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Novel nutrient-dense food sources: A comparison of macroalgae and bivalves with conventional land-based agriculture and animal production

Bachelor Thesis
in
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List of Abbreviations

Gt	Gigaton
GDP	Gross domestic product
EAA	Essential amino acid
NEAA	Non-essential amino acid
CHO	Carbohydrate
AI	Adequate Intake
DW	Dry weight
s.p.	Species
AI	Adequate intake
RDA	Recommended dietary allowance
UL	Tolerable Upper Intake Level
ALA	Alpha-linolenic acid
EPA	Eicosapentaenoic acid
DHA	Docosahexaenoic acid
AAS	Amino acid score
DIAAS	Digestibility indispensable amino acid score
PTWI	Provisional tolerable weekly intake
TWI	Tolerable weekly intake

Abstract

Continued and expanded use of current agricultural food sources and production methods are not only insufficient to sustain a human population expected to reach 9.8 Billion by 2050, but also will prevent achievement of the goal set by the Paris Agreement to limit the increase in global temperature to below 2 degrees Celsius above pre-industrial levels. Novel sources and methods of economically, ecologically, and ethically produced nutrient-rich food are therefore necessary in order to provide future global food security while lowering greenhouse gas emissions and preserving environmental biodiversity and stability.

To sustain future life on earth there needs to be a drastic change in how human food and animal feed is grown and produced. Three dimensional underwater aquaculture farms consisting of various species of macroalgae and shellfish can provide higher yields and more nutrient dense food than conventional land-based agriculture. This model of regenerative mariculture presents a carbon-negative solution to reversing climate change and protecting and restoring ocean habitats, while preserving terrestrial biodiversity, sparing natural resources, and mitigating environmental run-off and unethical animal food production. Various species of macroalgae and bivalve mollusks particularly of interest for human exploitation and commercialization were searched in the scientific literature and examined for their chemical composition and compared to corresponding terrestrial alternatives to assess their potential of reducing nutritional deficiency in general and at-risk populations, as well as extent to which they may contribute to the nutrition of future generations.

Zusammenfassung

Die fortgesetzte und erweiterte Nutzung der derzeitigen landwirtschaftlichen Nahrungsquellen und Produktionsmethoden reicht nicht nur nicht aus, um eine Bevölkerung zu versorgen, die bis 2050 voraussichtlich 9,8 Milliarden Menschen erreichen wird, sondern wird auch verhindern, dass das im Pariser Abkommen festgelegte Ziel erreicht wird, den Anstieg der globalen Temperatur auf unter 2 Grad Celsius gegenüber dem vorindustriellen Niveau zu begrenzen. Neue Quellen und Methoden für wirtschaftlich, ökologisch und ethisch erzeugte nährstoffreiche Lebensmittel sind daher notwendig, um die zukünftige globale Ernährungssicherheit zu

gewährleisten, gleichzeitig die Treibhausgasemissionen zu senken und die biologische Vielfalt und Stabilität der Umwelt zu bewahren.

Um das zukünftige Leben auf der Erde zu erhalten, muss sich die Art und Weise, wie menschliche Lebens- und Futtermittel angebaut und produziert werden, drastisch ändern. Dreidimensionale Unterwasser-Aquakulturen, die aus verschiedenen Arten von Makroalgen und Muscheln bestehen, können höhere Erträge und nährstoffreichere Nahrungsmittel liefern als die konventionelle landgestützte Landwirtschaft. Dieses Modell des regenerativen Marikulturbaus stellt eine kohlenstoff-negative Lösung für die Umkehrung des Klimawandels und den Schutz und die Wiederherstellung der Lebensräume der Meere dar, während gleichzeitig die irdische Biodiversität erhalten, die natürlichen Ressourcen geschont und der umweltbedingte Abfluss und die unethische Produktion von tierischen Lebensmitteln abgeschwächt werden. Verschiedene Arten von Makroalgen und Muscheln, die für die menschliche Nutzung und Vermarktung besonders interessant sind, wurden in der wissenschaftlichen Literatur recherchiert und auf ihre chemische Zusammensetzung untersucht und mit entsprechenden Landalternativen verglichen, um ihr Potenzial zur Verringerung des Nährstoffmangels in der allgemeinen und den Risikopopulationen sowie das Ausmaß, in dem sie zur Ernährung künftiger Generationen beitragen können, zu bewerten.

1 Introduction

With global population expected to reach 9.8 billion by 2050 (UN DESA, 2017), the corresponding increase in food production necessary to sustain such growth has been estimated at 26-68%, depending on projection model (Hunter et al., 2017, p. 388). These projections contrast previously widely accepted and cited assertions that food production must increase from 1.6 to 2 fold respectively (Alexandratos & Bruinsma, 2012, p. 7; Tilman, Balzer, Hill, & Befort, 2011, p. 20260), but more closely represent recent data from the FAO for a 50% increase in production by 2050 (FAO, 2017, p. 136).

While such growth is not unattainable, it presents a complex challenge. Conventional agriculture systems which fueled the Green Revolution beginning in the 1950s have had a tremendous impact of human civilization with food production more than tripling between 1961 and 2011 (FAO, 2017, p. 46). They are described as high-input large-scale monoculture systems requiring off-site resources including heavy-duty machinery, synthetic and chemical fertilizers and pesticides, use of irrigation, and selective breeding of high-yield hybrid crop varieties (Fess & Benedito, 2018, p. 5). While economically successful, these agricultural practices have given little attention to environmental impacts.

According to the FAO, “Agriculture, Forestry, and Other Land Use” contributes to an estimated 21 % of total global greenhouse gas (GHG) emissions, mainly due to deforestation, animal production, and soil and nutrient management (FAO, 2016, p. 6), with livestock production alone making up an estimated 14.5% of global GHG emissions in 2015 (Kim, Neff, Santo, & Vigorito, 2015, p. 2).

Global dietary patterns based on forecasts by the FAO are principally explained as a result of increased meat and dairy intake as a function of rising per GDP per capita and population growth in low- and middle-income countries (FAO, 2017, pp. 82–83; Tilman et al., 2011, p. 20260). If these patterns continue in a business-as-usual scenario, GHG emissions from agriculture alone will approach 21 Gt of carbon dioxide equivalents per year by 2050 (Kim et al., 2015, p. 2). Remaining below this threshold, as agreed upon by the United Nations Conference of the Parties 21 (COP21) in Paris, has been estimated to provide at least a 66% chance of limiting global temperature rise below 2º C of that of pre-industrial levels. After a rise of 2º C the probability of severe and irreversible effects of global warming and climate change is expected to increase dramatically (Kim et al., 2015, pp. 1–2). Therefore, a considerable reduction in consumption of animal products is essential for averting catastrophic climate change.

