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Edible algae allergenicity – a short report

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Abstract
The use of seaweed and algal derived products in the food industry has grown rapidly in recent times. Major areas of expansion have been in Western countries where algae derived commodities are being utilised as edible foods or sources of high value ingredients. However, studies focused on potential allergenicity attributed to these food items, prevalence of allergenicity, and public health awareness are limited. Therefore, the current research summarises the existing literature focused on algal induced allergy in humans. Of the available literature, a total of 937 titles were identified, and 33 articles underwent subsequent full-text screening. Most research focused on prevalence and were derived from studies conducted in Europe (58%), North America and Canada (33%), and the remainder Australia and South Korea (9%). No studies addressed the need for public education or labelling of algal products. Our review reports that the available evidence identified points to algal derived products as being potential sources of allergens in the human food chain. Several components have been characterised that are shown to induce allergic responses in humans. Few studies have assessed the prevalence of algal allergenicity in the general population and as such further research is warranted given the increased usage of these products in the food industry.

Keywords Food allergy · Seaweed · Edible algae · Allergenicity · Scoping review

Introduction

Several hundred edible seaweed and microalgal species are recognised, with many being widely used in the food industry as foods, additives, extracts, and sources of functional ingredients (Pereira 2011; Cai et al. 2021). Such is the demand for algal derived products, that the global algal market has seen significant growth viz. an estimated value of US$20.16 billion in 2021, looking to grow at a compound annual growth rate (CAGR) of 10.9% from 2022 to 2031; with food being the predominant application at 37.0% and pharma and nutraceuticals at 8.1% (Transparency Market Research 2022). Red seaweeds (Rhodophyta) and brown seaweeds (Phaeophyceae) are the most prominent species used (FAO 2018, 2021). Similarly, microalgae production reached 56,456 tonnes in 2019, and this figure was largely dominated by *Spirulina* (*Arthrospira* spp) (totalling, 56,208 tonnes), and to a lesser extent other green microalgae species (totalling, 248 tonnes), (FAO 2021). Demands have spawned a rapid growth in algal commodity markets, particularly in Western regions, with reported growth of seaweed-flavoured foods and drinks in many European countries (Mintel 2016). Given the increased use and the interest in the further usage of algal products as sustainable new food sources in the food production chain (FAO 2022), research has become more focussed on the composition and nutritional quality of proteins, polysaccharides, lipids, vitamins, minerals, and various antioxidants present in the tissues of these commodity food sources (Dawczynski et al. 2007; reviewed in Wells et al. 2017). In addition, researchers have highlighted potential concerns relating to the safety of algal based foods products (Banach et al. 2020a, b). These concerns relate to the bioaccumulation of heavy metal ions in tissues (Hwang et al. 2010; Smith et al. 2010; Taylor and Jackson 2016; Circuncisão et al. 2018), excess iodine intake in consumers (Crawford et al. 2010; Bouga and Combet 2015), the accumulation of various toxicants such as polychlorinated biphenyls (PCBs), dioxins, and microplastics (Hanaoka et al. 2001; García-Rodríguez et al. 2012; García-Salgado et al 2012; Gutow et al. 2016), radioactive materials (Goddard

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and Jupp 2001) and potential allergenicity to algal components (Cherry et al. 2019).

Food allergenicity, follows the induction of an immune response after exposure to an ingested item, via dermal contact or through inhalation of food allergen particulates. The National Institute of Allergy and Infectious Diseases (NIAID/NIH) recognises food allergy as key to public health initiatives and is of clinical significance to the general population. Current estimates show that globally approximately 8% of children and 3–10% adults are affected by food allergy (Zarkadas et al. 1999; Sicherer 2011; Gupta et al. 2018, 2019; Messina and Venter 2020), associated with a spectrum of food items including various nuts, shellfish, fish, egg, milk, wheat, soy, some fruits and vegetables, and various seeds (Codex Alimentarius 2020; FAO and WHO 2022). Various proteinaceous allergens have been identified in algal food sources and have been documented within the Allergome database (allergome.org), though some of these have not yet been biochemically characterised and require further study (listed in Table S1, supplementary materials). Therefore, given the increased growth in the macro- and microalgal production systems, and the promotion of algal based products in the food industry, it seems timely to report on current data on the allergenicity to algal products encountered in the human food chain.

Materials and methods

The current scoping review was conducted to assess the state of primary research into the allergenicity of edible algal sources emerging in food systems, and employed the framework set out by Arksey and O'Malley (2005) and Levac et al (2010). A scoping review differs from a systematic review in relation to the research question posed, as scoping reviews favour broader and more open-ended questions (Arksey and O'Malley 2005). Objectives and methods were identified, and the respective search terms and inclusion criteria adapted during the search process as the scope of the literature evolved.

Review questions

This scoping review sought to answer the following questions:

1) What algal food allergens have been introduced into food systems?
2) What research has been conducted on these algal food allergens?
3) What are the known health effects on humans?
4) How does the safety of these algal food allergens need to be addressed?
5) What are the priorities for future research into algal food allergens?

Identifying relevant studies

Relevant studies were determined following a trial of possible search terms, this to gain an overview of the literature, and to define key concepts. Initially, the search terms 'Allergy AND Algae' were used in a search of PubMed. The titles and abstracts of the articles were scanned, and recent reviews were read in full (Banach et al. 2020a, b; Borsani et al. 2021; Hadi and Brightwell 2021), allowing the identification of key concepts and areas of relevant research. These concepts were used to develop a search matrix for a systematic like literature search (Table 1), and to refine inclusion and exclusion criteria as recommended by Levacet al. (2010).

For the scoping review, all searches were conducted using two databases PubMed and Web of Science, and identical search terms were used. The most recent searches were completed on 28 April 2022. After screening study titles and abstracts, the reference lists of relevant articles were searched to identify additional studies to be incorporated. The literature search uncovered a wide range of uses for algal sources in food systems (Wells et al. 2017; Ścieszka and Klewicka 2019; Francezon et al. 2021; Mendes et al.

Table 1 Table depicting the search process of PubMed and Web of Science and displaying the findings

Search	Search Terms	PubMed	Web of Science
1	(Allerg*) AND (Human) AND (Alga*)	201	392
2	(Allerg*) AND (Human) AND (Seaweed*)	39	27
3	(Allerg*) AND (Human) AND (Spirulina)	16	17
4	(Allerg*) AND (Human) AND (Chlorella)	19	36
5	(Allerg*) AND (Human) AND (Carrageenan)	43	81
6	(Allerg*) AND (Human) AND (Microalga*)	16	21
7	(Allerg*) AND (Human) AND (Duckweed)	3	4
8	(Allerg*) AND (Human) AND (Kelp)	15	7
Total references identified in database		352	585

2022). This review only focused on those health outcomes associated with the ingestion of algal food products (and potential exposure to allergens), rather than allergic reactions caused by inhalation or skin contact. Key metrics linked to the year of publication, geographic location of study, and population age/demographic were not restricted. As such this review includes primary research in humans in which algal allergens were ingested or administered during allergenicity testing. Studies were excluded if they were not primary peer reviewed studies, not written in English, studies were based on animal or cell culture models, the research was not focused on algal food allergy, or were studies duplicated results.

Study screening

The process of article screening is summarised in the flow diagram in Fig. 1. Following database searching, title and abstract screening were carried out using the defined inclusion and exclusion criteria stated above. Once found, included articles were read in full and the data extracted. Microsoft Excel was used to collate relevant information following assessment of the available data. These metrics including the location, study population, study design/purpose, definition of food allergy/food hypersensitivity, algal food allergen, type of reaction, prevalence, and outcomes. Due to a scoping review aiming to quickly highlight the gaps and areas in a field of research, the quality of research is not considered a priority (Armstrong et al. 2011), therefore no systematic quality assurance process was applied to the search. Study characteristics and key available data were tabulated to enable easy comparison of the findings.

