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Title

Seaweed as food: survey of the UK market and appraisal of opportunities and risks in the context of iodine nutrition.

Short running title

Seaweed food survey and iodine

Abstract

Purpose

Seaweeds are gaining broader interest in Western societies, through use in product development and the health-food industry. High nutritional value, low carbon footprint and sustainability are key drivers for seaweed uptake in Europe; yet high iodine intake from seaweed remains a concern. This paper seeks to identify to seaweed food products available on the United Kingdom retail market between 2018 and 2021 and assess their safety in the context of iodine exposure.

Methodology

Here, we conducted a market survey (n=37-40 retailers) in three annual waves to evaluate seaweed food product availability in the United Kingdom. The iodine dose of products was estimated based on a comprehensive literature review of seaweed iodine content.

Findings

We show a young, dynamic market, with 2.3-fold increase in seaweed food product availability since the last available published data (2015). Specific iodine content labelling remains uncommon, and median iodine doses in a single serving of food exceeded 400 µg in all years. Some products, especially seaweed supplements, provide iodine doses above the tolerable upper limit and upper level of tolerance.

Originality

This study presents the most contemporary and comprehensive overview of the market for seaweed food products in the United Kingdom. With increasing popularisation of seaweed as a food, we highlight the need for improved dialogue between producers, retailers, legislators, and public health specialists to address the risk of iodine excess, and the concurrent scope for processing methods to reduce the iodine content in seaweeds.

Keywords

iodine; seaweed; kelp; macroalgae; product survey; algae

Introduction

Over 30 million tonnes of marine macroalgae (seaweed) are harvested yearly, with seaweed a staple food in Asian cultures (>12 g/day estimated consumption in Japan)(Doumeizel et al., 2020, Zava and Zava, 2011). In contrast, besides Atlantic coastal communities, seaweeds have not been a significant component of Western-style diets (Mouritsen et al., 2013). Yet, research has shown emerging seaweed food product availability across leading retailers in the last decade (Bouga and Combet, 2015). With attractive nutritional profiles, seaweeds hold potential to contribute to food systems as a sustainable source of essential micronutrients (iodine, iron, potassium, zinc (Circuncisão et al., 2018)), unique polysaccharides (fucoidan, laminarin, porphyran), and bioactive compounds (carotenoids, polyphenols)(Peñalver et al., 2020). Accordingly, seaweeds have garnered interest not only as a 'functional food' (Holdt and Kraan, 2011), but also as part of a more comprehensive nutrition strategy for addressing the burden of global hunger and micronutrient deficiencies (Doumeizel et al., 2020). Seaweed consumption is, however, not without risk. High doses of iodine and heavy metal ingestion (arsenic, lead, cadmium) can follow seaweed consumption, owing to their inherent biological capacity to accumulate these compounds (Besada et al., 2009, Roleda et al., 2018).

Excessive exposure to iodine, a core component of thyroid hormones, can result in thyroid dysfunction (Leung and Braverman, 2014). Consequently, different intake limits are set at 600 µg/day (EFSA Panel on Dietetic Products and Allergies, 2014) (European tolerable upper limit (TUL)) and 1100 µg/day (Institute of Medicine (US) Panel on Micronutrients, 2001) (adult upper level of tolerance (ULT)) to reflect this risk. Iodine concentration varies greatly within and between seaweed species, with certain species containing particularly high levels of iodine (>7000 µg/g (Roleda et al., 2018)). Despite this risk, evidence of seaweed food iodine content monitoring is limited. An Italian market analysis found high iodine concentrations in fresh and dried seaweed products, with 1 kelp (*Laminaria* sp.) product exceeding the ANSES maximum recommended level of iodine (2000 mg/kg) ~3 times (Filippini et al., 2021). Norwegian kelp products also contained high levels of iodine, 128-168,000 µg per portion, ~100 times the TUL (Aakre et al., 2021). More recently, a survey of UK retailers highlighted emerging availability of seaweed food products, with >200 unique products identified (median iodine content 585 µg/serving (IQR 105-2520 µg)) and only 10% explicitly reporting their iodine content (Bouga and Combet, 2015).

Recent publications (e.g., UN Seaweed Manifesto (Doumeizel et al., 2020), European Commission 'Blue Economy Strategy' (European Commission, 2021)) and the formation of macroalgae-focused working groups in the EU (GENIALG, 2020, European Cooperation in Science and Technology, 2015, ALEHOOP, 2021) highlight the growing European interest in macroalgal aquaculture and seaweeds as foods, driven by a desire for healthy, innovative, and environmentally sustainable products to feed a growing population. Although seaweeds undoubtedly offer attractive nutritional qualities, high iodine concentrations reported in seaweed products (Bouga and Combet, 2015, Filippini et al., 2021, Aakre et al., 2021) pose a potential health risk to consumers. Surveying and monitoring the current market for seaweed products allows for evaluation of product availability, composition, labelling, and traceability data, which together provide an insight into the safety of seaweed inclusion in diets.

This survey comprehensively evaluates seaweed food products available on the UK market between 2018 and 2021, collating information of relevance to consumers, the seaweed industry, and the wider legislative authorities responsible for ensuring the safety of foods.

Methods

Product search strategy

Food products and supplements were surveyed systematically on retailer websites. Retailers were considered eligible for inclusion in the product search if they had in-store retail outlets in the UK, sold products from a '.co.uk' web address, or sold products from a '.com/.eu' web address and offered payment in GBP and shipping to the UK. Following identification, retailers were categorized into three groups: traditional supermarkets (e.g., Morrisons, Tesco), specialist health stores (e.g., Holland & Barrett), and independent companies/brands. The search strategy was adapted from a previous survey(Bouga and Combet, 2015). All original search terms were included ("seaweed", "kelp", "algal", "Arame", "Kombu", "Dulse", "*Laminaria*", "*Ascophyllum*", "lava bread", "miso soup", and "sea vegetable"), with the addition of several terms for enhanced search coverage ("laver", "sushi", "sea greens", "nori", "wakame", "hijiki", "sea lettuce", "sea spaghetti", "*Porphyra*", and "*Saccharina*").

The survey was carried out in three distinct waves: wave 1 (W1) between December 2018 and January 2019, wave 2 (W2) between December 2019 and February 2020, and wave 3 (W3) between December 2020 and January 2021. Results from the 2015 survey are referred to as Wave 0 (W0) henceforth (Bouga and Combet, 2015).

Product data collection

For each product, data was recorded on price, country of origin, serving size, seaweed type and proportion, iodine labelling and content, and any health claims made on the packaging relating to either iodine or seaweed. If more than one retailer sold the product at different prices, the average price was recorded. Where a serving size was not indicated on the product packaging or online description, serving size was estimated per the requisite food category using the demographic average portion sizes specified in Nutritics dietary analysis software (Nutritics, 2020).

Iodine content

The iodine content of each product was extracted from product packaging (if visible in the product photograph) or online information. If the information was not available, iodine content was estimated if the type and proportion of seaweed were listed. Estimations were based on published data relating to the iodine content of seaweeds (Supplementary Table 1).

Health claims

All information relating to either seaweed or iodine present on visible packaging (i.e., photographs of the products online) and in the online description was transcribed verbatim and stored alongside product information. Claims were compared against the European

Register of Nutrition and Health Claims (The European Commission, 2020) and classified as either an authorised or non-authorised claim. There are currently 6 authorised health claims for iodine in the register, and none relating to seaweed. Products that mentioned authorised health claims for iodine in relation to seaweed (e.g., kelp contributes to the normal production of thyroid hormones), without specifying that these claims were specific to iodine, were considered non-authorised.