With 52 g protein per day from animal sources representing roughly half of total daily protein intake in high-income countries in 2011 (FAO, 2017, p. 84), these calls to alarm have led to exploring sustainable and nutrient-dense sources of nutrition and protein, including algae, seaweed, insects and shellfish (Lal, 2016, p. 248; Shumway et al., 2003, p. 15).

Marine bivalve and macroalgae aquaculture have several economic and ecological benefits over terrestrial agriculture. It does not require freshwater, of which agriculture accounts for 70% of global withdrawals and is considered a major factor in rising freshwater scarcity worldwide (Alexandratos & Bruinsma, 2012, p. 116). Furthermore, ocean aquaculture requires no land use. 38% of Earth's terrestrial surface area (about 56.5 million km^2) is used for agriculture, of which about 39.6 million km^2 is dedicated to animal production (Lal, 2016, p. 244), producing an estimated 330 million tons of meat in 2018 (Statista, 2018).

In contrast, 31 million km^2 of ocean area has been deemed environmentally suitable for farming mollusks, which could produce 65 million tons per km^2 per year (National Research Council, 2010, p. 93; Oyinlola, Reygondeau, Wabnitz, Troell, & Cheung, 2018, p. 7), enough to provide roughly 2 billion tons of bivalves per year, using less than 0.1% of total ocean area. Moreover, when bivalves and seaweeds are cultivated together in synergistic models, also known as integrated multitrophic aquaculture (IMTA), yields can be increased by approximately 20% in mussels and up to 35% in brown macroalgae *Saccharina latissima* (National Research Council, 2010, pp. 88–89).

Beyond GHG emissions, insufficient soil and nutrient management of conventional agriculture has also led to the phenomenon of eutrophication, where nutrient run-off entering waterways contribute to massive algae blooms downstream, creating hypoxic environments and leading to so-called "dead zones" in coastal regions around the globe, posing major threats to marine life and fisheries as seen in Figure 1 (Hunter et al., 2017, p. 389).

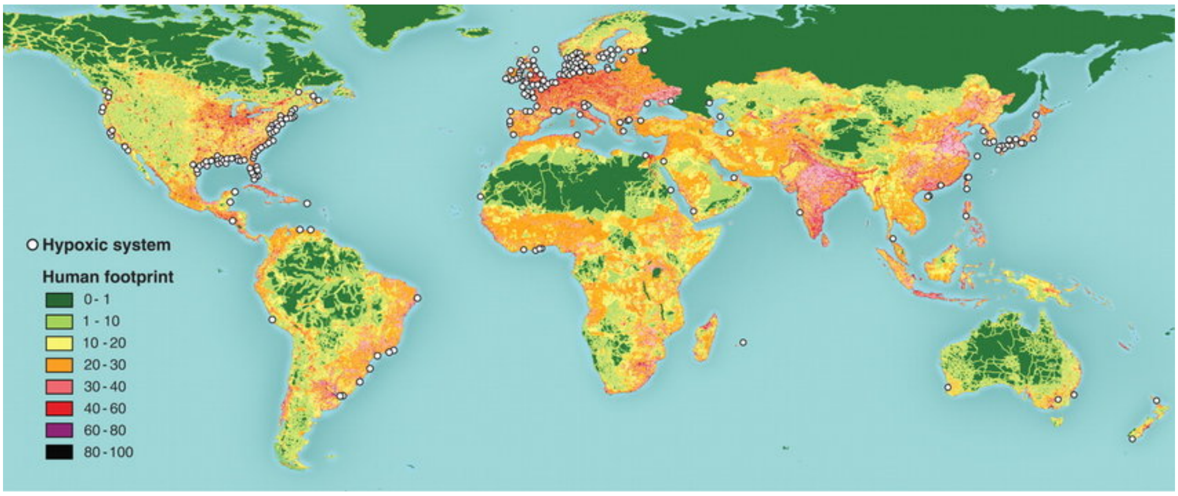

Figure 1: Global Distribution of Dead Zones (Diaz & Rosenberg, 2008)

Marine bivalves and macroalgae are often referred to as extractive species and can mitigate the effects of eutrophication by acting as living filters and improving water quality. Filter feeders, such as bivalves, remove large and small particulate organic matter (POM), while dissolved nutrient absorbers, in the case of macroalgae, remove dissolved inorganic matter (DIN), in the form of inorganic nitrogen, phosphorus, and carbon (Buck, Nevejan, Wille, Chambers, & Chopin, 2017, p. 25; FAO, 2018b, p. 21).

In addition to regenerating ocean dead zones by extracting excess nutrients, both macroalgae and bivalves may play important roles in carbon sequestration and ocean acidification. Marine bivalve shells are composed of calcium carbonate, which when deposited beneath the seafloor or buried on land after consumption prevent carbon from reentering the atmosphere. Alternatively, bivalve shells discarded in the ocean can act as a buffer to acidification (National Research Council, 2010, pp. 126–127). Macroalgae on the other hand, does not tend to accumulate where it grows, but rather to a significant extent reaches shelf sediments and the deep ocean, where upon sinking below 1000 meters requires centuries before renewed atmospheric interaction (Krause-Jensen et al., 2018, p. 2,4). Through photosynthesis and respiration, macroalgae decrease CO_2 and increase O_2 levels, raising pH and improving, among other things, bivalve calcification (Wahl et al., 2018, p. 16). Lowering sea CO_2 saturation consequently increases the ocean's capacity to absorb more atmospheric emissions.

Finally, assessing the role animal products may play in the future of the human diet requires ethical considerations. To the degree that invertebrates like bivalves feel pain and therefore suffering is an area of contention. Mollusks possess µ-opioid receptors, produce the neurotransmitters serotonin, dopamine and histamine, as well as inflammatory cytokines, all indicating the production of painkillers and regulating pain within the nervous system (Cadet & Stefano, 1999, p. 244; Harrison et al., 2015, p. 5; Stefano, Hall, Makman, & Dvorkin, 1981, p. 928). Arguments for bivalve consumption contend however that although they may indeed experience pain, due to the lack of a centralized nervous system and need for space, this may be less than other animals in captivity, and when considering animal products for food consumption,

> "In general, non-fed invertebrates are likely better than fed invertebrates or any vertebrates. Of all the aquatic animal species groups that we eat as food, bivalves appear to be the most promising in terms of minimizing ecological harm (in some cases they may even be beneficial), minimizing food security harm (as highly nutritious organisms that do not rely on outside food sources), and minimizing animal welfare concerns related to captive rearing." (Jacquet, Sebo, & Elder, 2017).

Despite the series of advantages marine bivalve and macroalgae cultivation may have over traditional terrestrial agriculture and animal production, the extent to which these novel food sources can play a role in the everyday human diet is uncertain. The goal of this paper is to examine the nutrient qualities of specific edible macroalgae and bivalves and present comparisons with analogous land-based vegetables and animal products.

