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Published version

BROWNLEE, Iain, FAIRCLOUGH, Andrew, HALL, Anna and PAXMAN, Jenny (2012). The potential health benefits of seaweed and seaweed extract. In: POMIN, Vitor H., (ed.) Seaweed : ecology, nutrient composition and medicinal uses. Marine Biology : Earth Sciences in the 21st Century . Hauppauge, New York, Nova Science Publishers, 119-136.

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THE POTENTIAL HEALTH BENEFITS OF SEAWEED AND SEAWEED EXTRACTS

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ABSTRACT

Edible seaweeds have historically been consumed by coastal populations across the globe. Today, seaweed is still part of the habitual diet in many Asian countries. Seaweed consumption also appears to be growing in popularity in Western cultures, due both to the influx of Asian cuisine as well as notional health benefits associated with consumption. Isolates of seaweeds (particularly viscous polysaccharides) are used in an increasing number of food applications in order to improve product acceptability and extend shelf-life.

Epidemiological evidence suggests regular seaweed consumption may protect against a range of diseases of modernity. The addition of seaweed and seaweed isolates to foods has already shown potential to enhance satiety and reduce the postprandial absorption rates of glucose and lipids in acute human feeding studies, highlighting their potential use in the development of anti-obesity foods. As seaweeds and seaweed isolates have the potential to both benefit health and improve food acceptability, seaweeds and seaweed isolates offer exciting potential as ingredients in the development of new food products.

This review will outline the evidence from human and experimental studies that suggests consumption of seaweeds and seaweed isolates may impact on health (both positively and negatively). Finally, this review will highlight current gaps in knowledge in this area and what future strategies should be adopted for maximising seaweed's potential food uses.

1. INTRODUCTION

Biologically, seaweeds are classified as macroalgae, with subclassification as brown (Phaeophyta), red (Rhodophyta) or green algae (Chlorophyta). Some examples of these edible algae are outlined in Table 1. The nutritional properties of these seaweeds are discussed earlier in this edition and reviewed elsewhere [1,2]. In 1994/95 over 2,000,000 tonnes (dry weight) of seaweed was harvested [3]. Much of this may be consumed as whole seaweed products, while a large proportion is also used in the production of over 85,000 tonnes of viscous polysaccharides for various food and industrial applications [4].

Historically, seaweed is a readily available food source that has been consumed by coastal communities likely since the dawn of time [15,16]. Seaweed is consumed habitually in many countries in South-East Asia [17]. However, as a wholefood it is not considered a habitual component of the Western diet [2]. In the West, seaweed isolates (e.g. alginate from brown algae and agar or carrageenan from red algae) are typically used industrially [18]. Seaweed consumption has gained a measure of acceptance in some Westernised cultures such as Hawaii, California and Brazil, where there are large Japanese communities who have had a tangible influence on the local dietary practices [19,20]. Low consumer awareness regarding potential health benefits and a lack of previous experience of seaweed challenges its use in the daily diet [21].

Table 1. Examples of edible algae

Subclassificaton	Genus	Common Name
Brown algae (Phaeophyta)	Alaria	Kelp/ bladderlocks
	Himanthalia/ Bifurcaria	Sea spaghetti, fucales
	Laminaria	Kelp/ kombu/ kumbu/ sea tangle
	Saccharina	Sugar wrack
	Undaria	wakame
	Ascophyllum	Egg wrack
	Fucus	Bladder wrack, rockweed
	Sargassum	Mojaban/Indian brown seaweed
	Hizikia	Hijiki
	Sargassum	Sea holly
	Dictyotales	
	Eisenia	Arame
Red algae (Rhodophyta)	Rhodymenia/ Palmaria	Dulse
	Porphyra	Nori/ haidai/ kim/ gim
	Chondrus	Irish moss/ carrigeen
	Mastocarpus/ Gigartina	Stackhouse, Guiry
	Gracilaria	
	Asparagopsis	Limu Kohu
	Grateloupia	
Green algae (Chlorophyta)	Ulvaria/ Enteromorpha	Laver/sea lettuce/ sea grass/nori

Adapted from [2,5,6]. Further details from [7-14].

2. Seaweed as a Whole Food

Consumption of seaweed in Europe and North America is minimal at present [22]. While instruments within Japan and Korea have been developed to assess dietary intake of seaweed [23,24], consumption is so infrequent in most Western cultures that it is not considered within nationwide dietary intake assessment surveys. In the USA and Canada seaweed is cultivated in onshore tanks and the market for it is growing. In Ireland there is a renewed interest in seaweed that once formed part of the traditional diet. Recipe books promoting the use of 'sea vegetables' or 'marine vegetables' [25] in home cooking are becoming more popular. As consumer health and nutrition become more influential in the food industry, the use of seaweed as an ingredient is on the rise [25], and product development involving salads and wraps appears to be slowly evolving.