Results

Eligibility and study characteristics

Nine hundred thirty seven research papers were identified. These were reduced to 33 papers via title and abstract screening. Further scrutiny via full text screening led to the removal of 20 papers. In addition, a further 700 research articles were excluded due to them not being related to algal food allergy in humans or focused on one of the following key areas namely, prevalence, burden, labelling information, or education strategies. A further 32 papers were excluded due to not being written in English. Subsequently, 191 articles were excluded on the basis of publication type, as these represented conference abstracts, review articles and letters to the editor. Following the removal of duplicate sources, 12 relevant articles were identified, and data extraction was performed to allow for the final analysis. The paper selection process is summarised in Fig. 1.

Of the 12 included articles selected, 33% were published between the years (1989 to 1999), 25% (2000 to 2010) and 42% (2011 to 2022), suggesting increased interest in research of food allergic reactions to algal foods and associated products. The studies identified were, 8 case studies, 2 studies of prevalence, 1 randomised control trial and a comparative study (Table 2). These reports were composed of research conducted in several geographic locations with the majority (58%) based in European countries. 58% of the selected papers are more than a decade old, published between 1989 to 2010. A further 3 studies were performed in United States of America

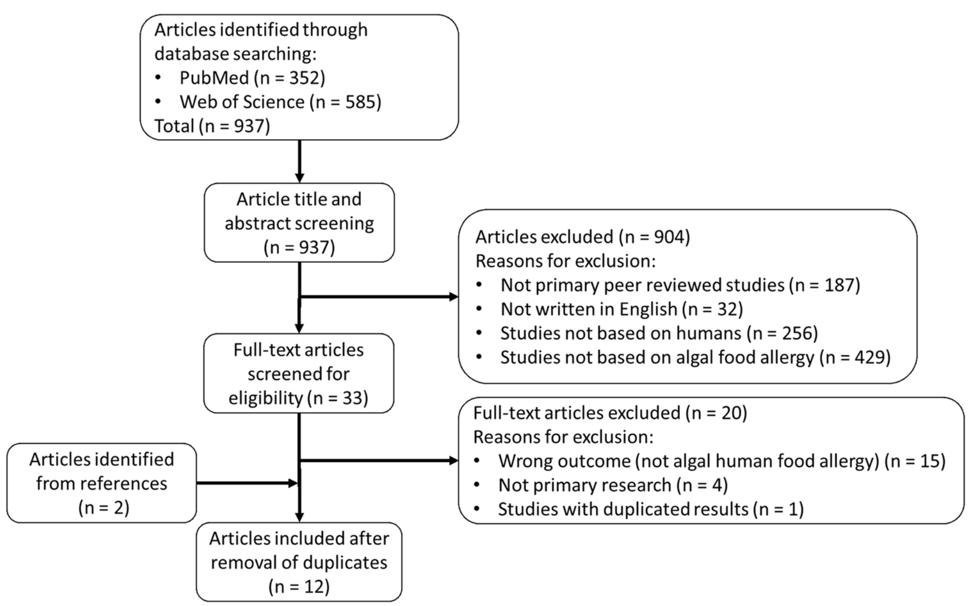

Fig. 1 Flow diagram depicting the process of paper selection in the current work following the interrogation of PubMed, and Web of Science, respectively

Table 2 Location, population demographics, design and definition of food allergy (FA)/food hypersensitivity (FH) of the included studies

Author(s), Year	Location	Study Design	Study Population		Definition of FA/FH
			Sample Size and characteristics	Controls	
Abasszade et al. (2020)	Australia	Case report	75-year-old male	ND	Clinical symptoms of allergy and elevated blood tryptase levels indicative of anaphylaxis
Thomas et al. (2019)	UK	Case report	27-year-old male	5 healthy controls	Patient history of clinical symptoms of allergy and positive SPT
Kular et al. (2018)	Canada	Case report	10-month-old infant	ND	Clinical symptoms of allergy and positive SPT
Vojdani and Vojdani (2015)	USA	Randomised control trial	288 healthy participants of different ethnicities aged 18–65 yrs, (M:144, median age 35.5 yrs; F:144, median age 36.2 yrs)	4 positive controls (gum allergy), 4 negative controls (no gum allergy)	Positive to indirect ELISA testing (% elevation in IgG and IgE antibodies at 2 SDs above the mean)
Le et al. (2014)	Netherlands	Case report	17-year-old male	7 controls (5 with house dust mite sensitization and allergy and 2 non-atopic)	Clinical symptoms of allergy and positive SPT
Petrus et al. (2010)	France	Case report	14-year-old adolescent	ND	Clinical symptoms of allergy, positive SPT and oral challenge test
Yim et al. (2007)	South Korea	Case report	11-year-old male	ND	Clinical symptoms of allergy and positive SPT
Lauerma et al. (2001)	Finland	Case report	22-year-old male	1 non-atopic patient and 3 sera pools from atopic mould-allergic patients	Clinical symptoms of allergy, positive SPT (≥ 3 mm) and serum IgE (immunospot)
Tarlo et al. (1995)	Canada	Case report	26-year-old female	8 patient controls (3 for SPTs, 2 with high IgE and 3 with normal IgE)	Clinical symptoms of allergy with diet history, positive double blind SPT (≥ 2 mm) and specific IgE (RAST)
Tiberg et al. (1995)	Sweden	Cross-sectional	246 children: Group 1—94 (aged 7 yrs) (M:55 F:39); Group 2—129 (aged 6–17 yrs, mean 11 yrs), (M:69 F:60); Group 3—23 (aged 10–17 yrs, mean 13.4 yrs), (M:14 F:9)	ND	Positive SPT (≥ 3 mm) and positive specific IgE (RAST) (> 0.20 PRU mL^{-1})
Tiberg et al. (1990)	Sweden	Cross-sectional	46 atopic children sensitized to moulds (M:24 F:22), aged 6–17 yrs (mean 12.1 yrs)	ND	Positive SPT (≥ 3 mm) and positive specific IgE (RAST) (≥ 0.20 PRU mL^{-1})
Tiberg and Einarsson (1989)	Sweden	Comparative	3 patients allergic to *Chlorella*	ND	Positive specific IgE (RAST) class 2 (≥ 1.7 PRU mL^{-1})

or Canada (25%), 2 of which were published in the last decade (2012 to present, 2022). The 2 most recent studies were carried out in Australia and South Korea. Of the 12 identified articles, 6 focused exclusively on younger populations (ages ranging from 10 months – 17 years) with the remainder looking at adults of ages ranging from 18 to 75 years. Assessment of the 12 research articles allowed for the identification of two key themes from the available papers focused on allergenicity to edible algal species and associated clinical outcomes of allergenicity. These themes will be addressed below.

Edible algae and allergenicity

Most research focused on microalgal species, notably, *Spirulina* (*Arthrospira*) and *Chlorella* (58%) and spanned cases ranging from simple allergic reaction through to anaphylaxis (summarised in Tables 2 and 3). Reports were limited to papers associated with allergic responses to macro-algae. Of the available studies, red algae, *Chondrus crispus* and *Palmaria palmata*, and the algal derived component carrageenan (a polysaccharide), isolated from a number of sources including *Chondrus crispus, Eucheuma* and *Gigartina* seaweeds respectively, were noted. Results from these studies included information on case studies, population details, diagnostic tests used, and treatment regime as defined in each study.