2 Methods

Extensive literary review for chemical composition for macroalgae and bivalves was carried out using PubMed and Google Scholar with keywords including macroalgae, seaweed, chemical composition, bivalves, mollusks, molluscs, nutrition, protein, amino-acid, fatty-acid, mineral composition, heavy metals, as well as searches for individual species in their Latin name. Primary species of choice for comparative analysis included native and commercially relevant species of Northern Europe, as ocean eutrophication in the region is especially concentrated and relevant for increased mariculture practice. However, less applicable species for European cultivation with a long history of human exploitation and documented data were selected for comparison where data was incomplete. Emphasis was made to only include reviews of multiple studies and findings with high sample numbers, but due to lack of robust data smaller analyses were necessary in evaluation.

All reference values are expressed as recommended by the German Nutrition Society for adults between the ages of 25–51, with values for energy expenditure based on 2000 kcal/day.

Nutritional composition of macroalgae can differ widely not only between species, but also depending on geographic location and season, which combined with limited understanding of these factors can make assessment of their dietary values challenging (Mahadevan, 2015, p. 361; Renaud & Luong-Van, 2006, pp. 385–386)

When assessing nutritional values, the context of typical consumption must be taken into account. Firstly, it must be differentiated between wet and dry weight. Similar to leafy green vegetables, macroalgae have a high moisture content: about 80% of fresh weight (Holdt & Kraan, 2011, p. 541; Maehre, Malde, Eilertsen, & Elvevoll, 2014, p. 3285). However, seaweed is rarely consumed fresh, but often is sun dried or hot air dried upon harvesting and rehydrated before consumption. In Japan, where macroalgae consumption in traditional diets remain high, average daily consumption is reported between 4–11 g dry weight per day. (Fleurence, 2016, p. 151; MacArtain, Gill, Brooks, Campbell, & Rowland, 2007, p. 536; Wells et al., 2017, p. 950; Zava & Zava, 2011, p. 2). Since typical daily consumption is still very small, this makes direct comparisons with common foods impractical. Therefore, comparisons in this paper with common foods are based on 100 g dry weight macroalgae as well as per portion analysis of 8 g dry weight. Literature regarding further bioactive compounds such as phytochemicals in macroalgae is diverse and neither conclusive nor fully-understood and thus was excluded from analysis.

Bivalves were compared with most common sources of animal production: beef, pork, and poultry. Meat products were selected with lowest fat content, as this corresponds to dietary recommendations calling for preference of low-fat meat products. As dairy products and eggs have significantly lower environmental impacts, they were not included for comparison. Amino acid scores were calculated by dividing the limiting amino acid per gram of crude protein by that set by the FAO (Institute of Medicine, 2005, p. 689).

3 Results

3.1 Macroalgae and Terrestrial Foods

3.1.1 Seaweed background information

Macroalgae, also referred to as seaweeds, are described as multi-cellular marine algae, of which there are an estimated 10,500 species and are classified by pigmentation: brown (Phaophyta), red (Rhodophyta), and green (Chlorophyta)(Buck et al., 2017, p. 27; Hamid et al., 2015, p. 193; S. Lobban & Harrison, 1997, p. 1). They mainly differ from land plants in that they do not possess complex root systems and lack the differentiating organs (leaves, flowers, and seeds), allowing the whole organism to be consumed (Hamid et al., 2015, p. 193; Levine, 2016, p. 1).

Macroalgae have been documented in the human diet of various cultures and regions for thousands of years, with earliest archaeological evidence dating back to 14 000 yBP in southern Chile (Dillehay et al., 2008, p. 785). Although more recently becoming ubiquitous in the modern western diet characterized by processed foods in the form of hydrocolloids such as agars, alginates, and carrageenans used as thickening agents in food and beverages (Wells et al., 2017, p. 950), consumption of macroalgae in recognizable form has largely been limited to Asian cuisine, with almost 96 % of global farmed seaweed being cultivated in China, Indonesia, Philippines, and South Korea in 2016 (FAO, 2018b, p. 25), the most commonly eaten species being the brown algae *Undaria pinnatifida* (wakame) and *Saccharina japonica* (kombu or kelp), as well as the red algae *Porphyra* sp. (nori, laver) (Maehre et al., 2014, p. 3281).

3.1.2 Energy Density

The energy density of macroalgae is comparable to that of non-starchy green vegetables, and therefore negligible in the context of the diet as a whole. Cornish, Critchley and Mouritsen argue that when macroalgae is looked at as an integral part of the human diet, it must be recognized that it may only contribute to a small part of the overall diet, since it does not contain enough calories for complete nutrition (Cornish, Critchley, & Mouritsen, 2015, p. 652). Table 1 shows the energy density of kelp, laver and wakame along some common leafy-green vegetables. Since cereals are the most dominant food group globally with corn, rice, and wheat comprising more than half of global food energy supply, these are included as well for comparison (FAO, 2015, p. 24).

Table 1: Average energy density in seaweed, leafy vegetables and cereals

Food type	kcal/100g
Macroalgae[a]	
Kelp, raw	43
Laver, raw	35
Wakame, raw	45
Vegetables[b]	
Kale	44
Spinach	21
Lamb's lettuce	16
Cabbage	31
Cereals[b]	
Maize, whole grain	342
Rice, unpolished	349
Wheat, whole grain	323

[a](USDA Agricultural Research Service, n.d.-c) [b](Souci, Fachmann, & Kraut, 2016)

3.1.3 Carbohydrates

Macroalgae contain large amounts of polysaccharides, in some species providing up to 76 % of dry weight (Holdt & Kraan, 2011, p. 545). This is, however, to a great extent in the form of dietary fiber. Small amounts of digestible forms of carbohydrate found in macroalgae include glucose, mannose, and galactose (Rajapakse & Kim, 2011, p. 19). Table 2 shows carbohydrate content of several macroalgal species along with common high-fiber whole foods.