The rich mineral and trace element content of seaweed compared to terrestrial plant foods can however, impact negatively on its sensory characteristics [2]. As an ingredient of composite foods, it has been shown to be acceptable to consumers when baked into breads (Ascophyllum nodosum up to 5% w/w; Hall et al., 2010; Mahadevan and Fairclough, personal communication) and added to pasta (Wakame - Undaria pinnatafida - up to 10% w/w;[26]). Further from these applications, seaweed has been added to low fat meat products where it contributes to water retention and gel formation [27]. Collectively, these results suggest that seaweed may be successfully included as an ingredient in a number of food applications. As dried seaweed is high in dietary fibre, along with a range of other potentially bioactive components, this addition has the potential to enhance the nutritional quality of a product.

Habitual consumption of seaweed may offer a nutritionally rich addition to the diet. However, micronutrient intakes in excess of the RNI could be of concern to nutritionists, particularly where bioavailability is high.

3. Whole Seaweed Use in Foods

Whole seaweeds have been incorporated into a range of foods including meat, and bakery products. Fairclough and Williams (personal communication) have recently successfully incorporated Ascophyllum nodosum into sausages. This usage has also previously been reported with Laminaria japonica (sea tangle) powder [28]. Previous authors have included Himanthalia elongate (sea spaghetti), Undaria pinnatifida (Wakame) and Porphyra umbilicalis (Nori) in frankfurter type products (gel/emulsion meat systems [29] and H. elongate in frankfurters [27,30,31]. More recently, U. pinnatifida and H. elongate have been incorporated into beef patties and restructured poultry steaks, respectively [32,33]. Recent work has also resulted in the production of an acceptable wholemeal bread enriched with Ascophyllum nodosum [34]. Locally, our research group has also added Ascophyllum nodosum to pizza bases, cheese and frozen meat products. Prabhasankar and colleagues have incorporated Sargassum marginatum (Indian brown seaweed) and U. pinnatifida into pasta [26,35]. The previously published literature described above reports mixed success in terms of acceptability of whole seaweed-enriched food products. There may also be issues involved in the large-scale processing of whole seaweed-enriched foods.

4. Antimicrobial Properties of Whole Seaweeds

The incorporation of seaweed into foods has also been shown to have a preservative effect, particularly with regards to Gram-negative bacteria (Gupta et al., 2010), reducing the need to add salt. The antimicrobial properties of seaweed extracts have been well documented over the years [36-39]. However, there would appear to be a lack of published information regarding the antimicrobial properties and preservative effects when seaweed as a 'whole food' is incorporated into a food matrix. Previous studies would suggest that the overall antimicrobial capacity of seaweeds appears to be linked to their antioxidant content [40].

Several studies have been undertaken at Sheffield Hallam University where seaweed (Ascophyllum nodosum, Seagreens®) as a dried whole-food has been incorporated into various products for example processed meat products and bread products.

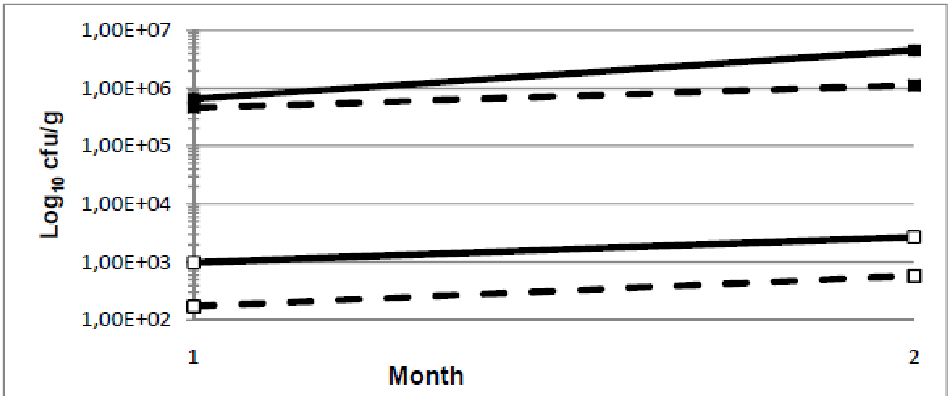

Figure 1. Changes in Total Viable Count (TVC ■) and coliform numbers (□) over shelf-life in frozen processed meat products containing seaweed (dashed line). Control product (no seaweed added) is shown by continuous line.