In reference to macro-algae, several studies have reported on food allergy to seaweed. These studies are summarised in Tables 2 and 3. One randomised control trial was identified in the current analysis. This assessed seaweed derived carrageenan (Vojdani and Vojdani 2015) and comprised 288 healthy participants of different ethnicities and ages (18–65 yrs). Of these participants, 57 (20%) had positive immunoglobulin E (IgE)-specific immune reactivity to carrageenan. Seaweed associated allergenicity was found in 4 case reports (Tarlo et al. 1995; Lauerma et al. 2001; Kular et al. 2018; Thomas et al. 2019). The report by Kular et al. (2018) documents the first reported case of IgE-mediated reaction following carrageenan ingestion. In this case, carrageenan was obtained from *Eucheuma*, *Chrondrus*, and *Gigartina* seaweed. Similarly, in the case identified by Tarlo et al. (1995) there was an IgE-mediated reaction to carrageenan, though this was identified during a barium enema study. Lauermaet al. (2001) identified positive IgE binding and skin prick tests to agar–agar and seaweed extract, as they were components of a consumed antacid that resulted in an anaphylactic reaction. Thomas et al. (2019), indicated generalized urticaria, facial angioedema, lip and tongue tingling, throat tightening, and nose congestion following a positive skin prick tests to red seaweeds *Porphyra, C. crispus*, and *P. palmata*, whereas *Ulva* spp. and *Undaria pinnatifida* were negative. In this study, patient history and positive skin test results suggested an immunoglobulin E-mediated response (Thomas et al. 2019). As a likely mechanism, studies have highlighted the link between the chemical structure of carrageenan containing the oligosaccharide epitope galactose-α-1,3-galactose (alpha-gal) and the potential for this structure to produce IgE mediated reactions in humans (Tobacman 2015; McGuire et al. 2020; Borsani et al. 2021), which have also been documented in exposure to meat products from mammalian sources and tick bites (Steinke et al 2015; Wilson et al. 2019).

Furthermore, protein sequence similarities have subsequently been found for food allergens from the green seaweed *Ulva* with known allergens (Polikovsky et al. 2019). Indeed, dried *Porphyra* spp. (nori), reportedly contains components with immunoreactivity similar to that of known lobster allergens (Motoyama et al. 2007). It is widely known that crustaceans, such as shrimp, lobster, and crab, induce IgE mediated allergies. Therefore, the possibility that dried nori products could potentially cause severe allergic reactions in people sensitive to crustaceans cannot be ruled out and further work is needed (Bito et al. 2017). Similarly, Mildenberger et al. (2022) identified marine allergenic proteins from crustaceans (crustacean tropomyosin), molluscs (mollusc tropomyosin) and fish (fish parvalbumin) in the seaweed *Saccharina latissima* when produced using growth methods such as Integrated Multi-Trophic Aquaculture. Whether some crustacean associated allergens are due to direct contamination of seaweed products cannot be ruled out.

By far the most widely reported indication of allergy to edible algal products comes from reports linked to unicellular species of both *Spirulina* and *Chlorella*. These algae are widely used in the supplementation industry, with *Spirulina* (*Arthrospira*) and *Chlorella* comprising the largest proportion of seaweed-based supplements produced worldwide (5,000 and 2,000 t of dry matter per year respectively), with an estimated global production values of about US$40 million each, per year (Enzing et al. 2014). Of the included research, 2 studies documented algal allergens within *Chlorella* spp. identified at 13, 17, 19, 25–26, 46–50, 72 kDa (Tiberg and Einarsson 1989; Tiberg et al. 1990) and 1 study discovered the algal allergen C-phycocyanin beta subunit at 15–35 kDa, within *Arthrospira platensis*. Another study examining *Spirulina* (*Arthrospira*) conducted by Yu et al. (2002) has also identified a similar algal allergen of C-phycocyanin beta subunit in *Arthrospira maxima* using in silico methods.

This review identified 9 papers, each using skin prick tests in the assessment of allergy to microalgae (75%), and 7 articles (58%) documented positive IgE measures in participants in response to exposure. 7 (88%) of the included case reports highlighted allergenicity to skin prick tests in individuals challenged with algal sources (Tarlo et al. 1995;

Table 3 The identification of algal food allergens and the prevalence of adverse reactions to these products

Author(s), Year	Algal food allergen	IgE testing	Skin prick testing	Clinical symptoms	Prevalence
Abasszade et al. (2020)	*Chlorella vulgaris* (powdered supplement)	NP	NP	Anaphylaxis, systolic blood pressure of 50 mmHg, wheeze, widespread urticarial rash, cool peripheries, disorientation and elevated tryptase levels	First reported clinical case of anaphylaxis to *C. vulgaris*, one subject included
Thomas et al. (2019)	Nori and other red seaweeds, *Chondrus crispus* and *Palmaria Palmata*	NP	Positive: fresh Nori seaweed (13 mm wheal), *Chondrus crispus* (8 mm wheal) and *Palmaria Palmata* (7 mm wheal)	Generalized urticaria, facial angioedema, lip and tongue tingling, throat tightening, nose congestion	First case of food allergy to red (Nori) seaweed, positive SPT in patient and negative in 5 healthy controls
Kular et al. (2018)	Carrageenan (obtained from *Eucheuma, Chrondrus*, and *Gigartina* seaweed)	NP	Positive to Carrageenan (10 × 8 mm wheal)	Lip angioedema	First reported case describing IgE-mediated reaction following carrageenan ingestion
Vojdani and Vojdani (2015)	Carrageenan	57 participants had positive IgE-specific immune reactivity to *carrageenan*	NP	ND	20% (n = 57) of participants had positive IgE-specific immune reactivity and 27% (n = 78) of participants had positive IgG-specific immune reactivity to carrageenan
Le et al. (2014)	Spirulina (*Arthrospira platensis*) tablet	NP	Positive to *Spirulina* tablet and *Spirulina platensis* algae	Anaphylaxis, within 10 min, tingling of the lips, angioedema of the face, an itching exanthema and urticaria of arms and trunk, nausea, abdominal pain, wheezing, dyspnoea and inspiratory stridor	Positive SPTs in patient and negative in all 7 controls
Petrus et al. (2010)	Spirulina (*Arthrospira platensis*)	NP	Positive to *spirulina*	Anaphylaxis, urticaria, labial oedema and asthma	First case report of anaphylaxis to *Spirulina*, one subject included
Yim et al. (2007)	*Chlorella* (food supplement tablets)	Blood serum levels of IgE were increased, *chlorella* specific IgE test NP	Positive to *chlorella* (wheal 5.6 mm × 7.1 mm)	Allergic reaction inducing acute tubulointerstitial nephritis	First reported case of *Chlorella*-induced nephritis
Lauerma et al. (2001)	Antacid, Agar–agar, seaweed	Strong IgE binding to agar–agar, seaweed and antacid	Positive SPTs to agar–agar (3 mm) and antacid (20 mm on first test, after 3 months with other batches 7–8 mm)	Anaphylactic reaction, face was erythematous, eyes red and wet, coughing and breathing became difficult	Positive SPTs in patient and negative in all controls. Positive IgE in patient, negative in non-atopic control and faint binding to the antacid extract by mould-allergic controls

Table 3 (continued)

