wider contamination risks mean nitrates in seaweed are generally not considered a food safety risk.

Melamine

Melamine is a nitrogen-rich organic compound manufactured for use in resins, adhesives, coatings, treatments and flame retardants. It can also form as a degradation product of cyromazine (a veterinary and agricultural insecticide) and cleaning agents. Melamine is associated with serious health effects, primarily involving the kidneys and urinary tract. The deliberate addition of melamine to infant formula in China – a scandal exposed in 2008 – triggered assessment in the EU and specific import controls that were later codified into law. In the UK and EU, maximum levels are set at 2.5 mg/kg for most foods (Regulation No 2023/915, 6.2.1).

There are no reports of melamine detection in seaweed. Scientific studies on composite materials have incorporated seaweed into melamine-derived polymers. However, these are engineering and remediation studies unrelated to food risk assessment. It is unlikely that there is any risk of melamine contamination in seaweed.

Perchlorate

Perchlorate (ClO_4^-) is a highly water-soluble anion that can contaminate food through environmental sources (e.g. industrial emissions, fertilisers) and via food processing (e.g. use of hypochlorite disinfectants). Disinfection by-products are likely to be the more relevant source for seaweed. Perchlorate can block iodide uptake and lower circulating levels of thyroid hormones. Maximum levels are set in EU law at 0.75mg/kg for ingredients used for herbal infusions (Regulation No 2023/915, 6.3.2).

Seaweed has been shown to bioconcentrate perchlorate from seawater (Martinelango et al. (2006). Perchlorate has been detected in the main three species of seaweed consumed in Korea (Yang et al., 2014), with a maximum level of 0.62mg/kg DW in Saccharina japonica. However, appropriate processing controls (e.g. rinsing surfaces) should minimise risk of perchlorate contamination. It is worth noting that perchlorate can be detected in seaweed extracts produced using sodium hypochlorite (Li et al, 2025). However, this is not relevant to the processing of whole seaweed.

Pesticides

Environmental contamination by pesticides has widespread implications for biodiversity and human health. Intensive use in agriculture, urban pest control and amenity management has led to the persistent presence of pesticides in soil, water and non-target organisms. Robust regulatory frameworks governing pesticide approval and use are in place. Nevertheless, environmental residues of both legacy and currently authorised compounds are detected in monitoring programmes. A wide range of chemicals are used as pesticides and there can be overlap with other contaminant categories (e.g. cyromazine and melamine). Understanding the extent of pesticide application in Scotland is therefore critical for informing risk assessment at a local level.

Agricultural use in Scotland

The Scottish Government publishes statistics on pesticide usage in Scotland, with reporting frequency varying according to crop type. Across all categories, approximately 1,500 tonnes of pesticides are applied every year in Scotland. Almost all of this volume is applied to arable crops (~90%), simply because cereals, potatoes and oilseeds account for the majority of Scottish agriculture. Pesticide applications and contamination risks of different crops are given in Table 7.3.

Overall, fungicides are the most widely used chemical treatment in Scotland, both by treated area and quantity applied. Approximately 50% of pesticides applied to crops in Scotland by weight in 2024 were fungicides. The two principal fungicides used in Scotland are folpet (388 tonnes applied to arable crops in 2024) and prothioconazole (224 tonnes applied to arable crops in 2024). Most of the pesticides used on potatoes are fungicides to control blight, which are applied across around a dozen treatments during the growing cycle. Important fungicides for potatoes are cymoxanil (82t applied in 2024) and macozeb (81t).

Table 7.3: Applications of pesticides on different crops in Scotland and overall contamination risk.

Crop	Pesticide usage[a]	Annual applications	Fungi-cides	Herbi-cides	Insecti-cides	Contamination risk
Potatoes (seed and ware)	305 tonnes on 7,340km^2 in 2024	0.34-0.47kg/Ha (11-13 treatments)	✷✷✷		🕷🕷	High (moderate usage and large area)
Cereals (barley, wheat, oats; spring & winter)	900 tonnes on 39,330km^2 in 2024	0.21-0.32kg/Ha (3-5 treatments)	✷✷✷	✿✿	🕷	Moderate (low usage, but large area)
Oilseed rape (spring & winter)	95 tonnes on 3,330km^2 in 2024	0.28kg/Ha (6 treatments)	✷✷	✿✿✿	🕷	Moderate (moderate usage and area)
Grassland and rough grazing	67 tonnes over 810km^2 in 2021	0.83kg/Ha		✿✿✿		Moderate (usage is high, but small area)
Soft fruit (strawberries, blackcurrants)	26 tonnes over 380km^2 in 2024	0.36-0.77kg/Ha (8-20 treatments)	✷✷	✿	🕷🕷🕷	Moderate (usage can be high, but small area)
Outdoor vegetables	61 tonnes over 1,660km^2 in 2023	0.23-0.54kg/Ha (2-14 treatments)	✷✷✷	✿✿	🕷	Low (usage can be moderate, but small area)
Fodder crops (e.g. turnips)	10 tonnes over 251km^2 in 2021	0.40kg/Ha	✷✷	✿✿✿	🕷	Low (usage is moderate, but small area)

[a] In most recent year for which data was published

Herbicides are the next most important category of pesticides in Scottish agriculture, especially on cereals and oilseeds. The key herbicides are glyphosate (151t applied to arable crops in 2024), metsulfuron-methyl (109t) and fluroxypyr (107t). Growth regulators are also widely used, especially in cereals (e.g. 54t of chlormequat applied in 2024). The term insecticide is in common use and generally includes chemicals specifically targeted at other invertebrate groups (e.g. molluscicides, nematicides, acaricides). The most widely used insecticide is the synthetic pyrethroid lambda-cyhalothrin (44t applied in 2024). A small proportion of pesticide usage is in seed treatments.

Pesticide testing typically covers hundreds of individual chemicals. If exactly the same material is sent in two different years, the list of pesticides in the analysis will likely change. The list of pesticide treatments used in Scotland is continually expanding: five new substances were recorded in the most recent arable crop survey (2024). Frequently used pesticides on Scottish crops are given in Table 7.4: these may be the more likely residues detected if seaweed is contaminated with agricultural runoff.

Uses beyond terrestrial agriculture

While the reporting framework for agricultural application is robust, pesticides are also applied in a variety of other settings.

Pesticides are applied to control weeds and mosses in public spaces (e.g. parks, pavements, road verges, sports pitches). Herbicides are the most commonly used chemicals in these settings, especially glyphosate-based products. Similarly, pesticides are sometimes used in conservation and biosecurity efforts, such as controlling invasive plant species (e.g. Japanese knotweed) or managing non-native pests. These applications are typically targeted and regulated but may still have local environmental impacts.

Pesticides are used in gardens, homes and allotments. This includes a variety of insecticides fungicides and herbicides (e.g. insect sprays, slug pellets, lawn treatments, wood preservatives, flea treatments). Insecticides are applied to control pests that pose risks to human health (e.g. rodents). These uses are particularly important in urban environments, waste management facilities, and food-handling premises. Golf courses apply herbicides for weed control (e.g. fluroxypyr, mecoprop-P) and fungicides for disease management (e.g. azoxystrobin, mefentrifluconazole).

Certain pesticides are used to protect materials and structures. This includes herbicides to control vegetation on railways and powerlines, antifouling biocides on boats and marine structures, treatments in industrial water systems and wood preservatives to prevent fungal decay. Chemotherapeutants are used to control pests in salmon farms in Scotland (e.g. emamectin benzoate, cypermethrin, deltamethrin and azamethiphos.

Although non-agricultural pesticides in the UK are regulated under the same approval framework as agricultural applications, they are often more spatially dispersed and closely linked to urban drainage systems.

Pesticide residues in seaweed

Seaweeds are studied as bioindicators of pesticide contamination because they absorb chemicals from surrounding water and sediment, reflecting the presence of historic and contemporary residues in coastal environments. A recent review summarised global patterns of pesticide residues in seaweed reported between 2015 and 2024 (Zilto-Azevedo et al., 2026). Only 12 studies met the inclusion criteria, meaning only 21 species were covered. None of the studies were of European or Atlantic species. The only two relevant species of seaweed were Fucus spiralis from the Pacific coast of North America and Ulva lactuca from India.

Table 7.4: Examples of pesticides applied to crops in Scotland

	Chemical	Treated crops: Potatoes	Cereals	Oil-seeds	Grass-land	Soft fruit	Outdoor vege-tables	Fodder crops
Fungicides	Folpet	✓	✓					
	Prothioconazole		✓	✓	✓			✓
	Tebuconazole		✓					
	Cymoxanil	✓						
	Cyazofamid	✓						
	Dimoxystrobin			✓				
	Mancozeb	✓						
	Boscalid					✓		
	Pyraclostrobin					✓		
	Azoxystrobin						✓	
Herbicides	Glyphosate		✓	✓				
	Fluroxypyr		✓	✓	✓			
	Metribuzin	✓						
	Metsulfuron-methyl			✓				
	Difluffenican		✓					
	Pendimethalin					✓	✓	
Insecticides	Lambda-cyhalothrin	✓		✓			✓	
	Pirimicarb						✓	
	Esfenvalerate	✓						
	Spirotetramat					✓		
Growth regulators	Chlormequat		✓					
	2-Chloroethyl-phosphonic acid		✓					

Organochlorine pesticides are notoriously long-lasting and were frequently detected, indicating a legacy of persistent contamination. It is clear that more research is needed to create standardised analysis and cover more species.

A recent study of Korean seafood by Kim et al. (2025) found that seaweed had the highest pesticide detection rate of the categories tested (none in cephalopods; only in shrimp in crustaceans; only in abalone and clams in molluscs). Estimated residue intake levels were calculated using average seafood consumption and found to be under 0.7% of acceptable daily intake for all samples. Despite Koreans having a relatively high dietary intake of seaweed (Park et al. 2022), pesticide residues pose a low risk to human health.

Although pesticide traces are commonly cited as a food safety hazard (e.g. Banach et al., 2020), levels are less well characterised in European seaweed. One of the few relevant studies is Pinto et al. (2014), where a range of pesticides were detected in Ulva sp. collected in Portugal, up to a maximum of 11μg/kg (lindane). However, this was after heavy rain and no pesticides were detected in a sample collected during the dry summer season. The authors suggest care should be taken when wild seaweeds are harvested after heavy rain.

Limits on pesticide residues

Around 500 active substances are approved for pesticide use under EU Regulation 1107/2009, with the number changing following approvals or withdrawals. European law (EC regulation 396/2005) sets maximum residue limits (MRLs) for pesticide residues in food and feed, including algae and prokaryotic organisms (available in the EU Pesticides Database). The majority of the approximately 500 MRLs set for pesticides for algae are between 0.01mg/kg and 0.1mg/kg (the pesticides with MRLs exceeding 0.1mg/kg are listed in Table 7.5). Under EU law, if a pesticide is not specifically approved for a crop, the default MRL is typically set at 0.01mg/kg (generally, this is the lowest level labs can reliably measure.

Table 7.5: All maximum residue levels (MRLs) for pesticides that exceed 0.1mg/kg in the EU Pesticides Database.

Pesticide	MRL
Phosphonic acid	1.5mg/kg
Furfural	1.0mg/kg
Pyrethrins	1.0mg/kg
Clopyralid	0.5mg/kg
Maleic hydrazide	0.2mg/kg

It is important to recognise that MRLs are not a measure of toxicity. Instead, they are the expected residue level to be expected according to good agricultural practice. Scientific risk assessments determine MRLs, factoring in application methods, controlled trials and toxicological safety. Therefore, MRLs are not uniform across different food products. A pesticide may break down quicker or reside longer on one food than another. Foods consumed in small quantities may have higher MRLs. In addition, accurate detection can sometimes be an issue for various reasons:

- Rapid degradation (e.g. folpet)
- Highly water-soluble (e.g. glyphosate)
- Volatile (e.g. phosphone)
- Present at extremely low levels (e.g. neocicotinoids)

- Food matrices incompatible with analysis (e.g. pyrethroids in fatty foods)

Some of the pesticides listed in Table 7.4 have been detected in non-European seaweed. Azoxystrobin was found in Korean seaweed (Kim et al, 2025) and studies reviewed by Zilto-Azevedo et al. (2026) detected metribuzin, cyhalothrin and permethrin.

Quaternary ammonium compounds

Quaternary ammonium compounds (QACs; sometimes 'quats') are widely used as disinfectants and hygiene chemicals in food production environments due to their effectiveness against bacteria, fungi and viruses. There is a potential food safety risk if residues of QACs or other biocides persist on surfaces after cleaning and sanitising operations. In some respects, QACs could be considered pesticides.

Seaweed is typically washed prior to drying and is at risk coming into contract with QAC residues. This is particularly the case if rinsing is insufficient or application rates exceed recommended concentrations. Persistent QAC residues may lead to chemical contamination of the final product and could present regulatory compliance issues, as some QACs are subject to maximum residue limits or restrictions in food products. The EFSA published an assessment in 2023 on benzalkonium chloride (BAC), didecyldimethyl ammonium chloride (DDAC) and chlorates on fish products in Europe and did not identify any consumer health risk.

Appropriate control measures should include validated cleaning procedures, correct chemical dilution and application, effective rinsing, staff training and routine monitoring to minimise the risk of QAC carryover into seaweed intended for human consumption. However, it is unlikely that traces of QACs in seaweed will be of concern for consumer health.

Recommendations to manage pesticide risks in seaweed

Seaweed should be sourced from locations with low risk of pesticide contamination. In particular, sites should be a distance from salmon aquaculture and freshwater influence (determined according to local setting). Foreshore harvest operations should consider the risks from smaller watercourses. Given Pinto et al. (2014) connected pesticide contamination to heavy rains, it may be necessary to adjust protocols during prolonged rainy weather (e.g. avoid harvesting on the upper shore). If biocidal chemicals cannot be avoided entirely, all factory equipment should be carefully rinsed after the application of hygiene chemicals.

FBOs may wish to consider carrying out pesticide residue analysis in background contamination assessments. If operating in an area with high agricultural land use, it may with worth conducting ongoing monitoring. In the event of a detection, the specific chemical should be researched to determine possible origin (e.g. Table 7.4). Seaweeds may be a viable source of natural herbicides, fungicides and repellents (reviewed by Sekar et al., 2025). It is possible that bioactive compounds naturally present in seaweed could lead to false detections of pesticide residues.

The UK Government carries out monitoring of residues in food, although seaweed is not part of the regime. The primary regulatory assumptions and enforcement systems are founded on misuse of pesticides. This is less relevant to edible seaweed as pesticides are not directly applied. Although the primary concern for seaweed is environmental contamination, MRLs still apply. Analytical techniques continually improve, delivering measurements as low as parts per billion. Therefore, a residue detection does not necessarily mean the product is illegal or unsafe. Detections exceeding MRLs may be reported to the relevant authority and escalated to the Food Standards Agency. A risk assessment would be carried out, which would likely determine that the residue poses little health risk given the amount of seaweed consumed compared to other foods.

Organic accreditation

Any organic accredited seaweed operation will need to take extra steps regarding contamination risk assessment and ongoing monitoring. Any detection of a residue will likely warrant investigation by the organic authority. For most food products, a detection could indicate pesticide application that compromises organic certification. This is unlikely to be the outcome for detection in seaweed as pesticides are not used in production. Nevertheless, the organic authority would likely work through an assessment to determine whether standards have been breached.

8. BIOGENIC TOXINS

Naturally occurring toxins pose a potential risk to human health. Seaweed can act as a substrate for microbial growth when in the water and during processing, creating conditions in which toxin-producing organisms may proliferate.

Mycotoxins

Mycotoxins are toxic compounds produced by fungi (mostly certain mould species) growing on various crops. Their importance in food safety is increasingly recognised worldwide. Hundreds of mycotoxins have been identified: they are ubiquitous, natural substances. Mycotoxins are diverse compounds with varying toxic effects (e.g. cytotoxins, genotoxins, hepatotoxins) causing acute poisoning or long-term issues like immune suppression, cancer and organ damage. Contamination can happen before harvest or during storage. Mould can grow rapidly and produce toxins in optimum conditions, which may not be destroyed during food processing. Many of the concerns around mycotoxins relate to cereals, plus products from animals fed on contaminated grains. Fruits, nuts, herbs and spices can also be infected. Complete and rapid drying prevents mould growth. In contrast, incomplete or slow drying creates warm and moist conditions to support proliferation.

The EU sets maximum levels for mycotoxins in various foods (Regulation No 2023/915 and amendments). A wide range of mycotoxins are covered (patulin, deoxynivalenol, zearalenone, fumonisins, citrinin, ergot compounds), but few have limits of any relevance to seaweed. There are limits in place for alfatoxins in specified dried spices. However, there are general limits for ochratoxin A in dried herbs (10μg/kg; 1.2.5) and dried spices (15μg/kg; 1.2.17) that could be used as a proxy.

The risk of mycotoxins in seaweed is less well characterised than other food safety concerns. There are studies using seaweed as an agent to reduce mycotoxins (e.g. adsorbent, detoxifier). For example, seaweed has also been used in biostimulants to reduce mycotoxin contamination in crops (e.g. Gunupuru et al., 2019). Li et al. (2018) analysed mycotoxins in samples of edible kelp species from China. While many mycotoxins were not detected, compounds of deoxynivalenol were found in the majority of samples.

A Russian research group has analysed mycotoxins from seaweed collected in the White Sea (Burkin et al., 2021; Kononenko et al., 2021, 2022; Burkin & Kononenko, 2023). All the mycotoxins included in the analysis were detected in fucoid wracks, especially Fucus vesiculosus. Only ergot

Table 8.1: Mean levels of ochratoxin A detected in seaweed sampled from the White Sea by a Russian research group

Species	Ochratoxin A
Ascophyllum nodosum	91μg/kg (N=10)[a] 46μg/kg (N=6)[b]
Fucus vesiculosus	200μg/kg (N=10)[a] 900μg/kg (N=7)[b]
Fucus serratus	750μg/kg (N=8)[b]
Pelvetia canaliculata	10μg/kg (N=6)[b]
Laminaria digitata	- (N=9)[b]
Saccharina latissima	- (N=5)[b]
Palmaria palmata	- (N=6)[b]

[a] Kononenko et al. (2022); [b] Burkin & Kononenko (2023).

compounds were detected in Laminaria digitata and Saccharina latissima. Mycotoxins were quantified for several species by Kononenko et al. (2022) and Burkin & Kononenko (2023). The mean levels of ochratoxin A are summarised in Table 8.1. Concentrations exceed the EU limits for dried spices in Ascophyllum nodosum, Fucus vesiculosus and Fucus serratus, with low levels detected in Pelvetia canaliculata. This indicates a particularly association with fucoid wracks, especially as no ochratoxin A was detected in Laminaria digitata, Saccharina latissima and Palmaria palmata. The full list of mycotoxins detected by Burkin et al. (2021), Kononenko et al. (2021, 2022) and Burkin & Kononenko (2023 is: aflatoxin B1, alternariol, citrinin, cyclopiazonic acid, deoxynivalenol, diacetoxyscirpenol, emodin, ergot alkaloids, fumonisins of group B, mycophenolic acid, ochratoxin A, PR-toxin, roridin A, sterigmatocystin, T-2 toxin and zearalenone.

Unfortunately, evidence remains limited on whether mycotoxins associated with seaweed are a significant food safety hazard. While seaweed is not included in EU Regulation No 2023/915 and amendments, quantification by Kononenko et al. (2022) and Burkin & Kononenko (2023) demonstrates that mycotoxins can exceed the limits in place for dried spices. This is specifically the case for fucoid wracks, although the results for seaweed harvested from northwestern Russia should be interpreted with caution. Further research effort should be put into characterising the risk, especially given the importance of drying on fungal proliferation. It may be worth seaweed processors including mycotoxin screening in ongoing monitoring.

Other biotoxins

Unlike mycotoxins, marine biotoxins are generally produced by algae, dinoflagellates, cyanobacteria or associated marine microorganisms. However, there is also a specific risk around kainic acid in Palmaria palmata.

Kainic acid in Palmaria palmata

Although Palmaria palmata has long been regarded as safe for consumption, studies have identified the presence of kainic acid – a naturally occurring amino acid. Kainic acid is structurally analogous to glutamate and acts as a potent agonist of kainate receptors in the central nervous system. In toxicological studies, excessive exposure has been associated with neuroexcitotoxicity and seizure activity in mammals. Although most toxicological data derive from laboratory studies, its presence in edible seaweed has raised regulatory and scientific concern.

A survey of commercially available Palmaria palmata products conducted by Jørgensen and Olesen (2018) detected kainic acid concentrations ranging from trace levels up to approximately 560µg/kg. Earlier studies found higher levels, but it is likely that ordinary dietary consumption of dulse – such as the 5 dry grams assumed in this report – will not result in health issues.

Palmaria palmaria is known to contain kainic acid

Nevertheless, several uncertainties remain around drivers of variation in concentration, effects of processing and viability of possible regulation.