Table 2: Carbohydrate and fiber content of macroalgae and common food

Food type	Total Carbohydrates	Total Fiber	Soluble Fiber	Insoluble Fiber	% of CHO as Fiber
Macroalgae (g/100g dry weight)					
Alaria esculenta[a]	51	42.9	n.d.	n.d.	84
Himanthalia elongata[b]	50	32.5	26.3	7.5	65
Saccharina latissima[c]	68.9	40.9	12.8	28.2	59
Palmaria palmata[b]	66.3	33.8	18.8	15	51
Porphyra sp.[b]	47.5	33.8	26.3	8.8	71
Ulva sp.[b]	41.3	37.5	21.3	16.3	91
Whole Food (g/100g)[d]					
Oats, rolled	58.7	10.0	4.9	5.1	17
Rice, unpolished	74.1	2.2	1.3	0.9	3
Wheat, whole grain	59.6	13.3	2.9	10	22
Lentils	40.6	17.0	1.6	15	42
Flaxseeds[e]	28.9	27.3	n.d.	n.d.	94
Chia Seeds[f]	42.1	34.4	n.d.	n.d.	82
Apples[d]	11.4	2.0	0.5	1.5	18
Bananas[d]	20.0	1.8	0.6	1.2	9

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[a](Pereira, 2007, p. 18) b(MacArtain, 2007, p. 537) [c](Neto et al, 2018, p. 3) [d](Souci, Fachmann & Kraut, 2016) [e](USDA Agricultural Research Service, n.d.-b) [f](USDA Agricultural Research Service, n.d.-a)

Table 3: Carbohydrate and fiber content in 8 g serving of macroalgae

Food type	Total Carbohydrates	Total Fiber	Soluble Fiber	Insoluble Fiber	% of DGE Recommendation[d]
Macroalgae (g/8g dry weight)					
Alaria esculenta[a]	4.0	3.4	n.d.	n.d.	11.3
Himanthalia elongata[b]	4.0	2.6	2.1	0.6	8.7
Saccharina latissima[c]	5.5	3.3	1.0	2.3	11
Palmaria palmata[b]	5.3	2.7	1.5	1.2	9
Porphyra sp.[b]	3.8	2.7	2.1	0.7	9
Ulva sp.[b]	3.3	3.0	1.7	1.3	10

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[a](Pereira, 2007, p. 18) [b](MacArtain, 2007, p. 537) [c](Neto et al, 2018, p. 3) [d](German Nutrition Society, n.d.-b)

In the above depicted macroalgae, up to 91% of carbohydrate is in the form of dietary fiber. Aside from *Saccharina latissima* which contains more insoluble fiber, soluble fiber represents 56 – 81% of total dietary fiber. An 8g serving of *Alaria esculenta* provides about 11% of the minimum value for adequate intake (AI) by the German Nutrition Society of 30 grams of fiber per day for adults, in comparison to a largesized apple (140g) or medium-sized banana (120g) providing 9% and 6% of minimum AI, respectively (aid Infodienst, 1991, p. 5,7).

3.1.4 Protein

Protein content in seaweed varies between species, with the highest amount being described in the red macroalgae *Porphyra* sp. (nori) at 31.7% of dry weight, which was less than that of soybean flour with 41% but more than wheat germ, as seen in table 4. Conversely, lowest amounts were identified in kelp species, where protein made up 6.2% of dried weight in the kelp *Laminaria digitata*. *Porphyra* sp. (nori/laver), also had the highest relative amount of essential amino acids (EAA), suggesting a slightly higher quality is to be expected than in other varieties, but still much less than peas, which contain almost 60% of protein as EAA.

Macroalgae protein quality is evaluated using several methods and standards, making comparisons of published data unfeasible. Therefore, examination of protein quality as seen in table 4 is limited to the ratio of essential amino acid to non-essential amino acid (EAA:NEAA). According to Holdt and Kraan, most species contain all the EAA (Holdt & Kraan, 2011, p. 557). This was confirmed in the literature concerning the macroalgae listed in table 4. For most seaweed species, aspartic and glutamic acids make up a large part of the amino acid profile, glutamic acid being the main component in the taste perception “umami”. The flavor enhancer monosodium glutamate (MSG) was originally derived from *Laminaria japonica*, another species of kelp similar to *Laminaria digitata* (MacArtain et al., 2007, p. 540; Wells et al., 2017, p. 953).

In the red seaweed *Palmaria palmata*, Galland-Irmouli, et al. also showed that protein quality was high in that essential amino acids accounted for 26–50% of total amino acids with an essential amino acid profile close to that of egg protein, and an amino acid profile similar to soybean, except that a relative lack of lysine was detected in samples gathered in summer months (Galland-Irmouli et al., 1999, p. 357). In an analysis of five seaweeds, Dawczynski et al. identified tryptophan as the first limiting amino acid in all varieties. Other limiting amino acids in red algae included leucine and isoleucine, while low concentrations of methionine, cysteine, and lysine were identified in brown algae (Dawczynski, Schubert, & Jahreis, 2007, p. 895).

Table 4: Protein composition in macroalgae and whole food

Food type	Protein Content % DW	Relative amount EAA %	g Protein per 8g serving
Macroalgae			
Alaria esculenta[a]	10.7	33.5	0.86
Laminaria digitata[a]	6.2	40.9	0.50
Palmaria palmata[a]	14.4	38.6	1.15
Porphyra sp.[b]	31.4	70	2.5
Ulva lactuca[c]	11.7	37.9	0.94
Undaria pinnatifida[c]	13.1	32.9.	3.43
Whole Food[f]			
Soy flour	41	36.3	
Wheat germ	29	40.2	
Lentils	23	43.9	
Chickpeas	19	44.2	
Peanuts	30	32.0	
Peas	23	65.9	

[a](Maehre et al., 2014, p. 3284) [b](Dawcyznski, et al., 2007, p. 894) [c](Edavilakathil P. & Vinoj Kumar, 2007, p. 36) [e](Je et al., 2009, p. 876) [f](Souci et al., 2016)

3.1.5 Fatty acids

Fatty acid (FA) content in macroalgae is generally very low, which is reported always being less than 4% of dry weight, and a characteristic of all plants adapted to salty environments (Herbreteau, Coiffard, Derrien, & De Roeck-Holtzhauer, 1997, p. 26). Saturated fatty acids (SFA) tend to be found in lower amounts in brown and green seaweeds at 20–34 % DW, respectively, with higher amounts described in red varieties of *Porphyra* sp. and *Palmaria* sp., up to 65%. The most common SFA in all species described is 16:0 (palmitic acid) (Dawczynski et al., 2007, p. 896; Holdt & Kraan, 2011, p. 565; Sánchez-Machado, López-Cervantes, López-Hernández, & Paseiro-Losada, 2004, p. 442). Relatively speaking, monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) are present in high amounts in macroalgae, with 18:1 oleic acid making up on average 27% of total fatty acid content in the green seaweed *Ulva* sp., 28% in *Laminaria* sp. and 19% in *Porphyra* sp. (Holdt & Kraan, 2011, p. 565; Sánchez-Machado et al., 2004, p. 442).

Although not a significant source of essential fatty acids, macroalgae as well as microalgae are the only plant-based sources of eicosapentaenoic acid (EPA) and contain favorable n-6:n-3 ratios, as depicted in table 5 alongside other fatty acid constituents.

EPA amounts are shown in table 6 with theoretical values of that in some common whole foods high in ALA and reveal that while macroalgae do not provide a sufficient source of EPA to meet dietary recommendations, they can provide more per 8 g serving than that which could be expected to result from 8 g of chia seeds, linseeds and walnuts.