Author(s), Year	Algal food allergen	IgE testing	Skin prick testing	Clinical symptoms	Prevalence
Tarlo et al. (1995)	Carrageenan (*Chondrus crispus*)	Patient's serum contained IgE antibodies to carrageenan (sodium *carrageenan* constituent binding of 10.5%)	Positive SPT (10 mm mean wheal diameter) to barium enema solution, to 0.4% sodium carrageenan constituent (8 mm mean wheal diameter) and commercial carrageen gum preparation was borderline (2 mm mean wheal)	Anaphylactic reaction (abdominal cramps, mild generalized pruritus, generalized urticaria, hypotension, transient loss of consciousness, chest tightness, wheezing and cyanosis) from barium enema and worsening gastrointestinal symptoms on ingestion of *carrageenan*	Carrageenan is a previously unreported cause of anaphylaxis during barium enema. Positive SPTs in patient and 2 controls tested negative to barium enema solution. 3 controls tested were negative to 0.4% sodium carrageenan constituent. Higher serum IgE in patient, lower in controls (2 controls with high IgE 3.5% and 2.8% and 3 normal controls 2.6%, 3.2%, and 2.2%)
Tiberg et al. (1995)	*Chlorella homosphaera*	Positive IgE to *Chlorella* in 2 patients from Group 2 and 6 from Group 3	Positive SPT to *Chlorella* in 9 patients from Group 2 and 7 from Group 3	Not able to identify any symptoms specifically related to *Chlorella* sensitization, as most patients reacting to *Chlorella* were also sensitized to many other allergens	Group 1—no *Chlorella* specific IgE Group 2—7% (n = 9) of children had positive SPT to *Chlorella*. 29% (n = 2) were positive with SPT and IgE for *Chlorella* Group 3 – 30% (n = 7) of mould sensitive children had positive SPT to *Chlorella*. 6 patients with positive SPT and 2 with negative SPT had positive IgE for *Chlorella*
Tiberg et al. (1990)	*Chlorella homosphaera*	Positive *Chlorella* specific IgE in 23 patients (range: 0.21–11.5 PRU mL^{-1}, median: 1.3 PRU mL^{-1})	Positive SPT to *Chlorella* in 6 patients	ND	Of the 18 patients tested 33% (n = 6) had positive SPT to *Chlorella*. 50% (n = 23) of mould allergic children had positive *Chlorella* specific IgE

Table 3 (continued)

Author(s), Year	Algal food allergen	IgE testing	Skin prick testing	Clinical symptoms	Prevalence
Tiberg and Einarsson (1989)	*Chlorella homosphaera* *Chlorella vulgaris 211-11j* *Chlorella vulgaris 211–81* *Chlorella vulgaris 211-11f* *Chlorella vulgaris 211-11p* *Chlorella saccharophila 211-9b* *Chlorella saccharophila 211-1a* *Chlorella fusca 211-8c*	IgE-binding components (*n*): *Chlorella homosphaera* (10), *Chlorella vulgaris* 211-11j (8), *Chlorella vulgaris* 211–81 (10), *Chlorella vulgaris* 211-11f (8), *Chlorella vulgaris* 211-11p (10), *Chlorella saccharophila* 211-9b (7), *Chlorella saccharophila* 211-1a (13) and *Chlorella fusca* 211-8c (20)	NP	ND	RAST inhibition % relative potency (%): *Chlorella homosphaera* (82%), *Chlorella vulgaris* 211-11j (73%), *Chlorella vulgaris* 211–81 (70%), *Chlorella vulgaris* 211-11f (111%), *Chlorella vulgaris* 211-11p (105%), *Chlorella saccharophila* 211-9b (23%), *Chlorella saccharophila* 211-1a (38%) and *Chlorella fusca* 211-8c (22%)

Key:

ND not documented, *NP* not performed, *CIE* crossed-immunoelectrophoresis, *CRIE* crossed-radioimmunoelectrophoresis, *SPT* skin prick test, *RAST* radio-allergosorbent test, *PRU* phadebas RAST units, *ELISA* enzyme-linked immunosorbent assay, *IgE* immunoglobulin E

Lauerma et al. 2001; Yim et al. 2007; Petrus et al. 2010; Le et al. 2014; Kular et al. 2018; Thomas et al. 2019). These articles were conducted in males and females, reporting on the severity of reaction ranging from localised inflammation to anaphylaxis. Interestingly, no questionnaire-based screening was used in any studies to scope for known allergic reactions to algal foods in the selected populations. Common symptoms associated with allergenicity included oedema (33%), gastrointestinal symptoms (25%), urticaria or erythematous (rash) (42%), anaphylaxis (42%, 5 of 12 papers).

Discussion

It is widely reported that algal species are good sources of fibre, various vitamins, minerals, and that several algal derived bioactives have anti-inflammatory properties when tested in models of inflammation (Lee et al. 2017; Ismail et al. 2020; Alkhalaf 2021; Cuevas et al. 2021; Chen et al. 2022; Mihindukulasooriya et al. 2022). These beneficial properties have spawned growth in the algal food production industry and algal products are largely good for health. However, less widely reported is the potential for edible algae to induce allergenicity and studies in this area are sadly lacking. Several studies using rodent models show that some algal derived components like carrageenan can induce intestinal inflammation, and to significantly alter gastrointestinal tract microbiota composition (Benard et al. 2010; Chassaing et al. 2017). Some algal based constituents like carrageenan are widely used to induce the innate immune response in animal models of inflammation, and points to the possibility of immune modifying properties for some algal species or constituents (Wei et al. 2016; El-Dershaby et al. 2022; Yi et al. 2022). Indeed, several studies have reported inflammatory responses of human colonic epithelial cells to carrageenan (Borthakur et al. 2007; Bhattacharyya et al. 2008; Choi et al. 2012). And recent assessment of edible seaweed species in Denmark (two brown and one red), indicate immunogenicity and allergenicity in rat models, and the capacity to raise IgG1 and IgE levels to elicit an allergic reaction (Vega et al. 2021). Moreover, in the last five years, the first reported incidence of carrageenan induced allergy via ingestion has been published (Kular et al. 2018). In view of these studies and rapid growth in the edible algal industry, the current scoping review was conducted to summarize the available information relating to the incidence of edible algal allergenicity in the general population. It is hoped that this will prompt further interest in the field and may indicate the need for more research in this area.

Most studies identified were case reports, and were conducted in Europe, with additional research from Asia, and North America (summarised in Table 2). A broad literature search was adopted in this work to capture all available pieces of evidence linked to edible algae and allergy. Of the studies identified, only 12 were suitable for further analysis. The research by Vojdani and Vojdani (2015) gave an indication of the prevalence of algal allergenicity in the general population, identifying that the sera of 20% of the 288 individuals tested had IgE-specific reactivity to carrageenan. One other study by Tiberg et al. (1995), conducted in 94 Swedish children, showed no specific IgE to *Chlorella*. These two studies point to significant gaps in our knowledge, particularly in reference to the incidence of algal allergenicity in the general population, the differing and developing use of algae in the food industry, consumption rates and relative exposure to algal based products. Moreover, there is a significant gap in our understanding and characterisation of potential algal allergens in food commodities and the levels of contamination of algal products with marine derived allergens. Adventitious allergen cross-contact of algal products with seafood allergens has been considered when other marine-based products are being grown near seaweed such as when implementing integrated multi-trophic aquaculture (Banacha et al. 2020a; Mildenberger et al. 2022). In the United States of America, researchers have highlighted the potential of seaweed cultivated on longlines, to be contaminated by organisms including crustacean shellfish allergens (e.g. tropomyosin) (Concepcion et al. 2020). Further studies have identified that crustacea in the form of amphipods can be present in raw or dried seaweed products and have the potential to cause serious allergic reactions within the general public in those with crustacean allergy (Motoyama et al. 2007; Bito et al. 2017). The global prevalence of allergy to crustacea has been documented by the FAO and WHO (2022) as mixed due to some regions having > 1% (Lao-araya and Trakultivakorn 2012; Lyons et al. 2019; Li et al. 2020) and others having populations ranging from 0.5–1.0% (Ben-Shoshan et al. 2010; Lyons et al. 2020). Food allergy to crustacea is more prevalent in Thailand and Southeast Asia, Australia and areas of Europe, including Spain, where crustacean seafoods are consumed more widely (FAO and WHO 2022). Tropomyosin is considered the major crustacean food allergen followed by other clinically relevant allergens viz. arginine kinase and myosin light chain, these allergens demonstrate high levels of homology amongst crustacean shellfish species and are accountable for cross-reactive allergies (Lopata et al. 2010; Hajeb and Selamat 2012; Ruethers et al. 2018).