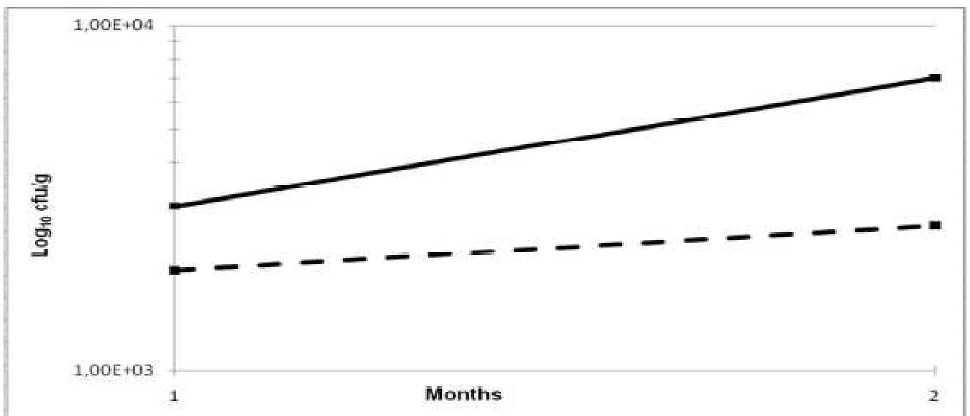

Figure 2**.** Changes in the population of lactic acid bacteria (LAB) in meat products containing Seagreens® (Ascophyllum nodosum). The dashed line represents the seaweed-enriched product, while the control product is denoted by a continuous line.

Figure 1 shows that the 3% w/w dried seaweed added to this processed meat product results in an overall 0.3 $\log_{10}$ cfu/g reduction in the total viable count over the two month trial period; however, when looking at specific populations of micro-organisms, this antimicrobial activity is particularly effective against Gram negative micro-organisms such as coliforms (showing a 0.7 $\log_{10}$ reduction cfu per gram of product) which is to be expected since Gram negative micro-organisms have a thinner cell wall than Gram positive micro-organisms making them more susceptible to antimicrobial agents. However, there is a significant reduction in the Gram positive lactic acid bacteria (LAB) population over shelf-life (0.5 $\log_{10}$ **-** see Figure 2). Other data suggest similar reductions in yeast and mould populations (data not shown).

Interestingly when a methanolic extract of the seaweed is used in a typical antimicrobial susceptibility test then the trend is also mirrored with Gram positive organisms, on the whole, showing more susceptibility to the antimicrobial agent(s) contained within the seaweed;

especially Bacillus cereus and Staphylococcus aureus, which show the greatest sensitivity to the extracted agent (see Table 2). Listeria monocytogenes also shows a noticeable susceptibility to the extract although to a lesser extent than the organisms named above.

Table 2. Antimicrobial effects of a methanolic extract from Seagreens® (Ascophyllum nodosum)

Micro-organism	Sensitivity
Bacillus cereus (NCTC 7464)	+++
Staphylococcus aureus (NCTC 12981)	+++
Listeria monocytogenes (NCTC 7973)	++
Bacillus subtilis (NCTC 10400)	+
Listeria innocua (NCTC 11288)	-
Enterococcus faecalis (NCTC 775)	-
E. coli (NCTC 12241)	±
E. coli 0157 * (NCTC 12900)	±
Pseudomonas fluorescens	-
Salmonella typhimurium (NCTC 12023)	+

+++ - zone of clearance ≥ 7.5mm, ++ - zone of clearance 2.5 - 7.5 mm, + - zone of clearance ≤ 2.5 mm, - - no discernible zone of clearance, ± - indeterminate zone of clearance.