Table 5: Fatty acid composition of macroalgae and whole food

Food type	SFA	MUFA	PUFA	n-6 FA	n-3 FA	EPA	n-6:n-3
Macroalgae							
Alaria esculenta[a]	37.4	25.4	33.2	12.8	20.4	n.d.	0.6
Himanthalia elongata[f]	39.1	22.8	38.2	15.1	18.7	5.5	0.81
Laminaria sp.[b]	28.3–42.1	13–28	46	21	25	5.4–16	0.8
Palmaria sp.[b]	30.5	2.8	28.1	2.1	26	47	0.1
Porphyra sp.[b]	65	19	15.2	8.0	7.2	6–54	0.6–1.8
Ulva sp.	34[b]	16.3[c]	42.6[c]	10.5[c]	32.1[c]	0.9[c]	0.3
Undaria pinnatifida[b]	20	11	67	22	45	2.9–15	0.5
Whole Food							
Chia Seeds[e]	8.7	11.0	80.4	0.27	59.8	0	0.4
Flaxseeds[d]	3.0	0.1	69	14	55	0	0.3
Hemp Seeds[f]	10.8	13.7	75.4	57.5	18.0	0	3.3
Walnut[d]	11	18	67	54	12.5	0	4.3

*values given in mean (% of total fatty acid)

[a](Maehre et al., 2014, p. 3288) [b](Holdt & Kraan, 2011, pp. 564–565) [c](Maehre et al., 2014, p. 3284) [d](Souci et al., 2016) [e](Ciftci, Przybylski, & Rudzińska, 2012, p. 3) [f](Galasso et al., 2016, pp. 5–7) [f](Sánchez-Machado et al., 2004, p. 442)

SFA = saturated fatty acid; MUFA = monounsaturated fatty acid; PUFA = polyunsaturated fatty acid; FA = fatty acid; EPA = eicosapentaenoic acid

Table 6: EPA levels in macroalgae and possible amounts in whole foods

Food type	EPA	Food type	ALA	EPA$_{min}$*	EPA$_{max}$**
Macroalgae[a] (mg/8g DW)		**Whole Food (mg/8g)**			
Himanthalia elongata	2.1	Chia Seeds[b]	1673.3	3.3	167.3
Laminaria sp.	6.3	Flaxseeds[c]	1360	2.7	136
Palmaria sp.	34.6	Walnut[c]	626.4	1.3	62.4
Porphyra sp.	5.0				
Undaria pinnatifida	7.9				

*Conversion rate = 0.2% **Conversion rate = 10%

[a](Sánchez-Machado et al., 2004, pp. 442–443) [b](Ciftci et al., 2012, p. 3) [c](Souci et al., 2016)

ALA = α-linolenic acid; EPA = eicosapentaenoic acid; DW = dry weight

3.1.6 Minerals

Seaweeds are considered valuable sources of micronutrients, especially minerals. Because of various cell wall structure polysaccharides which differ from terrestrial plants, macroalgae possess the ability to absorb tremendous amounts of inorganic material from the environment. This ability can be further compounded depending on environmental conditions including geographical location, season, wave exposure, seawater temperature, salinity, seawater mineral levels and pH (Mišurcová, Machů, & Orsavová, 2011, pp. 372, 383–384).

Tables 7 and 8 show aggregated the data from several publications depicting mineral content of various seaweeds based on 100 g DW and 8 g DW.

Table 7: Macromineral composition of seaweeds in mg/100g DW

Food type	Na	K	P	Ca	Mg
Macroalgae					
Alaria esculenta[a]	n.d.	n.d.	230	800	870
Himanthalia elongata[b,c]	2000–4100	4500–8250	240	100–720	300–435
Laminaria sp.[a,b,c]	2620–3818	4300–12,200	120–300	225–2210	550–2445
Palmaria palmata[a,b,c]	1595–2500	7000-9000	235–270	360–930	170–610
Porphyra sp.[b,c]	570–3627	2030–3500	235	300–440	370–950
Ulva sp.[a,b,c]	3400	2450	50–140	350–3250	2600–4650
Undaria pinnatifida[b,c]	1600–7000	650–6810	235–450	680–1380	405–820

[a](Maehre et al., 2014, p. 3288) [b](Pereira, 2011, p. 19) [c](MacArtain et al., 2007, p. 538)
Na = Sodium; K = Potassium; P = Phosphorus; Ca = Calcium; Mg = Magnesium; n.d. = no data

Table 8: Macromineral content of daily portion of seaweed and whole food

Food type	Na	K	P	Ca	Mg
Macroalgae*					
Alaria esculenta[a]	n.d.	n.d.	18	64	70
Himanthalia elongata[b,c]	160–328	360–660	19	8–58	24–35
Laminaria sp.[a,b,c]	210–305	344–976	10–24	18–177	44–196
Palmaria palmata.[a,b,c]	128	560–720	19–22	29–74	14–49
Porphyra sp.[b,c]	46–290	162–280	19	24–35	30–76
Ulva sp.[a,b,c]	272	196	4–11	28–260	208–372
Undaria pinnatifida[b,c]	128–560	52–545	19–36	54–110	32–66
Whole Food**					
Kale	35	451	87	212	31
Spinach	69	554	46	117	62
Lamb's Lettuce	4	421	49	35	13
Mangold	90	376	39	103	n.d.
Soybean	5	1800	550	200	220
Reference Values***					
D-A-CH	1500	4000	700	1000	350 (m) 300 (w)

*values given in mg/8g DW **values given in mg/100g ***values given in mg/day
[a](Maehre et al., 2014, p. 3288) [b](Pereira, 2011, p. 19) [c](MacArtain et al., 2007, p. 538)
Na = Sodium; K = Potassium; P = Phosphorus; Ca = Calcium; Mg = Magnesium; n.d. = no data

As evident in table 7, sodium content in macroalgae can reach levels considerably higher than that of some common leafy green vegetables. The amounts of potassium are relatively similar, although the brown macroalgae species *Laminaria* sp. can contain amounts in 8 grams nearing 25% of AI. Additionally, of note is the calcium and magnesium content in *Ulva* sp., which can provide up to 25% of the recommended dietary allowance (RDA) for calcium and over 100% of the RDA of magnesium in 8 grams of dried seaweed. Soybeans seem to have tremendous micronutrient density when compared to seaweeds. Important to consider however is that these values, both in seaweeds and soybeans, are likely over-estimates and may not reflect actual absorption, since along with food preparation and cooking method, other components in the diet such as dietary fiber, phytate, phenolic compounds as well nutrient synergistic or antagonistic interactions may decrease bioavailability (Mišurcová et al., 2011, pp. 385–386).