In the United States, the European Union, and other countries, labelling of all ingredients, including major allergenic sources is required. In the European Union 14 major allergens are outlined by Annex II of the 'Council Regulation (EU) No.1169/2011 on the provision of food information to consumers' (2011): cereals containing gluten (wheat, rye, barley, oats, spelt, kamut or their hybridised strains), crustaceans, eggs, fish, peanuts, soybeans, milk, nuts (almonds (*Amygdalus communis*), hazelnuts (*Corylus avellana*), walnuts (*Juglans regia*), cashews (*Anacardium occidentale*), pecan nuts (*Carya illinoinensis*), Brazil nuts (*Bertholletia excelsa*), pistachio nuts (*Pistacia vera*), macadamia or Queensland nuts (*Macadamia ternifolia*)), celery, mustard, sesame seeds, sulphur dioxide/sulphites at concentrations > 10 mg kg^{-1} or 10 mg L^{-1} (total SO_2), lupin, molluscs and products thereof. Similarly, in the US eight major allergens are currently recognised under Food Allergen Labelling and Consumer Protection Act (FALCPA) (2004), namely: milk, eggs, fish, crustacean shellfish, tree nuts, peanuts, wheat and soybeans, with sesame being added as the 9th major food allergen under the Food Allergy Safety, Treatment, Education, and Research (FASTER) Act (2021), effective 1 January 2023. Currently, no such requirement is needed for algal based components and no studies were identified that addressed labelling of algal products or ingredients. However, it is worth noting the novel food status of different algae species to be potentially used as food and food supplements, subject to the pre-market authorisation requirements of the 'Council Regulation (EU) 2015/2283 on novel foods' (2015) before they can be freely placed in the European market.

In recent times, the use of algal derived ingredients in the food production industry has increased as a result of the numerous reported health benefits like antioxidant, anti-inflammatory, anti-acne, anti-microbial and anti-aging properties (Montero et al. 2018; Hannan et al. 2020; Thiyagarasaiyar et al. 2020; Ashaolu et al. 2021). In addition, algae have many beneficial nutritional attributes being rich in proteins, carbohydrates, lipids and providing good sources of vitamins and minerals such as vitamin A, B1, B2, B6, B12, C, E, potassium, iron, magnesium, calcium and iodine (Wells et al. 2017; Koyande et al. 2019). Due to this, many algal sources are being developed to meet the growing demand for dietary proteins to sustain an increasing human population, and environmental impacts of conventional protein production routes (Bleakley and Hayes 2017). The rapid growth in commercial and wild algal farming sector was recently acknowledged by the Food and Agriculture Organisation of the United Nations and highlights the importance of this sector in modern food production systems (FAO 2021). While this is a positive shift in driving commodity food markets and future food sustainability, questions still remain as to the potential allergenicity of algal derived products, and this justifies the current research. As it currently stands, only a handful of studies have shown macroalgae to induce allergy in humans (Table 3). These studies centre on skin prick assessment of seaweed extracts in sensitive individuals. Moreover, in the last few years, allergy associated with seaweeds are becoming more widely reported, however, the potential significance of this is not known (Thomas et al. 2019). Several studies have identified potential allergens in seaweeds namely, phlorotannins (Barbosa et al. 2018), polysaccharides (Borthakur et al. 2012) and proteins (Polikovsky et al. 2019) respectively. These constituents having varying degrees of potency at inducing allergy. Whether these molecules drive allergenicity in humans requires further investigation. Research has also been conducted into the aquaculture and production of brown seaweeds *Laminaria digitata* and *S. japonica* and their applications within pharma- or nutraceuticals, due to bioactive molecules and health benefits (Vadalà and Palmieri 2015; Li et al. 2022), as well as functional foods for example flavouring materials or food additives such as thickening agents or to decrease lipid oxidation in cooked meat products (Shirosaki and Koyama 2011; Purcell-Meyerink et al. 2021). However, allergic reactions, including anaphylaxis, have been documented in humans during medical procedures inserting *Laminaria* spp. with positive skin testing and specific IgE (Kim et al. 2003; Sierra et al. 2015; McQuade et al. 2020). Due to this, further examination is needed into these relationships and the possibility that the introduction of this item into products for human consumption could trigger allergic reactions.

More is known regarding microalgae like *Spirulina* (*Arthrospira*) and *Chlorella* and these species were the most commonly reported to induce allergic reactions in humans. These microalgae are used in a variety of products ranging from supplements through to single-cell food protein resources currently in development. Therefore, cases may reflect increased usage of these products. Historically these unicellular algae have been used in a sustainable manner for human consumption (Mooney and Klamczynska 2017) since they contain high concentrations of protein (51%–70% of dry matter) and are rich in amino acids, vitamins, dietary fibre and a variety of antioxidants, bioactive materials and chlorophylls (Bernaerts et al. 2019). However, several immunological studies have shown *Chlorella* to contain constituents that bind to IgE antibodies (Tiberg and Einarsson 1989). In addition, in assays of relative allergen potency determined using radio-allergosorbent test (RAST) inhibition, significant variation is reported between strains of *Chlorella* (Tiberg et al. 1990). This indicates that natural variation in the levels and composition of allergens in *Chlorella* is common and this may translate to cases of allergenicity in the general population. More recently, Bianco et al. (2022) used in silico assessment of algal protein sequences of *Spirulina* (*Arthrospira platensis*) and *Chlorella* (*Chlorella vulgaris*) using the AllergenOnline (AO) (**AllergenOnline.org**) and Allergome databases (**allergome.org**) to identified six proteins of interest. These proteins were identified in spirulina and exhibit significant homology with several known food allergens including thioredoxins, superoxide dismutase, a glyceraldehyde-3-phosphate dehydrogenase, triosephosphate isomerase and C-phycocyanin beta subunit, respectively. Importantly, the first case report of spirulina induced anaphylaxis was associated with phycocyanin (Petrus et al. 2010). Potential allergens in chlorella are also reported and have been shown to share sequence homology to calmodulin (A0A2P6TFR8), troponin c (D7F1Q2), and fructose-bisphosphate aldolase (A0A2P6TDD0). Allergic properties of chlorella have been reported on several occasions (Pukhova et al. 1972; Stewart et al. 2006). Taken together, the current work highlights a significant lack of studies, particularly prospective studies focused on food allergens linked to edible algae. Given the current expansion in the algal commodities market, particularly those targeting the human food chain, more work is needed in this area. Of the available evidence, several case studies point to the possibility that algal based food could be a source of allergic reactions and is of public health interest.

Conclusion

Growth in the production of macro- and microalgae and the continual promotion of algal based products in food systems will support drives in sustainable food production systems. The available evidence points to the presence of allergens in edible algae, but what significance this has to the general population remains largely unknown. Allergenicity to edible algal species has been reported and induces several clinical outcomes ranging from urticaria and gastrointestinal symptoms to oedema and anaphylaxis. Therefore, further research is needed to assess the allergenicity of edible algae species. This will enable the provision of information for clinicians, industry, regulators and legislators to put in place controls to manage algal allergens and provide information to protect public health and educate consumers.

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Declarations

Competing interests The authors declare they have no competing interests.