General risks from shellfish-related toxins

Marine biotoxins are more traditionally associated with bivalve shellfish (e.g. mussels, oysters, clams, scallops) that filter seawater and accumulate toxins. However, seaweeds share the same marine environment and may adsorb, accumulate or carry toxin-producing microorganisms on their surfaces. Consequently, seaweed products harvested from affected waters may theoretically serve as vectors for shellfish-associated toxins. The principal shellfish poisoning syndromes relevant to seaweed safety include paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), diarrhetic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP) and ciguatera-related toxins.

Seaweeds are generally considered lower-risk foods for shellfish poisoning because they do not actively filter seawater. Nevertheless, dissolved toxins could adsorb to seaweed or be formed by epiphytes on seaweed. Although documented cases of human poisoning directly attributable to seaweed-mediated transfer of shellfish toxins remain rare, the expanding commercial seaweed industry has prompted increased scientific attention. EFSA and other food safety bodies note that marine biotoxins should be considered within broader seaweed hazard assessment frameworks. This is especially the case where harvesting occurs in regions prone to harmful algal blooms, which includes Scottish coasts (especially during summer months).

Climate change may exacerbate risks around marine biotoxins. Rising sea surface temperatures and eutrophication are associated with expanding range and frequency of outbreaks, especially for toxins linked to dinoflagellates.

Although severe intoxications linked directly to edible seaweed remain uncommon, the combination of increasing commercial production, climate-driven expansion of harmful algal blooms and incomplete regulatory frameworks highlights the need for improved monitoring and risk assessment. In their analysis of cyclic imines – an emergent class of marine biotoxin – Rambla Alegre et al. (2017) detected pinnatoxins on European Saccharina latissima and Laminaria digitata. There is a knowledge gap concerning the accumulation of phycotoxins by seaweeds. It will be important for producers of seaweed to pay attention to scientific literature.

Limits on plant biotoxins

EC Regulation No 2023/915 includes limits for a wide range of biotoxins. These are generally not likely to be relevant to seaweed as they are designed around toxins sometimes detected in terrestrial plants and fungi. Nevertheless, applications for seaweed are included: herbal infusions for tropane alkaloids (2.2) and pyrrolizidine alkaloids (2.4). Therefore, seaweed producers should be mindful of these limits if their products are being used for these applications: customers may require independent testing to demonstrate compliance.

9. ALLERGENS

Food allergens present a significant and well-recognised risk within the food industry, with the potential to cause life-threatening reactions in sensitive individuals. Effective allergen management is a critical component of food safety risk assessment and legal compliance. The hazards around allergen content are intricately linked to sourcing, processing and handling. Therefore, Seaweed Scotland cannot take a position on the allergenic risks of seaweed at a broad scale. However, this section outlines broad considerations around allergens and the key risks associated with allergens in seaweed.

Managing food allergens

While there are many food and drink products that may cause allergies or intolerances, there are 14 groups of products and ingredients listed in Annex II of the EU Food Information for Consumers Regulation (No. 1169/2011; EU FIC). The core requirements of EU FIC were retained in UK law after Brexit: these rules are now within the Food Information Regulations 2014 (as amended). While the items in Annex II are often referred to as the 14 major allergens, some are single ingredients (e.g. 3 - Eggs, 10 - Mustard, 13 - Lupin) and others are defined categories (e.g. 1 - Cereals containing gluten, 8 - Eight named species of nuts). The 14 major allergens must be emphasised within ingredient lists, known as mandatory allergen labelling. It is important to note that there are many other foods that cause allergenic reactions. Sabouraud-Leclerc et al. (2025) analysed allergic responses reported between 2002 and 2023 and identified eight foods frequently implicated but not currently listed in EU FIC. Four were proposed for inclusion: milk from goats/sheep, buckwheat, peas/lentils and pine nut, all of which were more frequently linked to cases than fish. This demonstrates that the landscape for food allergens will evolve over time. Because it is not always possible to predict how severely an individual will react to a given allergen, regulators tend to adopt a precautionary approach.

It is standard practice in food processing facilities to operate a nut-free policy. If nuts – as nuts defined in the EU FIC – are not handled or used as an ingredient, they will generally be banned from the premises. This will extend to where the seaweed is sourced. For example, nuts and products containing nuts should not be consumed on a boat when harvesting seaweed.

A FBO must manage the risk of all allergens on site. Significant attention is paid to allergen risks in food supply chains. Customers buying seaweed for food use will almost always require an assessment of allergen handling on site in addition to status of the product itself. A thorough approach may include listing:

- Allergens present in site production areas (e.g. fish processed in separate area and always kept physically apart from seaweed)
- Allergens used on the same product lines (e.g. fish processed on the same line as seaweed but at different times).
- Allergens stored on site (e.g. contract-manufactured fish sauce containing seaweed warehoused on site).

Failure to demonstrate allergen controls could lead to the product being handled by customers as an allergen, potentially restricting use.

Cross-contamination with major allergens

Seaweed is not included in Annex II of EU FIC, but the animals living on and around seaweed include groups that are:

2 - Crustaceans and products thereof

4 - Fish and products thereof

14 - Molluscs and products thereof

The animals most likely to be present are principally snails (14 - Molluscs) and amphipods (2 - Crustaceans). These are typically small in size (<1cm) and not easily removed from seaweed. Larger animals such as crabs and fish are less likely to reach factory intake and are more likely to be removed during processing (e.g. washing, visual inspection).

Evidence of marine allergens on seaweed

While there are many different allergenic compounds, tropomyosin is the major allergen of concern. Tropomyosin functions as a structural muscle protein in molluscs and crustaceans. It is highly heat-stable and resistant to digestion, which contributes to its clinical significance as a food allergen. Tropomyosins from crustaceans and molluscs share a high degree of structural similarity, leading to frequent cross-reactivity in allergic individuals (i.e. a shellfish allergy sufferer). However, there are minor differences that influence the strength and specificity of immune responses. In general, crustacean tropomyosin is considered the primary sensitising allergen, with mollusc tropomyosin often causing reactions due to cross-reactivity rather than independent sensitisation. These similarities and differences are important in allergen risk assessment, as they underpin both co-allergy risks and the challenges of specific detection and labelling. Fish allergy is driven by a small number of well-characterised proteins, but the primary allergen is parvalbumin. Like tropomyosin, it is highly stable to heat and digestion and is responsible for most reactions and broad cross-reactivity between different fish species. While multiple proteins can contribute, parvalbumin is the key allergen of concern.

Small grazing molluscs – such as the snail Lacuna vincta – settle on cultivated seaweed during spring and are difficult to remove

With increasing use of seaweed as a food and the known risk of cross-contamination, there have been more studies of allergens in recent years (mostly on Norwegian seaweed). Mildenberger et al. (2022) tested crustacean tropomyosin and molluscan tropomyosin in Saccharina latissima grown in integrated aquaculture systems in Norway. The levels for crustacean tropomyosin were up to 1.45mg/kg, which likely relates to increased likelihood of fouling by amphipod crustaceans in farmed seaweed. The content for mollusc tropomyosin were lower (max 0.22mg/kg). Results for parvalbumin were near limit of detection. Mildenberger & Rebours (2024) found that Alaria esculenta and Saccharina latissima farmed in Norway can contain low levels of marine allergens – specifically from crustaceans, molluscs and fish. Furthermore, it is likely these allergens were due to environmental presence rather than deriving from the seaweed itself. Allergen levels varied depending on various factors, with higher levels observed in certain conditions (e.g. later harvesting). Processing methods like blanching and fermentation did not significantly reduce allergen levels. Overall, the highest values detected were 20.6mg/kg of crustacean tropomyosin, 1.8mg/kg of molluscan tropomyosin and 106.5mg of cod equivalents (a metric for parvalbumin). Fassen et al. (2024) detected crustacean tropomyosin in Norwegian Saccharina latissima at 0.56mg/kg and continued to find it at all stages of the production chain (but not in all samples). Banach et al. (2024) showed that tropomyosin varied between batches of culitvated Norwegian Saccharina latissima. The average content was 0.86mg/kg, with the three highest concentrations all from one batch (2.7, 3.0 and 3.3mg/kg). Dong et al. (2025) assessed how pre-treatment and drying methods influence levels of tropomyosin and parvalbumin in Alaria esculenta. Overall, the findings highlight that processing methods can significantly impact allergen presence, and that heat-based drying and ultrasound treatments may be effective strategies for allergen control. However, it is difficult to justify processing methods can eliminate allergen risk.

Precautionary allergen labelling

Although there is a clear risk that allergens can be present, this does not necessarily mean the quantity of allergenic material will be enough to elicit a response in a sensitive individual. Furthermore, overuse of advisory labelling can lead to customer confusion.

The Allergen Bureau's VITAL® (Voluntary Incidental Trace Allergen Labelling) Programme is a scientifically based risk assessment system designed to help food businesses consistently manage unintended allergen cross-contact and determine when precautionary allergen labelling (PAL) is necessary. It uses established reference doses derived from clinical data to define action levels, which are then applied to estimated allergen exposure from a specific food portion size. Based on this assessment, products are assigned to action levels that indicate whether PAL is not required or should be applied. The programme promotes a quantitative, evidence-based approach, supporting clearer communication to consumers while maintaining safety for allergic individuals. The current version of VITAL® is issue 4.0.

Mildenberger & Rebours (2024) determined that the allergens in the studied samples were below critical levels associated with an allergenic risk. Therefore they would not require labelling according to the VITAL® guideline. However, they used VITAL® 3.0 and there are marked changes in the current issue. In particular, the eliciting dose has moved from provoke a reaction in no more than 1% of individuals with allergies up to 5%. This aligns with other international approaches (e.g. FAO/WHO) and does not significantly increase the likelihood of severe outcomes.

Each FBO handling seaweed will need to carry out their own assessment on the need for PAL on their products. However, the new reference doses in VITAL® 4.0 mean that PAL is less likely to be necessary if using this framework.

If a precautionary statement is applied, then it should state that it may contain the allergens of concern (i.e. "may contain traces of molluscs and crustaceans") rather than use generic terms like shellfish. Some seaweed products are labelled with warnings on suitability regarding iodine allergy; such a statement is incorrect and should be avoided.

Allergen free status

Even if a minimal risk of allergenic material has been determined, it does not necessarily mean that a seaweed product can be described as free from that allergen. The unavoidable presence of molluscs and crustaceans around seaweed means that a FBO must be careful to limit use of terms like 'allergen-free'. Products marketed as free from certain allergens will typically undergo additional testing. Status is to some extent determined by the sensitivity of the analysis; methods usually evolve over time and limits of detection improve (see Allergen testing section). It may be possible for a production system to completely eliminate the risk of allergens (e.g. land-based tank cultivation), which could make an allergen-free claim viable.

Allergens within seaweed

Allergenicity is likely linked with proteins within the seaweed itself. However, these are not as well characterised as the allergenic proteins in common foods. Carrageenan (a polysaccharide extracted from red algae) has been implicated in hypersensitivity reactions, although this is rare.

James et al. (2023) reviewed the allergenic potential of seaweed and algal-derived ingredients. A detailed analysis of 33 relevant publications indicated seaweed products may act as potential allergens in humans, with some allergenic components identified. However, there is a lack of data on how common these reactions are in the general population. Therefore, James et al. (2023) conclude that while allergenicity is possible, there is insufficient evidence on prevalence. Kedar et al. (2026) recently published an allergenicity assessment of a species of Ulva from Israel. There were no allergen responses reported among the trial participants, but this is not unexpected in a small screening exercise.

Despite limited research, it is unlikely that there is significant allergenicity associated to seaweed itself. However, FBOs should carry out independent assessment and keep up to date with the science as it develops. Kedar et al. (2026) is likely to be the most up-to-date overview of allergens in seaweed.

Recommendations for allergens and seaweed

All FBOs should take steps to minimise the risk of cross-contamination with major allergens. In many cases, testing is likely to be necessary to provide reassurance to customers.

Minimising cross-contamination

Every effort should be made to minimise cross-contamination. Seaweed can be briefly washed in seawater at the point of harvest. In most cases, washing at the factory will help remove molluscs and crustaceans from seaweed.

Some seaweed will be fouled to the point that it is not practical to remove molluscs and crustaceans. This could be the case of farmed kelp harvested late in the season or for wild seaweed picked from a sheltered shore. Some species will be more prone to fouling. For example, marine snails tend to hide within wracks on the upper shore at low tide.

There should be clear quality controls to manage rejection of fouled material at point of harvest, factory intake and during factory processing. Such quality control checks are standard in a food production system, but particular attention should be placed to degree of fouling.

Recording allergen risk

An allergen risk assessment is required in all food businesses and could be integrated within a HACCP plan. It involves systematically reviewing all raw materials and suppliers for possible allergen contamination (e.g. shared facilities or transport) and assessing risks across product flow (storage, handling and processing). There should also be evaluation of non-standard processes (e.g. rework) or cleaning procedures that could introduce cross-contamination. The overall risk should be assessed, ideally using a framework like VITAL®. Decisions must be evidence-based and proportionate to the actual risk.

Allergen testing

Food allergen detection is most commonly carried out using immunoassay-based test kits, particularly enzyme-linked immunosorbent assays (ELISA). In general, laboratory-based ELISA methods are considered more accurate and more analytically reliable than rapid on-site kits, as they provide quantitative results with higher sensitivity and better reproducibility under controlled conditions. In contrast, rapid lateral flow test kits offer practical advantages for operational use (e.g. rapid swabbing for post-hygiene verification) but they are typically less precise and more variable. Polymerase Chain Reaction (PCR) methods detect DNA markets from allergenic organisms. This can be less meaningful for allergen risk. There may also be technical issues with seaweed as a test material for PCR. Overall, ELISA-based laboratory testing is generally regarded as the gold standard for accuracy and precision in allergen detection. This distinction is important in risk assessment, where rapid methods support routine monitoring, but confirmatory testing is often required for robust allergen validation and compliance assurance.

On-site verification swabs (e.g. for crustacean tropomyosin) will be of little help in demonstrating the allergen risk of edible seaweed. Mildenberger & Rebours (2024) advised that allergen analysis should be carried out for all batches, given that allergens were detected at low concentrations. This would require ELISA-based laboratory testing, incurring cost and necessitating positive release of materials. Test kits are available for the antigens parvalbumin (associated to fish) and tropomyosin (associated to molluscs and crustaceans. Ongoing allergen testing is recommended, but an annual or quarterly basis may be sufficient if justified through risk assessment (especially given the adjusted reference doses with VITAL® 4.0). Given the increased awareness of allergens, it is likely customers will require allergen test certificates for reassurance.

10. MICROBIOLOGICAL HAZARDS

Microbiological contamination is one of the principal hazards associated with food production and processing. Microorganisms – bacteria, viruses, yeasts and moulds – are naturally present in the environment and can enter food products via water, equipment, personnel, handling or inadequate storage conditions. While many microorganisms are harmless, some are capable of causing spoilage or leading to foodborne illness in consumers. The microbiological safety of seaweed products is a critical consideration for food business operators (FBOs), particularly as seaweed increasingly enters mainstream food markets.

Seaweed presents some unique microbiological considerations because it is harvested from the marine environment, often with minimal processing prior to consumption. Environmental contamination, handling practices, moisture content and post-harvest processing all strongly influence microbiological risk. Effective control measures rely on understanding the conditions that promote or inhibit microbial growth and implementing appropriate preservation and hygiene controls throughout the supply chain.

Factors influencing microbial growth

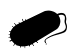
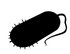
The growth and survival of microorganisms in food are strongly influenced by environmental conditions. Three of the most important parameters are water activity, temperature and pH. Compared with many bacterial pathogens, fungal spoilage organisms are less constrained by environmental conditions.

Water activity

Water activity (A_w) is one of the most important controls in preserved foods. Water activity measures the amount of free water available for microbial growth. It is related to, but distinct from, moisture content.

Most bacteria require relatively high water activity to grow, while yeasts and moulds can tolerate lower values (Table 10.1). Drying seaweed reduces water activity to levels that prevent the growth of most microorganisms (i.e. <0.60), making this one of the most effective and widely used preservation methods for seaweed products. An effective drying system aims to remove moisture quickly to minimise the time that microorganisms can proliferate. Water activity in seaweed will generally fall quickly, limiting bacterial growth. The moisture content of the dried material may

Table 10.1: Proliferation of microorganisms at different water activity levels.

Water activity	Growth potential	Bacteria range	Yeast & Mould range
>0.91	Rapid – higher risk product		
0.88-0.91	Reduced bacterial growth		
0.80-0.88	Bacterial growth largely inhibited		
0.60-0.80	Only dry-tolerant fungi can grow	-	
<0.60	No growth – stable product	-	-

determine the completion of drying in order to optimise onward handling and processing (e.g. milling). Furthermore, dried seaweed is likely to take up some moisture from the air during handling and storage. If the final product does not achieve sufficiently low water activity, there is an increased risk of spoilage by yeasts and moulds. It would be realistic to aim for a lower water activity that provides tolerance (e.g. variability across a batch, moisture uptake during handling). Therefore, the target water activity for a drying process is often lower than the 0.60 limit for proliferation of dry-tolerant yeasts and moulds. Equally, excessive drying should be avoided to maximise throughput and minimise costs.

Water activity – not moisture content – is a critical control point in a drying process. A target water activity for a seaweed drying process could be set at 0.50. A water activity meter will be required, internally verified on a regular basis (e.g. monthly) and externally calibrated periodically (e.g. annually).

Temperature

Temperature is a critical determinant of microbial proliferation in food (Table 10.2). Most foodborne pathogens grow between approximately 5°C and 60°C, often referred to as the "temperature danger zone." Chilling a product to below 5°C slows microbial growth significantly, while freezing halts growth although it may not eliminate microorganisms entirely. The highest food poisoning risk is between 20°C and 50°C. Many pathogenic bacteria are adapted to rapidly proliferate at temperatures similar to the human body, which means that the temperatures of greatest concern are 35-40°C.

Several spore-forming bacteria are capable of growth at 50-60°C (e.g. thermotolerant and thermophilic species within the genera Bacillus and Clostridium). These organisms are important because their spores can survive heat treatments and subsequently germinate if conditions become favourable (e.g. dried material is rehydrated). For many spore-forming bacteria, sporulation is promoted by environmental stresses (e.g. nutrient depletion, decreased water activity, temperatures at the upper end of the growth range). Generally, such species are more strongly associated with spoilage than illness. A product will generally be considered cooked if heated above 70°C. Pasteurisation conditions depend on the product, target microorganisms and processing method. It is achieved through a combination of high temperature and time (e.g. 2 minutes at 70°C, 30 seconds at 75°C), but targets vegetative pathogens not spores.

In seaweed production, temperature control is particularly important for fresh products with high moisture content. Low-temperature drying is commonly used in seaweed processing because it helps preserve quality (e.g. colour, flavour) and composition (e.g. heat-liable compounds). However, it may present risks if the drying process does not rapidly reduce moisture content. Unlike higher-temperature drying processes, low-temperature drying may not significantly reduce microbial populations and can allow survival of vegetative bacteria, yeasts, and moulds present on the raw material. Extended drying periods at moderate temperatures may also create conditions favourable for growth of certain microorganisms, particularly if airflow and humidity are not controlled. In addition, some thermotolerant and spore-forming bacteria may survive the process entirely. For these reasons, low-temperature drying systems should be carefully validated to demonstrate consistent reduction in water activity, supported by appropriate hygiene controls, environmental monitoring, and microbiological verification testing.

High temperature exposure can be used to reduce microbial loads on food products. For example, dried seaweed can be heat-treated by rapid exposure to high temperatures. Again, such approaches require careful validation and ongoing verification.

Table 10.2: Proliferation of bacteria at different temperatures.

Temperature range	Typical effect on foodborne bacteria	Preservation and food safety relevance
<0°C	Growth halted; many organisms survive freezing	Freezing preserves food but does not reliably kill most foodborne bacteria
0-5°C	Very slow growth for most pathogens (but Listeria monocytogenes can proliferate)	Refrigeration important for extending shelf life of fresh product
5-20°C	Slow to moderate growth	Prolonged storage can be unsafe at room temperature
20-35°C	Rapid growth; optimal for some pathogens (e.g. Bacillus cereus)	High food poisoning risk
35-40°C	Peak proliferation rate for many enteric bacteria (similar to human body temperature; e.g. E. coli)	
40-50°C	Some bacteria still grow rapidly (e.g. Campylobacter jejuni, Clostridium perfringens)	
50-60°C	Growth increasingly inhibited, but certain spore-formers remain problematic (e.g. thermophilic Bacillus species)	Hot holding threshold zone Spores can survive heat treatment and may germinate if conditions become favourable
60-70°C	Most foodborne pathogens inactivated over time	Safe hot holding range Pasteurisation possible for prolonged periods
>70°C	Rapid destruction of most vegetative pathogens	Typical cooking target Pasteurisation achieved in short duration

pH

Microbial survival and growth is also influenced by pH. Many pathogenic bacteria grow best in neutral or slightly acidic pH conditions. Strongly acidic environments inhibit their proliferation. Fermentation processes exploit this principle by encouraging the growth of acid-producing microorganisms, resulting in a lower pH that suppresses pathogens and spoilage organisms. This is an important factor in choosing fermentation and ensiling as preservation methods for seaweed that avoid drying, either for specific food products (e.g. seaweed kimchi) or for downstream applications (e.g. animal feed). Food can also be preserved in acids to prevent spoilage (e.g. pickled vegetables).