Table 9: Trace mineral content of seaweeds

Food type	Fe	Zn	Mn	Cu	I	Se
Macroalgae						
Alaria esculenta[a]	8.7	4.9	0.56	0.24	22.0	0.0041
Himanthalia elongata[b,c]	16.3–59	n.d.	n.d.	0.375	14.7–35	n.d.
Laminaria sp.[a,b,c]	1.2–276	0.9–2.4	0.13–0.65	0.19–1.75	15.9–690	0.0021–0.0033
Palmaria sp.[a,b,c]	10–80	2.9	1.1	0.376–2.5	26–100	0.014
Porphyra sp.[b,c]	10–46.3	2–10	2–3	<0.63–1.47	1.7–17.3	n.d.
Ulva sp.[a,b,c]	21–152.5	0.8	1.1	0.6–3.125	2.1–16.25	0.0049
Undaria pinnatifida[b,c]	1.5–40.8	0.94	0.33	0.185–0.875	22–40	n.d.

*values given in mg/100g DW
[a](Maehre et al., 2014, p. 3288) [b](Holdt & Kraan, 2011, pp. 564–565) [c](Maehre et al., 2014, p. 3284)
Fe = Iron; Zn = Zinc; Mn = Manganese; Cu = Copper; I = Iodine; Se = Selenium

In comparison to some common non-starchy vegetables, certain macroalgae appear to be a favorable source of iron, copper and certainly iodine. However, iron inhibits zinc absorption, which is already represented in lower levels in macroalgae than in leafy green vegetables (Mišurcová et al., 2011, p. 386). Of nutritional significance in the investigated macroalgae appears to be the *Porphyra* genus of the Rhodophyta family, more commonly known as laver or nori and found in sushi (Fleurence, 2016, p. 151). *Porphyra* sp. contain the lowest identified amounts of sodium and iodine, and a relatively low amount of calcium and iron, which may improve zinc bioavailability, of which it contains higher levels than other varieties examined.

Table 10: Trace mineral content of seaweeds and common food

Food type	Fe***	Zn	Mn	Cu	I	Se
Macroalgae*						
Alaria esculenta[a]	0.7	392	45	19	1760	0.3
Himanthalia elongata[b,c]	1.3–4.7	n.d.	n.d.	30	1176–2800	n.d.
Laminaria sp.[a,b,c]	0.1–22.1	72–192	10–52	15–140	1272–55200	0.2–0.3
Palmaria palmata[a,b,c]	0.8–6.4	232	88	30–200	2080–8000	1.1
Porphyra sp.[b,c]	0.8–3.7	160–800	160–240	<50–118	136–1384	n.d.
Ulva sp.[a,b,c]	1.7–12.2	64	88	48–250	168–1300	0.4
Undaria pinnatifida[b,c]	0.1–3.3	75	26	15–70	1760–3200	n.d.
Whole Food**						
Kale	1.9	330	550	56	4.5	1.4
Spinach	3.4	617	599	91	12	0.8
Lamb’s lettuce	2.0	430	n.d.	110	n.d.	n.d.
Mangold	2.7	340	n.d.	76	n.d.	n.d.
Soybean	6.6	4200	2700	1200	6.3	19
Reference Values[d]						
D, A	10 (m) 15 (w)	10000 (m) 7000 (w)	2000–5000	1000–1500	200	70 (m) 60 (w)
WHO, CH					150	

*values given in µg/8g DW
**values given µg/100g
***values given in mg
[a] (Maehre et al., 2014, p. 3288) [b] (Pereira, 2011, p. 19) [c] (MacArtain et al., 2007, p. 538) [d] (German Nutrition Society, n.d.)
Fe = Iron; Zn = Zinc; Mn = Manganese; Cu = Copper; I = Iodine; Se = Selenium; D = Germany; A = Austria; WHO = World Health Organization; CH = Switzerland (m) = values for men; (w) = values for women

3.1.7 Vitamins

As a result of exposure to sunlight, seaweeds contain various antioxidants, such as vitamins and protective pigments. Both water- and fat-soluble vitamins may be present, namely vitamins A, B, C, and E (MacArtain et al., 2007, p. 539). MacArtain et al. report on vitamin content of various species and are related to some common whole foods in table 10.

Table 11: Vitamin composition of seaweeds and common whole food

Food type	B_1	B_2	B_3	B_6	B_9	C	E	B_{12}*
Macroalgae[a] (mg/8g DW)								
Ascophyllum nodosum	0.216	0.058	0.000	0.001	3.648	0.654	0.029	0.131
Laminaria digitate	0.011	0.011	4.896	0.513	0.000	2.842	0.275	0.495
Undaria pinnatifida	0.403	0.936	7.198	0.015	0.528	14.779	1.392	0.345
Porphyra umbilicalis	0.077	0.274	0.761	n.d.	1.003	12.885	0.114	0.769
Palmaria palmata	0.024	0.080	0.800	0.002	0.021	5.520	1.296	1.840
Ulva sp.	0.060	0.030	8.000	n.d.	0.012	10.000	n.d.	6.300
Whole Food[b] (mg/100g)								
Kale	0.100	0.250	2.1	0.250	0.187	105	1.7	n.d.
Spinach	0.092	0.202	0.620	0.221	0.145	51	1.4	n.d.
Lamb's lettuce	0.065	0.080	0.380	0.250	0.145	35	0.600	n.d.
Mangold	0.098	0.160	0.650	n.d.	0.030	0.039	n.d.	n.d.
Soybean	1.030	0.460	2.7	1.0	0.250	n.d.	1.5	n.d.
Reference Values[c]								
m	1.2	1.4	15	1.5	0.300	110	14	4.0
w	1.0	1.1	12	1.2		95	12	

*values given in µg

[a](MacArtain et al., 2007, p. 538) [b](Souci et al., 2016) [c](German Nutrition Society, n.d.)

B_1 = Thiamin; B_2 = Riboflavin; B_3 = Nicotinamide; B_6 = Pyridoxin; B_9 = Folate; C = Ascorbic acid; E = Vitamin E activity B_{12} = Cobalamin; (m) = values for men; (w) = values for women; n.d. = not determined/no data

Levels of Thiamin (B_1), Riboflavin (B_2), Nicotinamide (B_3), and Vitamin E activity are similar in some seaweeds in comparison with some leafy green vegetables. Ascorbic acid (C) is found in lesser amounts in seaweed than the selected terrestrial plants and Pyridoxin (B_6) is significantly lower in the above described seaweeds where data is available with the exception of the brown kelp species *Laminaria digitata*, which can contain roughly two times as much B_6 as kale, spinach and lamb's lettuce. Folate, formerly referred to as Vitamin B_9, is also shown to vary greatly between species, with little to none described in *Ulva* sp., *P. palmata*, and *L. digitata*, while amounts far exceeding those of leafy green vegetables were reported in *A. nodosum* and *P. umbilicalis,* providing 1216% and 334% of RDA respectively, in 8 grams of dried seaweed. Cobalamin (B_{12}) was also shown to be present in seaweeds at varying concentrations, with over 6 µg in eight grams of dried *Ulva* sp.. Micro- and macroalgae are two of very few plant sources of Vitamin B_{12} and have been suggested as an alternative source for vegetarians or vegans (MacArtain et al., 2007, p. 540). It is however important to consider that the ultimate source of B_{12} is bacteria and amounts found reflect the cyanobacteria communities associated with the specific species and environment. Furthermore, the majority of cyanobacteria, such as spirulina, which are described as prokaryotic bacteria that photosynthesize light and produce oxygen, only produce pseudocobalamin, which due to its altered ligand structure has a low affinity to the mammalian B_{12} binding protein intrinsic factor in the human digestive tract, consequently limiting bioavailability (Wells et al., 2017, p. 961). On the other hand, macroalgae, similar to animals, require B_{12} for growth and there is evidence showing green and purple laver (nori) contain considerable amounts of four biologically active B_{12} analogues (Watanabe et al., 1999, p. 2342).