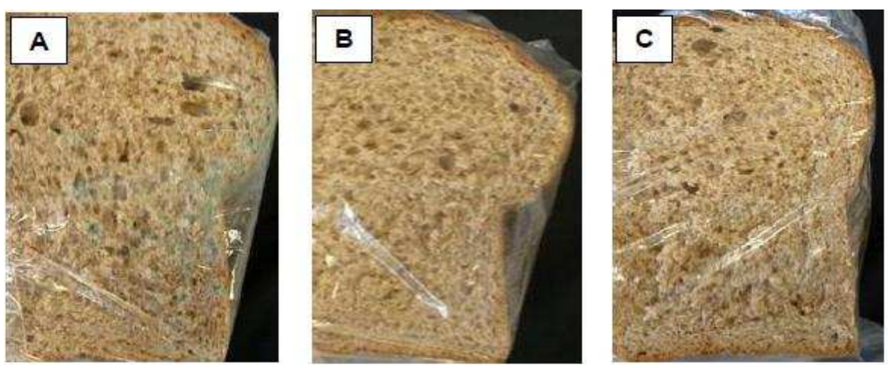

Figure 3. Mould growth at nine days post-production in wholemeal breads containing differing amounts of Seagreens®. Photograph A - control loaf with standard salt content. Photograph B - loaf containing a 50:50 mix of added salt and Seagreens®. Photograph C - loaf with Seagreens® instead of added salt.

When Seagreens® is incorporated into bakery products especially wholemeal bread as a replacement for salt (as sodium chloride) there is a suppression of mould growth for up to 9 days in preservative-free bread when compared to preservative-free control bread containing 5 g of salt (as sodium chloride) and no Seagreens®. Similar results have been recorded in all the other bread varieties baked at Sheffield Hallam University; with the exception of white bread where no significant suppression has been seen and mould growth occurs after 3 to 4 days. Figure 3 shows wholemeal breads containing different amounts of Seagreens® at 9 days.

5. COMPONENTS OF SEAWEEDS

As previously stated, the use of seaweeds in Western diets is predominantly limited to use in food additives or extracts [41]. In line with other natural foods like fruits, vegetables and grains, there has been marked interest within the scientific community to assess which fractions of seaweeds may be linked to the historically observed health benefits. For the purpose of this review, these factors are considered under two relatively crude banners: seaweed phytochemicals and seaweed polysaccharides. Seaweed proteins have also previously been assessed for their nutritional value [42-47] but will not be discussed within this chapter. As with other foods that have historically been consumed whole (e.g. fruits, vegetables and grain products), it must also be noted that isolation of such bioactive components may allow the development of food products and/or supplements with potential health benefits. This should not however preclude a drive to increase population-wide consumption of the original whole foods.

5.1. Seaweed Polysaccharides

Each seaweed subclassification differs in the type of dietary fibres they contain. Brown seaweeds for example contain the dietary fibres alginates, fucans and laminarans; red seaweeds contain galactans, agar and carageenans; whereas green seaweeds contain soluble ulvans and other insoluble fractions such as cellulose.As with plant polysaccharides, non-starch entities play a vital role in seaweed structure both at a microscopic and macroscopic level. The varying roles of these polysaccharides within the macroalgae structure should be considered when comparing these different types of polysaccharides.

In alginates, the presence and arrangement of carboxyl groups on spans of 3 or more guluronic acid residues can act to interact with hydrogen ions and divalent cations (particularly calcium) to cause gelation [48]. This allows gelation in specific formulations at room temperature. The presence and position of sulphate ester groups in carrageenans and other seaweed polysaccharides also appears to affect their gelation and ability to interact with other factors in composite foods [49,50]. The physicochemical variations in these polysaccharides allow for a wide variety of applications within the food industry. Polysaccharides of different viscosities that react differently under various conditions of temperature, pH and food chemistry are important tools in the arsenal of food formulators in order produce products with increased acceptability.

Seaweed polysaccharides are extensively used as thickening agents in sweet and savoury sauces and condiments [51-53]. A number of applications of seaweed polysaccharides are also utilised in order to stabilise food products against degradation, staling and heating or cooling/freezing. These applications also act to improve the consumer acceptability of such products, as well as extending the shelf-life. A further novel applications of seaweed polysaccharides in food manufacture are discussed elsewhere [54].

Seaweed polysaccharides are generally water-soluble and very hydrophilic. Their action as stabilizers within food oil-water emulsions is suggested to be a result of their ability to precipitate/adsorb onto oil droplets and sterically stabilize emulsions against flocculation and coalescence [55,56].

Previous studies have also suggested that seaweed polysaccharides may be used at fat replacers in a range of food applications. Where this is carried out, seaweed polysaccharides and other hydrocolloid thickening agents can be used to reduce or replace added fats within foods in order to produce an end-product with reduced total fat content, while still allowing for a product with improved moisture retention and consistency. This role is crucial in the development of low-fat products with high consumer acceptability. This use of seaweed polysaccharides has been shown to facilitate the production of low fat versions of meat-based, starch-based, fat-based and fruit/vegetable-based products [51,52,57-59].