Data analysis

Data were collated, manually de-duplicated, and cleaned in Microsoft Excel (2016). Descriptive statistics were used to describe product characteristics in each survey wave. Data presented are median and interquartile range due to the non-parametric nature of the data, as assessed by Shapiro-Wilk test, with significance set at $p<0.05$. Differences between survey waves were evaluated using the Kruskal-Wallis H test, with Bonferroni correction for multiple testing. Data analysis was performed using a combination of Microsoft Excel (2016), IBM SPSS Version 27.0 (IBM Corp., 2016), and the R environment for statistical computing (R Core Team, 2013) in RStudio (RStudio Team, 2015). Statistical analyses were conducted using IBM SPSS Version 27.0. All figures were produced primarily using the 'ggplot2' package for R (Wickham, 2016).

Results

Retailer identification

In total, n=42 retailers were identified for inclusion in the product search (Supplementary Table 2), of which n=40 had an online presence and were searched in W1, reducing to n=39 in W2 and n=37 in W3. The retailers searched comprised n=9 traditional supermarkets, n=15 specialist health stores, and n=16 independent brands/companies (n=15 in W2 and n=14 in W3).

Product availability and distribution

In W1, n=450 unique products were identified from n=40 retailers, a 2-fold increase since 2015 (W0)(Bouga and Combet, 2015). Product availability increased 1.2-fold from W1 to W2, with n=515 unique products identified, and remained stable in W3 (n=523 products; 1.02-fold increase). The proportion of products available from each retailer category remained stable across the 3 waves, with 26-30% of products sold by traditional supermarkets, 59-62% sold by specialist health stores, and 9-12% sold by independent brands. In all waves, most products (61-75%) were available exclusively from online retailers, with the remainder available to purchase both online and in-store.

Market dynamism

Of the 450 products identified in W1, 60% (n=269) were also found in the W2 survey (Figure 1). Although 38% (n=173) of products from W1 were not identified in W2, 241 novel products were identified, accounting for 47% of total W2 products. Of 515 products identified in W2, 65% (n=334) were also found in the W3 survey, whilst 34% (n=176) were not found. There

were 156 novel products identified in W3 that had not been seen in previous surveys, accounting for 30% of total W3 products. Additionally, 45% (n=204) of products from W1 recurred in both W2 and W3, with 4% (n=19) of W1 products not appearing in W2 but recurring in W3.

[FIGURE 1]

Figure 1. Number of seaweed food products identified in each wave of the survey. The number of products lost each year (i.e., those present in 1 wave but not identified in the next wave) and new products (i.e., products not identified previously) are noted.

Product categorization

Products were classified into 12 categories: bread and confectionery, condiments, drinks, noodles and pasta, salads, seaweed (as a whole food), snacks, soup, sushi, supplements, ready meals, and others, per Bouga & Combet (Bouga and Combet, 2015). Through W1-3, supplements, seaweed, and snacks maintained a consistently high prevalence. Whilst proportions of seaweed and snacks remained stable, the proportion of supplement products increased from 18% (n=80) of all products in W1 to 29% (n=153) of products by W3 (Figure 2).

Several categories exhibited substantial expansion between W0 and W1, including seaweed (2.4-fold growth), supplements (7.3-fold increase), soup (2-fold increase), and snacks (6.4-fold increase). Between W1 and W2, condiments, drinks, and bread & confectionery categories expanded more than 2-fold, with expansion also evident in condiments, snacks, sushi, and supplement categories (Figure 2). Between W2 and W3, no categories expanded more than 1.2-fold. Five categories (condiments, drinks, snacks, sushi, and ready meals) decreased in number, some by almost half (e.g., drinks, 53% decrease).

[FIGURE 2]

Figure 2. Change in percentage contribution to total product availability from each product category from Wave 0 (2014-15(Bouga and Combet, 2015)) to Wave 3 (2020-21).

Product price, size, and energy provision

Product price increased between W1 (£3.99, IQR £2.70-£7.99) and W3 (£5.45 IQR £2.99-£14.30) ($H(2)=13.806$, $p=0.001$) (Appendix 1), with no detectable change between W1 and W2, and W2 and W3. When products were separated into 'food' and 'supplements' categories, the median price, packaging size, and serving size did not differ between waves. Food products had a median price (per whole product) of ~£3.50 and supplement products ~£17.00, across all waves of the survey.

The energy content of all products and food products did not change between waves ($H(2)=0.329$, $p=0.846$), with a decrease in the energy content (~200 kcal) of supplement products ($H(2)=6.444$, $p=0.040$) in W3.

Packaging size for all products did not change between waves ($H(2)=0.32$, $p=0.984$). Median product serving size did not vary between waves for the food category or the supplement

category. However, packaging size was different between waves for all products (H(2)=13.340, p=0.001)), decreasing from W1 (15 g, IQR 4-49 g) to W2 (10 g, IQR 2-33 g) (p=0.004), and staying at this level into W3 (10 g, IQR 2-33 g) (Appendix 1).

Product origin

Across the 3 survey waves, products originated from n=19 different countries, spanning n=4 continents (Appendix 4). Generally, product origin was poorly defined, with most of the products in W1 (n=181, 40%), W2 (n=242, 47%) and W3 (n=255, 49%) having no origin labelling on their packing or available in the information provided online (Box A, Appendix 4). In W1, over a third of products (n=151, 34%) originated from the UK, with Japan (n=31, 7%) and Spain (n=22, 5%), contributing the next largest number of products. Notable origin differences between products identified in W0 and W1 included expansion of seaweed product production in North America (18-fold increase) and Europe (excluding the UK) (38-fold increase). The proportion of products with no origin information also increased from 25% in W0 to 40% in W1. In W2, products originated mainly from the UK (n=133, 26%), followed by South Korea (n=27, 5%) and Japan (n=27, 5%). In W3, products with origin labelling again originated mainly from the UK (n=150, 29%). Spain (n=26, 5%) and Japan (n=25, 5%) contributed the second and third largest number of products.

Seaweed type and proportion in food and supplement products

Kelp (*Laminaria* and *Saccharina* spp., 19-25% of products) and nori (*Porphyra* spp., 11-14% of products) were the main seaweed types used in products in all 3 waves, followed by either wakame (*Undaria pinnatifida,* W1: 10%, W3: 7% of products) or wrack (W2: 8% of products) (Table 1). Products containing a blend of 2 or more seaweeds accounted for 6-9% of products across the 3 waves. Up to a quarter of products (21% in W1 and W3, 27% in W2) provided no information on seaweed type in the products, similar to data from 2014-15 (22%).

Table 1. Seaweed type used in products in each survey wave (n, %).

[TABLE 1]

[1] Products containing more than one type of seaweed. Further details on seaweed species categorization into the types listed here can be found in Supplementary Table 1.

To further explore the utilization of seaweed in foods, products were separated into 'food' and 'supplement' categories. The proportion of seaweed in food products, as noted in the ingredients list on product packaging, was over 65% in each wave. Similarly, supplement products contained a high proportion of seaweed, over 90% in all waves (Table 2). Notably, however, around half of food products (48-51%) and three-quarters of supplement products (75-88%) provided no information on the proportion of seaweed used in product preparation.