3.2 Bivalves and Conventional Animal Products

3.2.1 Bivalve background information

Bivalve mollusks such as mussels, clams, scallops and oysters are soft-bodied invertebrates that have an external covering in the form of a two-part hinged shell. Similar to fish, bivalves breathe, but also as filter feeders gather nutrients from the environment through their gills. Some species include a “foot” which protrudes from the shell, enabling them to move or dig into the sea floor. They are ancient creatures, having evolved some 440–510 million years ago, comprising an estimated 9200 different species, and inhabit some freshwater bodies and essentially the entire world ocean in tropical as well as sub-zero arctic locations, in both deep and shallow waters, and on sandy and rocky coastlines (Morton, 2018; National Oceanic and Atmospheric Administration, 2018).

Mollusk consumption is thought to have played a crucial role in human evolution, as protein from freshwater and marine sources made up an estimated 10–40% of the diet in early modern humans of the Mid–Upper Paleolithic period. The extension of the diet to seafood and with that high concentrations of DHA at this stage corresponds to expansion of gray matter in the brain, as the cerebral cortex more than doubled in one million years from *Homo erectus* to *Homo sapiens*, while 3 million years of evolution changed very little in the early hominids *Australopithecus* sp. (Bradbury, 2011, p. 530)

Today, mussels, clams, scallops and oysters are the most traded and economically relevant species of bivalves, comprising 16.1 million tons in 2015, representing 3.2% of the total value of fish and fish products globally, with China being the largest exporter, exporting nearly three times more than the next leading exporter, Chile. The European Union however, is the largest single market for bivalves (FAO, 2018b, pp. 64, 67, 153).

3.2.2 Energy Density

As evident in table 11, bivalves contribute less energy to the diet than conventional meat products, as low as 21% fewer calories when oyster is exchanged with chicken and up to about 50% when soft-shelled clam is chosen over beef. Obviously, even greater differences can be expected when meat products with higher fat content are matched up with bivalves.

Table 12: Energy density per 100g of edible bivalves and conventional meat products

Food type	kcal	kJ
Bivalves		
Mussel	69	291
Soft-shelled clam	54	226
Scallop	63	269
Oyster	81	344
Meat Products		
Beef, muscle meat	107	455
Pork, muscle meat	105	443
Chicken breast, no skin	102	413

(Souci et al., 2016)

3.2.3 Protein

In comparison with conventional meats as seen in table 12, bivalves contribute less protein per 100g. The highest protein content is found in scallops, equating to about 70% of that found in beef, pork or chicken breast, while oysters provide only 40% the amount of protein in the same 100g serving. Traditional livestock have a higher ratio of essential amino acids when likened to bivalves, implying they are likely a higher quality protein than the described mollusks. Tryptophan was the limiting amino acid in all of the analyzed food sources with as little as 80mg present in oysters, suggesting that although containing the highest ratio of EAA to NEAA in the bivalves, protein derived from oyster may be of the least quality, as reflected in an amino acid score (AAS) of 1.3. Conversely, soft-shelled clam had the highest amount of tryptophan per gram crude protein (CP), equating to an amino acid score higher than beef, pork, and poultry.

Table 13: Protein content per 100g of edible bivalves and conventional meat products

Food type	g	EAA*	NEAA*	EAA:NEAA	Trp/g CP*	AAS
Bivalves						
Mussel	10.5	4.12	6.38	0.65	11.4	1.6
Soft-shelled clam	10.5	4.61	5.89	0.78	15.2	2.2
Scallop	15.6	n.d.	n.d.	n.d.	n.d.	n.d.
Oyster	9.0	4.05	4.95	0.82	8.9	1.3
Meat Products						
Beef, muscle meat	22.0	10.83	11.17	0.97	13.2	1.9
Pork, muscle meat	22.0	11.06	10.94	1.01	14.1	2.0
Chicken breast, with skin	22.2	10.83	11.37	0.95	14.0	2.0

*Values given in mg
(Souci et al., 2016)
EAA = essential amino acid; NEAA = non-essential amino acid; Trp = tryptophan; CP = crude protein; AAS = amino acid score

3.2.4 Fatty acids

As fat amounts can vary greatly depending on which animal cut is consumed, total fat amounts per 100g are impractical. In table 14, the relative amounts of fat contents in mussels and oysters are listed alongside commonly consumed beef, pork and chicken products. SFA constitutes similar amounts of total fat among bivalves, pork, and chicken with around 30%, whereas 42% of total fat in beef is in the form of saturated fat. As much as 2.3% of FA as trans-fat is found in some meat products, which is otherwise not identified in bivalves. PUFAs are found in greater amounts in bivalves in comparison with conventional meat products, making up to 35% of total fatty acids in oysters. Of the polyunsaturated fatty acids, n-3 fats are of substantially higher concentration in bivalves, especially SDA, EPA, DPA, and DHA, which comprise roughly 19% and 31% of total fatty acid content in mussels and oysters respectively, thus making bivalves excellent sources of these long-chain polyunsaturated fatty acids. Conversely, these PUFAs are present in only limited amounts in conventional meat products, contributing 3.2% of total fat in chicken, 2.6 % in pork, and just 0.3% in beef.