High viscosity polysaccharides are likely to have detrimental effects both in terms of the manufacturing process and product acceptability. As with other types of viscous polysaccharides, low viscosity fractions of the indigestible carbohydrate material from seaweeds could be used to develop food products with higher fibre content.

5.2. Seaweed Phytochemicals

Seaweeds also contain a range of unique phytochemicals not present in terrestrial plants. As such, edible seaweeds may be the only relevant dietary source of some of these factors. A wide range of studies have described the high antioxidant capacity of a range of edible seaweeds [18,60-62]. This capacity is endowed by the presence of sulphated polysaccharides [63], polyphenolic compounds [64] and antioxidant enzymes [65]. Oxidative stress may play a key role in the development of cancers and cardiovascular disease [66]. Phytochemical-rich foods should clearly form part of a healthy balanced diet. However, the human body has a number of physiological, biochemical and enzymatic processes by which it can combat oxidative stress outside of dietary intake. The routes by which the wide variety of phenolic compounds enter the circulation is not well characterised, nor is the bioavailability and half-life/distribution of such factors in the human body. Previous intervention studies where dietary antioxidant intake has increased have not evidenced a parallel change in the total antioxidant capacity of the body [67,68]. While this casts doubt on the benefit of increasing polyphenolic consumption from the perspective of reducing oxidative stress, it must be noted that such compounds may have other physiological effects.

Previous studies in animal models and cell culture have suggested that seaweed phytochemicals have the potential to inhibit the progression of carcinoma formation [69,70]. In vitro studies have also suggested a potential for phenolic compounds from seaweeds to inhibit the action of digestive enzymes [71,72]. Such an action would be considered to have the potential to affect macronutrient uptake and act as a therapeutic agent to help combat metabolic diseases. Further from these findings, a recent study has suggested that a polyphenol-rich extract of Ecklonia stolonifera improved glycaemic control in a non-insulin dependent diabetic mouse model [73]. A similar effect was also noted in a chemically-induced diabetic mouse model [74]. Anti-inflammatory properties of a phlorotannin-rich extract from Ecklonia cava have also been demonstrated in vitro [75].

The above experimental evidence highlights some interesting ways in which these phytochemical compounds isolated from seaweed could benefit health. Certainly there has been great interest from the pharmaceutical industry in the high-throughput analysis of macroalgal compounds for the development of novel drugs [76-78]. The new, more stringent regulations on novel food ingredients within the EU is likely make the inclusion of specific seaweed phytochemicals as bioactives more problematic than whole seaweed or seaweed polysaccharides, both of which have been used historically within this context. This should not act as a barrier to research that characterises the physiological effects of this range of interesting compounds and potential therapeutic agents, however.

6. Seaweeds and Health

Previous studies on seaweed consumption in humans have centred in the areas of the world where reasonable amounts of seaweeds are habitually consumed (particularly South-East Asia). The evidence detailed below outlines a variety of potential benefits to health, with much of the research in whole seaweeds either focussed around their impact on metabolic disease (associated with increased phytochemical and fibre intake) or breast cancer (linked to increased iodine consumption). Both of these topics are reviewed in detail elsewhere [79,80].

6.1. Experimental Studies

Numerous researchers have studied the health benefits of seaweed incorporation in the diets of rats, particularly with reference to their effects on blood lipid profiles. Wong et al. (1999) examined the lipid changing effects of 4 types of seaweed (1 red, 1 green and 2 brown at 5% dry weight of feed) compared to a control group (cellulose) in 60 male Sprague Dawley rats. Comparisons were made between serum total cholesterol, HDL cholesterol, LDL cholesterol, triglycerides and hepatic cholesterol. The results suggested that the red algae Hypnea charoides had the greatest hypocholesterolaemic effect; however no significant reductions in cholesterol were seen between any of the seaweeds. On the contrary, Colpomenia sinuosa (a brown algae) induced a significant ($p<0.05$) increase in total serum cholesterol [81].

Carvalho et al. (2009) showed that the total cholesterol levels of rats fed a hypercholesterolaemic diet increased significantly ($p<0.05$) when supplemented with cellulose as opposed to the green seaweed Ulva fasciata (24% dry weight seaweed meal). The seaweed containing diet was able to keep the total cholesterol at levels similar to baseline, leading the authors to suggest the incorporation of seaweed into the diet might be important in the reduction of total cholesterol [41].

Bocanegra et al. (2009) conducted a study in groups of ten rats that were fed a diet containing a cholesterol raising agent with either a cellulose-wheat starch mix, Nori algae or Konbu algae (7% weight as freeze-dried material). Rats fed the Nori and cholesterol-raising diet had lower postprandial cholesterolaemia, and a more positive lipid profile with regards to HDL and LDL lipid fractions ($p<0.05$) when compared to the comparable Konbu diet [82].