Microorganisms of concern

As a marine product, seaweed microbiological hazards are often considered in the context of shellfish and fish. However, many microorganisms of concern in seafood are internal (e.g. accumulated within an oyster during growth), whereas the risks associated with seaweed are generally linked to the surrounding seawater during growth. There may be an elevated risk of contamination by pathogens if seaweed is grown in integrated multi-trophic aquaculture: bacteria and viruses may be more likely to transfer to and adhere to biofilms. Microorganisms can also cross-contaminate seaweed during processing and handling.

Pathogenic bacteria

Several pathogenic bacteria species are relevant to seaweed products, primarily due to environmental contamination or poor hygiene practices during handling and processing. Some bacteria are considered opportunistic pathogens, meaning they rarely causes disease in healthy people but can cause infections under certain conditions.

Primarily from seawater contamination

Escherichia coli

The presence of Escherichia coli (E. coli) may indicate faecal contamination or inadequate hygiene controls during harvesting and processing. Overall, it is more likely to derive from seawater contamination (e.g. agricultural runoff). While not all strains are pathogenic, detection of E. coli is generally undesirable in ready-to-eat foods and may indicate increased risk of other pathogens. Laboratory analysis aims to determine total level of E. coli, with further identification required to discern the presence of pathogenic strains (e.g. E. coli O157).

Salmonella species

Salmonella is a significant pathogen of concern because even low levels can cause illness. Salmonella should be absent in ready-to-eat seaweed products. It generally indicates faecal contamination from the environment, wash water or poor personnel hygiene.

Primarily from post-handling contamination

Staphylococcus aureus

Staphylococcus aureus is a concern because heat-stable toxins can sometimes be produced. It should be absent in ready-to-eat seaweed products. Although environmental contamination may be the cause, Staphylococcus aureus is more likely to come from poor personnel hygiene from the point of harvest.

Listeria monocytogenes

Listeria monocytogenes is especially dangerous for vulnerable individuals (e.g. young, elderly), causing listeriosis. It can grow in cold temperatures and thrives in humid processing environments. While there may be a risk of introduction via seawater, it is more likely Listeria monocytogenes will come from an unhygienic processing facility. There are a wide range of

Listeria species, many of which are not harmful. As for E. coli, screening tends to determine if any Listeria species are present ahead of identifying if Listeria monocytogenes is detected.

Storage-related spore formers

Spore-forming bacterium can proliferate and survive in a wider range of conditions than other pathogenic bacteria (Table 10.2). This makes it more likely they will survive drying and, potentially, regrow if seaweed is rehydrated. They are one of the most frequently reported causes of food poisoning, but typically linked to cooked products held at moderate temperatures for extended periods.

Clostridum perfringens

Clostridum perfringens can potentially grow in fresh seaweed, although it is less commonly associated with seaweed than other pathogenic bacteria. Clostridum perfringens produces toxins after ingestion.

Bacillus cereus

Bacillus cereus is widely found in soil and causes different forms of poisoning. Although it is more likely to be detected in starchy foods (e.g. rice), meat and dairy products, it can be associated with seafood.

Vibrio species

Most Vibrio bacteria are naturally occurring marine organisms living in seawater and estuaries. The risk of Vibrio species (e.g. Vibrio parahaemolyticus) is greater in warm, tropical waters. Warming temperatures are increasing prevalence in northern seas, which means Vibrio species may become more of a food safety issue for Scottish seaweed. Filter-feeding shellfish (e.g. mussels and clams) are more vulnerable. Irrespective of risk, customers may expect testing to align with analysis of conventional seafood products.

Enterobacteriaceae and hygiene indicators

Enterobacteriaceae are commonly used in food microbiology as indicator organisms for hygiene and process control. Enterobacteriaceae is a large bacterial family including pathogens originating from intestines (e.g. Escherichia coli, Salmonella spp.), but also bacteria found naturally in soil, water and processing environments that do not generally cause illness in healthy individuals (e.g. Enterobacter spp., Citrobacter spp.). Monitoring Enterobacteriaceae can provide useful information about the overall microbiological condition of a process or facility. In seaweed production, elevated counts of Enterobacteriaceae may indicate environmental contamination, poor hygiene or contaminated equipment. Routine testing for indicator organisms is more practical than testing for a wide range of individual pathogens and can support verification of hygiene controls.

Faecal coliforms – a subgroup of coliform bacteria that grow at elevated temperatures – are also used to indicate organisms of intestinal origin. They are more closely associated with faecal material than total coliforms or Enterobacteriaceae and were an important indicator of hygiene. However, some environmental bacteria can still give positive results and generally E. coli enumeration is a preferred measure.

Environmental hygiene monitoring is an important component of microbiological control in food manufacturing facilities. Hygiene swabbing is commonly used to verify the effectiveness of cleaning and sanitation procedures on equipment, food contact surfaces, and production environments. Persistent positive results may indicate inadequate cleaning procedures, poor equipment design, or harborage sites for microorganisms. In seaweed processing facilities, hygiene monitoring is particularly important because marine raw materials may introduce high environmental microbial loads. Routine environmental monitoring supports verification of cleaning effectiveness and helps demonstrate due diligence within a food safety management system such as HACCP.

Viruses

Foodborne viruses are a major cause of gastrointestinal illness worldwide. Unlike bacteria, viruses cannot multiply in food. However, they can survive on food and infect people when contaminated products are eaten. Seaweed itself is usually considered a lower-risk food than other seafood products. Ready-to-eat seaweed products are the main concern because there may be no cooking step to inactivate viruses.

Norovirus

Norovirus is the most common foodborne virus. It can be found in sewage, but contamination can also occur through handling by infected workers. Norovirus is extremely infectious and survives well in the environment, making it the most important virus for seaweed food safety.

Hepatitis A virus

Hepatitis A virus is considered uncommon in many high-income countries, which makes it of less concern in Scotland. It will be more likely to derive from infected food handlers, but control can be complicated by the long incubation period (typically 2–6 weeks). Overall, risk from Hepatitis A virus is comparatively low.

Yeasts and moulds

Yeast and mould growth in seaweed products is mainly a sign of poor moisture control and storage. The most common consequences are spoilage and reduced shelf life, including musty odours, off-flavours, discoloration and sliminess. Visible mould growth is less likely.

The main food safety concern is the potential for some moulds, such as Aspergillus or Penicillium, to produce mycotoxins under damp storage conditions (see Mycotoxin section). Although seaweed is generally considered a lower-risk food for mycotoxins than other dried foods, visible mould growth should still be treated as a potential safety issue because toxins can remain even if the mould is removed.

Preservation of seaweed

The microbiological risk profile of seaweed products will depend on factors such as harvesting environment, product type, degree of processing and intended use. Products intended for direct consumption without further cooking require more stringent controls.

Fresh seaweed

Fresh seaweed is a highly perishable product due to its naturally high moisture content and nutrient availability. Once harvested, microbial populations can increase rapidly if the product is not appropriately handled and stored. Cold storage is the only practical option to minimise growth. Fresh seaweed may require storage in refrigerated conditions if harvested in warmer months of the year or there will be a delay prior to primary processing. This can be particularly relevant to farmed seaweed. In contrast, seaweed gathered from foreshore in winter months may not need to be stored in cold conditions. Each supply chain and process should be independently assessed.

Failure to maintain adequate chilling can result in spoilage through microbial activity, leading to reduced product quality (e.g. discoloration, odour, texture degradation). Consequently, fresh seaweed products generally have a relatively short shelf life (i.e. “Use by…”) and require clear storage instructions, effective cold chain management and appropriate shelf-life validation.

Fermented seaweed products

Fermentation is increasingly being explored as a preservation method for seaweed products. During fermentation, beneficial microorganisms convert sugars into organic acids, reducing product pH and creating conditions that inhibit many spoilage organisms and pathogens.

Low pH is a key microbiological control factor in fermented seaweed. Acidification limits the ability of many pathogenic bacteria to survive or proliferate, contributing to product stability and safety. However, fermentation processes must be carefully controlled to ensure consistent acid production and prevent the growth of undesirable microorganisms during production.

Although fermentation can improve microbial stability, it does not eliminate the need for good hygiene and appropriate process controls. Verification of pH and microbiological quality remains important to demonstrate product safety and consistency. Stevant et al. (2025b) recently published a report into the microbiology of fermented Saccharina latissima.

Dried seaweed

Drying is the most common preservation method used for edible seaweed because it produces a shelf-stable product with extended storage life. Temperature and water activity are controlled (critical factors for controlling microbial growth). Properly dried seaweed is generally considered microbiologically stable when stored under suitable conditions. However, dried seaweed is hygroscopic and may absorb moisture from humid environments if packaging is poorly designed or compromised. Variability in drying conditions, product thickness or packaging integrity may result in localised areas of elevated moisture where microorganisms can survive or proliferate (most likely yeasts and moulds). Consequently, drying processes should be validated and carefully monitored.

Studies of relevant seaweed species

The microbiological profile of edible seaweeds in Europe is becoming better understood. Lytou et al. (2021) is an important study for microbiological risks in Scottish seaweed. Samples of cultivated Alaria esculenta and Saccharina latissima from SAMS were assessed over two seasons, stored under controlled conditions. Results showed that the initial population of microorganisms depended on the year of harvest. No Salmonella, E. coli and Staphylococcus aureus were present in any samples. Listeria monocytogenes was found in one sample of Alaria esculenta, but the authors stated it probably derived from cross contamination after harvest. Lytou et al. (2021) found twelve isolates of Vibrio species on farmed Alaria esculenta, none of which belonged to the strains more commonly linked to poisoning from seafood (e.g. Vibrio parahaemolyticus). However, two strains were identified as Vibrio alginolyticus, which is generally considered an opportunistic pathogen and less likely to cause gastrointestinal illness. Lytou et al. (2021) found no pathogenic bacteria on Saccharina latissima, but Barberi et al. (2019) detected Vibrio species on Saccharina latissima cultivated in Maine, US. Oliviera et al. (2024) analysed a wide range of edible seaweed collected in Portugal, covering many of the relevant seaweed species. No sample contained Salmonella species. Blikra et al. (2019) analysed Alaria esculenta and Saccharina latissima farmed in Norway, showing that no pathogenic Vibrio species or Listeria monocytogenes were detected. When both seaweeds were heat treated, viable spore-forming bacteria (e.g. Bacillus pumilus) and this demonstrates the need to control the growth of toxin-producing bacteria.

Akomea-Frempong et al. (2023) completed a challenge test on Saccharina latissima cultivated in Maine, US. Samples of the seaweed were inoculated with pathogenic bacteria (including E. coli, Listeria monocytogenes, Vibrio parahaemolyticus and Salmonella enterica) in a controlled laboratory setting. All pathogens survived during storage at 4°C, 10°C, and 22°C. However, survival rates were higher at ambient temperature.

Norovirus from Asian seaweed has been linked to outbreaks of illness (e.g. Sakon et al., 2018). Alcaine-Bellido et al. (2026) assessed methods for enteric virus detection in European edible seaweed. A strain of norovirus was detected in commercial samples of Ulva spp. from two different suppliers. However, Oliviera et al. (2024) did not detect any norovirus in their analysis of Portuguese seaweed.

Microbiological specifications for seaweed

Microbiological specifications for products vary depending on category, intended use and customer requirements. Dried seaweed is generally expected to demonstrate low yeast and mould counts and absence of significant pathogenic bacteria. Specifications may also include low limits for E. coli and occasionally coagulase-positive staphylococci depending on product risk profile. Total viable counts and Enterobacteriaceae levels may be included in specifications, but could be less relevant to food safety considerations. As seaweed products increasingly enter international markets, customer and retailer microbiological requirements may become more stringent, particularly for ready-to-eat applications.

Testing should be risk-based and supported by validated sampling plans. Results should be interpreted alongside process controls, environmental monitoring, and shelf-life data. As microbiology testing is generally cheaper than other contaminant analysis, customers will often expect to receive certificates for each batch supplied. An FBO will often group batches, recording the framework to justify testing frequency. Trend analysis is particularly important for signalling increased microbiological risks even if individual batches still meet specification.

For lower-risk, stable products (e.g. dried seaweed), routine periodic testing will be appropriate. In contrast, higher-risk foods (e.g. fresh seaweed) may require more intense testing. Microbiological testing should not be the primary food safety control; it is a verification tool within a broader HACCP system. Because testing only samples a small portion of production, businesses should place greater emphasis on preventive controls (e.g. supplier approval, environmental monitoring, sanitation, water quality maintenance, staff hygiene).

Given the range of processes and applications for seaweed, it is beyond the scope of this document to provide complete microbial specifications for Scottish seaweed. Most customers will set their own limits for suppliers to comply with and the information presented here provides guidance on the potential microbial hazards of seaweed.

11. RADIONUCLIDES

Radioactive material from nuclear accidents, improper waste disposal and industrial fallout can enter the food chain through contamination of water, soil and air. If food contaminated with radionuclides is consumed, these particles may be absorbed in the body and expose tissues to harmful ionizing radiation. Radioactive isotopes can accumulate in certain tissues (e.g. iodine-131 in the thyroid, strontium-90 in bones, caesium-137 in muscles, plutonium-239 in the liver), risking cellular damage and cancers in those parts of the body. Exposure can increase the likelihood of health problems, especially in vulnerable populations.

Seaweed is known to concentrate radionuclides from seawater and are therefore widely used as a bioindicator for radioactive marine pollution. Intensive monitoring of radioactive contamination takes place in the UK, which includes analysing common seaweed species.

Radioactivity in Food and the Environment report

The Radioactivity in Food and the Environment (RIFE) Report is published annually in the UK, collating and summarising the results of monitoring of radioactivity in food and the environment by the RIFE partners (Food Standards Scotland and the Scottish Environment Protection Agency in Scotland). There are six facilities across Scotland that are included in the RIFE monitoring programme: three nuclear power stations (Chapelcross, Dumfries & Galloway; Hunterston, North Ayrshire; Torness, East Lothian), two defence establishments (Faslane and Coulport, Argyll & Bute; Rosyth, Fife) and one research establishment (Dounreay, Highland). There are also sources of radioactivity in the north of Wales and England that could transfer contaminants into Scottish waters (there are no sources in Northern Ireland). Table 11.1 summarises the total dosage to the population around nuclear facilities in the north of the UK: levels are very low across Scotland. Radioactive contaminants are more likely to originate from Cumbria and, to a lesser extent, North Wales and Lancashire. The Sellafield complex is the most important source of radioactive contamination for the coastline of Scotland.

According to the most recent RIFE-30 report (published in October 2025), medical procedures are the most significant man-made source of radiation that affects the public routinely (14% of total exposure). Artificial radioactivity in the environment – from the nuclear industry and from past testing of nuclear weapons, accidental releases and occupational exposure – accounted for <0.3% of the exposure to the UK population.

Analysis of radioactivity typically covers a suite of radionuclides. This includes naturally occurring radionuclides (often shortened to NORM) not exploited for their properties: these are the main source of exposure in the UK. Natural radionuclides can have their exposure and concentrations increased by human activity, in which case they are referred to as technologically enhanced naturally occurring radionuclides (sometimes shortened to TENORM). Then there are anthropogenic, man-made radionuclides that do not exist in nature, or at least are largely irrelevant in their natural form. Table 11.2 provides a summary of the radionuclides relevant to seaweed in Scotland. Some radionuclides have long residency times in seawater (carbon-14, iodine-129), persist in marine sediment (americium-241, plutonium-239) or accumulate in seafood (caesium-137, lead-210, polonium-210).

Table 11.1: Total dosage due to radioactive waste discharges and direct radiation around the north of the UK in 2024 (adapted from Table TS in RIFE 30).

Region	Location	Activity	Dose (mSv/yr)	Proportion of national UK limit*
North Wales	Trawsfynydd, Gwynedd	Nuclear power station	0.010	1.0% ↑
	Wylfa, Isle of Anglesey	Nuclear power station	0.008	0.8% ↑
Northwest England	Heysham, Lancashire	Nuclear power station	0.016	1.6% ↑
	Barrow, Cumbria	Defence establishments	0.061	6.1% ↑
	Cumbrian coast (including Sellafield)	Nuclear fuel production and reprocessing	0.200	20.0% ↑
West Scotland	Chapelcross, Dumfries & Galloway	Nuclear power station	0.007	0.7% ↓
	Hunterson, North Ayrshire	Nuclear power station	0.006	0.6% ↓
	Faslane and Coulport, Argyll & Bute	Defence establishments	0.005	0.5% ↑
North Scotland	Dounreay, Highland	Research establishments	0.021	2.1% ↓
East Scotland	Rosyth, Fife	Defence establishments	0.011	1.1% ↑
	Torness, East Lothian	Nuclear power station	0.011	1.1% ↑
Northeast England	Hartlepool, County Durham	Nuclear power station	0.007	0.7% ↓

* Arrow represents an increase or decrease from RIFE 29 (2024)

Considerable effort is put into monitoring radionuclide contamination around the UK, with findings aggregated via the RIFE programme. RIFE 30 includes the results for samples of seawater tested in 10 locations around Scotland, with greater emphasis on the southwest given the proximity to Sellafield (Table 11.3). Soluble radionuclides (e.g. technetium-99, caesium-137) are dispersed from the Sellafield area by currents, likely reaching the coast of Scotland within one year.

Table 11.2: Summary of anthropogenic, technologically enhanced and natural radionuclides in the UK and relevance to seaweed in Scotland.

Category	Radionuclide	Half-life	UK sources	Relevance to seaweed
Anthropogenic	Americium-241 (^{241}Am)	Centuries	Nuclear fallout and reactor discharges (Sellafield)	Partial (persistent in marine sediment)
	Caesium-134 (^{134}Cs)	Years	Nuclear reactor discharges (limited recently)	Minimal
	Caesium-137 (^{137}Cs)	Years	Nuclear fallout and reactor discharges (Sellafield)	Partial (known to accumulate in seafood
	Cobalt-60 (^{60}Co)	Years	Nuclear reactor discharges (Sellafield, Dounreay)	Minimal
	Iodine-129 (^{129}I)	Millenia	Nuclear reactor discharges (Sellafield), some from nuclear fallout	Partial (long residence dissolved in seawater, iodine abundant in seaweed)
	Iodine-131 (^{131}I):	Days	Used only for medical therapy	Minimal
	Plutonium isotopes (e.g. ^{239}Pu, ^{240}Pu)	Millenia	Nuclear reactor discharge and research sites (Sellafield, Dounreay)	Partial (persistent in marine sediment)
	Ruthenium-106 (^{106}Ru)	Days	Nuclear reactor discharges (Sellafield)	Minimal
	Silver-110m (^{110m}Ag)	Days	Nuclear reactor discharges (Sellafield, Dounreay)	Minimal
	Strontium-90 (^{90}Sr)	Years	Nuclear reactor discharges (Sellafield), some from nuclear fallout	Minimal
	Technetium-99 (^{99}Tc)	Millenia	Nuclear reactor discharges (Sellafield), in decline	Partial (known to accumulate in seaweed, but low toxicity)
Anthropogenic (and natural)	Sulphur-35 (^{35}S)	Days	Produced naturally from cosmic ray interaction and also in nuclear reactors	Minimal
	Tritium (^{3}H):	Years	Produced naturally from cosmic ray interaction and also in nuclear reactors (Heysham, Torness, Sellafield)	Minimal
Technologically enhanced (and natural)	Carbon-14 (^{14}C)	Millenia	Produced naturally from cosmic ray interaction and also in nuclear reactors (Sellafield)	Partial (persistent in dissolved inorganic carbon in seawater)
	Lead-210 (^{210}Pb)	Years	Natural geologic sources, associated with oil and gas industry and phosphate processing (Cumbria)	Partial (known to accumulate in seafood)
	Polonium-210 (^{210}Po)	Days	Natural geologic sources, associated with oil and gas industry and phosphate processing (Cumbria)	Partial (dominates radiation dose from seafood)
	Radium isotopes (e.g. ^{226}Ra, ^{228}Ra)	Years - Centuries	Natural geologic sources, associated with oil and gas industry and produced water discharges	Minimal
	Thorium-232 (^{232}Th):	Millenia	Natural geologic sources, associated with oil and gas industry	Minimal
	Uranium-238 (^{238}U)	Millenia	Natural geologic sources, associated with oil and gas industry and nuclear discharges (Sellafield, Dounreay)	Minimal
Natural	Potassium-40 (^{40}K)	Millenia	Ubiquitous naturally occurring radionuclide that contributes significantly to background radioactivity	Partial (known to accumulate in seaweed, but no toxicity)

Table 11.3: Concentration of radionuclides in seawater samples taken by the Scottish Environment Protection Agency around Scotland in 2024 (mean radioactivity concentration, in Bq/l; adapted from Table 8.10 in RIFE 30).