Table 2. The proportion of seaweed used in food and supplement products.

[TABLE 2]

Iodine content labelling

There was a marked improvement in the proportion of products explicitly labelling iodine content on product packaging across the 3 waves (W1: 9%, W2: 16%, W3: 22%). The proportion of products providing information on iodine content increased for both food (W1: 4%, W2: 10%, W3: 14%) and supplement categories (W1: 29%, W2: 34%, W3: 43%) across the 3 waves, remaining consistently higher for supplement products compared to food products. However, the provision of compositional information (i.e., seaweed type and percentage) was poor across all survey waves (Tables 1 and 2). The proportion of products providing neither specific information on iodine content nor sufficient information to allow for estimation remained high in all 3 waves (W1: 60%, W2: 60%, W3: 57%).

Iodine content

Median iodine content per serving for all products and food products remained relatively stable from W1 to W2, at over 400 μg/serving (Figure 3). With very high variability within each wave, there was no difference in median iodine content of all products between W2 (411 μg/serving (IQR 96-1353) and W3 713 μg/serving (IQR 107-2668).

Whilst there was no change between waves for median iodine content per serving in the food product category, the median iodine content of supplement products increased close to 3-fold from 595 μg/serving (IQR 150-890) in W1 to 1050 μg/serving (IQR 682-3724) in W3 ($H(2)=7.536$, $p=0.023$) (Appendix 2, Figure 3).

In all 3 waves, 10-17% of all products identified (including those for which iodine content was incalculable) would provide, in a single serving, an iodine dose exceeding the 1100 μg/day ULT (Institute of Medicine (US) Panel on Micronutrients, 2001) and the European TUL of 600 μg/day (EFSA Panel on Dietetic Products and Allergies, 2014) (Appendix 2), with no difference between waves ($p=0.130$). For food products, 16-18% of all food products would provide a supra-TUL dose, whilst 11-15% of products provided a supra-ULT dose. Between 8 and 10% of supplement products would provide a supra-TUL dose, and 5-8% would provide a supra-ULT dose.

[FIGURE 3]

Figure 3. A) Median iodine content (μg/serving) of food products by each survey wave: W0 – 2014-15 (data from Bouga and Combet, 2015), W1: 2018-19, W2: 2019-20, W3: 2020-21. **B)** Median iodine content (μg/serving) of supplement products by each survey wave: W0 – 2014-15 (data from Bouga and Combet, 2015), W1: 2018-19, W2: 2019-20, W3: 2020-21. For both figures, only products with a calculable iodine content are displayed as points and the red dashed line represents 600 μg of iodine, the European Tolerable Upper Limit (TUL) set by the European Food Safety Authority (EFSA)(EFSA Panel on Dietetic Products and Allergies, 2014).

Health claims

A minority of products (6-9% across the 3 waves) carried a health claim on either packaging or online information supporting the products (Appendix 2) – of these, most were approved by the European Commission (The European Commission, 2020), and focused on the 6 approved health claims for iodine. Products carrying non-approved health claims (n=5 in W1, n=5 in W2, n=15 in W3) focused on involvement of iodine in processes such as detoxification, immunity, and fertility (Appendix 3).

Discussion

Since 2015, seaweed food product availability has increased 2.3-fold with a large expansion in products with a European origin (excluding the UK), highlighting the attractiveness of seaweed as a commercial proposition for Western diets, especially as a component of snack foods and dietary supplements. These increases may be due to the potential of seaweeds for addition to 'functional foods' (Holdt and Kraan, 2011) and the rise in health consciousness amongst consumers (Birch et al., 2019). Additionally, in each wave of the survey, over 30% of products identified were novel and had not appeared in previous survey waves, emphasizing this market's dynamism and innovative capacity. A similar proportion of products were lost from wave to wave, a possible result of novel products competing for what remains a niche market.

The growing availability of seaweed food products in the UK represents an opportunity to increase iodine intake in some UK population groups, in the context of iodine insufficiency (Vanderpump et al., 2011). Encapsulated seaweed (*Ascophyllum nodosum*) has been successfully used to increase the iodine status of women with an insufficient habitual iodine intake without adverse effects (Combet et al., 2014), suggesting that seaweed as an ingredient or stand-alone food, could be effective as an iodine source. Most products in the 3 survey waves had a high proportion of seaweed as a main composition ingredient, with a minority of products using seaweed as a rich source of iodine. Product packaging size decreased between W0 and W3, while median price increased to £5.45, reflecting the growth in the more expensive seaweed supplement category. Increasing prices of seaweed may act to niche rather than democratize seaweed, prohibiting the wider inclusion of seaweed in UK diets.

Iodine content labelling was uncommon and increased marginally across waves. The reliability of this labelling is unclear without further information on analysis techniques used and frequency of product analysis. Variability in seaweed iodine content between species and growth conditions (Roleda et al., 2018) is an added challenge to defining precise content. High iodine content is driven by seaweed choice in products - kelps (*Laminaria* and *Saccharina* spp.), a seaweed used in ~25% of all products, can contain more than 7000 μg/g iodine (e.g., *S. latissima*, sugar kelp) (Roleda et al., 2018); with other popular species, such as wakame or nori containing comparatively lower amounts (38-160 μg/g iodine). The poor labelling practices noted for iodine content extend to seaweed species with increasing numbers of products failing to note the type of seaweed used, prohibiting iodine content estimation. Given concerns over high iodine doses from seaweed, food manufacturers may wish to consider utilising processing methods such as boiling, soaking, washing, or dehydration of seaweed prior to use to reduce iodine concentrations (Nitschke and Stengel, 2016).

The median iodine dose of products in all waves was high, over 400 μg/serving consistently with supplements containing markedly higher iodine per serving, despite being more likely to be consumed on a regular basis compared to food products. One serving of 21-26% of all products in all 3 waves would be sufficient to meet the daily reference nutrient intake for iodine (140 μg/day), highlighting the opportunity seaweed provides for increasing iodine

intake in the UK, especially through food reformulation. However, consumers often overestimate portion sizes (Almiron-Roig et al., 2013), which could lead to high iodine intakes following consumption of seaweed food products, despite the median iodine doses from recommended serving sizes remaining sub-TUL. Across waves, a single serving of 11-17% of products would afford an iodine intake above the European or the IoM upper recommended doses. One-off consumption of high iodine doses usually does not represent a threat to the thyroid (which acclimates to occasional high iodine intakes via the Wolff-Chaikoff effect), rendering occasional high intakes of seaweed-derived iodine relatively safe. However, repeated, regular intake may have adverse consequences. Vulnerable individuals (i.e., those with autoimmune thyroid disease, current iodine insufficiency, surgical patients) may fail to adapt to high doses of iodine, leading to thyroid dysfunction (Leung and Braverman, 2014). Medical case reports, dating back to the 1970s, describe iodine-induced thyroid dysfunction (ranging from goitre and hypothyroidism to thyrotoxicosis and thyroid cancer) as a result of seaweed consumption, often in individuals with no history of thyroid disease (Arum et al., 2009, Okamura et al., 1978, Crawford et al., 2010).