These studies, among othersof similar design, hint towards the variability of the biological effects of different varieties of edible seaweeds. They also highlight the potential for cardiovascular health benefits in certain cases. As with most animal-based dietary interventions, the amounts of seaweed incorporated in the diet are extremely high and do not bear resemblance to the amounts eaten within the human diet.

6.2. Epidemiological Studies

The lack of a dietary intake assessment tool alongside the likely exceedingly low intake of seaweeds at a population level means that observational data linking seaweed intake to reduced disease risk have only been collected in South East Asian populations. The most recent, accessible data are summarised in Table 4.

Such data should be interpreted with caution, firstly as they do not necessarily represent a causal relationship between seaweed intake and health outcomes, but rather an association between the two factors. Also, different species of edible seaweeds appear to have different effects on disease risk. In a Korean case-controlled study, increasing frequency of Porphyra species consumption was associated with reduced risk of breast cancer, whereas Undaria pinnatifida consumption did not [15]. These results highlight the wide variability in the bioactive content of seaweed species. Even within a specific type of seaweed, previous research has suggested there are significant seasonal variations in nutritional content [83-85], which is likely to impact the biological effects of edible components. As outlined in the section below on the negative impact of seaweed intake, certain population groups may be at risk from global or national guidelines based on high seaweed consumption.

However, these data suggest that achievable daily intakes of seaweed (equating to approximately 30 g of fresh seaweed [15,24,86] or 2 g of dry seaweed [15] a day) appear to reduce disease risk compared to the lowest (close to zero intake) percentiles of seaweed consumption. Such data are also routinely extrapolated to represent lifelong patterns that reduce a disease risk and are therefore a rational basis on which to develop prudent lifestyle choices across the whole life-course.

6.3. Intervention Studies

Relatively few human intervention studies have assessed the impact on seaweed consumption on risk factors for future disease. One previous study [91] has assessed the impact of seaweed consumption over a number of weeks on markers of cardiovascular disease risk. The physiological effects of seaweed supplementation were investigated in terms of effect on a number of markers of health, including blood glucose levels and blood lipid profiles in males and females with type II diabetes mellitus and a BMI of $<35 kg/m^2$. Dried brown seaweeds (sea tangle and sea mustard) incorporated into a pill were consumed 3 times a day for 4 weeks as a food supplement. Total daily consumption of seaweed was 48g. After random assignment to either the control group or the seaweed supplementation group, and the completion of the trial, fasting blood glucose levels ($p<0.01$) and 2 hour postprandial glucose levels ($p<0.05$) were significantly lower in the seaweed supplemented group. However, while serum concentrations of triglycerides decreased, and HDL cholesterol levels significantly increased ($p<0.05$), levels of total and LDL cholesterol were not affected by seaweed supplementation. Nutrient intake (% energy from macronutrients) was identical over the 4 weeks, but the study had a relatively small sample size (n= 20), and while there was a control group (n=11), the study did not have a cross over design.

Table 4. Summary of recent observational studies relating to dietary seaweed intake and health

Disease/health concern	Study design	Odds ratio (95% CI) of highest seaweed to lowest	Reference
Serum total cholesterol	Retrospective study in the Japanese population with data from 1980 and 1990 for > 7000 people. Data were adjusted for age, BMI and total energy intake.	Not reported. No significant effect of seaweed consumption	[87]
Type II diabetes and prediabetes	3,405 Korean individuals, aged 20 - 65 y. Retrospective study. Adjusted for diet and lifestyle.	0.66 (0.43-0.99) for men and 0.80 (0.51-1.24) for women	[24]
Osteoporosis	214 Japanese elderly participants. Prospective study assessing calcaneus stiffness changes over 5 years. No adjustment of data.	0.22 (0.07-67) in all individuals	[88]
Obesity	3760 Japanese women aged 18-20 y. Cross-sectional study assessing 3 different eating patterns.	0.57 (0.37-0.87) for BMI >25.0[a]	[89]
Cardiovascular disease mortality	40547 Japanese men and women aged 40-79 y. Prospective study over seven years of follow-up. Not adjusted.	0.73 (0.59 -0.90)[a]	[90]
Allergic rhinosinusitis	1002 pregnant Japanese women. Cross-sectional study. Data adjusted for lifestyle and risk factors.	0.51 (0.30–0.87)	[86]
Breast cancer occurrence	South Korean case-control study. 362 cases (30-65y) with controls matched for age and menopausal status. Data adjusted for multivitamin supplement use, number of children, breastfeeding, dietary factors, education, exercise, oral contraceptive use.	0.48 (0.27-0.86)	[15]

[a]Seaweed was included as part of a healthy/traditional Japanese eating pattern (i.e. high intakes of vegetables, mushrooms, seaweeds, potatoes, fish and shellfish, soy products, processed fish, fruit and salted vegetables) and was not assessed independently.