References

Abasszade JH, Rama Raj P, Tinson AJ (2020) Anaphylaxis following enteral exposure to *Chlorella vulgaris*. BMJ Case Reports 13(11):e237054

Alkhalaf MI (2021) Chemical composition, antioxidant, anti-inflammatory and cytotoxic effects of *Chondrus crispus* species of red algae collected from the Red Sea along the shores of Jeddah city. J King Saud Univ Science 33:101210

Arksey H, O'Malley L (2005) Scoping studies: towards a methodological framework. In J Soc Res Meth 8:19–32

Armstrong R, Hall BJ, Doyle J, Waters E (2011) 'Scoping the scope' of a Cochrane review. J Public Health (Oxf) 33:147–150

Ashaolu TJ, Samborska K, Lee CC, Tomas M, Capanoglu E, Tarhan Ö, Taze B, Jafari SM (2021) Phycocyanin, a super functional ingredient from algae; properties, purification characterization, and applications. Int J Biol Macromol 193:2320–2331

Banach JL, Hoek-van den Hil EF, van der Fels-Klerx HJ (2020a) Food safety hazards in the European seaweed chain. Compr Rev Food Sci Food Saf 19:332–364

Banach JL, van den Burg SWK, van der Fels-Klerx HJ (2020b) Food safety during seaweed cultivation at offshore wind farms: An exploratory study in the North Sea. Mar Policy 120:04082

Barbosa M, Lopes G, Valentão P, Ferreres F, Gil-Izquierdo Á, Pereira DM, Andrade PB (2018) Edible seaweeds' phlorotannins in allergy: A natural multi-target approach. Food Chem 265:233–241

Benard C, Cultrone A, Michel C, Rosales C, Segain J, Lahaye M, Galmiche J, Cherbut C, Blottière HM (2010) Degraded carrageenan causing colitis in rats induces TNF secretion and ICAM-1 upregulation in monocytes through NF-κB activation. PLoS ONE 5(1):e8666

Ben-Shoshan M, Harrington DW, Soller L, Fragapane J, Joseph L, St Pierre Y, Godefroy SB, Elliot SJ, Clarke AE (2010) A population-based study on peanut, tree nut, fish, shellfish, and sesame allergy prevalence in Canada. J Allergy Clin Immunol 125:1327–1335

Bernaerts TMM, Gheysen L, Foubert I, Hendrickx ME, Van Loey AM (2019) The potential of microalgae and their biopolymers as structuring ingredients in food: a review. Biotechnol Adv 37:107419

Bhattacharyya S, Dudeja PK, Tobacman JK (2008) Carrageenan-induced NF-kappaB activation depends on distinct pathways mediated by reactive oxygen species and Hsp27 or by Bcl10. Biochim Biophys Acta 1780:973–982

Bianco M, Ventura G, Calvano CD, Losito I, Cataldi TRI (2022) A new paradigm to search for allergenic proteins in novel foods by integrating proteomics analysis and in silico sequence homology prediction: Focus on *Spirulina* and *Chlorella* microalgae. Talanta 240:123188

Bito T, Teng F, Watanabe F (2017) Bioactive compounds of edible purple laver *Porphyra* sp. (Nori). J Agric Food Chem 65:10685–10692

Bleakley S, Hayes M (2017) Algal proteins: extraction, application, and challenges concerning production. Foods 6:33

Borsani B, De Santis R, Perico V, Penagini F, Pendezza E, Dilillo D, Bosetti A, Zuccotti GV, D'Auria E (2021) The role of carrageenan in inflammatory bowel diseases and allergic reactions: Where do we stand? Nutrients 13:3402

Borthakur A, Bhattacharyya S, Dudeja PK, Tobacman JK (2007) Carrageenan induces interleukin-8 production through distinct Bcl10 pathway in normal human colonic epithelial cells. Am J Physiol Gastrointest Liver Physiol 292:829–838

Borthakur A, Bhattacharyya S, Anbazhagan AN, Kumar A, Dudeja PK, Tobacman JK (2012) Prolongation of carrageenan-induced inflammation in human colonic epithelial cells by activation of an NFκB-BCL10 loop. Biochim Biophys Acta – Mol Bas Dis 1822:1300–1307

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

Cai J, Lovatelli A, Stankus A, Zhou X (2021) Seaweed revolution: Where is the next milestone? FAO Aquacult Newsl 63:13–16

Chassaing B, Van de Wiele T, De Bodt J, Marzorati M, Gewirtz AT (2017) Dietary emulsifiers directly alter human microbiota composition and gene expression ex vivo potentiating intestinal inflammation. Gut 66:1414–1427

Chen P, Lo Y, Huang S, Liu H, Yao Z, Chang C, Wen Z (2022) The anti-inflammatory properties of ethyl acetate fraction in ethanol extract from *Sarcodia suiae* sp. alleviates atopic dermatitis-like lesion in mice. Biosci Biotechnol Biochem 86:646–654

Cherry P, O'Hara C, Magee PJ, McSorley EM, Allsopp PJ (2019) Risks and benefits of consuming edible seaweeds. Nutr Rev 77:307–329

Choi HJ, Kim J, Park S, Do KH, Yang H, Moon Y (2012) Pro-inflammatory NF-κB and early growth response gene 1 regulate epithelial barrier disruption by food additive carrageenan in human intestinal epithelial cells. Toxicol Lett 211:289–295

Circuncisão AR, Catarino MD, Cardoso SM, Silva AMS (2018) Minerals from macroalgae origin: Health benefits and risks for consumers. Mar Drugs 16(11):400

Codex Alimentarius (2020) Code of practice on food allergen management for food business operators. Rome: FAO/WHO. Available at: https://www.fao.org/fao-who-codexalimentarius/shproxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXC%2B80-2020%252FCXC_080e.pdf. Accessed 2/5/22

Concepcion A, DeRosia-Banick K, Balcom N (2020) Seaweed production and processing in Connecticut: A guide to understanding and controlling potential food safety hazards. Connecticut: Connecticut Sea Grant and Connecticut Department of Agriculture Bureau of Aquaculture. Available at: https://seagrant.uconn.edu/wpcontent/uploads/sites/1985/2020/01/Seaweed-Hazards-Guide_Jan2020_accessible.pdf. Accessed 1/11/22

Council Regulation (EU) (2011) No.1169/2011 on the provision of food information to consumers. Official Journal L304/18, ELI: http://data.europa.eu/eli/reg/2011/1169/oj. Accessed Sep 2022

Council Regulation (EU) (2015) 2015/2283 on novel foods. Official Journal L327/1, ELI: http://data.europa.eu/eli/reg/2015/2283/oj. Accessed Sept 2022

Crawford BA, Cowell CT, Emder PJ, Learoyd DL, Chua EL, Sinn J, Jack MM (2010) Iodine toxicity from soy milk and seaweed ingestion is associated with serious thyroid dysfunction. Med J Aust 193:413–415

Cuevas B, Arroba AI, de Los Reyes C, Gómez-Jaramillo L, González-Montelongo MC, Zubía E (2021) Diterpenoids from the brown alga *Rugulopteryx okamurae* and their anti-inflammatory activity. Mar Drugs 19(12):677

Dawczynski C, Schubert R, Jahreis G (2007) Amino acids, fatty acids, and dietary fibre in edible seaweed products. Food Chem 103:891–899

El-Dershaby NH, El-Hawash SA, Kassab SE, Dabees HG, Abdel Moneim AE, Abdel Wahab IA, Abd-Alhaseeb MM, El-Miligy MMM (2022) Rational design of biodegradable sulphonamide candidates treating septicaemia by synergistic dual inhibition of COX-2/PGE2 axis and DHPS enzyme. J Enzyme Inhib Med Chem 37:1737–1751

Enzing C, Ploeg M, Barbosa M, Sijtsma L (2014) Microalgae-based products for the food and feed sector: an outlook for Europe. Publications Office of the European Union, Luxembourg, 78 pp

FAO (2018) The global status of seaweed production, trade and utilization, vol 124. Globefish Research Programme, Rome, 120 pp. Licence: CC BY-NC-SA 3.0 IGO

Food Agricultural Organisation and World Health Organisation (2022) Risk assessment of food allergens: part 1: review and validation of Codex alimentarius priority allergen list through risk assessment: meeting report. Rome: Food Agricultural Organisation/World Health Organisation. Available at: https://www.who.int/publications/i/item/9789240042391. Accessed 1/7/22

Food Agricultural Organisation (2021) Global seaweed and microalgae production, 1950–2019, World Aquaculture Performance Indicators (WAPI) factsheet. pp. 172. Available at:https://www.fao.org/3/cb4579en/cb4579en.pdf. Accessed 7/5/22