Seaweeds can also bioaccumulate arsenic, cadmium, lead, and mercury, the ingestion of which can lead to renal and hepatic dysfunction, various cancers, and reduced neurological function in children (in the case of prenatal exposure)(Circuncisão et al., 2018). At present, France is the only EU country with established legislation for the limits of heavy metals in seaweed for human consumption (Besada et al., 2009). The publication of EU recommendation 2018/464 suggests that EU Member States in collaboration with food and feed business operators should monitor the levels of iodine, cadmium, arsenic, mercury, and lead in products and report values to the European Food Safety Authority (The European Commision, 2018). However, this recommendation enforces no legal obligation upon EU Member States or companies producing seaweed for human consumption to enact the proposed monitoring. The lack of legislation in this area paired with the relatively high cost of toxic compound monitoring by inductively-coupled plasma mass spectrometry (Todorov and Gray, 2016), could result in a lack of adherence to this recommendation and subsequently the sale of seaweed food products with high iodine or heavy metal levels on the UK market.

The environment in which seaweeds are grown has a direct impact on the bioaccumulation of iodine and heavy metals. As such, origin labelling is important, yet an increasing proportion of products - 40 to 49% from W1 to W3 - did not disclose origin. This lack of information makes establishing the conditions under which the seaweed was grown or harvested impossible and is a further barrier to risk assessment. Although the majority of surveyed products had a UK origin, ~10% each year originated from Asia, with looser food safety regulation (Barbier et al., 2019) and where mercury pollution of the sea is prevalent in some coastal areas (Li et al., 2009). Additionally, product origin labelling refers to the whole product, rather than the individual components, further concealing the origin of the seaweed. More specific seaweed origin labelling on seaweed food products would help to provide traceability and would allow consumers to make informed decisions regarding the source of their foods, important factors in food security and public safety.

The presence of non-approved health claims surrounding improved immunity, fertility, digestive health, detoxification and weight control, raise further public safety concerns and indicate that consumers may not be receiving the high level of protection that current regulatory frameworks should provide. The use of non-approved health claims is a breach of European Parliament Regulation 1924/2006 – stating that all food products put on the market (imported and non-imported) should be safe, adequately labelled, and any health claims should be backed by sufficient scientific evidence (The European Parliament, 2006). Consumers may purchase seaweed products marketed as a 'natural source of iodine' perceiving them as safe, and potentially conferring nutritional or physiological advantages. Subsequent over-consumption of these products could lead to excessive iodine or heavy metal intakes, a particular risk for vulnerable individuals with compromised thyroid function or existing iodine insufficiency, pregnant women, and young children. Products containing a high level of iodine (>600 μg/serving), should therefore be labelled as 'high in iodine' include a visible warning on the dangers of over-consumption.

This survey provides a contemporary and comprehensive report of the current availability of seaweed food products in the UK. The variable nature of seaweed iodine content renders determination of the true iodine content of products challenging without laboratory analysis. We recommend that all seaweed producers analyse their products for iodine content on a periodic basis (at least once per harvest) to ensure that seaweed sold to food producers can be used responsibly, with safe iodine nutrition in mind. Our estimations of product iodine content are based on the available literature, providing an approximate appraisal of the opportunity and risk linked to iodine intake. Although this survey does not consider the seaweed available to purchase in smaller independent stores, in restaurants, and generally out of home, our survey covers an estimated 83% of the current UK grocery market share (Kantar World Panel, 2020) and therefore provides a representative account of the current availability of seaweed food products in the UK.

The recorded growth in availability of seaweed food products from 2015 to 2021 coupled with the observed high iodine doses, indicates that the use of seaweed in food products requires careful management in the context of benefit and risk to health if this dynamic market continues to expand. Although seaweed undoubtedly offers a plant-based, sustainable option for increasing iodine intakes in at-risk populations, the risk of iodine toxicity, following inappropriate species usage or high seaweed content in products, cannot be ignored. Increased awareness and uptake among food producers of processing methods to reduce seaweed iodine content could reduce risks to health, and the addition of adequate iodine content labelling or warnings on the consequences of over-consumption on products could offer further consumer protection. A stronger dialogue is needed between seaweed producers, retailers, and public health specialists to ensure that the health of the consumer is at the forefront of consideration, within an appropriate legislative framework.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics statement

This study did not require ethics approval

Funding statement

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Figures

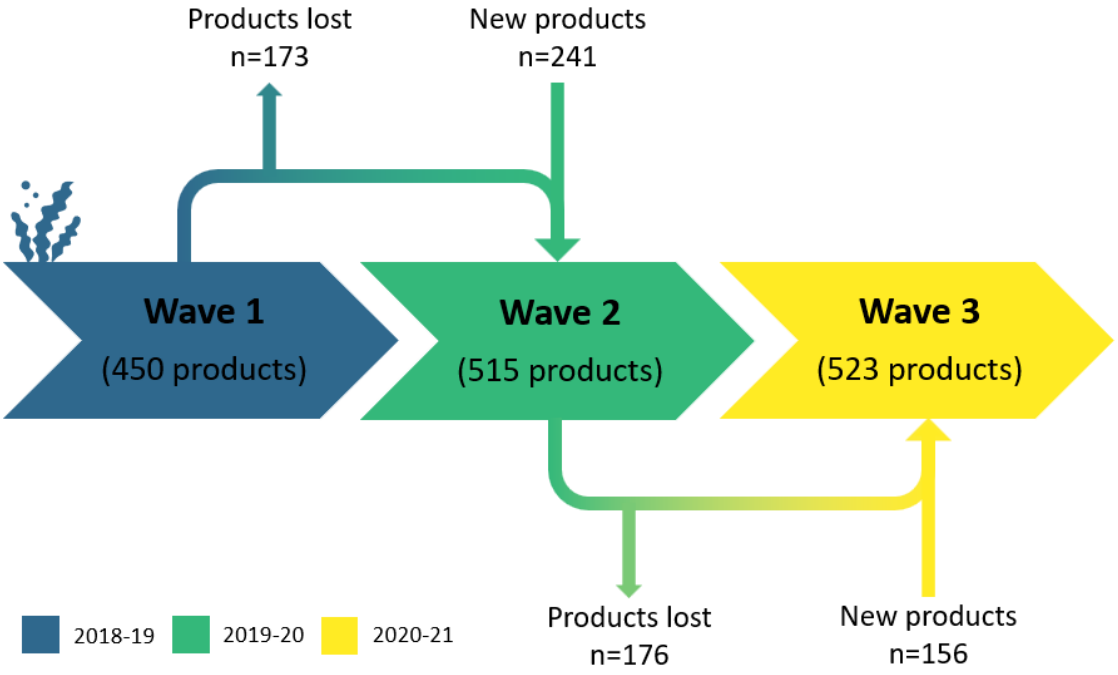


Figure 1. Number of seaweed food products identified in each wave of the survey. The number of products lost each year (i.e., those present in 1 wave but not identified in the next wave) and new products (i.e., products not identified previously) are noted.