The amount of seaweed consumed within this intervention was very high compared to the amounts consumed in the observational studies above that appeared to have a biological effect. As such, they may not be sustainable within the diet of individuals on a long-term basis if such an amount were not consumed in pill-form. Nonetheless, these findings warrant the development of further participant-based interventions involving long-term seaweed consumption and cardiovascular health.

In a study with twelve healthy female volunteers of healthy BMI, inclusion of 3 g of Nori (in capsules) 15 minutes before eating significantly blunted the postprandial glycaemic rise elicited from consumption of a white bread meal (containing 50 g of starch) [92]. These results were not duplicated in a recent study where the impact of inclusion of Ascophyllum nodosum as an integral ingredient within bread, consumed within a composite meal, was compared to a standard seaweed-free meal [93].

Daily supplementation with seaweed (20 g of Laminaria japonica diluted in water or a beverage) was administered in combination with diet, exercise and behavioural therapy to female, Korean college students (19-24y) over 8 weeks. Pre-post test analysis showed there were significant improvements, consistent with recommendations for weight management, across a range of anthropometric measures. However, the lack of a control group prohibits the authors from attributing such effects to any particular aspect of the intervention. There were no significant changes in blood lipids during this time [94].

Dietary supplementation with seaweed (5 g of Alaria esculenta in capsule form) consumption (Alaria esculenta (L.)) did not signficantly affect serum oestradiol concentrations in a recent randomised, placebo-ontrolled crossover trial in fifteen healthy, postmenopausal females [95] . However, it was noted in this study that there was a signficant inverse correlation between seaweed dosage (expressed in terms of mg/kg body weight) and serum oestrodiol concentrations. The same intervention also elicited a significant increase in circulating levels of thyroid-stimulating hormone [96]. It was calculated that c.75mg/kg of body weight of seaweed would need to be ingested to have this oestodiol lowering effect, which would equate to approximately 4 - 5 g/day of dry seaweed consumption for females weighing between 55 and 75 kg. These preliminary results highlight the potential for seaweed as an important dietary factor in the prevention of breast cancer.

There is a growing body of evidence on the acute benefits of alginate consumption to health-related parameters. Alginates are widely researched due to their unusual gelling properties and relatively low viscosity, meaning that higher amounts can be incorporated in foods or beverages than other types of seaweed polysaccharide. Relevant food products could be used to deliver other types of seaweed polysaccharide in such studies. An example of this is the work of Panlasigui et al. (2004) in which carrageenan in a powdered form was incorporated into 4 food products common in the Philippines: a yeast bread, a corn pudding, fish balls and a gruel like product [97]. Following a two-week intervention with these products, participants had significant improvements to plasma concentrations of total and HDL cholesterol compared to the control group (no intervention).

Hoad et al. (2004) investigated the gastric emptying rates of a strong gelling (high-G) and a weaker gelling (low-G) alginate meal compared to a guar-based meal and a control (without added fibre). In vitro characterisation of the gelling properties of both alginate meals showed the formation of intragastric ‘lumps’ which were shown to be associated with feelings of fullness and a reduction in hunger in the strong-gelling alginate condition[98]. The authors purport that acid-gelling agents, such as alginates, may be useful for those aiming to adhere to a weight-reducing diet.

To that end, Paxman and colleagues (2008) demonstrated the capacity for a strong-gelling alginate formulation to restrict free-living energy intake compared to a commercially available control formulation. The 7% (134.8 kcal) reduction in reported daily energy intake was consistent with published guidelines for weight management [99]. Similar significant findings were reported previously in overweight and obese women [100]. Such effects may be explained by the potential for seaweed isolates, particularly alginate to enhance satiety [101].

The potentially satiating effects of seaweed isolates are by no means unaminously reported in the literature, however. Findings from a well-controlled intervention show an alginate and guar-based breakfast bar had no effect on energy and macronutrient intake when incorporated into the habitual diet over 5 days [102]. The breakfast bar was consumed daily for 5 days and food intake recorded on 3 randomly selected days, however the authors purport that poor intragastric gelation of the fibres may explain the lack of a treatment effect. Similarly, acute ad libitum food intake was reportedly unaltered after a meal replacer containing alginate (0.4% and 0.8%) compared to a meal replacer alone [103], though hunger was significantly reduced for several hours following the treatment.