Local authority	Location	^{3}H	^{35}S	^{60}Co	^{106}Ru	^{110m}Ag	^{134}Cs	^{137}Cs	^{144}Ce	^{241}Am
Dumfries & Galloway	Seafield (near Chapelcross)	<1.0		<0.10	<0.50	<0.10	<0.10	<0.10	<0.27	<0.10
	Southerness	<1.0		<0.10	<0.66	<0.11	<0.10	<0.10	<0.39	<0.11
	Auchencairn	<1.0		<0.10	<0.35	<0.10	<0.10	<0.10	<0.24	<0.10
	Port Patrick	<1.0		<0.10	<0.25	<0.10	<0.10	<0.10	<0.15	<0.10
North Ayrshire	Hunterston	<1.0	0.50	<0.10	<0.56	<0.10	<0.10	<0.10	<0.31	<0.10
Argyll & Bute	Faslane (Carnban)	<1.6		<0.10	<0.56	<0.10	<0.10	<0.10	<0.33	<0.11
Highland	Dounreay Sandside Bay)	<1.0		<0.10	<0.49	<0.10	<0.10	<0.10	<0.28	<0.10
	Dounreay (Brims Ness)	<1.0		<0.10	<0.53	<0.10	<0.10	<0.10	<0.29	<0.10
Fife	Rosyth	<1.0		<0.10	<0.45	<0.10	<0.10	<0.10	<0.27	<0.10
East Lothian	Torness	250	0.89	<0.10	<0.44	<0.10	<0.10	<0.10	<0.25	<0.10

All have two sampling observations; Blank cells denote no analysis undertaken

Exposure to radionuclides

Exposure from radioactive particles

Radioactive particles are found in two areas of Scotland, but these are less relevant to radioactivity in food as the contamination is solid and not soluble in water.

Dalgety Bay, Fife

After the Second World War, radium-painted instrument panels from scrapped aircraft were burned or dumped along the foreshore at Dalgety Bay in western Fife. Coastal erosion over the following decades released thousands of radioactive particles, making Dalgety Bay one of the UK's most significant non-nuclear radiation sites. From the 1990s onward, SEPA repeatedly detected contaminated particles on the beach. This led to public warnings, scientific investigations and political pressure on the Ministry of Defence (MOD). Concerns focused on the risk of people coming into contact with radium-226. Access to parts of the foreshore was once restricted and the public advised to not remove any material from the beach. The MOD completed a major remediation programme in 2023, removing thousands of radioactive particles. While access is no longer restricted, monitoring is ongoing and particles may still appear due to coastal erosion and tidal movements.

Dounreay, Highland

Fragments of irradiated nuclear fuel have been found on the seabed around the Dounreay outfall in Caithness. Routine monitoring around Dounreay detected radioactive particles in the early 1980s and practices were amended to avoid further discharges. Current advice is that the risk to the public is very low, with no access restrictions on nearby beaches. However, fishing and shellfish harvesting has been banned within a 2km exclusion zone around Dounreay since 1997, under the Food and Environment Protection Act. Radioactive particles continue to be found near the outfall. Risk of radioactive contamination of seafood remains minimal, with monitoring continuing outside the exclusion zone. There are no equivalent fishing and seafood harvesting exclusion zones around any other facility in Scotland (as listed in Table 11.1).

Exposure from seafood

Discharges into the marine environment mean that seafood is exposed to radioactive contamination. Therefore, the RIFE programme includes comprehensive monitoring of fish, crustaceans and bivalves. The majority of the dosage from consuming seafood is from natural radionuclides. For high seafood consumers in the Cumbrian coastal community, just 10% of the total dose from seafood is from artificial radionuclides. Bivalves tend to have the highest concentration of radionuclides as they are filter feeders known to accumulate contaminants. The most important radionuclide in fish, crustaceans and bivalves is polonium-210, with caesium-137 present at lower levels. Lead-210 is also detected in crustaceans and bivalves.

Radionuclides in seaweed

Dose calculations based on dietary intake do not factor in seaweed. However, the biomonitoring characteristics of seaweed mean that it continues to be an important component of the RIFE programme. Table 11.4 provides the levels of 15 radionuclides in named species of seaweed tested on the coastline of Scotland and Northern Ireland in the most recent report (RIFE-30). The majority of testing is conducted on Fucus vesiculosus, with some monitoring including Ascophyllum nodosum and Fucus serratus.

A very small proportion of all potassium in the natural environment is the radionuclide potassium-40. Because bananas are known to be a source of potassium, they provide a useful reference for radioactivity exposure – the banana dose equivalent – to highlight the comparatively low risk from food intake. Although potassium concentrations may be higher in seaweed than bananas, the minimal amount of seaweed consumed means the quantity of potassium-40 ingested is less. There is no health risk from potassium-40 and it is not usually included in seaweed radionuclide analysis.

Table 11.4: Concentration of radionuclides in named species of seaweed sampled in 2024 by the Scottish Environment Protection Agency and the Northern Ireland Environment Agency (mean radioactivity concentration, in Bq per fresh kg; adapted from Table 8.2a in RIFE 30).

Local authority	Location	^{54}Mn	^{60}Co	^{65}Zn	^{95}Zr	^{95}Nb	^{99}Tc	^{106}Ru	^{110m}Ag	^{125}Sb	^{134}Cs	^{137}Cs	^{144}Ce	^{154}Eu	^{155}Eu	^{241}Am
Dumfries & Galloway	Auchencairn[1]	<0.10	<0.10	<0.18	<0.16	<0.14	110	<0.47	<0.11	<0.14	<0.10	1.1	<0.36	<0.11	<0.17	<1.6
	Garlieston[1]	<0.10	<0.10	<0.19	<0.19	<0.23	35	<0.51	<0.12	<0.17	<0.10	1.9	<0.37	<0.11	<0.19	6.3
	Port William[1]	<0.10	<0.10	<0.17	<0.16	<0.17	41	<0.44	<0.10	<0.13	<0.10	0.33	<0.33	<0.11	<0.16	0.58
Argyll & Bute	Campbeltown[1]	<0.10	<0.10	<0.26	<0.22	<0.18	16	<0.80	<0.11	<0.23	<0.10	0.24	<0.48	<0.13	<0.22	<0.17
	Islay[1]	<0.10	<0.10	<0.24	<0.22	<0.21	9.1	<0.70	<0.10	<0.20	<0.10	0.12	<0.50	<0.14	<0.25	<0.28
Eilean Siar	Lewis[1]	<0.10	<0.10	<0.21	<0.29	<0.41	13	<0.54	<0.10	<0.14	<0.10	0.11	<0.41	<0.10	<0.12	<0.10
Highland	Kinlochbervie[1]	<0.10	<0.10	<0.24	<0.19	<0.15	13	<0.65	<0.10	<0.20	<0.10	0.18	<0.51	<0.14	<0.28	<0.21
Shetland	Lerwick[1]	<0.10	<0.10	<0.10	<0.18	<0.19	3.7	<0.45	<0.10	<0.13	<0.10	<0.10	<0.34	<0.10	<0.18	<0.10
Aberdeen	Nigg Bay[1]	<0.10	<0.10	<0.17	<0.19	<0.20	8	<0.49	<0.10	<0.14	<0.10	<0.10	0.27	<0.11	<0.21	<0.22
County Down	Carlingford Lough[1]	<0.07	<0.04	<0.14	<0.23	<0.12	12	<0.36	<0.05	<0.09	<0.05	0.16	<0.30	<0.13	<0.85	<0.24
	Ardglass[1]	<0.05	<0.04	<0.16	<0.08	<0.09	3.4	<0.22	<0.04	<0.06	<0.04	0.22	<0.18	<0.12	<0.09	0.15
	Ardglass[2]	<0.04	<0.05	<0.09	<0.16	<0.22		<0.30	<0.06	<0.08	<0.03	0.08	<0.13	<0.15	<0.05	<0.07
County Antrim	Portrush[3]	<0.07	<0.07	<0.32	<0.19	<0.17		<0.60	<0.09	<0.15	<0.07	<0.09	<0.37	<0.25	<0.17	<0.27

[1] Fucus vesiculosus, [2] Ascophyllum nodosum, [3] Fucus serratus (only locations with seaweed identified to species level included); Between 1 and 4 sampling observations for each; Blank cells denote no analysis undertaken

Anthropogenic radionuclides

The majority of the results in RIFE-30 are below level of detection. Table 11.5 compares the levels of three anthropogenic radionuclides consistently found in seaweed and seafood (i.e. combined data for fish and shellfish) from Cumbria and Dumfries & Galloway. Generally, levels of caesium-137 and americium-241 are higher in seaweed than in seafood. This is relatively insignificant, especially when considering low dietary intake of seaweed. Americium-241 and caesium-137 are discharged from Sellafield and tend to be higher in Cumbria than Dumfries & Galloway (Table 11.5), continuing to be detected in Fucus vesiculosus sampled on the west of Scotland (Table 11.4).

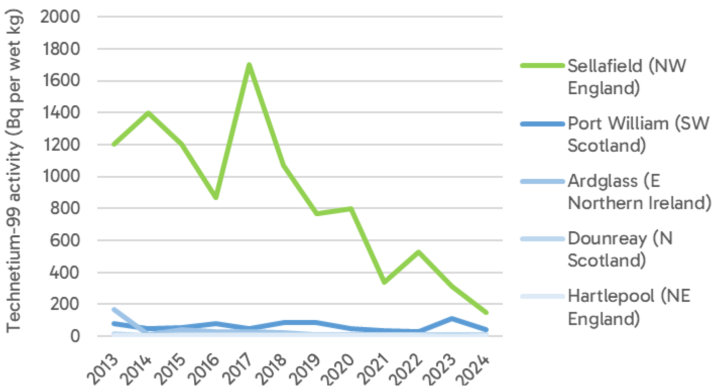


Figure 11.1: Levels of technetium-99 in fresh Fucus vesiculosus harvested at Sellafield and other regions across the north of the UK since 2013 (adapted from mean radioactivity concentration, in Bq per fresh kg; adapted from data in Figure 3.10 in RIFE 30).

Levels of technetium-99 are much higher in seaweed than seafood and consistent between Cumbria and Dumfries & Galloway (Table 11.5). Sellafield is the major source of technetium-99 in the UK, but emissions from Sellafield have reduced significantly in recent decades. This has led to a decline in the levels of technetium-99 in Fucus vesiculosus harvested near Sellafield (Figure 11.1, adapted from RIFE-30). Levels of Technetium-99 radioactivity at Sellafield have fallen from a peak of 62,000 Bq per fresh kg in 1996 to 150 Bq per fresh kg in 2024. This is approaching the low levels measured in Fucus vesiculosus in other regions across the north of the UK since 2013 (Figure 11.1). Importantly, levels of technetium-99 in Fucus vesiculosus are not a food safety concern. Other studies show decreased radioactivity levels in Scottish seaweed with increasing distance from Sellafield. For example, Kinch (2019) found that activity in seaweed reached close to background levels 100km from Sellafield (i.e. the sample site near Stranraer in Dumfries & Galloway).

Table 11.5: Comparison of selected anthropogenic radionuclide levels in seaweed and shellfish and fish from Cumbria and Dumfries & Galloway sampled in 2024 (mean radioactivity concentration, in Bq fresh kg-1; adapted from Tables 3.5, 3.6, 3.7 & 3.11 in RIFE 30).

	Cumbria		Dumfries & Galloway		
Radionuclide	Shellfish & Fish	Seaweed	Shellfish & Fish	Seaweed	Guideline level[a]
Caesium-137	0.81 (N=14)	1.58 (N=5)	0.37 (N=12)	1.11 (N=3)	1,250
Americium-241	2.15 (N=15)	3.54 (N=5)	0.88 (13)*	2.56 (N=3)*	80
Technetium-99	3.84 (N=14)*	60.2 (N=5)	3.92 (N=9)*	62.0 (N=3)	1,250

* Includes at least one result below level of detection, for which 0.5×LD is assumed as a value; [a] As stated in Table 11.6.

Limits during radiological emergencies

Under normal circumstances, there are no limits in place for radionuclides in food in Europe. However, in the event of a radiological emergency, maximum permitted levels of selected radionuclides will be implemented to protect public health (Council regulation (Euratom) 2016/52; retained in UK legislation after Brexit). The maximum levels vary depending on the isotope and the type of food (Table 11.6). Seaweed is not stated within the list of the Minor foods

(Annex II) – for which there are higher tolerances given low usage rates – although agar agar is listed as an example of a thickening agent from plants. Seaweed would likely fall under the 'Other food' category (Annex I). The limits for radionuclides most relevant to seaweed (Table 11.2) are the sum of isotopes of iodine (e.g. iodine-129; 2,000 Bq/kg), sum of alpha-emitting isotopes of plutonium and transplutonium elements (e.g. americium-241 and plutonium-239; 80 Bq/kg) and sum of all other nuclides of half-life greater than 10 days (e.g. technetium-99, caesium-137 and lead-210; 1,250 Bq/kg).

Table 11.6: Maximum levels of radionuclides permitted in food in the event of a radiological emergency, as stated in the Annexes of Council regulation (Euratom) 2016/52.

Radionuclide	Other food	Liquid food	Minor food
Sum of isotopes of strontium (notably ^{90}Sr)	750 Bq/kg	125 Bq/kg	7,500 Bq/kg
Sum of isotopes of iodine (notably ^{131}I)	2,000 Bq/kg	500 Bq/kg	20,000 Bq/kg
Sum of alpha-emitting isotopes of plutonium and transplutonium elements (notably ^{239}Pu and ^{241}Am)	80 Bq/kg	20 Bq/kg	800 Bq/kg
Sum of all other nuclides of half-life greater than 10 days (notably ^{134}Cs and ^{137}Cs)	1,250 Bq/kg	1,000 Bq/kg	12,500 Bq/kg

Annex I also has limits for Infant food and Dairy produce, which seaweed would not apply to; Annex II lists Minor foods by CN number; ^{14}C, ^{3}H and ^{40}K are not included in the limits.

Animal feeds are also included in Council regulation (Euratom) 2016/52 (Annex III). Limits only apply to the sum of caesium-134 and caesium-137: 5,000 Bq/kg in feed for the majority of animals and down to 1,250 Bq/kg in feed for pigs.

As shown in the results in Table 11.4 and Table 11.5, the levels reported in recent monitoring of Scottish seaweed are substantially below the European exigency limits (Table 11.6). This provides additional reassurance that radioactivity is not a food safety concern.

Recommendation for monitoring

Overall, there are no food safety concerns regarding radionuclides in Scottish seaweed, aligning with conclusions made elsewhere in Europe (e.g. Duinker et al., 2020; Banach et al., 2020, 2024).

Given the lack of health concerns and the extensive analysis of radionuclides in Scottish seaweed through RIFE, there is no need for any monitoring by seaweed producers in most of Scotland. It may be prudent to carry out one-off or occasional testing if operating in southwestern Scotland, using the information in this report as a guide to relevant radionuclides for analysis. This will largely serve to provide reassurance to customers, given that there are no fixed limits for radionuclides in food. It is important to review the RIFE Report soon after its annual publication to determine if risk profiles have changed (e.g. evidence of local discharges, changes in activity). Also, it is prudent to mirror the 2km fishing and shellfish exclusion zone in place at Dounreay at other facilities around Scotland.

12. PHYSICAL CONTAMINATION

Unlike chemical or microbiological hazards, physical contamination typically causes immediate, mechanical injuries such as dental damage, choking and gastrointestinal perforation. Furthermore, just a single fragment can result in significant harm. One in six food recalls in the UK between 2016 and 2021 were for physical contamination (Yue et al., 2022).

The main physical hazard of concern in seaweeds are pieces of stones and shells inadvertently taken during harvest. However, there are other categories of physical contamination relevant to seaweed (e.g. microplastics). Physical contamination can come from both the marine environment and downstream processing. This review focuses mostly on the former, given controls for physical contamination are standard in food production. Environmental contaminants are easier to remove from fresh seaweed: fragments may become trapped within fronds or adhere to seaweed during drying.

Sand

Sand would typically be considered contamination under food hygiene standards. However, sand is largely inert and not toxic. This means that consuming small amounts are unlikely to cause significant harm. Physical damage to teeth is possible. Moreover, sand can carry other environmental contaminants (e.g. anthropogenic pollutants, pathogens).

From a quality and acceptability standpoint, sand is a significant issue for consumers. Even small amounts create an unpleasant texture and would likely make the product unacceptable to consumers. Food producers are expected to control foreign body contamination and commercial processing should include washing and visual inspection to minimise the presence of sand. However, the primary control measure is avoiding harvesting seaweed contaminated with sand. Many species thrive on rocks adjacent to sandy beaches because they are adapted to the dynamic scouring (e.g. Porphyra spp., Ulva spp.): these seaweeds may require more intense washing and inspection to remove sand prior to onward processing.

Overall, sand is a low-risk physical hazard. Nevertheless, it must be controlled and minimised through good harvesting and processing practices.

Seaweed harvested from sandy beaches will require more intense washing

Shell and stone fragments

Fragments of stone and shell represent a notable physical hazard to consumers of edible seaweed. Environmental factors at the harvesting site – such as wave energy, tidal currents and sediment load – can influence the prevalence of stones and shell fragments. As for other forms of contamination, particles will be less likely to adhere to seaweed at an exposed site with changeable wave action.

Specifications for agricultural grade seaweed will often include maximum number of stone fragments. Hand harvesting offers greater control over raw material quality than mechanical harvesting. There is also variation within manual harvesting. Cutting with scissors or a knife will reduce the likelihood of taking fragments attached to the holdfast. In contrast, some harvesters work by pulling or tearing the seaweed by hand: this is more likely to remove the holdfast and the underlying hard surface.

Fucus serratus is particularly vulnerable to fouling by annelid worms with calcified shells

It is reasonable to assume that gastropod molluscs grazing on the seaweed will be the primary source of shell fragments. While it is impractical to avoid gathering molluscs during harvest, there are generally fewer grazers on seaweed on wave exposed shores. Crustaceans will not present a significant hazard for physical contamination. An important fouling species is Spirorbis spirobis – an annelid worm with a calcified shell that is fixed to the surface of the seaweed and cannot be washed off. While present on many species, spirorbid worms can be abundant on Fucus serratus in the right conditions. This will lead to contamination equivalent to sand in dried and milled Fucus serratus.

Sheltered farm sites are more vulnerable to fouling (e.g. Visch et al., 2020), although the nature of the community – and therefore risk of physical contamination – will vary. There is clearly overlap with the allergen risk associated with fouling organisms (see Allergen Section). Similarly, there is a burden on the seaweed producer to characterise and control the risk of contamination and assessment requires specific operational knowledge. For example, fouling species could be enumerated on target species to characterise the risk.

Metal, glass and plastic fragments

Contamination from fragments of metal, glass and plastic in edible seaweed is a low-frequency but high-risk physical hazard. Environmental debris is an obvious source, but controls should be in place to minimise intake of seaweed exposed to marine litter. It is more likely that harvesting tools will contaminate seaweed prior to factory intake (e.g. parts of scissors, cut gloves, rope fragments). It is standard for a food operator to manage inspection of metal cutting equipment, reporting loss or damage. It is best practice to extend condition checks to all items that could contaminate the harvested material. Transportation is an important phase and controls must be in place to minimise contamination.

Metal, glass and rigid plastic contamination is a well-recognised physical hazard in food processing. Therefore, hazards from factory intake are generally well characterised. Glass is generally avoided in food processing areas and rigid plastic components subject to regular inspection. Contamination will typically arise from equipment wear, breakage and accidental inclusion during handling. Common sources include cutting blades, sieves, conveyor systems and machinery components.

Microplastics

Seaweeds are susceptible to contamination by the microplastics that are ubiquitous in the marine environment. Generally defined as fragments less than 5mm in size, microplastics are known to attach to the surface of seaweed and enter the marine food chain. Gutow et al. (2016) demonstrated that microplastics readily adhere to the surface of Fucus vesiculosus and are subsequently ingested by the grazing snail Littorina littorea, providing clear evidence that seaweeds can act as vectors for the transfer of microplastics into coastal food webs. Beale and Turner (2025) found a correlation between abundance of beachcast seaweed and microplastic contamination on a beach in Cornwall. In addition to the physical hazard, microplastics can serve as carriers of chemical contamination such as POPs.

Li et al. (2020) confirmed that microplastics are present at low concentrations (0.9-3.0 items per dry gram) in samples of commercial nori farmed in Asia, with contamination arising from both environmental exposure and processing stages. The study showed that microplastic abundance on seaweed is directly linked to concentrations in surrounding water, highlighting macroalgae as passive collectors of microplastic pollution. Recent European research demonstrates that seaweeds accumulate particles and fibres on their surfaces in response to local environmental conditions.

Rimmer et al. (2024) assessed anthropogenic microparticles on seaweed in three locations in southwest England, covering Ascophyllum nodosum, Fucus vesiculosus, Fucus serratus, Himanthalia elongata, and Ulva lactuca. Total particle numbers attached to the surface reached a maximum of 110 per gram (dry weight). Reflective glass beads used in road markings were detected in Fucus vesiculosus sampled near stormwater discharge. Two-thirds of the fibres identified in analysis were semi-synthetic rayon (46%) and natural cotton (21%), with petroleum-based fibres (e.g. PET and polyester) making up the final third. More fibres were detected in a commercial sample of unwashed Himanthalia elongata than a commercial sample of washed Ulva lactuca, demonstrating that the conclusions reached on Asian seaweed by Li et al. (2020) translate to edible seaweed produced in the UK.