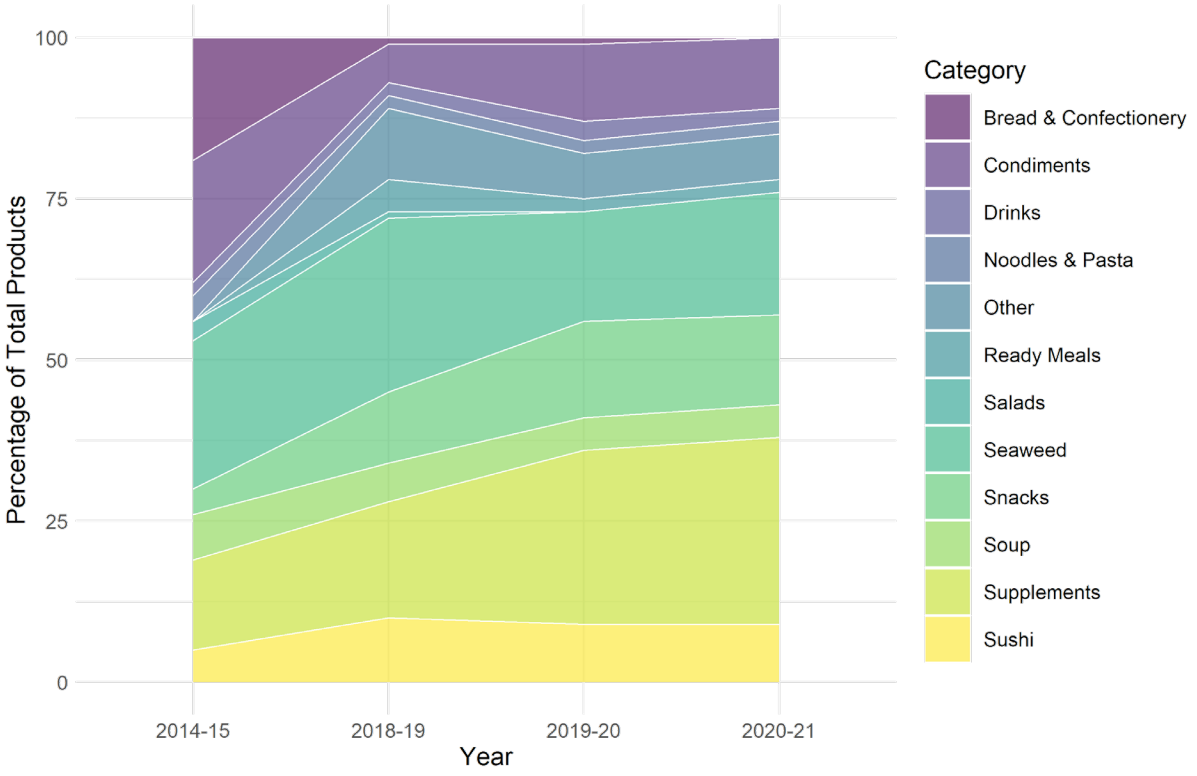


Figure 2. Change in percentage contribution to total product availability from each product category from Wave 0 (2014-15(Bouga and Combet, 2015)) to Wave 3 (2020-21).

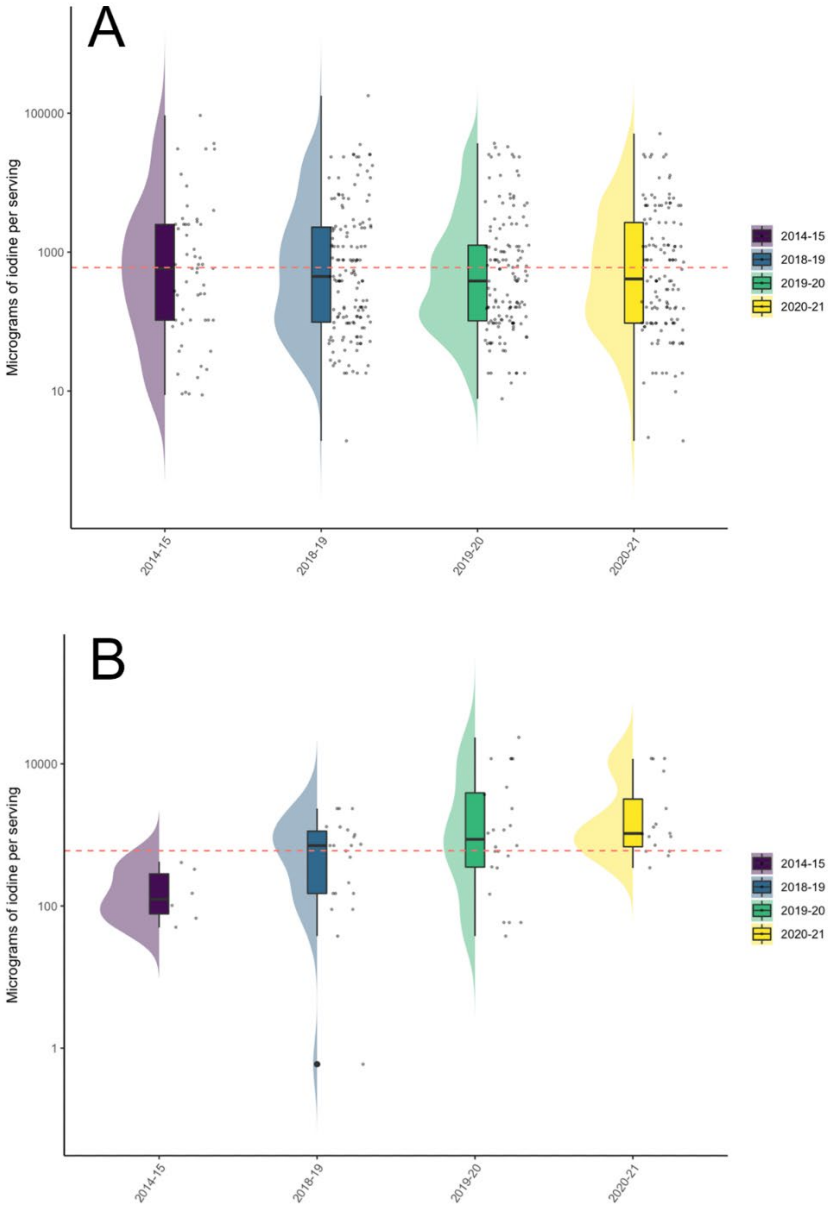


Figure 3. A) Median iodine content (μg/serving) of food products by each survey wave: W0 – 2014-15 (data from Bouga and Combet, 2015), W1: 2018-19, W2: 2019-20, W3: 2020-21. **B)** Median iodine content (μg/serving) of supplement products by each survey wave: W0 – 2014-15 (data from Bouga and Combet, 2015), W1: 2018-19, W2: 2019-20, W3: 2020-21. For both figures, only products with a calculable iodine content are displayed as points and the red dashed line represents 600 μg of iodine, the European Tolerable Upper Limit (TUL) set by the European Food Safety Authority (EFSA)(EFSA Panel on Dietetic Products and Allergies, 2014).

Tables

Table 1. Seaweed type used in products in each survey wave (n, %).

Seaweed Type	Wave 1 (2018-19)		Wave 2 (2019-20)		Wave 3 (2020-21)	
	n	%	n	%	n	%
Kelp	97	22%	99	19%	130	25%
Kombu	17	4%	22	4%	17	3%
Wrack	27	6%	39	8%	20	4%
Hijiki	2	0%	2	0%	2	0%
Dulse	23	5%	22	4%	26	5%
Wakame	43	10%	37	7%	39	7%
Arame	2	0%	4	1%	4	1%
Nori	63	14%	66	13%	58	11%
Sea Lettuce	1	0%	2	0%	2	0%
Laver	10	2%	12	2%	7	1%
Other type	38	8%	41	8%	62	12%
Blend of seaweeds[1]	38	8%	32	6%	46	9%
No information provided	89	20%	137	27%	109	21%

[1] Products containing more than one type of seaweed. Further details on seaweed species categorization into the types listed here can be found in Supplementary Table 1.