Numerous authors have reported beneficial effects of seaweed isolates on postprandial glycaemia. 5.0 g of sodium alginate, added to food significantly attenuated the postprandial glycaemic response in type 2 diabetics by 31% compared to the control meal [104]. Wolf et al. (2002) incoporated 1.5 g of sodium alginate into a 100 g liquid glucose-based preload along with an acid-soluble calcium source to produce an acid-induced viscosity complex. The authors reported a non-significant fall in peak glycaemia and a significant reduction in incremental change from baseline AUC in healthy, non-diabetic adults following ingestion of the acid-induced viscosity complex compared to a soluble fibre-based control [105]. Williams and colleagues (2004) investigated the glycaemic response to a novel induced viscosity fibre (IVF) "crispy bar" (including 5.5 g guar gum and 1.6 g sodium alginate) compared to an alginate free bar in healthy adults. Postprandial glycaemia was significantly reduced at 15, 30, 45, and 120 minutes. The positive iAUC was significantly reduced by 33% following the IVF “crispy bar” compared to the control [106]. Previous work suggested that the existing positive correlation between AUC glycaemia and body fat percentage (control condition) could be attenuated when an ionic gelling sodium alginate preload was ingested prior to a test lunch. This finding suggests the enhanced postprandial glycaemic response at higher body fat percentages could be normalised in response to alginate ingestion [107].

Effects on lipid uptake are less well-reported. In subjects with ileostomies, alginate added to a meal increased the ileal output of fatty acids [108]. Similar to the previously reported findings for postprandial glycaemia, Paxman and colleagues suggested that the existing positive correlation between AUC cholesterolaemia and body fat percentage was also eliminated by ingestion of an ionic gelling sodium alginate preload [107].

6.4. Potential Negative Effects of Seaweed or Seaweed Isolate Consumption

In Japan and Korea seaweed (often added to soup) is ingested by lactating mothers who believe it to promote an adequate supply of breast milk. Iodine, found in high concentrations in seaweed, is transmissible from mother to infant through breast milk and this local practice has led to documented cases of neonatal iodine toxicity and consequent hypothroidism, with its associated negative clinical consequences [109]. Toxic blue-green algae species can grow on edible seaweed and have been noted in the literature to be the causative factor in a number of food poisoning occurrences [110].

Components of seaweed bind to adsorb heavy metals [111], meaning that seaweed is particularly prone to contamination from polluted water, and its consumption is a potential route of toxic heavy metals entering the body. However, a recent Korean study assessed that high seaweed consumption (8.5 g/day) would result in exposure of individuals to significantly less than 10% of the toxic quantities of arsenic, mercury, lead and cadmium [112]. Associated with this is the action of alginates and other seaweed polysaccharides in binding divalent cations. This has led to a concern over whether their inclusion in the diet could affect the bioavailability of calcium, iron and some trace elements (reviewed in [113]). However, it would be likely that these cations would be absorbed in the large intestine as dietary fibre breaks down. There is no evidence that alginate inclusion in the diet drives micronutrient deficiency in the toxicity studies previously carried out. Carrageenan intake has been linked to breast cancer progression by in vitro studies, which have become somewhat magnified in the safety literature [114].

SUMMARY

Seaweed is a foodstuff that has been historically consumed around the globe but is only consumed in appreciable amounts in certain areas of the world today. Seaweed polysaccharides have been used within the food industry in a wide number of important applications aimed at improving the sensory properties and shelf-life of food products. Previous research would suggest that incorporation of whole seaweeds and seaweed polysaccharides into foods is generally acceptable to the consumer. Seaweed or seaweed-isolate enrichment may not only benefit the nutritional value of a food product, but may also benefit the product in terms of improving the shelf-life and in some cases actually improving the sensorial properties.

While chemical analysis would suggest a number of nutritional benefits of seaweed consumption, there is a need for a more evidence relating dietary intake to health. Acute intervention studies would suggest alginate consumption could have long-term benefits to parameters of cardiovascular health and in appetite regulation. As with whole seaweeds, there is a need for long-term dietary intervention studies in this area. Design of intervention studies is crucial to their success. As such, nutrition or health researchers should collaborate early on with food technologists/food industry in order to design and develop suitably appealing products with these ingredients.

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