Plastic grow lines may mean farmed seaweed is more at risk of microplastic contamination

It is important to recognise that the ropes used to cultivate seaweed at sea will shed microplastic during use. A recent study of offshore fish farms in the Black Sea by Yandi et al. (2026) highlighted aquaculture mooring systems as a significant source of microplastic pollution. A total of 3,068 tonnes of mooring rope were deployed across the farms surveyed, with an estimated 22 tonnes of plastic released annually. Cultivated seaweed may have a higher risk of microplastic contamination given the proximity to plastic fibres.

Microplastics can have marine and terrestrial origins, but are likely to be a more serious hazard on developed shorelines where there is urban runoff. It is important that seaweed producers continue to review this emerging source of contamination. As for many other pollution risks, the likelihood of contamination will be less on more remote, wave-swept coastline.

Post-harvest controls

Washing

Washing is likely to be an effective control of physical contamination in most situations. Washing has been shown to reduce microplastic content in seaweed (Sundbæk et al., 2018). Ideally, seaweed will be washed in potable fresh water immediately prior to drying. This helps minimise risk of cross contamination. Salt water (either filtered seawater or artificially made with food grade sea salt) is likely to retain the quality of fresh seaweed, which could be rapidly lost if fresh water is used.

Most physical contamination is dense and will fall down to the bottom of a sink or trough. Spray washing on belts may be less successful as it risks shifting particles down but not removing from the seaweed.

Seaweed can be washed to remove physical contamination

Detectors

Although X-ray detectors are routinely integrated into scaled food manufacturing process lines to intercept physical contamination, the purchase and operation of such advanced equipment will be beyond most seaweed operators. Detection limits vary (e.g. orientation, density, moisture content), but X-ray systems are highly effective for dense foreign bodies. Unfortunately, performance drops significantly for low-density contaminants and so smaller fragments can go undetected (typical limits are 2-3mm for glass, 2-4mm for minerals, 3-5mm for rigid plastic). Indeed, low density contaminants like soft plastic cannot be reliably detected.

Metal detectors are widely used in food processing. Metal detection is a critical control measure used to identify, and usually remove, metallic contaminants (e.g. ferrous, non-ferrous and stainless steel fragments as small as 1-3mm). A metal detector is typically installed at a key point along a production line, especially immediately after size reduction and final packing. They may operate either with an alarm-only function or with an integrated rejection mechanism, with the former requiring manual intervention to locate and remove contaminated product. Detection systems with an automatic rejection facility (e.g. via air blast or diverter) are preferred as they ensure consistent and reliable control. As a result, rejection-enabled systems are considered more robust. Metal detectors must be set up with knowledge of the composition of the product subject to detection (i.e. moisture, packaging). It may even be necessary to own two different machines if substantially different products are supplied from one facility. A detector must be regularly verified with test wands (e.g. every operation) and externally calibrated by qualified engineers (e.g. annually).

Magnetic traps are used by food processors to remove ferrous metal contamination from particulate materials. High-strength magnets capture small metal particles as product flows past, preventing downstream contamination. Although they are well suited to integration in seaweed milling systems, they are limited to magnetic materials and require regular cleaning. Overall, magnetic traps a useful tool to deploy after size reduction but metal detectors provide greater reassurance that metal is absent in the final product.

Most seaweed is sold for food use following some form of size reduction, which is a process that increases the likelihood of metal fragments. Therefore, customers will likely interrogate metal contamination controls. It is best practice to integrate metal detectors into all food production, especially products sold directly to consumers. Supplying seaweed on a wholesale basis may justify not operating a metal detector, but additional controls may be necessary.

13. SEAWEED SCOTLAND MEMBER RESULTS

Sample sourcing

Results were collated by Seaweed Scotland in late 2025 and early 2026, sourced in two ways: dried samples of seaweed supplied for external analysis or certificates from accredited analytical companies for samples they had produced.

Dried samples for new external analysis

Dried samples of seaweed were supplied by members of Seaweed Scotland from across Scotland. Members provided information regarding the provenance of each sample (date of harvest, location, part of plant, produced under HACCP, washing, drying method). In addition, members stated whether a species was cultivated or wild harvested. These samples were sent in two phases and sent away for analysis by Eurofins.

A total of 38 samples were supplied and sent for testing: 33 certificates were received in January 2026, 5 in February 2026.

Certificates held from internal testing

Seaweed Scotland members provided certificates for seaweed samples held on file. These needed to be from accredited companies (e.g. Eurofins, ALS), with certificates containing enough detail to provide sufficient provenance (i.e. species name, harvest month). Members gave supplementary information when available. Seaweed Scotland also held certificates of analysis previously supplied by members for various projects and workshops. No samples or certificates for allergens or microbiology as these hazards are highly process dependent.

In total, certificates were supplied covering testing of 57 samples produced by Scottish Seaweed members.

Combined results

Samples and certificates were collated from eight different members of Seaweed Scotland, with additional samples harvested at various locations specifically for this project. The sourcing of the 95 samples and certificates is summarised in Table 13.1. Across new analysis and historic certificates, 14 different species of Scottish seaweed (including almost all of the relevant seaweed species) were covered. Testing was weighted to the key commercial species in Scotland: the top six species were Alaria esculenta, Saccharina latissima, Fucus serratus, Ascophyllum nodosum, Fucus vesiculosus and Palmaria palmata. Samples were supplied from regions covering a significant proportion of the Scottish coast, with 45% from wild harvest and 55% from cultivation. Just over half the samples were produced under HACCP (54%). Similarly, just over half the samples were washed prior to drying (54%).

Many samples were subjected to multiple tests, providing a substantial dataset for contaminants in Scottish seaweed. There are 336 results from analysis of elements, comprising

54 results for essential trace minerals (mostly iodine), 280 results for characterised toxic trace elements (e.g. mercury, cadmium) and 2 for other toxic trace elements (tin). There are also results for anthropogenic compounds, although the majority are traces of pesticide residues (19 samples screened). Two samples were sent for mycotoxin analysis and historic certificates were provided for analysis of PAHs in two samples.

Table 13.1: Dried samples and historic certificates provided by members of Seaweed Scotland.

				Harvest region (SW coast clockwise to SE coast)							
Group	**Species**	**Farmed samples**	**Wild harvested samples**	**Ayrshire & Clyde**	**Lorne**	**Mull**	**Ardna-murchan**	**Skye**	**Western Isles**	**Caithness**	**Fife**
Brown wracks	Ascophyllum nodosum	-	8	1	2				2	3	
	Pelvetia canaliculata	-	3							3	
	Fucus spiralis	-	3	1						2	
	Fucus vesiculosus	-	6		2					4	
	Fucus serratus	-	10		2					8	
	Himanthalia elongata	-	2							2	
Brown kelps	Alaria esculenta	25	5		7	3	1	14		5	
	Saccharina latissima	12	2		3	1	2	6		2	
	Saccorhiza polyschides	5	-				1	4			
	Laminaria digitata	-	4	1						2	1
	Laminaria hyperborea	-	1		1						
Red seaweeds	Palmaria palmata	-	6							3	3
	Porphyra spp	-	1	1							
Green seaweeds	Ulva lactuca	-	1		1						
	All species	**52**	**42**	**4**	**18**	**4**	**4**	**24**	**2**	**34**	**4**

Results

Excess nutrients & toxic elements

Essential trace minerals

Table 13.2 summarises the results in the Seaweed Scotland member samples for iodine and copper. Iodine levels were similar to the literature review dataset, broadly varying by species as expected. There is unlikely to be any geographic variation to iodine content, but the results confirm that levels in Scottish seaweed are aligned to those seen across Europe. Overall, copper results appear to be marginally lower in Scottish seaweed. However, the levels of this trace mineral are generally low and not of concern for food safety.

Table 13.2: Levels of essential trace minerals in samples supplied by Seaweed Scotland members compared with the dataset from the literature review of European seaweed composition.

	Seaweed Scotland member samples				Dataset from literature review			
Essential trace mineral	N Results	Median	25th-75th Percentile Range	90th Percentile	Median	25th-75th Percentile Range	90th Percentile	Comment on Seaweed Scotland samples
Iodine	30	750 mg/kg	466-1,208 mg/kg	4,436 mg/kg	650 mg/kg	200-2,674 mg/kg	4,643 mg/kg	Similar – variation by species as expected
Copper	26	1.5 mg/kg	1.2-2.3 mg/kg	3.2 mg/kg	2.7 mg/kg	1.4-6.0 mg/kg	13.0 mg/kg	Marginally lower in Seaweed Scotland samples

Toxic trace elements

Table 13.3 summarises the results for toxic trace elements, with a species breakdown provided in Table 13.5. Generally, the levels for most toxic trace elements in the Seaweed Scotland member samples were all similar to the results from the literature review (i.e. cadmium, lead, mercury, tin). Only samples of Scottish kelp species were tested for aluminium. Interestingly, the median levels of aluminium in Saccharina latissima were nearly identical in the two sets of data (233 vs 236mg/kg).

Total arsenic and inorganic arsenic concentrations varied by species in the Seaweed Scotland member samples, broadly as seen in the dataset. Although total arsenic levels are similar, it appears that levels of inorganic arsenic are higher in the Seaweed Scotland member samples. Table 13.4 breaks out the inorganic arsenic levels in four brown seaweed species that were frequently tested: concentrations of inorganic arsenic are higher in the Seaweed Scotland member samples than those seen in the dataset. This indicates there may be a risk of higher inorganic arsenic in Scottish seaweed, most likely of natural geogenic origin. There have been few studies of inorganic arsenic in Scottish seaweed (e.g. Ownsworth et al., 2019; Raab et al., 2025). Consequently, the analysis of inorganic arsenic in samples sourced by Seaweed Scotland is an important addition to the scientific understanding of seaweed food safety.

Table 13.3: Levels of toxic trace elements in samples supplied by Seaweed Scotland members compared with the dataset from the literature review of European seaweed composition.

	Seaweed Scotland member samples				Dataset from literature review			
Toxic trace mineral	N Results	Median	25th-75th Percentile Range	90th Percentile	Median	25th-75th Percentile Range	90th Percentile	Comment on Seaweed Scotland samples
Arsenic (inorganic)	64	0.66 mg/kg	0.32-1.05 mg/kg	2.38 mg/kg	0.21 mg/kg	0.10-0.45 mg/kg	0.88 mg/kg	Marginally higher – variation by species as expected
Arsenic (total)	52	46.1 mg/kg	27.4-57.9 mg/kg	68.1 mg/kg	44.3 mg/kg	20.7-66.0 mg/kg	89.6 mg/kg	Similar – variation by species as expected
Cadmium	64	0.68 mg/kg	0.21-1.18 mg/kg	1.82 mg/kg	0.59 mg/kg	0.21-1.20 mg/kg	2.02 mg/kg	Similar
Lead	52	0.29 mg/kg	0.13-0.62 mg/kg	1.20 mg/kg	0.33 mg/kg	0.16-0.83 mg/kg	1.44 mg/kg	Similar
Mercury	63	0.015 mg/kg	0.008-0.021 mg/kg	0.030 mg/kg	0.016 mg/kg	0.006-0.030 mg/kg	0.050 mg/kg	Similar
Aluminium	13	130 mg/kg	90-732 mg/kg	731.5 mg/kg	120 mg/kg	25-357 mg/kg	787.1 mg/kg	Similar
Tin	3	0.07 mg/kg	0.03-0.54 mg/kg*	-	0.03 mg/kg	0.02-0.16 mg/kg	0.22 mg/kg	Similar – single higher level of no concern

* Lowest and highest values as only three results

Table 13.4: Levels of inorganic arsenic in samples of frequently-tested species supplied by Seaweed Scotland members compared with the dataset from the literature review of European seaweed composition.

	Seaweed Scotland member samples				Dataset from literature review			
Species	N Results	Median	25th-75th Percentile Range	90th Percentile	Median	25th-75th Percentile Range	90th Percentile	Comment on Seaweed Scotland samples
Ascophyllum nodosum	7	0.97 mg/kg	0.77-1.65 mg/kg	1.92 mg/kg	0.11 mg/kg	0.10-0.16 mg/kg	0.47 mg/kg	Higher
Fucus vesiculosus	7	0.60 mg/kg	0.29-0.65 mg/kg	2.23 mg/kg	0.22 mg/kg	0.11-0.24 mg/kg	0.31 mg/kg	Higher
Saccharina latissima	7	0.68 mg/kg	0.43-1.08 mg/kg	1.44 mg/kg	0.22 mg/kg	0.14-0.57 mg/kg	2.06 mg/kg	Higher
Alaria esculenta	17	0.75 mg/kg	0.50-1.00 mg/kg	1.28 mg/kg	0.55 mg/kg	0.19-0.83 mg/kg	1.95 mg/kg	Marginally higher

Table 13.5: Results for arsenic (total and inorganic), cadmium, lead and mercury in seaweed samples supplied by Seaweed Scotland members, either via certificates from independent testing by members or sent by Seaweed Scotland for analysis

Group	Species	Arsenic (total)	Inorganic arsenic	Cadmium	Lead	Mercury
Brown wracks	Ascophyllum nodosum	14.3 - 58.9 mg/kg	0.20 - 2.10 mg/kg	0.14 - 0.32 mg/kg	0.13 - 0.62 mg/kg	0.013 - 0.030 mg/kg
	Pelvetia canaliculata	20.9 mg/kg	0.30 & 0.71 mg/kg	0.19 & 0.30 mg/kg	0.05 mg/kg	0.015 - 0.030 mg/kg
	Fucus spiralis	8.2 & 30.5 mg/kg	0.08 - 0.31 mg/kg	0.24 - 1.49 mg/kg	0.12 & 3.36 mg/kg	0.010 - 0.015 mg/kg
	Fucus vesiculosus	61.4 & 69.0 mg/kg	<0.10 - 3.80 mg/kg	0.07 - 1.02 mg/kg	0.02 - 0.72 mg/kg	0.015 - 0.019 mg/kg
	Fucus serratus	42.6 - 77.1 mg/kg	0.30 - 2.50 mg/kg	0.76 - 2.31 mg/kg	0.13 - 1.12 mg/kg	0.008 - 0.025 mg/kg
	Himanthalia elongata	26.3 mg/kg	<0.10 & 0.32 mg/kg	0.98 & 1.15 mg/kg	0.06 mg/kg	0.003 & 0.015 mg/kg
Brown kelps	Alaria esculenta	27.7 - 61.0 mg/kg	<0.10 - 2.80 mg/kg	0.67 - 2.81 mg/kg	<0.05 - 2.95 mg/kg	<0.005 - 0.031 mg/kg
	Saccharina latissima	11.0 - 68.6 mg/kg	0.10 - 1.50 mg/kg	0.27 - 0.82 mg/kg	0.10-1.24 mg/kg	0.015 – 0.087 mg/kg
	Saccorhiza polyschides	28.4 mg/kg	0.60 mg/kg	0.36 mg/kg	1.18 mg/kg	0.018 mg/kg
	Laminaria digitata	56.0 & 88.3 mg/kg	3.80, 31.2 & 46.0 mg/kg	0.04 - 0.07 mg/kg	0.10 & 2.31 mg/kg	0.015 - 0.042 mg/kg
	Laminaria hyperborea	34.3 mg/kg	6.70 mg/kg	0.04 mg/kg	0.43 mg/kg	0.033 mg/kg
Red seaweeds	Palmaria palmata	6.7 – 10.5 mg/kg	<0.10 - 0.60 mg/kg	0.09 - 0.21 mg/kg	0.10 - 0.70 mg/kg	0.003 - 0.009 mg/kg
	Porphyra spp	42.4 mg/kg	0.77 mg/kg	0.14 mg/kg	1.18 mg/kg	0.011 mg/kg
Green seaweeds	Ulva lactuca	4.6 mg/kg	0.48 mg/kg	0.07 mg/kg	2.35 mg/kg	0.028 mg/kg
Interquartile range in member samples (25th-75th Percentiles)		27.4 – 57.9 mg/kg	0.32 – 1.05 mg/kg	0.21 - 1.18 mg/kg	0.13 - 0.62 mg/kg	0.008 - 0.021 mg/kg
Interquartile range in dataset (25th-75th Percentiles)		20.7 - 66.0 mg/kg	0.10 - 0.45 mg/kg	0.21 - 1.20 mg/kg	0.16 - 0.83 mg/kg	0.006 - 0.030 mg/kg
Recommended limit (N exceeding out of N tested)		N/A	3mg/kg (5 out of 64)	3mg/kg (0 out of 64)	3mg/kg (1 out of 52)	0.1mg/kg (0 out of 63)

Orange highlight = at least one result exceeds the recommended limit
Text colour compares results to dataset from literature review: Green text = result in lower quartile of dataset (0-25%);
Yellow text = result bounded by middle quartiles of dataset (25-75%); Red text = result in upper quartile of dataset (75-100%).

Levels above recommended limits

Table 13.5 highlights results for samples supplied by Seaweed Scotland members that exceeded recommended limits. There were no results above recommended limits for mercury (0.10mg/kg; max. 0.09mg/kg) or cadmium (3.0mg/kg; max. 2.8mg/kg). One result out of 52 samples tested for lead exceeded the recommended limit (3.0mg/kg): Fucus spiralis collected from the Clyde (3.4mg/kg). There are no limits for tin, but concentrations on certificates supplied by members were low (max 0.5mg/kg) and far below any level that would impact human health. Although there are no limits for aluminium, there were four results in the Seaweed Scotland samples above 500mg/kg (max. 1,217mg/kg in a sample of Alaria esculenta from the west coast).

Inorganic arsenic

There were five results in the Seaweed Scotland samples above the recommended limit of 3.0mg/kg for inorganic arsenic:

- 3.8mg/kg in Fucus vesiculosus (collected from Lorne; 1 in 7 samples exceeding)
- 6.7mg/kg in Laminaria hyperborea (collected from Lorne; possible misidentification with Laminaria digitata; 1 of 1 exceeding)
- 3.8, 31.2 and 46.0mg/kg in Laminaria digitata (from three distinct regions; 3 of 3 exceeding)

While only three samples were tested, the levels in Laminaria digitata are aligned with the range seen in this species in the literature review. This confirms that the risk of excess intake in Laminaria digitata applies to Scotland. Furthermore, the three samples were taken from the west coast, north coast and east coast of Scotland: the risk does not apply specifically to one region. It is possible that Laminaria digitata was accidently harvested along with or in place of Laminaria hyperborea, given it is rare for this species to have an elevated inorganic arsenic content. Unfortunately, only one sample of Laminaria hyperborea was tested. The exceedance for Fucus vesiculosus is less concerning: the concentration of inorganic arsenic was marginally over the 3.0mg/kg recommended limit and the six other samples were well below (next highest 0.66mg/kg).

It is worthwhile noting that there were seven samples with inorganic arsenic levels between 1.5mg/kg and the recommended limit of 3.0mg/kg. These samples were from four species of brown seaweed (Ascophyllum nodosum, Fucus serratus, Alaria esculenta and Saccharina latissima) from four regions of Scotland. There is probably less risk of elevated inorganic arsenic in red and green seaweed species in Scotland, but this should be caveated by the limited testing in this project (results for just six samples).

Anthropogenic compounds

The majority of results for anthropogenic compounds were pesticide residue screens: 10 of the 26 samples screened contained no traces of any pesticide or QAC. In addition, there were two results for PAHs supplied by members.

Polycyclic aromatic hydrocarbons (PAHs)

Certificates with PAH results were available from the Seaweed Scotland membership for just two samples (Alaria esculenta and Fucus vesiculosus). Levels were low: the upperbound sum of four PAHs were 1.9 and 2.0μg/kg. There is no limit in place for seaweed, but EC Regulation No 2023/915 states a limit of 50μg/kg for various applications and parallel products (powders of food of plant origin for the preparation of beverages, 5.1.2; dried herbs, 5.1.3; dried spices, 5.1.10; food supplements containing botanicals or spirulina, 5.1.16). Although testing in this project is limited, it appears that PAHs are of lower risk.

Pesticides

A total of 26 samples were sent for pesticide residue screening. This covers a wide range of groups (e.g. organochlorine pesticides, pyrethroid pesticides, organophosphorus pesticides) and hundreds of chemicals, but only detections are stated on the certificates. Residues of pesticides were detected in nine samples. There were no species or geographic patterns: detections covered five species (Alaria esculenta, Saccharina latissima, Fucus serratus, Palmaria palmata and Porphyra sp.) and six regions (covering west, north and east coasts).

Folpet (phthalimide)

Folpet was detected in seven samples, which were from samples sourced from six members and one sample collected by Seaweed Scotland. The highest result was in a sample of Alaria esculenta from the west coast of Scotland: 0.54mg/kg. The limit of quantification in the analysis was 0.01mg/kg and most samples were just over this level; the next highest result was 0.07mg/kg.

Folpet is a protectant fungicide primarily used on cereals and potatoes. Usage increased following the ban on more hazardous fungicides and it is the mostly widely used fungicide in Scotland (both in terms of quantity applied and area treated; Scottish Government Statistics). Therefore, it is reasonable to assume that agricultural runoff is the source of folpet.