Table 2. The proportion of seaweed used in food and supplement products.

	Food Products		Supplement Products	
	Proportion of seaweed in products (median, IQR)	Number of products not reporting proportional seaweed content (n, % of total)	Proportion of seaweed in products (median, IQR)	Number of products not reporting proportional seaweed (n, % of total)
Wave 1 (2018-19) (n=370 food products, n=80 supplement products)	65% (4-100)	186 (50)	93% (0.7-100)	60 (75)
Wave 2 (2019-20) (n=377 food products, n=139 supplement products)	69% (10-100)	192 (51)	100% (26-100)	110 (80)
Wave 3 (2020-21) (n=370 food products, n=153 supplement products)	100% (10-100)	179 (48)	100% (26-100)	135 (88)

Supplementary Information

Supplementary Table 1. Iodine content estimation of seaweeds, collated at the outset of data collection in 2018. Data presented are averages (± standard deviation).

Seaweed Type		Iodine content (µg/g), average (standard deviation)	
Common name/s	**Scientific name**	**Fresh**	**Dried**
Kelp (average)		**1079 (65)**	**2352 (2296)**
Fingered tangle / oarweed	*Laminaria digitata*[1-5]	1008 (436)	6530 (2470)
Oarweed	*Laminaria longicruris*[5]	-	1304 (-)
Kelp	No species indicated[5, 6-8]	-	1513 (1808)
Tangle (kelp)	*Laminaria hyperborea*[3]	1136 (-)	5661 (-)
Wild kelp	No species indicated[5]	-	1356 (-)
Bull kelp	*Nereocystis luetkeana*[8]	-	407 (-)
Split kelp	*Laminaria setchellii*[8]	-	1070 (-)
Sugar kelp	*Laminaria saccharina / Saccharina latissima*[3, 8-11]	1094 (-)	3214 (1918)
Winged kelp	*Alaria marginata*[8]	-	151 (-)
Giant kelp	*Macrocystis integrifolia*[8]	-	240 (-)
Paddleweed / Sea bamboo / kelp	*Ecklonia maxima*[5]	-	2123 (-)
Sea palm / kelp	*Postelsia palmaeformis*[5]	-	871 (-)
Kelp	*Laminaria ochroleuca*[12]	-	6138 (-)
Kombu (average)		**234 (-)**	**2544 (18)**
Kombu	No species indicated[7, 5, 13]	-	2523 (720)
	Laminaria japonica[8, 14-15]	234 (-)	2555 (629)
	Saccharina japonica[9]	-	2555 (-)
Wrack (average)		**150 (102)**	**595 (426)**
Knotted wrack	*Ascophyllum nodosum*[2-5]	206 (-)	707 (617)
Bladderwrack	*Fucus vesiculosus*[3, 5, 8]	127 (-)	546 (229)
Flat wrack	*Fucus spiralis*[3]	52 (-)	211 (-)
Toothed wrack	*Fucus serratus*[3]	298	1265

Seaweed Type		Iodine content (µg/g), average (standard deviation)	
Common name/s	**Scientific name**	**Fresh**	**Dried**
		(-)	(-)
Channelled wrack	*Pelvetia canaliculata*[3]	70 (-)	248 (-)
Hijiki (average)		**88** **(-)**	**436** **(126)**
Hijiki	*Hizikia fusiformis / Sargassum fusiforme*[5, 7, 8, 14]	88 (-)	436 (126)
Dulse (average)		**100** **(4)**	**77** **(249)**
Dulse	*Palmaria palmata*[2, 5, 7, 10, 12, 17]	100 (4)	77 (249)
Wakame (average)		**29** **(15)**	**121** **(56)**
Wakame	No species indicated[7, 13, 15]	-	161 (59)
	Undaria pinnatifida[2, 5, 8, 12, 14]	29 (15)	81 (163)
Arame (average)		**-**	**600** **(70)**
Arame	*Eisenia bicyclis*[5, 7, 8]	-	600 (70)
Nori (average)		**37** **(-)**	**38** **(8)**
Nori	No species indicated[13]	37 (-)	-
	Porphyra purpurea[16]	-	43 (-)
	Porphyra tenera[5, 7, 8, 16]	-	29 (40)
	Porphyra yezoensis[16]	-	43 (-)
Sea Lettuce (average)		**27** **(21)**	**82** **(27)**
Sea lettuce	*Ulva* spp.[2, 4]	16 (-)	121 (58)
	Ulva lactuca[3]	14 (-)	63 (-)
	Ulva intestinalis[3, 17]	51 (59)	79 (-)
	Ulva rigida[12]	-	66 (-)
Laver (average)		**11** **(3)**	**50** **(36)**
Laver	*Porphyra umbilicalis*[2, 3, 12, 16]	11 (3)	50 (36)
Other			
Sea spaghetti	*Himanthalia elongata*[2-4, 12]	66 (59)	166 (126)
Irish moss / carrageen moss	*Chondrus crispus*[2, 3]	70 (13)	267 (41)
Agar-agar	From *Gelidium sesquipedale*[12]	-	77

Seaweed Type		Iodine content (µg/g), average (standard deviation)	
Common name/s	Scientific name	Fresh	Dried
			(-)

570 1, (Ar Gall et al., 2004); 2, (MacArtain et al., 2007); 3, (Nitschke and Stengel, 2015); 4, (Nitschke et al., 2018); 5,
571 (Teas et al., 2004); 6, (Aquaron et al., 2002); 7, (Lee et al., 1994); 8, (van Netten et al., 2000); 9, (Lüning and
572 Mortensen, 2015); 10, (Roleda et al., 2018); 11, (Sharma et al., 2018); 12, (Romarís-Hortas et al., 2012); 13,
573 (Yeh et al., 2014); 14, (Dominguez-Gonzalez et al., 2017); 15, (Nagataki, 2008); 16, (Watanabe et al., 1999); 17,
574 (Nitschke and Stengel, 2016)
575 Hyphens (-) indicate that only one value was available for this seaweed type and the average and standard
576 deviation were, therefore, incalculable.
577

578 **Supplementary Table 2.** Retailers included in product survey (2018-2020)

Retailer Type	Retailer Name	Retailer Website	Searchable Products - 2018/19 (Wave 1)	Searchable Products - 2019/20 (Wave 2)	Searchable Products – 2020/21 (Wave 3)
Traditional Supermarket	Tesco	www.tesco.com/groceries/	Y	Y	Y
Traditional Supermarket	Sainsbury's	www.sainsburys.co.uk/shop/gb/groceries	Y	Y	Y
Traditional Supermarket	Asda	www.groceries.asda.com/?cmpid=ahc-_-ghs-_-asdacom-_-hp-_-quicklink-_-ghs	Y	Y	Y
Traditional Supermarket	Morrisons	www.groceries.morrisons.com/webshop/startWebshop.do	Y	Y	Y
Traditional Supermarket	Aldi	www.aldi.co.uk/	Y	Y	Y
Traditional Supermarket	Co-Op	www.food.coop.co.uk/	N[1]	N[1]	N[1]
Traditional Supermarket	Lidl	www.lidl.co.uk/en/Our-Products-601.htm	N[1]	N[1]	N[1]
Traditional Supermarket	Waitrose	www.waitrose.com/ecom/shop/Browse/Groceries	Y	Y	Y
Traditional Supermarket	Iceland	www.groceries.iceland.co.uk/	Y	Y	Y
Traditional Supermarket	Marks & Spencer	www.marksandspencer.com/c/food-to-order	Y	Y	Y
Traditional Supermarket	Ocado	www.ocado.com/webshop/startWebshop.do	Y	Y	Y
Specialist Health Store	Holland & Barrett	www.hollandandbarrett.com/	Y	Y	Y
Specialist Health Store	Healthy Supplies		Y	Y	Y
Specialist Health Store	Revital	www.revital.co.uk/	Y	Y	Y