Food Agricultural Organisation (2022) Thinking about the future of food safety – A foresight report. Food Agricultural Organisation, Rome. https://www.fao.org/3/cb8667en/cb8667en.pdf. Accessed 5/5/22

Food Allergen Labeling and Consumer Protection Act of 2004, Pub. L. No. 108–282, 118 STAT. 905. 2004. Available at: https://www.fda.gov/food/food-allergensgluten-free-guidance-documents-regulatory-information/food-allergen-labeling-and-consumer-protection-act-2004-falcpa. Accessed 29/5/22

Food Allergy Safety, Treatment, Education, and Research Act of 2021, Pub. L. No. 117–11, 135 STAT. 262 (2021) Available at: https://www.congress.gov/117/plaws/publ11/PLAW-117publ11.pdf. Accessed 29/5/22

Francezon N, Tremblay A, Mouget JL, Pasetto P, Beaulieu L (2021) Algae as a source of natural flavors in innovative foods. J Agric Food Chem 69:11753–11772

García-Rodríguez D, Cela-Torrijos R, Lorenzo-Ferreira RA, Carro-Díaz AM (2012) Analysis of pesticide residues in seaweeds using matrix solid-phase dispersion and gas chromatography–mass spectrometry detection. Food Chem 135:259–267

García-Salgado S, Quijano MA, Bonilla MM (2012) Arsenic speciation in edible alga samples by microwave-assisted extraction and high-performance liquid chromatography coupled to atomic fluorescence spectrometry. Anal Chim Acta 714:38–46

Goddard CC, Jupp BP (2001) The radionuclide content of seaweeds and seagrasses around the coast of Oman and the United Arab Emirates. Mar Pollut Bull 42:1411–1416

Gupta RS, Warren CM, Smith BM, Blumenstock JA, Jiang J, Davis MM, Nadeau KC (2018) The public health impact of parent-reported childhood food allergies in the United States. Pediatrics 142:e20181235

Gupta RS, Warren CM, Smith BM, Jiang J, Blumenstock JA, Davis MM, Schleimer RP, Nadeau KC (2019) Prevalence and severity of food allergies among US adults. JAMA Netw Open 2:e185630

Gutow L, Eckerlebe A, Giménez L, Saborowski R (2016) Experimental evaluation of seaweeds as a vector for microplastics into marine food webs. Environ Sci Technol 50:915–923

Hadi J, Brightwell G (2021) Safety of alternative proteins: Technological, environmental and regulatory aspects of cultured meat, plant-based meat, insect protein and single-cell protein. Foods 10(6):1226

Hajeb P, Selamat J (2012) A contemporary review of seafood allergy. Clin Rev Allergy Immunol 42:365–385

Hanaoka K, Yosida K, Tamano M, Kuroiwa T, Kaise T, Maeda S (2001) Arsenic in the prepared edible brown alga hijiki, *Hizikia fusiforme*. Appl Organomet Chem 15:561–565

Hannan MA, Sohag AAM, Dash R, Haque MN, Mohibbullah M, Oktaviani DF, Hossain MT, Choi HJ, Moon IS (2020) Phytosterols of marine algae: Insights into the potential health benefits and molecular pharmacology. Phytomedicine 69:153201

Hwang YO, Park SG, Park GY, Choi SM, Kim MY (2010) Total arsenic, mercury, lead, and cadmium contents in edible dried seaweed in Korea. Food Addit Contam B 3:7–13

Ismail MM, Alotaibi BS, El-Sheekh MM (2020) Therapeutic uses of red macroalgae. Molecules 25(19):4411

Kim SH, Chang YH, Kim WK, Kim YK, Cho SH, Kim YY, Min KU (2003) Two cases of anaphylaxis after *Laminaria* insertion. J Korean Med Sci 18:886–888

Koyande AK, Chew KW, Rambabu K, Tao Y, Chu D, Show P (2019) Microalgae: A potential alternative to health supplementation for humans. Food Sci Hum Wellness 8:16–24

Kular H, Dean J, Cook V (2018) A case of carrageenan allergy in a pediatric patient. Ann Allergy Asthma Immunol 121:S119

Lao-araya M, Trakultivakorn M (2012) Prevalence of food allergy among preschool children in northern Thailand. Pediatr Int 54:238–243

Lauerma AI, Petman L, Makinen-Kiljunen S (2001) IgE-mediated anaphylaxis to antacid. Allergy 56(6):580

Le T, Knulst AC, Röckmann H (2014) Anaphylaxis to *Spirulina* confirmed by skin prick test with ingredients of Spirulina tablets. Food Chem Toxicol 74:309–310

Lee D, Nishizawa M, Shimizu Y, Saeki H (2017) Anti-inflammatory effects of dulse (*Palmaria palmata*) resulting from the simultaneous water-extraction of phycobiliproteins and chlorophyll *a*. Food Res Intl 100:514–521

Levac D, Colquhoun H, O'Brien KK (2010) Scoping studies: advancing the methodology. Implement Sci: IS 5:69

Li J, Ogorodova LM, Mahesh PA, Wang MH, Fedorova OS, Leung TF, Fernandez-Rivas M, Mills E, Potts J, Kummeling I, Versteeg SA, van Ree R, Yazdanbakhsh M, Burney P, Wong G (2020) Comparative study of food allergies in children from China, India, and Russia: The EuroPrevall-INCO surveys. J Allergy Clin Immunol Pract 8:1349-1358.e16

Li HY, Yi YL, Guo S, Zhang F, Yan H, Zhan ZL, Zhu Y, Duan JA (2022) Isolation, structural characterization and bioactivities of polysaccharides from *Laminaria japonica*: a review. Food Chem 370:131010

Lopata AL, O'Hehir RE, Lehrer SB (2010) Shellfish allergy. Clin Exp Allergy 40:850–858

Lyons SA, Burney P, Ballmer-Weber BK, Fernandez-Rivas M, Barreales L, Clausen M, Dubakiene R, Fernandez-Perez C, Fritsche P, Jedrzejczak-Czechowicz M, Kowalski ML, Kralimarkova T, Kummeling I, Mustakov TB, Lebens A, van Os-Medendorp H, Papadopoulos NG, Popov TA, Sakellariou A, Welsing P, Potts J, Mills ENC, van Ree R, Knulst AC, Le TM (2019) Food allergy in adults: Substantial variation in prevalence and causative foods across Europe. J Allergy Clin Immunol Pract 7:1920–1928

Lyons SA, Clausen M, Knulst AC, Ballmer-Weber BK, Fernandez-Rivas M, Barreales L, Bieli C, Dubakiene R, Fernandez-Perez C, Jedrzejczak-Czechowicz M, Kowalski ML (2020) Prevalence of food sensitization and food allergy in children across Europe. J Allergy Clin Immunol Pract 8:2736–2746

McGuire BE, Hettle AG, Vickers C, King DT, Vocadlo DJ, Boraston AB (2020) The structure of a family 110 glycoside hydrolase provides insight into the hydrolysis of α-1,3-galactosidic linkages in λ-carrageenan and blood group antigens. J Biol Chem 295:18426–18435

McQuade M, Barbour K, Betstadt S, Harrington A (2020) Intubation and intensive care after *Laminaria* anaphylaxis in second-trimester abortion. Am J Emerg Med 38:163.e1-163.e2

Mendes MC, Navalho S, Ferreira A, Paulino C, Figueiredo D, Silva D, Gao F, Gama F, Bombo G, Jacinto R, Aveiro SS, Schulze P, Gonçalves AT, Pereira H, Gouveia L, Patarra RF, Abreu MH, Silva JL, Navalho J, Varela J, Speranza LG (2022) Algae as food in Europe: an overview of species diversity and their application. Foods 11(13):1871