The default MRL for folpet in algae is 0.03mg/kg, but this is set for good agricultural practice and not health concern (toxicity is low). Three of the seven detections for folpet in this project were below 0.03mg/kg. It is important to note that the current MRL definition for folpet is the sum of folpet and phthalimide. Phthalimide may come from sources other than folpet. Therefore, the MRL for folpet should not be applied in cases where there is reasonable justification that folpet is not the source of the phthalimide residue. While phthalimide may come from fungicide runoff, the possibility cannot be ruled out that phthalimide compounds are naturally found in seaweed. Nevertheless, there is no concern regarding health impact from consumption of edible seaweed with traces of folpet residues.

Dichlobenil (dichlorobenzonitrile)

Dichlobenil is a benzonitrile herbicide formerly approved for use on fruit crops, but generally it is used to control weeds in non-agricultural applications (industrial areas, transport infrastructure; Björklund et al., 2011). It is water soluble, making it more prone to transfer into coastal areas via runoff and watercourses.

Dichlobenil was detected in one sample of Saccharina latissima cultivated on the west coast of Scotland, at 0.02mg/kg. This is marginally above the default MRL for dichlobenil in algae is 0.01 mg/kg (default). It is likely to originate from land, but dichlobenil has low toxicity and is not a concern for human health in this case.

Diethyltoluamide (DEET)

Diethyltoluamide (DEET) is one of the most established insecticides and is a common active ingredients in insect repellent (where it can account for over 50% of the formulation). DEET is not used in agriculture and so does not appear in the EU Pesticides Database. Therefore, there is no MRL in place.

DEET was detected at 0.03mg/kg in a single sample of Saccharina latissima, farmed on the west coast of Scotland. This is a relatively low level and not a concern for human health. The most likely origin is insect repellent on the skin of a person handling seaweed during harvest. Hygiene controls will be in place in a factory, making it unlikely that cross-contamination would occur during processing. Although this highlights the importance of ensuring good hygiene practices at the point of harvest, the detection of DEET is not a health concern in this instance.

Quaternary ammonium compounds (QACs)

The pesticide residue screening included quaternary ammonium compounds (QACs), which were detected in 13 of the 26 samples sent for analysis. Table 13.6 lists the specific QACs detected and their range of levels. Didecyldimethylammonium chloride (DDAC), benzyldimethyldodecylammonium chloride (BAC-C12), miristalkonium chloride (BAC-C14) and benzalkonium chloride (total; BAC) are all broad spectrum biocides and disinfectants used in surface cleaning wipes and sanitising sprays. Although they can also be found in some personal care products, residues in food generally derive from hygiene chemicals.

Table 13.6: QACs detected in pesticide residue screening of samples collated by Seaweed Scotland.

QAC	Number of detections	Number of species	Range of levels detected
Didecyldimethylammonium chloride (DDAC)	**6**	**6**	**0.12-0.48mg/kg**
Benzyldimethyldodecylammonium chloride (BAC-C12)	13	9	0.10-2.90mg/kg
Miristalkonium chloride (BAC-C14)	7	7	0.12-0.83mg/kg
Benzalkonium chloride (total; BAC)	**13**	**9**	**0.10-3.70mg/kg**

As for pesticides residue detections, there were no species or geographic patterns: detections covered nine species and five regions (covering west, north and east coasts). Table 13.7 explains the pattern of detections. QACs were detected in samples from almost all suppliers (detected in all samples from two suppliers; detected in some samples from four suppliers; no detections in samples from three suppliers). When accounting for the different compounds, there were 39 quantified levels of QACs across all the samples. The majority of these were below 0.2mg/kg (56%), with the highest level for total BAC at 3.7mg/kg.

Table 13.7: Results for QACs detected in pesticide residue screening of samples of different species collated by Seaweed Scotland.

	Samples with QAC detection				Samples without QAC detection		
Species	**N samples**	**Levels detected[a]**	**Number of suppliers[b]**	**Regions**	**N samples**	**Number of suppliers[b]**	**Regions**
Ascophyllum nodosum	1	0.27 mg/kg	1	North	4	3	West, Western Isles
Pelvetia canaliculata	-	-	-	-	1	1	North
Fucus spiralis	1	0.26 mg/kg	1	North	-	-	-
Fucus vesiculosus	-	-	-	-	2	1	West
Fucus serratus	1	0.41 mg/kg	1	North	1	1	West
Himanthalia elongata	1	2.00 mg/kg	1	North	-	-	-
Alaria esculenta	3	0.11, 0.24, 3.70mg/kg	2	West	3	2	West
Saccharina latissima	3	0.10, 0.11, 0.11mg/kg	2	West	1	1	West
Saccorhiza polyschides	1	0.16 mg/kg	1	West	-	-	-
Laminaria digitata	-	-	-	-	1	1	East
Porphyra sp.	1	1.70 mg/kg	1	West			
Palmaria palmata	1	1.70 mg/kg	1	East			
Total	**13**	**Max. 3.70 mg/kg**	**6 different suppliers**	**5 regions across all coasts**	**13**	**7 different suppliers**	**7 regions across all coasts**

[a] Total benzalkonium chloride (BAC), the QAC with the highest levels; [b] Including both direct collection by Seaweed Scotland and samples supplied by members

Detection of QACs typically signals cross-contamination from hygiene chemicals, largely because surfaces have not been rinsed down after sanitisation. This is particularly relevant to sinks or troughs where seaweed is washed. Although the detections could be associated with improper application of hygiene chemicals, one argument against this is the samples with detections came from six different members: this would imply widespread misuse of QACs. It is also possible that environmental contamination is the cause of the residues detected in the Seaweed Scotland samples. Most QACs in wastewater are removed in treatment plants, but will persist in sewage sludge that may be used in agricultural applications. Indeed, one of the samples with residues of QACs in this project was Porphyra sp. collected in the Clyde directly by Seaweed Scotland. This material was washed and dried at a domestic scale, never passing through a processing facility. Therefore, it is clear that QACs can be present in seaweed without factory cross-contamination. Detections of QACs in seaweed are been widely reported, although Fernandes et al. (2025) found compounds in brown seaweed collected in Brazil.

Although QACs have been detected in half of the samples tested in this project, the levels are not high enough to cause on concern for human health. More work is required to understand the origin and risks around QACs in seaweed.

Biogenic toxins

Mycotoxins

Three samples of Scottish seaweed for sent for mycotoxin analysis: two samples of Saccharina latissima (one of which was supplied by a member) and one sample of Ascophyllum nodosum. There were no detections in Saccharina latissima, but alfatoxin B1 was found in the sample of Ascophyllum nodosum at 0.29µg/kg (<0.1µg/kg on all other mycotoxins).

There is no relevant limit in EC Regulation No 2023/915 for seaweed, although there is a limit of 50µg/kg for certain spices (1.1.14, 1.1.15). Therefore, the detection of aflatoxin B1 is not a cause for concern. It is also important to stress that the detection was in a sample of seaweed that was collected directly by Seaweed Scotland and so it is possible that the drying process was less controlled. Finding a trace of aflatoxin B1 in one in three of the samples tested in this project does indicate more work is required to understand mycotoxin risks in seaweed.

14. REFERENCES

Note these citations include some studies from scientific literature used to gather data on trace nutrients and toxic elements, but not necessarily referenced in this report.

Aboal, J.R., Pacín, C., García-Seoane, R., Varela, Z., González, A.G. and Fernández, J.A. (2023) 'Global decrease in heavy metal concentrations in brown algae in the last 90 years', *Journal of Hazardous Materials*, 445, p. 130511.

Afonso, C., Matos, J., Guarda, I., Gomes-Bispo, A., Gomes, R., Cardoso, C., Gueifão, S., Delgado, I., Coelho, I., Castanheira, I. and Bandarra, N.M. (2021) 'Bioactive and nutritional potential of Alaria esculenta and Saccharina latissima', *Journal of Applied Phycology*, 33(1), pp. 501–513.

Akomea-Frempong, S., Skonberg, D.I., Arya, R. and Perry, J.J. (2023) 'Survival of inoculated Vibrio spp., Shigatoxigenic Escherichia coli, Listeria monocytogenes, and Salmonella spp. on seaweed (sugar kelp) during storage', *Journal of Food Protection*, 86(7), p. 100096.

Alcaine-Bellido, B., Rodrigo, D. and Randazzo, W. (2026) 'On the detection of foodborne viral contamination in edible seaweeds', *International Journal of Food Microbiology*, 453, p. 111733.

Alobwede, E., Leake, J.R., Pandhal, J. and Banwart, S.A. (2019) 'Decomposition of macroalgal wrack and its contribution to nutrient cycling in coastal ecosystems', *Geoderma*, 334, pp. 113–123.

Al-Soufi, S., Miranda, M., García, J., Muíños, A., Cegarra, E., Nicodemus, N., Herrero-Latorre, C. and López-Alonso, M. (2024) 'Elements in serum, muscle, liver and kidney of rabbits fed macroalgae-supplemented diets', *Marine Drugs*, 22(6), p. 263.

Al-Soufi, S., García, J., Muíños, A., Pereira, V., Piñeiro, V., Miranda, M., García-Vaquero, M. and López-Alonso, M. (2025) 'Assessment of macroalgae and macroalgal extracts as a source of minerals in need of fine-tuning in multiple livestock production systems', *Animal Feed Science and Technology*, 319, p. 116154.

Anastasakis, K. (2011) *The potential of the production of fuels and chemicals from marine biomass*. PhD thesis, University of Leeds.

Arlov, Ø., Nøkling-Eide, K., Aarstad, O.A., Jacobsen, S.S., Langeng, A.-M., Borrero-Santiago, A.R., Sæther, M., Rustad, T., Aachmann, F.L. and Sletta, H. (2024) 'Variations in the chemical composition of Norwegian cultivated brown algae Saccharina latissima and Alaria esculenta based on deployment and harvest times', *Algal Research*, 78, p. 103421.

Azevedo, G.Z., Dutra, F.S., Nunes, A., Lima, G.P.P. and Maraschin, M. (2026) 'Global patterns of pesticide residues in seaweeds: a systematic review', *Marine Pollution Bulletin*, 222(1), p. 118708.

Badmus, U.O., Taggart, M.A., Elbourne, P.D., Sterk, H.P. and Boyd, K.G. (2022). 'Effect of long-term storage and harvest site on the fatty acid profiles, mineral and antioxidant properties of selected edible Scottish seaweeds'. *Food Chemistry*, 377: 131955

Balina, K., Romagnoli, F., Blumberga, D. and Muizniece, I. (2016) 'Seaweed biorefinery concept for sustainable use of marine resources', *Energy Procedia*, 95, pp. 43–49.

Ballance, S., Rieder, A., Arlov, Ø. and Knutsen, S.H. (2024). 'Brown seaweed as a food ingredient contributing to an adequate but not excessive amount of iodine in the European diet. A case study with bread', *Journal of the Science of Food and Agriculture*, 104(14), pp. 8897–8906.

Banach, J.L., van der Fels-Klerx, H.J., Touwen, S.M., Kleter, G.A. and van Boekel, M.A.J.S. (2024). 'Food safety hazards in commercially available seaweed products and effects of processing on hazard levels', *Food Control*, 162, p. 110461.

Barberi, O.N., Byron, C.J., Burkholder, K.M., St. Gelais, A.T. and Williams, A.K. (2019) 'Assessment of bacterial pathogens on edible macroalgae in coastal waters', *Journal of Applied Phycology*, 32, pp. 683–696.

Barrat, J.-A., Heulin, T., Bayon, G., Waeles, M., Chauvaud, L. and Rouget, M.-L. (2024) 'Trace element uptake by macroalgae: organic colloids as a source of metals, including Fe and rare earth elements', *Chemosphere*, 369, p. 143849.

Beacham, T.A., Cole, I.S., DeDross, L.S., Raikova, S., Chuck, C.J., Macdonald, J., Herrera, L., Ali, T., Airs, R.L., Landels, A. and Allen, M.J. (2019) 'Analysis of seaweeds from South West England as a biorefinery feedstock', *Applied Sciences*, 9(20), p. 4456.

Beale, C. and Turner, A. (2025) 'Spatial and temporal distribution of large (1–5 mm) microplastics on the strandline of a macrotidal sandy beach (Polzeath, southwest England) and their association with beach-cast seaweed', *Micro*, 5(3), p. 43.

Beekmann, K., Sloot, S.J., Oey, S.B. and van Leeuwen, S.P.J. (2022) 'MCPD esters and glycidyl esters in food supplements of fish oils, algae oils and krill oils', *Food Control*, 136, p. 108865.

Biancacci, N., Cole, A.J., Black, K.D. and Black, K.D. (2022). 'Annual compositional variation in wild Osmundea pinnatifida (Hudson) Stackhouse from the west coast of Scotland.' *Journal of Applied Phycology*, 34: 1661–1675.

Biancarosa, I., Belghit, I., Bruckner, C.G., Liland, N.S., Waagbø, R., Amlund, H., Heesch, S., Lock, E.-J. and Bjerregaard, R. (2018) 'Chemical characterization of 21 species of marine macroalgae common in Norwegian waters: benefits of and limitations to their potential use in food and feed', *Journal of the Science of Food and Agriculture*, 98(5), pp. 2035–2042.

Bikker, P., Stokvis, L., van Krimpen, M.M., van Wikselaar, P.G. and Cone, J.W. (2020). 'Evaluation of seaweeds from marine waters in Northwestern Europe for application in animal nutrition'. *Animal Feed Science and Technology*, 263: 114460.

Bikker, P., van Krimpen, M.M., van Wikselaar, P., Houweling-Tan, B., Scaccia, N., van Hal, J.W., Huijgen, W.J.J., Cone, J.W. and López-Contreras, A.M. (2016) 'Biorefinery of the green seaweed Ulva lactuca to produce animal feed, chemicals and biofuels', *Journal of Applied Phycology*, 28, pp. 3511–3525.

Björklund, K.L., Vahter, M., Palm, B., Grandér, M., Lignell, S., Berglund, M. and Åkesson, A. (2011) 'Metals and trace element concentrations in breast milk of first-time healthy mothers: a biological monitoring study', *Science of the Total Environment*, 409(19), pp. 3732–3739.

Bjorkman, F., Axling, U., Krog, M.P., Hall, A.S. and Nyman, M. (2026). 'Impact of pickling and brining on the perceptual and nutritional characteristics of sea lettuce (Ulva fenestrata)'. *Future Foods,* 13: 100913.

Blanco, A., Sørensen, H.L., Løvstad, C.M., Steinhovden, K.B., Larsen, B.K., Eilertsen, H.C. and Johnsen, G. (2023). 'Effect of deployment and harvest date on growth and high-value compounds of farmed Alaria esculenta.' *Marine Drugs*, 21(5): 305.

Blikra, M.J. and Skipnes, D. (2024) 'Live storage of kelp under stressful conditions led to higher iodine reductions during subsequent blanching', *Journal of Applied Phycology*, 36, pp. 1407–1412.

Blikra, M.J., Skipnes, D. and Skara, T. (2022) 'On the use of pulsed electric field technology as a pretreatment to reduce the content of potentially toxic elements in dried Saccharina latissima', *LWT – Food Science and Technology*, 169, p114033.

Blikra, M.J., Løvdal, T., Vaka, M.R., Roiha, I.S., Lunestad, B.T., Lindseth, C. and Skipnes, D. (2019) 'Assessment of food quality and microbial safety of brown macroalgae (Alaria esculenta and Saccharina latissima)', *Journal of the Science of Food and Agriculture*, 99(3), pp. 1198–1206.

Bocio, A., Nadal, M. and Domingo, J.L. (2005) 'Human exposure to metals through the diet in Tarragona, Spain: temporal trend', *Biological Trace Element Research*, 104(3), pp. 193–201.

Boderskov, T., Werner, T., Bruhn, A., Rasmussen, M.B., Hoppe, M., Halkjær Nielsen, D. and Holdt, S.L. (2021). 'Potential of macroalgae biorefinery concepts for the circular bioeconomy: effects of biorefinery pre-treatments on anaerobic digestion and protein extraction'. *Algal Research,* 53: 102160.

Bruggraber, S.F.A., Chapman, T.P.E., Thane, C.W., Olson, A., Jugdaohsingh, R. and Powell, J.J. (2012) 'A re-analysis of the iron content of plant-based foods in the United Kingdom', *British Journal of Nutrition*, 108(12), pp. 2221–2228.

Bruhn, A., Dahl, J., Nielsen, M.M., Rasmussen, M.B., Markager, S. and Olesen, B. (2019). 'Fermentation of sugar kelp (Saccharina latissima): effects on sensory properties and content of minerals and metals'. *Journal of Applied Phycology,* 31: 3175–3187.

Bull, D., Wilcox, C. and Hardesty, B.D. (2017). 'The seaweed Fucus vesiculosus accumulates microplastic particles in the marine environment.' *Environmental Pollution*, 220: 228–233.

Burkin, A.A. and Kononenko, G.P. (2023). Mycotoxins in macroalgae from the Kandalaksha Gulf of the White Sea after natural and experimental alienation from the substrate. *Russian Journal of Marine Biology*, 49(5): 287–292

Burkin, A.A., Kononenko, G.P., Georgiev, A.A. and Georgieva, M.L., 2021. Toxic metabolites of micromycetes in brown algae of the families Fucaceae and Laminariaceae from the White Sea. *Russian Journal of Marine Biology*, *47*(1), pp.35-38.

Cabrita, A.R.J., Maia, M.R.G., Oliveira, H.M., Sousa-Pinto, I., Almeida, A.A., Pinto, E. and Fonseca, A.J.M. (2016) 'Tracing seaweeds as mineral sources for farm-animals', *Journal of Applied Phycology*, 28, pp. 3135–3150.

Campbell, M., Ortuño, J., Stratakos, A.C., Garcia-Vaquero, M., Loughnane, C., Hughes, H., Kerry, J.P. and Tiwari, B.K. (2020) 'Impact of dietary inclusion of Ascophyllum nodosum on growth performance, intestinal health, and skin pigmentation of Atlantic salmon (Salmo salar)', *Animals*, 10(6), p. 1019.

Cardoso, C., Lage-Yusty, M., López-Hernández, J., Miranda, M., Carvalho, M.L., Afonso, C. and Bandarra, N.M. (2023) 'Farming a wild seaweed and changes to its composition, bioactivity, and bioaccessibility: the Saccorhiza polyschides case study', *Foods*, 12(5), p. 1012.

Carrano, V., Mollo, E., Lorenti, M., Gavagnin, M. and Buia, M.C. (2021) 'Seasonal variation in biochemical composition of seaweeds and implications for coastal trophic dynamics', *Estuarine, Coastal and Shelf Science*, 262, p. 107531.

Casas-Agustench, P., López-Uriarte, P., Bulló, M. and Salas-Salvadó, J. (2024) 'Nitrate, nitrite, and iodine concentrations in commercial edible algae: an observational study', *Foods*, 13(16), p. 2615.

Cavallo, G., Lorini, C., Garamella, G. and Bonaccorsi, G. (2021) 'Seaweeds as a "palatable" challenge between innovation and sustainability: a systematic review of food safety', *Sustainability*, 13(14), p. 7652.

Chinese Nutrition Society (2023) *Dietary Reference Intakes for Chinese Residents (2023)*. Beijing: Science Press.

Choulot, M., Jabbour, C., Burlot, A.-S., Jing, L., Welna, M., Szymczycha-Madeja, A., Le Guillard, C. and Michalak, I. (2025). 'Application of enzyme-assisted extraction on the brown seaweed *Fucus vesiculosus* Linnaeus (Ochrophyta, Fucaceae) to produce extracts for a sustainable agriculture', *Journal of Applied Phycology*, 37, pp. 1325–1340

Čmiková, N., Galovičová, L., Miškeje, M., Borotová, P., Kluz, M. and Kačániová, M. (2022). Determination of antioxidant, antimicrobial activity, heavy metals and elements content of seaweed extracts. *Plants*, 11(11): 1493.

Correia, M., Sousa, S., Ramalhosa, M.J., da Silva, A.P., Afonso, C., Cardoso, C., Bandarra, N.M. and Domingues, V.F. (2021) 'Evaluation of toxic metals and essential elements in edible seaweeds from the Portuguese coast', *Food and Chemical Toxicology*, 155, p. 112385.

Costa, M., Cardoso, V., Pereira, O., Bessa, R.J.B., Alves, S.P., Alfaia, C.M., Coelho, D., Azevedo, V., Fontes, C.M.G.A. and Prates, J.A.M. (2022a) 'Effect of dietary Laminaria digitata with carbohydrases on broiler production performance and meat quality, lipid profile, and mineral composition', *Poultry Science*, 101(2), p. 101561.

Costa, M., Cardoso, V., Pereira, O., Coelho, D., Alfaia, C.M., Alves, S.P., Bessa, R.J.B., Fontes, C.M.G.A. and Prates, J.A.M. (2022b) 'Effect on broiler production performance and meat quality of feeding Ulva lactuca supplemented with carbohydrases', *Animals*, 12(8), p. 1009.

Dahlstedt, S.M.R., Stedt, A., Nylund, G.M., Pavia, H., Nielsen, M.M., Nielsen, S.L., Nielsen, S.M. and Holdt, S.L. (2026). 'Cultivation conditions, harvest, and hot water treatment affect the sensory profile, safety, and microelement composition of edible seaweeds Ulva fenestrata and Saccharina latissima', *Future Foods*, 13, p. 100995

Dong, G., Hu, Z., Zhu, X., McGuire, J., Sun, D.-W. and Tiwari, B.K. (2025) 'Multifactorial analysis of allergen variability in Alaria esculenta seaweed: influence of drying techniques, harvesting methods, and pre-treatments', *Algal Research*, 90, p. 104177.