Retailer Type	Retailer Name	Retailer Website	Searchable Products - 2018/19 (Wave 1)	Searchable Products - 2019/20 (Wave 2)	Searchable Products – 2020/21 (Wave 3)
Specialist Health Store	Real Foods	www.realfoods.co.uk/	Y	Y	Y
Specialist Health Store	Evergreen Health Foods	www.evergreenhealthfoods.co.uk/	Y	Y	N[2]
Specialist Health Store	Grape Tree	www.grapetree.co.uk/	Y	Y	Y
Specialist Health Store	Natural Grocery	www.naturalgrocery.co.uk/	Y	Y	Y
Specialist Health Store	The Vegan Kind	www.shop.theveganKind.com/	Y	Y	Y
Specialist Health Store	Roots, Fruits & Flowers	www.rootsfruitsandflowers.com/collections/vegan	Y	Y	Y
Specialist Health Store	Vegan Store	www.veganstore.co.uk/	Y	Y	Y
Specialist Health Store	Alternative Stores	www.alternativestores.com/vegan-vegetarian-shopping/	Y	Y	Y
Specialist Health Store	GreenBay	www.greenbaysupermarket.co.uk/	Y	Y	Y
Specialist Health Store	Indigo Herbs	www.indigo-herbs.co.uk/	Y	Y	Y
Specialist Health Store	Raw Living	www.rawliving.eu/	Y	Y	Y
Specialist Health Store	Napiers the Herbalist	www.napiers.net/	Y	Y	Y
Independent Brand/Company	Pukka Herbs	www.pukkaherbs.com/	Y	Y	Y
Independent Brand/Company	Clearspring	www.clearspring.co.uk/	Y	Y	Y
Independent Brand/Company	Maclean's Highland Bakery	www.macleansbakery.com/	Y	Y	Y
Independent Brand/Company	Donald Russell	www.donaldrussell.com/	Y	Y	Y
Independent Brand/Company	Stag Bakeries	www.stagbakeries.co.uk/	Y	Y	Y
Independent Brand/Company	Saladworx	www.saladworx.co.uk/	Y	Y	Y
Independent Brand/Company	Seagreens	www.seagreens.co.uk/	Y	Y	Y
Independent Brand/Company	Viridian	www.viridian-nutrition.com/	Y	Y	Y

Retailer Type	Retailer Name	Retailer Website	Searchable Products - 2018/19 (Wave 1)	Searchable Products - 2019/20 (Wave 2)	Searchable Products – 2020/21 (Wave 3)
Independent Brand/Company	Nosh Detox	www.noshdetox.com/	Y	Y	Y
Independent Brand/Company	Edible Love (formerly Dr Gaye)	www.edible-love.com (formerly www.drgaye.com)	Y	Y	Y
Independent Brand/Company	Mara Seaweed	www.maraseaweed.com/	Y	Y	Y
Independent Brand/Company	Atlantic Kitchen	www.atlantickitchen.co.uk/	Y	Y	Y
Independent Brand/Company	Just Seaweed	www.justseaweed.com/	Y	N[3]	N[3]
Independent Brand/Company	Seakura	www.seakura.net/	Y	Y	N[3]
Independent Brand/Company	A.vogel	www.avogel.co.uk/	Y	Y	Y
Independent Brand/Company	The Cornish Seaweed Company	www.cornishseaweed.co.uk/	Y	Y	Y

Abbreviations: Y, yes; N, no (N[1]: no online store available for product search; N[2]: online store closed due to COVID; N[3]: no website available to search

582

Appendices

Appendix 1. Changes in median (IQR) price, packaging size (g), serving size (g), and energy provision (kcal/100 g) across all waves of the survey.

	All products				Food Products				Supplement Products			
	W1	**W2**	**W3**	P-value[1]	**W1**	**W2**	**W3**	P-value	**W1**	**W2**	**W3**	P-value
Price (£)	3.99 (2.70-7.99)	4.65 (2.75-9.99)	5.45 (2.99-14.30)	*0.001*[c]	3.50 (2.38-5.50)	3.53 (2.25-5.25)	3.80 (2.39-5.99)	0.288	16.99 (9.98-27.67)	16.85 (9.97-24.99)	16.99 (10.95-25.79)	0.473
Packaging size (g)	100 (33-199)	88 (40-182)	90 (41-180)	0.984	100 (30-200)	90 (35-200)	100 (39-180)	0.953	60 (45-135)	75 (60-150)	90 (60-146)	0.539
Serving size (g)	15 (4-49)	10 (2-33)	10 (2-33)	*0.001*[a, c]	23 (6-79)	15 (5-68)	16 (5-56)	0.220	1 (1-6)	2 (1-4)	2 (1-3)	0.284
Energy (kcal/100g)	203 (145-403)	203 (144-378)	220 (144-386)	0.848	196 (144-395)	198 (144-377)	222 (147-393)	0.654	395 (324-491)	309 (135-393)	109 (70-138)	*0.040*[c]

Abbreviations, IQR, interquartile range; g, grams; kcal, kilocalorie; W1, wave 1 (2018-19); W2, wave 2 (2019-20); W3, wave 3 (2020-21).

[1] Kruskal-Wallis H test with Bonferroni correction for multiple tests (continuous data) – superscript letters following the p-value represent significant differences between groups ([a] between W1 and W2, [b] between W2 and W3, [c] between W1 and W3).

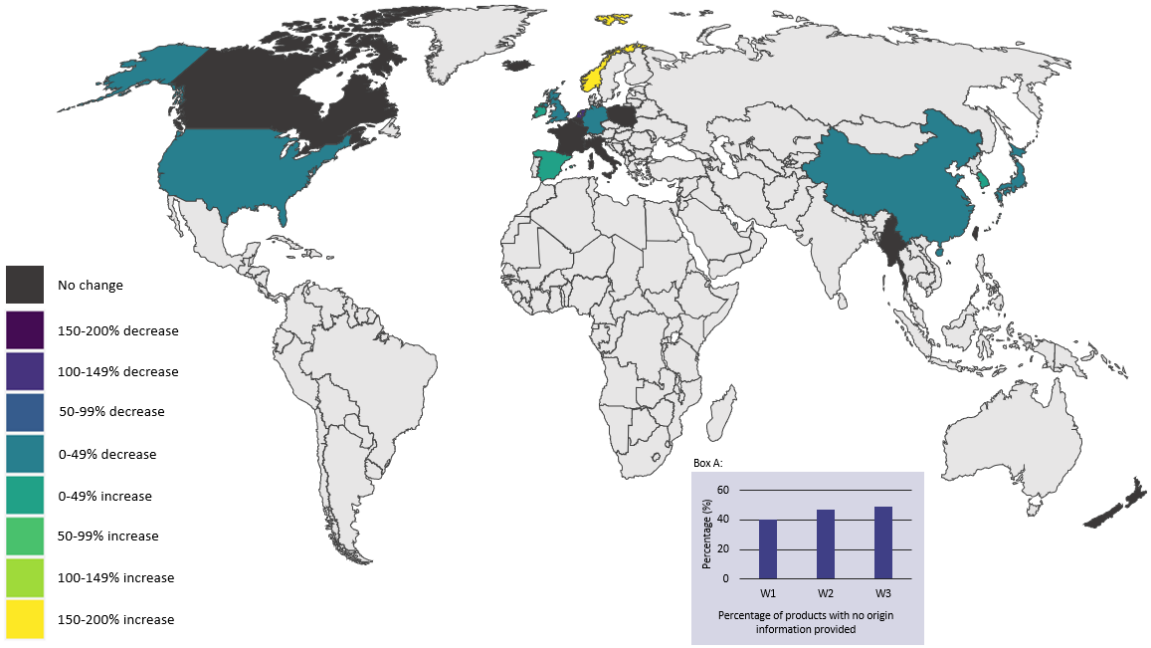
Appendix 2. Iodine content of products (μg/g and μg/serving) in each wave. Data presented are median and interquartile ranges.