Messina M, Venter C (2020) Recent surveys on food allergy prevalence. Nutr Today (Annapolis) 55:22–29

Mihindukulasooriya SP, Dinh DTT, Khinm H, Kim HJ, Han EJ, Cho J, Ko MO, Jeon YJ, Ahn G, Jee Y (2022) *Sargassum horneri* extract containing polyphenol alleviates DNCB-induced atopic dermatitis in NC/Nga mice through restoring skin barrier function. Histol Histopathol 37:18473–18473

Mildenberger J, Stangeland JK, Rebours C (2022) Antioxidative activities, phenolic compounds and marine food allergens in the macroalgae *Saccharina latissima* produced in integrated multi-trophic aquaculture systems. Aquaculture 546:737386

Mintel (2016) Seaweed-flavoured food and drink launches increased by 147% in Europe between 2011 and 2015. Available at: https://www.mintel.com/press-centre/food-and-drink/seaweed-flavoured-food-and-drink-launches-increased-by-147-in-europe-between-2011-and-2015. Accessed 25/5/22

Montero L, Del Pilar Sánchez-Camargo A, Ibáñez E, Gilbert-López B (2018) Phenolic compounds from edible algae: Bioactivity and health benefits. Curr Med Chem 25:4808–4826

Mooney W, Klamczynska B (2017) Heterotrophic microalgae: A scalable and sustainable protein source. In: Nadathur SR, Wanasundara JPD, Scanlin L (eds) Sustainable Protein Sources. Academic Press, Amsterdam, pp 327–339

Motoyama K, Hamada Y, Nagashima Y, Shiomi K (2007) Allergenicity and allergens of amphipods found in nori (dried laver). Food Addit Contam 24:917–922

Pereira L (2011) A review of the nutrient composition of selected edible seaweeds. In: Pomin VH (ed) Seaweed: Ecology, Nutrient Composition and Medicinal Uses. Nova Science Publishers, NY, pp 15–47

Petrus M, Culerrier R, Campistron M, Barre A, Rouge P (2010) First case report of anaphylaxis to spirulin: identification of phycocyanin as responsible allergen. Allergy 65:924–925

Polikovsky M, Fernand F, Sack M, Frey W, Müller G, Golberg A (2019) In silico food allergenic risk evaluation of proteins extracted from macroalgae *Ulva* sp. with pulsed electric fields. Food Chem 276:735–744

Pukhova II, Okladnikov IN, Liubetskaia LS (1972) The allergenic properties of *Chlorella*. Kosm Biol Med 6:23–28

Purcell-Meyerink D, Packer MA, Wheeler TT, Hayes M (2021) Aquaculture production of the brown seaweeds *Laminaria digitata* and *Macrocystis pyrifera*: Applications in food and pharmaceuticals. Molecules 26:1306

Ruethers T, Taki AC, Johnston EB, Nugraha R, Le T, Kalic T, McLean TR, Kamath SD, Lopata AL (2018) Seafood allergy: A comprehensive review of fish and shellfish allergens. Mol Immunol 100:28–57

Ścieszka S, Klewicka E (2019) Algae in food: a general review. Crit Rev Food Sci Nutr 59:3538–3547

Shirosaki M, Koyama T (2011) *Laminaria japonica* as a food for the prevention of obesity and diabetes. Adv Food Nutr Res 64:199–212

Sicherer SH (2011) Epidemiology of food allergy. J Allergy Clin Immunol 127:594–602

Sierra T, Figueroa MM, Chen KT, Lunde B, Jacobs A (2015) Hypersensitivity to *Laminaria*: a case report and review of literature. Contraception 91:353–355

Smith J, Summers G, Wong R (2010) Nutrient and heavy metal content of edible seaweeds in New Zealand. N Z J Crop Hortic Sci 38:19–28
Steinke JW, Platts-Mills TA, Commins SP (2015) The alpha-gal story: lessons learned from connecting the dots. J Allergy Clin Immunol 135:589–597
Stewart I, Robertson IM, Webb PM, Schluter PJ, Shaw GR (2006) Cutaneous hypersensitivity reactions to freshwater cyanobacteria-human volunteer studies. BMC Dermatol 6:6
Tarlo SM, Dolovich J, Listgarten C (1995) Anaphylaxis to carrageenan: A pseudo–latex allergy. J Allergy Clin Immunol 95:933–936
Taylor VF, Jackson BP (2016) Concentrations and speciation of arsenic in New England seaweed species harvested for food and agriculture. Chemosphere 163:6–13
Thiyagarasaiyar K, Goh B, Jeon Y, Yow Y (2020) Algae metabolites in cosmeceutical: An overview of current applications and challenges. Mar Drugs 18:323
Thomas I, Siew LQC, Watts TJ, Haque R (2019) Seaweed allergy. J Allergy Clin Immunol Pract 7:714–715
Tiberg E, Einarsson R (1989) Variability of allergenicity in eight strains of the green algal genus *Chlorella*. Int Arch Allergy Immunol 90:301–306
Tiberg E, Rolfsen W, Einarsson R, Dreborg S (1990) Detection of *Chlorella*-specific IgE in mould-sensitized children. Allergy 45:481–486
Tiberg E, Dreborg S, Björkstén B (1995) Allergy to green algae (*Chlorella*) among children. J Allergy Clin Immunol 96:257–259
Tobacman JK (2015) The common food additive carrageenan and the alpha-gal epitope. J Allergy Clin Immunol 136:1708–1709
Transparency Market Research (2022) Algae Market (Type: Microalgae and Macroalgae: and Production Method: Harvesting and Cultivation {Open Raceway Pond and Photobioreactors}) - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast, 2022–2031. Available at: https://www.transparencymarketresearch.com/algae-market.html (Accessed: 21/7/22)
Vadalà M, Palmieri B (2015) Dalle alghe ai "functional foods" [From algae to "functional foods"]. Clin Ter 166:e281–e300
Vega AIS, Aanestad TK, Thorslund B, Kiehl EN, Bøgh KL (2021) Potential allergenicity of the novel food seaweed. Allergy: Eur J Allergy Clin 76:340
Vojdani A, Vojdani C (2015) Immune reactivities against gums. Altern Ther Health Med 21:64–72
Wei W, Feng W, Xin G, Tingting N, Zhanghe Z, Haimin C, Xiaojun Y (2016) Enhanced effect of κ-carrageenan on TNBS-induced inflammation in mice. Int Immunopharmacol 39:218–228
Wells ML, Potin P, Craigie JS, Raven JA, Merchant SS, Helliwell K, Smith A, Camire ME, Brawley SH (2017) Algae as nutritional and functional food sources: revisiting our understanding. J Appl Phycol 29:949–982
Wilson JM, Schuyler AJ, Workman L, Gupta M, James HR, Posthumus J, McGowan EC, Commins SP, Platts-Mills T (2019) Investigation into the α-Gal Syndrome: Characteristics of 261 children and adults reporting red meat allergy. J Allergy Clin Immunol Pract 7:2348–2358
Yi J, Pan J, Zhang S, Mao W, Wang J, Wang W, Yan Z (2022) Improvement of chronic non-bacterial prostatitis by Jiedu Huoxue decoction through inhibiting TGF-β/SMAD signaling pathway. Biomed Pharmacother 152:113193
Yim HE, Yoo KH, Seo WH, Won NH, Hong YS, Lee JW (2007) Acute tubulointerstitial nephritis following ingestion of *Chlorella* tablets. Pediatr Nephrol 22:887–888
Yu P, Li JR, Cen PL (2002) Cloning and sequencing of the phycocyanin gene from *Spirulina maxima* and its evolutionary analysis. J Appl Phycol 14:307–310
Zarkadas M, Scott FW, Salminen J, Ham Pong A (1999) Common allergenic foods and their labelling in Canada—a review. Can J Allergy Clin Immunol 4:118–141

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