Duinker, A., Bergvik, M., Sivertsvik, M., Nøstvold, B., Frantzen, S. and Lunestad, B.T. (2020) *Knowledge Update on Macroalgae Food and Feed Safety*. Norwegian Scientific Committee for Food and Environment (VKM Report).

EFSA Panel on Contaminants in the Food Chain (CONTAM) (2014) 'Scientific opinion on the risks to public health related to the presence of chromium in food and drinking water', *EFSA Journal*, 12(3), p. 3595.

Ender, A., Persson, P.-E., Olin, A. and Skog, K. (2019) 'Determination of iodine in seaweed using inductively coupled plasma mass spectrometry', *Journal of Analytical Atomic Spectrometry*, 34, pp. 2295–2302.

Ervik, H. (2019) 'The kelp Laminaria hyperborea as a bioindicator', *Journal of Water Technology and Treatment Methods*, 2(1), p. 122.

European Food Safety Authority (EFSA) (2006) *Tolerable Upper Intake Levels for Vitamins and Minerals*. Parma: European Food Safety Authority.

European Food Safety Authority (EFSA) (2013) 'Scientific opinion on the re-evaluation of boric acid (E 284) and sodium tetraborate (borax) (E 285) as food additives', *EFSA Journal*, 11(10), p. 3407.

European Food Safety Authority (EFSA) (2023) 'Statement on risk assessment related to the presence of benzalkonium chloride (BAC), didecyldimethyl ammonium chloride (DDAC) and chlorates in/on fish and fish products', *EFSA Journal*, 21(5), p. 8019.

European Food Safety Authority (EFSA) (2025) 'The 2023 European Union report on pesticide residues in food', *EFSA Journal*, 23(5), e9398.

Feldmann, J., John, K., Pengprecha, P., Hamor, T., Vaughan, G.T. and Cullen, W.R. (2000) 'Arsenic metabolism in seaweed-eating sheep from northern Scotland', *Fresenius' Journal of Analytical Chemistry*, 368, pp. 116–121.

Fera Science Ltd. (2022) *Turmeric Survey – Final Report for the Food Standards Agency*, FR/002267.

Fera Science Ltd. (2025) *Chemical Contaminants in Wild Caught Fish and Crustaceans – Northern Ireland*. Food Standards Agency Research and Evidence.

Fera Science Ltd. (2025) *Chemical Contaminants in Wild Caught Fishery Products and Crustaceans – Northern Ireland*. Food Standards Agency Research and Evidence.

Fera Science Ltd. (2025) *Contaminants Monitoring Programme for Wild Caught Fish, Crustaceans and Cephalopods*. Food Standards Agency Research and Evidence.

Fera Science Ltd. (2025) *Contaminants Monitoring Programme for Wild Caught Fish, Crustaceans and Cephalopods (England and Wales)*. Food Standards Agency Research and Evidence.

Fernandes, P.D., Costa, M.S., Pereira, R.C. and Teixeira, V.L. (2025) 'A new prenylated guaiane from the brown seaweed Dictyota mertensii', *Química Nova*, 48(6), pp. 1–6.

Ferreira, J., Cardoso, C., Afonso, C., Bandarra, N.M. and Carvalho, M.L. (2025) 'Assessing high-value bioproducts from seaweed biomass: a comparative study of wild, cultivated and residual pulp sources', *Applied Sciences*, 15(10), p. 5745.

Ficheux, A.S., Boniou, B., Durand, G., Le Garrec, R., Pierre, O. and Roudot, A.C., 2023. 'Dietary exposure and risk assessment to trace elements and iodine in seaweeds.' *Journal of Trace Elements in Medicine and Biology,*78, p.127187.

Fjære, E., Aune, U.L., Rørvik, K.-A., Kristensen, D.M., Madsen, L. and Maehre, H.K. (2022) 'Effects of dietary seaweed supplementation on nutrient composition and metabolic health', *Foods*, 11(24), p. 3943.

Food Safety Authority of Ireland (FSAI) (2020) *Safety Considerations of Seaweed and Seaweed-Derived Foods Available on the Irish Market*. Dublin: FSAI.

Food Standards Australia New Zealand (2008) *Final Assessment Report: Proposal P230. Consideration of Mandatory Fortification with Iodine for New Zealand.*

Francisco, D., Moreno, H.M., Carballo, J. and Borderías, A.J. (2018) 'Nutritional and bioactive compounds of Fucus vesiculosus and their potential applications', *Journal of Food Composition and Analysis*, 69, pp. 20–29.

García-Seoane, R., Aboal, J.R., Fernández, J.A. and Carballeira, A. (2020b) 'Optimal number of Fucus vesiculosus samples to differentiate between sites affected by distinct levels of heavy metal contamination', *Marine Pollution Bulletin*, 150, p. 110691.

García-Seoane, R., Fernández, J.A., Aboal, J.R., Carballeira, A. and Real, C. (2020a) 'Biomonitoring trace element contamination using Fucus vesiculosus in estuarine and coastal environments', *Marine Pollution Bulletin*, 156, p. 111281.

García-Seoane, R., Fernández, J.A., Aboal, J.R., Varela, Z. and Carballeira, A. (2024) 'A field study of the molecular response of brown macroalgae to heavy metal exposure: an (epi)genetic approach', *Science of the Total Environment*, 912, p. 168912.

Gendebien, M. (2025) *Cadmium Accumulation and Food Safety Implications in Saccharina latissima Cultivated in Norway*. Master's thesis. Norwegian University of Science and Technology.

German Environmental Specimen Bank (Umweltprobenbank des Bundes) (2025). *Monitoring data archive and environmental specimen database*. Umweltbundesamt (UBA), Germany.

Geurts, L., van den Dool, J., de Haan, J.J., de Boer, H.C., van der Wielen, R.P.J., Wieringa, P.A., van der Veen, J.W., de Vries, J.H.M., Katan, M.B. and van den Berg, S.W. (2024). 'The effect of Sargassum fusiforme and Fucus vesiculosus on continuous glucose levels in overweight patients with type 2 diabetes mellitus: a feasibility randomized, double-blind, placebo-controlled trial', *Nutrients*, 16(12), p. 1837.

Gunupuru, L.R., Patel, S.D., Dasari, S., Nimmagadda, V.P., Ahmad, J., Hashem, A. and Abd_Allah, E.F. (2019) 'Evaluation of antibacterial and antibiofilm properties of seaweed extracts against foodborne pathogens', *PLoS ONE*, 14(8), p. e0220562.

Gutow, L., Bartl, K., Saborowski, R. and Beermann, J. (2019) 'Gastropod pedal mucus retains microplastics and promotes the uptake of particles by marine periwinkles', *Environmental Pollution*, 246, pp. 688–696.

Hrólfsdóttir, A., Sveinsdóttir, H.I., Arason, S. and Gudjónsdóttir, M. (2025) Alternative industrial processing of seaweed meal from Ascophyllum nodosum: Value adding and product development potential of liquid side-streams obtained with different separation methods. Food and Bioproducts Processing. 151, pp127-136

Hrolfsdottir, L., Jónsdóttir, R., Arason, S., Pétursdóttir, Á.H., Margeirsson, B., Sigurðsson, G.M., Stefánsson, H. and Guðjónsdóttir, M. (2024). 'Physicochemical and bioactive properties of acid preserved Alaria esculenta and Saccharina latissima during storage', *LWT – Food Science and Technology*, 199, p. 116109.

Hrolfsdottir, L., Kristinsson, H.G., Jónsdóttir, R. and Jónsdóttir, Ó.G. (2022) 'Bioactive compounds and antioxidant activity of Ascophyllum nodosum from Iceland', *Marine Drugs*, 20(6), p. 340.

Huang, S.X., Jiang, Q., Ding, Y.F., Wang, F.J. and Zhu, C. (2020) 'Arsenic contents and speciation at different growth stages of Sargassum fusiforme [Harv.] Setchell (Hijiki), an edible seaweed', *Applied Ecology and Environmental Research*, 18(1), pp. 1941–1952.

Institute of Medicine (US) (2021) *Food and Nutrition Board: Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium and Zinc*. Washington, DC: National Academy Press.

Institute of Medicine (US) Panel on Micronutrients (2001) *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc*. Washington, DC: National Academies Press.

Iordache, A.M., Voica, C., Roba, C. and Nechita, C. (2024) 'Lithium content and its nutritional beneficence, dietary intake, and impact on human health in edibles from the Romanian market', *Foods*, 13(4), p. 592.

James, C.A., Welham, S. and Rose, P. (2023) 'Edible algae allergenicity – a short report', *Journal of Applied Phycology*, 35, pp. 339–352.

Jones, R., Smith, L., Walker, H. and Green, P. (2025) 'Consumer perception and culinary applications of edible seaweeds in Northern Europe', *International Journal of Gastronomy and Food Science*, 31, p. 100812.

Jönsson, E. and Nordberg Karlsson, E. (2024) 'Biorefinery potential of cultivated Alaria esculenta and Saccharina latissima from Ireland and Norway', *Journal of Applied Phycology*, 36, pp. 1881–1894.

Jönsson, E., Harrysson, H., Hayes, M., Eimer, F., Carlsson, N.-G. and Nordberg Karlsson, E. (2023) 'Evaluation of compositional and bioactive variation in cultivated brown macroalgae from Nordic production systems', *Algal Research*, 75, p. 103258.

Jørgensen, K. and Olesen, P.T. (2018) 'Kainic acid in the seaweed Palmaria palmata (Dulse)', *Food Additives & Contaminants: Part B*, 11(3), pp. 198–200.

Kedar, O., Golberg, A., Obolski, U., Shalev, G., Langer, E., Peleg, R., Zilberman, M., Shpigel, M. and Guttman, L. (2026). 'Initial allergenicity assessment of Ulva sp. seaweed flour', *NPJ Science of Food*, 10, 1.

Kenny, C., Burke, R. and Barry-Ryan, C. (2026) 'Impact of pretreatment on iodine content in *Laminaria digitata* assessed by inductively coupled Plasma-Mass Spectrometry', *Applied Food Research*, 6(1), p. 101852

Kerrison, P.D., Innes, M., Macleod, A., McCormick, E., Elbourne, P.D., Stanley, M.S., Hughes, A.D. and Kelly, M.S. (2020). Comparing the effectiveness of twine- and binder-seeding in the Laminariales species *Alaria esculenta* and *Saccharina latissima*. *Journal of Applied Phycology*, 32: 2173–2181.

Kim, D.-J., Oh, E.-B., Moon, J.-H., Choi, J.-W., Kim, T.-H., Lee, S.-H., Park, J.-Y., Kwon, C.-H. and Kyung, K.-S. (2025) 'Monitoring and risk assessment of pesticide residues in seafood using LC-MS/MS', *Foods*, 14(18), p. 3198.

Kinch, H.R. (2019) *Sellafield-derived 14C and 129I in the UK west coast intertidal environment*. MSc(R) thesis. University of Glasgow.

Koester, J.A. (2022) *Trying to grow like a weed: The impact of partial harvests on Alaria esculenta yield, quality, and cost*. Master's thesis, University Centre of the Westfjords, Iceland / University of Akureyri.

Kollander, B., Rodushkin, I. and Sundström, B. (2023) 'Multi-Element Assessment of Potentially Toxic and Essential Elements in New and Traditional Food Varieties in Sweden', *Foods*, 12(9), p. 1831.

Kononenko, G.P., Burkin, A.A., Georgiev, A.A. and Georgieva, M.L. (2021). Mycotoxins in macroalgae from the Velikaya Salma strait of the Kandalaksha Gulf of the White Sea. *Russian Journal of Marine Biology*, 47(6): 480–488.

Kononenko, G.P., Burkin, A.A., Georgiev, A.A. and Georgieva, M.L., 2022. Composition and Content of Mycotoxins in the White Sea Fucoids. *Oceanology*, *62*(6), pp.833-838.

Kotthoff, M., Fliedner, A., Rüdel, H., Göckener, B., Bücking, M., Biegel-Engler, A. and Koschorreck, J. (2020) 'Per- and polyfluoroalkyl substances in the German environment – levels and patterns in different matrices', *Science of the Total Environment*, 740, p. 140116.

Kreissig, K.J. (2021) *Greenland Seaweeds for Human Consumption*. PhD thesis. Technical University of Denmark.

Kreissig, K.J., Hansen, L.T., Jensen, P.E., Wegeberg, S., Geertz-Hansen, O. and Sloth, J.J. (2021) 'Characterisation and chemometric evaluation of 17 elements in ten seaweed species from Greenland', *PLoS ONE*, 16(2), e0243672.

Krook, J.L., Duinker, A., Larssen, W.E., Birkeland, I.M., Skeie, S., Horn, S.J. and Stevant, P. (2023) ‘Approaches for reducing the iodine content of the brown seaweed Saccharina latissima—effects on sensory properties’, *Journal of Applied Phycology*, 36, pp. 783–796.

Kumblad, L., Wiklund, A.-K.E. and Rydin, E. (2024) ‘Long-term evaluation of potential Al toxicity after an Al treatment in a coastal bay’, *Water Research*, 264, p. 122242.

Küpper, F.C., Carpenter, L.J., McFiggans, G.B., Palmer, C.J., Waite, T.J., Boneberg, E.-M., Woitsch, S., Weiller, M., Abela, R., Grolimund, D. and Meyer-Klaucke, W. (2014) ‘Iodide accumulation provides kelp with an inorganic antioxidant impacting atmospheric chemistry’, *Proceedings of the National Academy of Sciences*, 105(19), pp. 6954–6958.

Lamminen, M., Mäntysaari, P., Kairenius, P., Stefański, T., Huhtanen, P., Vanhatalo, A., Bayat, A.R., Kuoppala, K., Halmemies-Beauchet-Filleau, A. and Shingfield, K.J. (2026). ‘Effects of protein source and seaweed supplementation on mineral intake, milk mineral concentrations, and iodine transfer efficiency from feed to milk in lactating dairy cows’, *Journal of Dairy Science*, 109(2), pp. 1202–1218

Larsen, E.H., Pritzl, G. and Hansen, S.H. (2005) ‘Determination of inorganic arsenic in white fish using microwave-assisted alkaline alcoholic sample dissolution and HPLC-ICP-MS’, *Analytical and Bioanalytical Chemistry*, 381, pp. 339–346.

Leri, A.C., Hay, M.B., Lanzirotti, A. and Rao, W. (2019) ‘Particulate organohalogens in edible brown seaweeds’, *Food Chemistry*, 272, pp. 126–132.

Li, Q., Feng, Z., Zhang, T., Ma, C. and Shi, H. (2020) ‘Microplastics in the commercial seaweed nori’, *Journal of Hazardous Materials*, 388, p. 122060.

Li, X., Zhang, Y., Wang, J., Liu, H., Chen, X. and Zhao, L. (2025). ‘Investigation of chlorate formation during agar extraction from Gracilaria: process kinetics, thermodynamics, and mechanistic insights’, *Food Bioscience*, 72, p. 107495.

Lopez-Hortas, L., Flórez-Fernández, N., Torres, M.D., Ferreira-Anta, T., Casas, M.P., Balboa, E.M. and Domínguez, H. (2022) ‘Applying seaweed compounds in cosmetics, cosmeceuticals and nutricosmetics’, *Food Chemistry*, 383, p. 132450.

Lopez-Santamarina, A., Miranda, J.M., Mondragon, A.C., Lamas, A., Cardelle-Cobas, A. and Franco, C.M. (2022) ‘Potential use of marine seaweeds as prebiotics: a review’, *Food Research International*, 156, p. 111156.

Lorenzo, J.M., Agregán, R., Munekata, P.E.S., Franco, D., Carballo, J., Şahin, S., Lacomba, R. and Barba, F.J. (2017) ‘Proximate composition and nutritional value of three macroalgae: Ascophyllum nodosum, Fucus vesiculosus and Bifurcaria bifurcata’, *Marine Drugs*, 15(11), p. 360.

Lüning, K. and Mortensen, L.M. (2015) ‘European aquaculture of sugar kelp (Saccharina latissima) for food industries: current yield and future potential’, *Botanica Marina*, 58(6), pp. 449–455.

Lytou, A.E., Schoina, E., Liu, Y., Michalek, K., Stanley, M.S., Panagou, E.Z. and Nychas, G.-J.E. (2021) ‘Quality and safety assessment of edible seaweeds Alaria esculenta and Saccharina latissima cultivated in Scotland’, *Foods*, 10(9), p. 2210.

MacDonald, A.M. and Ó Dochartaigh, B.É. (2005) *Baseline Scotland: an overview of available groundwater chemistry for Scotland*. British Geological Survey Commissioned Report CR/05/239N.

MacDonald, A.M., Fordyce, F.M., Shand, P. and Ó Dochartaigh, B.É. (2005) *Using geological and geochemical information to estimate the potential distribution of trace elements in Scottish groundwater*. British Geological Survey Commissioned Report CR/05/238N.

Maribu, I., Elvevold, K., Eilertsen, K.-E. and Blikra, M.J. (2025) 'Seasonal variation in the nutritional composition and potentially toxic elements of the red macroalga *Palmaria palmata* in the Arctic', *Food Research International*, 212, p. 116477.

Marschner, K., Kruse, J., Amelung, W. and Fendorf, S. (2019) 'Arsenic speciation in marine macroalgae using advanced chromatographic techniques', *Analytica Chimica Acta*, 1049, pp. 20–28.

Martinelango, P.K., Tian, K., Dasgupta, P.K. and Anderson, T.A. (2006) 'Perchlorate in seawater: bioconcentration of iodide and perchlorate by various seaweed species', *Analytica Chimica Acta*, 567(1), pp. 100–107.

Martín-León, V., González-Muñoz, M.J., Pablos, M.V. and Martín-Díaz, M.L. (2021) 'Human exposure to toxic metals (Cd, Pb, Hg) and nitrates (NO3−) from seaweed consumption', *Food and Chemical Toxicology*, 158, p. 112689.

Ministry of Health and Welfare, South Korea (2020) *Dietary Reference Intakes for Koreans*. Sejong: Ministry of Health and Welfare.

Ministry of Health, Labour and Welfare, Japan (2014) *Dietary Reference Intakes for the Japanese*. Tokyo: Ministry of Health, Labour and Welfare.

Mise, N., Ohtsu, M., Ikegami, A., Mizuno, A., Cui, X., Kobayashi, Y., Nakagi, Y., Nohara, K., Yoshida, T. and Kayama, F. (2019) 'Hijiki seaweed consumption elevates levels of inorganic arsenic intake in Japanese children and pregnant women', *Food Additives & Contaminants: Part A*, 36(1), pp. 84–95.

Mohammed, H., O'Connor, P., Hayes, M. and Garcia-Vaquero, M. (2022) 'An assessment of selected nutritional, bioactive, thermal and technological properties of brown and red Irish seaweed species', *Foods*, 11(15), p. 2287.

Moreda-Piñeiro, A., Moreda-Piñeiro, J., Romarís-Hortas, V. and Bermejo-Barrera, P. (2016) 'Determination of arsenic species in edible seaweeds by HPLC-ICP-MS after pressurized hot water extraction', *Talanta*, 150, pp. 229–235.

Niedzwiedz, S., Schmidt, C., Yang, Y., Burgunter-Delamare, B., Andersen, S., Hildebrandt, L., Pröfrock, D., Thomas, H., Zhang, R., Damsgård, B. and Bischof, K. (2024) 'Run-off impacts on Arctic kelp holobionts have strong implications on ecosystem functioning and bioeconomy', *Scientific Reports*, 14(1), p. 30506.

Nielsen, C.W., Holdt, S.L., Sloth, J.J., Marinho, G.S. and Sæther, M. (2020) 'Reduction of iodine in Saccharina latissima by water blanching from varying temperature, time and water-seaweed ratio', *Foods*, 9(5), p. 569.

Nitschke, U. and Stengel, D.B. (2015) 'Quantification of iodine loss in edible Irish seaweeds during processing', *Food Chemistry*, 172, pp. 326–334.

Nitschke, U. and Stengel, D.B. (2016) 'A new HPLC method for the detection of vitamin B12 analogues in edible seaweeds', *Journal of Applied Phycology*, 28, pp. 3527–3533.

Nitschke, U., Connan, S. and Stengel, D.B. (2018) 'Chlorophyll a fluorescence responses of temperate Phaeophyceae under fluctuating light and nutrient regimes', *Journal of Phycology*, 54(1), pp. 114–125.

Nøkling-Eide, S.D., Horn, S.J., Aasen, I.M. and Stevant, P. (2023) 'Effects of processing and preservation on the biochemical composition of cultivated Saccharina latissima', *Algal Research*, 69, p. 102951.

Nøkling-Eide, S.D., Horn, S.J., Aasen, I.M. and Stevant, P. (2024) 'Structural and functional properties of polysaccharides extracted from cultivated brown seaweeds', *Carbohydrate Polymers*, 325, p. 121557.