	All products				Food products				Supplement products			
	Wave 1	Wave 2	Wave 3	P-value[1]	Wave 1	Wave 2	Wave 3	P-value[1]	Wave 1	Wave 2	Wave 3	P-value[1]
	n=450	n=515	n=523		n=370	n=377	n=370		n=80	n=139	n=153	
Iodine content (μg/g)	77 (13-470)	77 (24-589)	77 (24-253)	0.631	74 (9-267)	38 (24-126)	77 (22-126)	0.858	595 (89-2023)	691 (515-2352)	1514 (353-2352)	0.093
Iodine (μg/serving)	479 (115-2154)	411 (96-1353)	713 (107-2668)	0.475	455 (98-2305)	383 (95-1208)	411 (95-2668)	0.507	595 (150-890)	884 (351-3928)	1050 (682-3724)	*0.023*[a]
Products exceeding the European TUL of **600 μg/day**[2]	76, 17%	75, 15%	75, 14%	-	68, 18%	61, 16%	63, 17%	-	8, 10%	14, 10%	12, 8%	-
Products exceeding the **1100 μg** ULT[2]	60, 13%	52, 10%	57, 11%	-	56, 15%	41, 11%	50, 14%	-	4, 5%	11, 8%	7, 5%	-
Products making approved health claims (n, %)[2]	25, 6%	28, 5%	31, 6%	-	7, 2%	12, 3%	12, 3%	-	20, 25%	16, 12%	19, 12%	-
Products making non-approved health claims (n, %)[2]	5, 1%	5, <1%	15, 3%	-	2, <1%	3, 1%	7, 2%	-	3, 4%	2, 1%	8, 5%	-

[1] Kruskal-Wallis H test with Bonferroni correction for multiple tests (continuous data) – superscript letters following the p-value represent significant differences between groups ([a] between W1 and W3), [2] Percentage presented is a proportion of all products available (noted in the third row.

Appendix 3. Non-authorised health claims found on products in Wave 1 (2018-19), 2 (2019-20) and 3 (2020-21) of the survey.

Year of survey	Product Category	Health claim made
2018-19 (Wave 1)	Snack	*'Naturally packed with nutrients, zinc, iron, B vitamins & iodine, a nutrient missing from most foods, vital for wellbeing and effective metabolism.'*
	Seaweed	*'Sea vegetables are a tasty and great source of fibre, calcium, iron, potassium, magnesium, and iodine. Fresh, unique and healthful sea vegetables. Delicious in their raw natural state or heated up. They are known to promote thyroid function (particularly useful for hypothyroid conditions) and are beneficial for skin support and dieting.'*
	Supplement	*'Kelp tablets made from pacific seaweed contain iodine which can aid thyroid function, nourish hair and skin and help detoxification.'*
	Supplement	*'Green Foods are high in nutrients and can be beneficial in many ways. They can aid in detox, weight loss, immune and digestive health.'*
	Supplement	*'…Iodine is an essential ingredient for the control of normal growth and development, immunity, fertility, metabolism, and weight control….'*
2019-20 (Wave 2)	Supplement	*'…Iodine is an essential ingredient for the control of normal growth and development, immunity, fertility, metabolism, and weight control….'*
	Supplement	*'Benefits include weight management, improved gut health, immune system support, stimulation of metabolism, strengthening skin/hair, reduction in fatigue and improvement in energy production'*
	Supplement	*'Over time their unique and complete balance of nutrients helps regulate metabolism, digestion and weight, cleanse, detoxify and alkalize the blood and body, and then maintain regularity and balance throughout the system.'*
	Seaweed	*'Naturally high in iodine – can increase metabolism and aid weight loss.'*
	Soup	*'Sea spaghetti is a seaweed which is naturally high in iodine and magnesium and has antioxidizing and anti-inflammatory properties.'*
2020-21 (Wave 3)	Pate	*'Kombu is popular for its nutritional benefits, as an aid to digestion…'*
	Supplement	*'Wakame seaweed aids in weight management and fat metabolism.'*
	Supplement	*'Sea kelp is a natural source of the mineral iodine, which supports weight management…'*
	Seaweed	*'Can regulate thyroid and aid digestion. Draws out heavy metals from the body'*
	Seaweed	*'Can increase metabolism and aid weight loss'*
	Seaweed	*'Can help boost the immune system and maintain a healthy heart'*
	Supplement (x 2)	*'Over time their unique and complete balance of nutrients helps regulate metabolism, digestion and weight, cleanse, detoxify and alkalize the blood and body, and then maintain regularity and balance throughout the system.'*
	Supplement (x 2)	*'It is a naturally quick and easy detox, allowing the body to cleanse during the sleeping hours.'*
	Supplement	*'It is also important for healthy hair and nails'*
	Supplement	*'…Iodine is an essential ingredient for the control of normal growth and development, immunity, fertility, metabolism, and weight control…*
	Seaweed	*'A deeply detoxifying and powerful sea vegetable'*
	Drink	*'Naturally alkalizing to help neutralize acidity, balance the system, and promote inner harmony'*
	Condiment	*'…cleanse, rejuvenate, alkalinize, support healthy intestinal flora…'*



Appendix 4. Changes in seaweed food product origin between Wave 1 (2018-19) and Wave 3 (2020-21). Change is expressed as the percentage change in product numbers, with positive change indicating an increase in the number of products identified and negative change indicating a decrease in the number of products identified. Box A shows the percentage of products from each wave where product origin information was neither provided on the visible product packaging or retailer's website (W1: 40%, W2: 47%, W3: 49%).

Acknowledgements

Authors

1. Ms Martha L Redway (Research Technician) – https://orcid.org/0000-0002-2462-6070
2. Professor Emilie Combet (Professor of Human Nutrition, corresponding author) – https://orcid.org/0000-000209302-8971

Affiliations

Human Nutrition, School of Medicine, Dentistry and Nursing, College of Medical, Veterinary and Life Sciences, University of Glasgow, New Lister Building, Glasgow Royal Infirmary, 10-16 Alexandra Parade, Glasgow, G31 2ER, UK.

Contact Information

1. marthalucyredway@gmail.com / m.redway.1@research.gla.ac.uk
2. emilie.combetaspray@glasgow.ac.uk

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Conflict of Interest Statement

EC has received research funding from InnovateUK and the National Biofilms Innovation Centre in collaboration with Seaweed & Co, unrelated to this project. MR is a researcher on one of these projects.