Nunes, N., Valente, S., Ferraz, S., Marques, J., Silva, J., Rodrigues, A., Pinto, I.S.S., Abreu, H. and Domingues, P. (2024). 'Seasonal and geographical variation in the biochemical composition of edible macroalgae', *Journal of Applied Phycology*, 36, pp. 811–830.

Oaten, A., Liu, Q., Rooker, M.M. and MacFarlane, G.R. (2017) 'Metal accumulation and metallothionein response in Fucus spiralis', *Marine Pollution Bulletin*, 117(1–2), pp. 457–463.

Obluchinskaya, E.D., Pozharitskaya, O.N., Flisyuk, E.V. and Shikov, A.N. (2023) 'Biochemical composition and antioxidant activity of Fucus spiralis collected from Norway and Iceland', *Marine Drugs*, 21(4), p. 215.

Obluchinskaya, E.D., Pozharitskaya, O.N., Flisyuk, E.V. and Shikov, A.N. (2024) 'Ascophyllum nodosum (Linnaeus) Le Jolis from Arctic: its biochemical composition, antiradical potential, and human health risk', *Marine Drugs*, 22(2), p. 74.

Oliveira, J.M., Pardal, M.A., Pereira, L., Matos, A.M. and Rodrigues, E.T. (2024) 'Portuguese macroalgae and halophytes for human consumption: minimal risk of norovirus and Salmonella infection', *Food Control*, 164, p. 110600.

Olsson, J., Toth, G.B. and Albers, E. (2020a) 'Biochemical composition of red, green and brown seaweeds on the Swedish west coast', *Journal of Applied Phycology*, 32, pp. 3305–3317.

Olsson, J., Toth, G.B. and Albers, E. (2020b) 'Biochemical composition and seasonal variation in Ulva species from the Swedish west coast', *Applied Phycology*, 1(1), pp. 80–92.

Ometto, F., Steinhovden, K.B., Kuci, H., Marinho, G.S., Horn, S.J., Johnsen, G. and Angelidaki, I. (2018). 'Seasonal variation of elements composition and biomethane potential in brown macroalgae from Norway', *Journal of Cleaner Production*, 172, pp. 1263–1272.

Oretomiloye, O., Adewole, D., Nyachoti, C.M. and Kiarie, E. (2025) 'Effects of seaweed-derived feed ingredients on animal performance and gut health', *Canadian Journal of Animal Science*, 105, pp. 1–9.

Ownsworth, E.J., Wear, E.K., O'Connor, W.A. and Ross, D.J. (2019) 'The influence of environmental conditions on metal accumulation in marine macroalgae', *Science of the Total Environment*, 685, pp. 259–272.

Pacín, C., Fernández, J.Á., Conde-Amboage, M., Lazzari, M., García-Seoane, R., Viana, I.G., Varela, Z., Real, C., Villares, R. and Aboal, J.R. (2025). 'Three Decades of Change in Potentially Toxic Elements in Brown Algae in the Northeast Atlantic Ocean.' *Environmental Science & Technology*, 59(21), 10476–10487.

Pålsson, J., Magnusson, K., Dahl, M., Holm-Roos, M. and Granberg, M.E. (2024) 'Conclusions from the 2022 VLSFO oil spill on the Swedish west coast', *Proceedings of the International Oil Spill Conference*, 2024.

Parjikolaei, B.R., Bruhn, A., Eybye, K.L., Larsen, M.M., Rasmussen, M.B. and Christensen, K.V. (2016) 'Valuable biomolecules from nine North Atlantic red macroalgae: amino acids, fatty acids, carotenoids, minerals and metals', *Natural Resources*, 7, pp. 157–183.

Park, G.-Y., Kang, D.-E., Davaatseren, M., Shin, C., Kang, G.-J. and Chung, M.-S. (2019) 'Reduction of total, organic, and inorganic arsenic content in Hizikia fusiforme (Hijiki)', *Food Science and Biotechnology*, 28, pp. 615–622.

Park, H., Lee, K.W. and Shin, D. (2022) 'Association of seaweed consumption with metabolic syndrome and its components: findings from the Korean Genome and Epidemiology Study', *Foods*, 11(11), p. 1635.

Pearson, A.J. and Ashmore, E. (2020). 'Risk assessment of antimony, barium, beryllium, boron, bromine, lithium, nickel, strontium, thallium and uranium concentrations in the New Zealand diet.' *Food Additives & Contaminants: Part A*, 37(3), pp. 451–464.

Pennington, J.A.T. and Jones, J.W. (1987) 'Molybdenum, nickel, cobalt, vanadium and strontium in total diets', *Journal of the American Dietetic Association*, 87(12), pp. 1644–1650.

Petursdottir, Á.H., Sloth, J.J., Feldmann, J. and Gunnlaugsdottir, H. (2019) 'Characterisation of arsenic species in commonly consumed edible seaweeds in Iceland', *Analytical and Bioanalytical Chemistry*, 411, pp. 4973–4985.

Pinto, M.I., Micaelo, C., Vale, C., Sontag, G. and Noronha, P. (2014) 'Screening of priority pesticides in Ulva sp. seaweeds by selective pressurized solvent extraction before gas chromatography with electron capture detector analysis', *Archives of Environmental Contamination and Toxicology*, 67, pp. 547–556.

Raab, A., Feldmann, J., Meharg, A.A. and Hansen, H.R. (2025) 'Differential prevalence of arsenic speciation in the kelps Laminaria digitata and Laminaria hyperborea', *[Journal title requires verification]*.

Rambla-Alegre, M., Miles, C.O., de la Iglesia, P., Fernández-Tejedor, M., Jacobs, S., Sioen, I., Verbeke, W. and Diogène, J. (2017) 'Occurrence of cyclic imines in European commercial seafood and consumer risk assessment', *Environmental Research*, 161, pp. 392–398.

Ratcliff, J., Wan, A.H.L., Edwards, M.D. and Soler-Vila, A. (2016) 'Characterisation of cultivated Laminaria digitata for applications in food and feed', *Journal of Applied Phycology*, 28, pp. 1769–1782.

Reynolds, C.K., Humphries, D.J., Künzel, S., Rodehutscord, M., Lignou, S., Fagan, C.C., Methven, L., Norton, G., Alzahrani, A., Feldmann, J., Desnica, N., Gunnlaugsdottir, H. and Pétursdóttir, Á.H. (2025) 'Effects of feeding dairy cows seaweed mixtures on feed intake, methane emission, milk production, and milk mineral and fatty acid composition', *Journal of Dairy Science*, 108(9), pp. 9487–9500.

Rimmer, C., Fisher, J. and Turner, A. (2024) 'Biomonitoring of microplastics, anthropogenic microfibres and glass retroreflective beads by marine macroalgae', *Environmental Pollution*, 348, p. 123801.

Rodrigues, D., Freitas, A.C., Pereira, L., Rocha-Santos, T.A.P., Vasconcelos, M.W., Roriz, M., Rodríguez-Alcalá, L.M., Gomes, A.M.P. and Duarte, A.C. (2015) 'Chemical composition of red, brown and green macroalgae from Buarcos Bay in Central West Coast of Portugal', *Food Chemistry*, 183, pp. 197–207.

Roleda, M.Y., Skjermo, J., Marfaing, H., Jónsdóttir, R., Rebours, C., Gietl, A., Stengel, D. and Nitschke, U. (2018) 'Iodine content in bulk biomass of wild-harvested and cultivated edible seaweeds: inherent variations determine species-specific daily allowable consumption', *Food Chemistry*, 254, pp. 333–339.

Roleda, M.Y., Marfaing, H., Desnica, N., Jónsdóttir, R., Skjermo, J., Rebours, C. and Nitschke, U. (2019) 'Variations in polyphenol and heavy metal contents of wild-harvested and cultivated seaweed bulk biomass: health risk assessment and implication for food applications', *Food Control*, 95, pp. 121–134.

Roleda, M.Y., Nitschke, U., Sørensen, A.-D.M., Marfaing, H., Holdt, S.L., Vasanth, V. and Fletcher, H.L. (2021). 'Effect of processing on nutritional composition and functional properties of Ulva species', *Food Chemistry*, 341, p. 127999.

Ronan, J.M., Stengel, D.B., Raab, A., Feldmann, J., O'Hea, L. and Bralatei, E. (2017) 'High proportions of inorganic arsenic in Laminaria digitata but not in Ascophyllum nodosum samples from Ireland', *Chemosphere*, 186, pp. 17–23.

Sá Monteiro, M., Sloth, J.J., Holdt, S.L. and Hansen, M. (2019) 'Analysis and risk assessment of seaweed', *EFSA Journal*, 17(Suppl. 2), e170915.

Sabouraud-Leclerc, D., Mariotte, D., Bradatan, E., Divaret-Chauveau, A., Metz-Favre, C., Beaumont, P., Dumond, P., Serrier, J., Karaca-Altintas, Y., Tscheiller, S., Pouessel, G. and Van der Brempt, X. (2025) 'Food anaphylaxis: eight food allergens without mandatory labelling highlighted by the French Allergy-Vigilance Network', *Clinical & Experimental Allergy*, 55(11), pp. 1118–1125.

Sakon, N., Sadamasu, K., Shinkai, T., Hamajima, Y., Yoshitomi, H., Matsushima, Y., Takada, R., Terasoma, F., Nakamura, A., Komano, J., Nagasawa, K., Katayama, K. and Kimura, H. (2018) 'Foodborne outbreaks caused by human norovirus GII.P17-GII.17–contaminated nori, Japan, 2017', *Emerging Infectious Diseases*, 24(5), pp. 920–923.

Samarasinghe, R.M., Hosseindoust, A., Lee, S.H., Kim, J.S., Choi, Y.H. and Chae, B.J. (2021) 'Effects of dietary seaweed supplementation on growth performance, nutrient digestibility and gut health in livestock', *Animal Feed Science and Technology*, 278, p. 115005.

Sartipizadeh, A., Hosseini, S.A., Yeganeh, S. and Ghaedi, A. (2023) 'Effects of seaweed-derived feed additives on aquaculture performance and health', *Aquaculture Nutrition*, 2023, p. 6664947.

Schiener, P., Black, K.D., Stanley, M.S. and Green, D.H. (2015) 'The seasonal variation in the chemical composition of Scottish seaweeds Laminaria digitata, Laminaria hyperborea, Saccharina latissima and Alaria esculenta', *Journal of Applied Phycology*, 27, pp. 363–373.

Schiener, P., Zhao, S., Theodoridou, K., Carey, M., Mooney-McAuley, K. and Greenwell, C. (2017) 'The nutritional aspects of biorefined Saccharina latissima, Ascophyllum nodosum and Palmaria palmata', *Biomass Conversion and Biorefinery*, 7(2), pp. 221–235.

Scottish Government, Food Standards Agency (FSA), British Oceanographic Data Centre and Food Standards Scotland (FSS) (2025) *Marine Strategy Assessment – Contaminants in Seafood.*

Sekar, S., Jeyachandran, S., Giri, J. and Aman, M. (2025) 'Advancing sustainable agriculture: the potential of seaweed-derived biopesticides from marine biomass', *Bioresources and Bioprocessing*, 12(1), p. 22.

Sim, J., Feldmann, J., Raab, A. and Krupp, E.M. (2023) 'Arsenic speciation and environmental chemistry in edible seaweeds', *Environmental Chemistry*, 20(2), pp. 55–65.

Sim, J., Feldmann, J., Raab, A. and Krupp, E.M. (2024a) 'A comprehensive analysis of water-soluble arsenicals in Icelandic macroalgae', *Environmental Chemistry*, 21(4), p. 24024.

Sim, J., Feldmann, J., Raab, A. and Krupp, E.M. (2024b) 'Inorganic arsenic in seaweed: a fast HPLC-ICP-MS method without coelution of arsenosugars', *Analytical and Bioanalytical Chemistry*, 416, pp. 1–12. DOI:

Sletta, H., Nøkling-Eide, S.D., Horn, S.J. and Stévant, P. (2025) 'Blanching of two commercial Norwegian brown algae for reduction of iodine and other compounds of importance for food safety and quality', *Foods*, 14(23), p. 4113.

Sneddon, A.A. (2023). *Heavy metal content in Scottish seaweeds: report for the Scottish Seaweed Industry Association*. University of Aberdeen, Aberdeen, UK. (unpublished industry report).

Soares, C., Sousa, S., Machado, S., Vieira, E., Carvalho, A.P., Ramalhosa, M.J., Morais, S., Correia, M., Oliva-Teles, T. and Domingues, V.F. (2021) 'Bioactive lipids of seaweeds from the Portuguese north coast: health benefits versus potential contamination', *Foods*, 10(6), p. 1366.

Stedt, A., Nylund, G.M., Pavia, H., Nielsen, M.M., Nielsen, S.L., Nielsen, S.M. and Holdt, S.L. (2025). 'From waste to value: cultivating Palmaria palmata in liquid seafood side-stream enhances its growth and nutritional composition', *Algal Research*, 92, p. 104371.

Steinhagen, S., Karez, R. and Weinberger, F. (2019) 'Cryptic, alien and lost species: risks and opportunities associated with seaweed cultivation', *European Journal of Phycology*, 54(3), pp. 466–483.

Stévant, P., Marfaing, H., Duinker, A., Fleurence, J., Rustad, T., Sandbakken, I. and Chapman, A. (2017) 'Biomass soaking treatments to reduce potentially undesirable compounds in the edible seaweeds sugar kelp (Saccharina latissima) and winged kelp (Alaria esculenta) and health risk estimation for human consumption', *Journal of Applied Phycology*, 30(3), pp. 2047–2060.

Stévant, P., Roleda, M.Y., Schmid, M., Maehre, H.K., Løvstad, C.M., Hansen, E., Jónsdóttir, R. and Holdt, S.L. (2025a). 'Iodine reduction and retention of nutrients and flavour-active compounds upon warm seawater treatment of the kelps Alaria esculenta and Saccharina latissima', *Algal Research*, 86, 103969.

Stévant, P., Zioga, E., Steenholdt Sørensen, J., Bang-Berthelsen, C.H., Dahl, T.H., Barnung, T., Kleppe, M. and Løvdal, T. (2025b) 'Fermentation of sugar kelp (Saccharina latissima): exploring the potential of the kelp's native microbiota as starter culture and the microbiological food safety of fermented products', *Frontiers in Food Science and Technology*, 4, p. 1490547.

Sund, K., Torkelsen, L., Skjermo, J., Aasen, I.M., Horn, S.J., Carvajal, A.K., Rustad, T. and Hansen, E. (2025a). 'Impact of post-harvest processing on Alaria esculenta and its application in a model fish-based product', *Applied Food Research*, 5(2), 101309.

Sund, K., Torkelsen, L., Skjermo, J., Aasen, I.M., Horn, S.J., Carvajal, A.K., Rustad, T. and Hansen, E. (2025b). 'Pulsed electric field processing as an alternative to warm water treatment for the reduction of potentially toxic elements in Saccharina latissima, *Journal of Applied Phycology*. 38, pp. 933–94

Sundbæk, K.B., Koch, I.D.W., Villaro, C.G., Hartmann, N.B., Gunnarsson, L.M., Lippe, S. and Strand, J. (2018) 'Sorption of fluorescent polystyrene microplastic particles to edible seaweed Fucus vesiculosus', *Journal of Applied Phycology*, 30, pp. 2923–2927.

Suther, H.L. (2024) *Legacy and Emerging Contaminants of Concern in Edible Seaweeds of the Salish Sea*. MSc thesis. Western Washington University.

Taylor, V.F. and Jackson, B.P. (2016) 'Concentrations and speciation of arsenic in New England seaweed species harvested for food and agriculture', *Chemosphere*, 163, pp. 6–13.

Thorsteinsson, T., Olafsdottir, G., Hansen, M.M., Jónsdóttir, R., Skjermo, J., Aasen, I.M., Marfaing, H., Fleurence, J. and Holdt, S.L. (2024). 'Potential of two northern European brown seaweeds (*Fucus serratus* and *Fucus vesiculosus*) as enteric methane inhibitors in dairy cows', *Journal of Dairy Science*, 107(12), pp. 10628–10640.

Tolpežnikaitė, E. (2024) 'Optimization of micro- and macroalgal biomass pretreatment for its conversion to higher-value feed materials', Doctoral dissertation, Lithuanian University of Health Sciences.

Trigo, J.P., Engström, N., Stevant, P., Horn, S.J. and Eikevik, T.M. (2023) 'Mild blanching prior to pH-shift processing of Saccharina latissima retains protein extraction yields and amino acid levels of extracts while minimizing iodine content', *Food Chemistry*, 405, p. 134814.

Ungureanu, G., Santos, S., Boaventura, R.A.R. and Botelho, C.M.S. (2015). Biosorption of antimony by brown algae S. muticum and A. nodosum. *Environmental Engineering and Management Journal*, 14(2): 455–463.

US EPA. 2012. Provisional peer-reviewed toxicity values for thallium (soluble salts). US EFA, Washington DC. EPA/690/R-12/026F.

Van Tuinen, S.T., Gsell, A., Faassen, E.J. and Beerman, A.A.A. (2023). *Correlations in the presence of contaminants in Ulva lactuca spp.: part of KB Project on Marine lower trophic systems (KB-34-007-004 1-2C-4)*. Wageningen Food Safety Research, WFSR Report 2023.009: 40 pp.

Vázquez-Arias, A., Boquete, M.T., Martín-Jouve, B., Tucoulou, R., Rodríguez-Prieto, C., Fernández, J.Á. and Aboal, J.R. (2024). 'Nanoscale distribution of potentially toxic elements in seaweeds revealed by synchrotron x-ray fluorescence', *Journal of Hazardous Materials*, 480: 136454.

Viana, T., Ferreira, N. and Pereira, E. (2024) 'Valorisation of acid mine drainage: studying biosorption and bioaccumulation of rare earth elements by seaweeds', *Science of the Total Environment*, 957, p. 177761.

Villares, R., Fernández-Lema, E. and López-Mosquera, E. (2013). Seasonal variations in concentrations of macro- and micronutrients in three species of brown seaweed. *Botanica Marina*, 56: pp49–61.

Visch, W., Nylund, G.M. and Pavia H. (2020). Growth and biofouling in kelp aquaculture (Saccharina latissima): the effect of location and wave exposure. *Journal of Applied Phycology*, 32: pp3199–3209

Wang, X., Blikra, M.J., Evensen, T.H., Skipnes, D. and James, P. (2022). Effects of site, depth and sori origin on the growth and mineral composition of cultivated Saccharina latissima (Phaeophyceae) in the north of Norway. *Journal of Applied Phycology*, 34: 529–541.

Wegeberg, S., Søndergaard, J. and Geertz-Hansen, O. (2023). Elements and sugars in kelp and fucoid species in Greenland, correlation and seasonality. *Algal Research*, 75: 103240.

Westby, T. (2018). *Investigation of the mineral profile of Fucus serratus Linnaeus aqueous extracts and examination of the routes of uptake of minerals both in vivo and in vitro*. PhD thesis, Institute of Technology Sligo, Ireland

World Health Organization (WHO) (1989) Iodine: evaluations of the Joint FAO/WHO Expert Committee on Food Additives (JECFA).

Woźniak,Ł. and Moya, M. S. P. (2024). Assessment of chemical risks and benefits connected with macroalgae consumption. *EFSA Journal*, 22(S1), e221109.

Yandi, Y., Lusher, A.L., Woodall, L.C., Hernandez-Milian, G., Gago, J., Pham, C.K., Stoll, S., Löder, M.G.J. and Gerdts, G. (2026). An overlooked source of marine plastic pollution: Depth-wise quantification of plastic emissions from offshore aquaculture mooring ropes. *Marine Pollution Bulletin*, 223: 119051.

Yang, M., Her, N., Ryu, J. and Yoon, Y. (2014). Determination of perchlorate and iodide concentrations in edible seaweeds. *International Journal of Environmental Science and Technology*, 11(3), pp. 565–570.

Yen, Y., Weisbjerg, M.R., Rautenberger, R., Fečkaninová, A., and Novoa-Garrido, M. (2021). Improving fermentation of Saccharina latissima and Alaria esculenta silages with additives for preserving biomass and antioxidants. *Journal of Applied Phycology*, 34, pp625–636.

Yeon-hee Kim, Wook-jin Ra, Solyi Cho, Shinai Choi, Bokyung Soh, Yongsung Joo & Kwang-Won Lee. 2021. Method Validation for Determination of Thallium by Inductively Coupled Plasma Mass Spectrometry and Monitoring of Various Foods in South Korea. Molecules. 26(21), 6729.

Yu, Y., Morales-Rodríguez, A., Zhou, G., Barrón Bueno, D., Sahuquillo Estrugo, À., and López-Sánchez, J.F. (2024). Survey of arsenic content in edible seaweeds and their health risk assessment. *Food and Chemical Toxicology*, 187, 114603

Yue, S.R., Shrivastava, R., Campbell, K. and Walker, M.J. (2023) 'Food allergen recalls in the United Kingdom: a critical analysis of reported recalls from 2016 to 2021', *Food Control*, 144, p. 109375.

Zettergren, P. (2022). *Nordic sea vegetables as a future edible crop: is it sustainable and safe?* Master's thesis, Swedish University of Agricultural Sciences (SLU), Alnarp, Sweden.