Table 14: Fatty acid constituents of bivalves and conventional meat products

	Bivalves		**Meat Products**		
	Mussel	Oyster	Beef, muscle	Pork, muscle	Chicken breast, with skin
SFA	30	27	42	35	31
MUFA	24	19	44	43	31
TFA	0	0	2.4	0	0.5
PUFA	27	35	5.6	14	24
LA (18:2n-6)	3	1.6	3.4	8.7	18
ALA (18:3n-3)	1	1	1.1	0.8	1.0
SDA (18:4n-3)	5.3	0.3	0	0.1	0
AA (20:4n-6)	3.4	0.4	0.8	1.9	2.6
EPA (20:5n-3)	6.7	19	0	1.3	0.1
DPA (22:5n-3)	1.7	0.1	0.3	0	1.3
DHA (22:6n-3)	5.7	11.7	0	1.2	1.8
n-6:n-3	0.31	0.06	3	3.12	4.90

(Souci et al., 2016)

*values given as % of total fat content

SFA = Saturated fatty acid; MUFA = Monounsaturated fatty acid; TFA = Trans fatty acid; PUFA = Polyunsaturated fatty acid; LA = Linoleic fatty acid; ALA = α-Linolenic acid; SDA = Stearidonic acid; AA = Arachidonic acid; EPA = Eicosapentaenoic acid; DPA = Docosapentaenoic acid; DHA = Docosahexaenoic acid

3.2.5 Minerals

Bivalves contain up to 4.5 times more sodium than conventional meat products per 100g serving, which is to be expected from an organism growing in a salty environment. Regarding other electrolytes, potassium levels appear to vary more widely between bivalve species, providing as little as 4.6% of adequate intake in oysters and up to 20% in soft-shelled clams. Of the analyzed meat products, an average of 338mg per 100g was determined, amounting to 8.5% of adequate intake. Oysters contain the highest amounts of calcium of the analyzed foods, comprising 8.2% RDA, whereas the highest amount found in meats would contribute 1.4% as identified in chicken. More than double the amount of magnesium can be found in 100g of soft-shelled clam than in beef or pork, with 63g representing nearly 18% RDA in adult males and 21% RDA in adult women ages 25–51.

Table 15: Macromineral composition per 100g bivalves and conventional meat products

Food type	Na	K	P	Ca	Mg
Bivalves[a]					
Mussel	296	286	200	24	30
Soft-shelled clam	121	800	310	12	63
Scallop	n.d.	n.d.	208	26	n.d.
Oyster	160	184	157	82	32
Meat Products[a]					
Beef, muscle	66	358	189	5.7	23
Pork, muscle	71	393	189	5.1	26
Chicken breast, with skin	66	264	212	14	n.d.
Reference Values[b]					
D-A-CH	1500	4000	700	1000	350 (m) 300 (w)

*values given in mg
[a](Souci et al., 2016) [b](German Nutrition Society, n.d.-b)
Na = Sodium; K = Potassium; P = Phosphorus; Ca = Calcium; Mg = Magnesium; n.d. = no data

More pronounced differences between bivalves and conventional meat products were identified in trace element content. This is due to the ability of bivalves as passive filter feeders to bioaccumulate foreign substances from their environment, of which the bioaccumulation of heavy metals has been documented (Zuykov, Pelletier, & Harper, 2013, p. 3). Of the essential trace elements listed in table 15, zinc, copper, iodine, and selenium appear in elevated concentrations. For example, 22mg zinc per 100g was identified in oyster compared to the highest amount in meat occurring in beef at 4.3mg. This amount exceeds the RDA for zinc by 220% for adult men and 314% for adult women, meaning that only 45g of oyster would be required to meet the RDA for an adult male, who would alternatively require a 232g portion of steak to reach the RDA.

Similar comparisons can be made with copper. With an AI level estimated at 1.0–1.5mg per day, 100g of oyster supplies over 91%. To achieve this same amount with conventional meat, one would need to eat over 1kg of pork. Iodine levels as well are much higher in bivalves with the highest average amounts of analyzed

species found in mussels with 150µg in comparison to 5.4µg in beef. 100g of mussel therefore fulfills 75% of the RDA for iodine when following dietary guidelines from the German and Austrian Nutrition Societies, and 100% of the RDA as recommended by Switzerland, the World Health Organization and the Institute of Medicine (US) Panel on Micronutrients (German Nutrition Society, n.d.-b; Medicine, 2001).
Lastly, selenium is present in high levels in bivalves, containing up to 80% of AI for adult men and 93% for adult women. Conversely, a 100g portion of pork provides 17% and 20% for adult men and women, respectively.

Table 16: Trace elements per 100g bivalves and conventional meat products

Food type	Fe*	Zn*	Mn*	Cu*	I**	Se**
Bivalves						
Mussel	4.2	1.8	2.3	0.181	150	56
Soft-shelled clam	0.57	1.6	n.d.	0.431	120	n.d.
Scallop	1.8	n.d.	n.d.	n.d.	n.d.	51
Oyster	3.1	22	0.14	0.916	58	25
Meat Products						
Beef, muscle	2.1	4.3	0.017	0.087	5.4	5.4
Pork, muscle	1.0	2.4	0.026	0.088	4.5	12
Chicken breast with skin	1.1	n.d.	n.d.	n.d.	n.d.	6.2
Reference Values[d]						
D, A	10 (m) 15 (w)	10.0 (m) 7.0 (w)	2.3–5.0	1.0–1.5	200	70 (m) 60 (w)
WHO, CH					150	

*values given in mg
**values given in µg
[a](Souci et al., 2016) [b](German Nutrition Society, n.d.)
Fe = Iron; Zn = Zinc; Mn = Manganese; Cu = Copper; I = Iodine; Se = Selenium D = Germany; A = Austria; WHO = World Health Organization; CH = Switzerland (m) = values for men; (w) = values for women

3.2.6 Vitamins

Table 16 shows water- and fat-soluble vitamins found in bivalves and conventional meat products. Pork has far higher levels of Vitamin B_1 in comparison with all other foods examined, providing 90% of RDA per 100g in adult women, whereas mussel and oyster could contribute only 10%.
Noticeable differences can also be observed in the case of folate, where 100g mussel can provide 11% of RDA in contrast to chicken breast, which can supply 3%. Bivalves are ideal sources for Vitamin B_{12}, with amounts exceeding most other foods aside from liver. Soft-shelled clams in particular contain high levels with 153 µg per 100g, however oyster (15µg) and mussel (8.0µg) also contribute significant amounts

exceeding RDA by 200–375% and delivering 3–10µg more per 100g serving than beef. Since there is no tolerable upper intake level determined for Vitamin B_{12}, higher amounts of ingestion are considered safe (German Nutrition Society, 2018). Vitamin D was identified in oyster with 8µg, but was not found in any other bivalves or meat products examined, however smaller amounts can be found in beef and chicken liver, with 1.7 and 1.3µg respectively (Souci et al., 2016, p. 283,406).

Table 17: Vitamin composition per 100g bivalves and conventional meat products

Food type	B_1	B_2	B_3	B_6	B_9*	B_{12}*	A	D*	E
Bivalves[a]									
Mussel	0.16	0.22	1.6	0.76	33	8.0	0.05	n.d.	0.75
Clam	0.10	0.19	1.4	n.d.	2.6	153	0.03	n.d.	n.d.
Scallop	0.04	0.08	1.3	n.d.	11	1.9	n.d.	n.d.	n.d.
Oyster	0.16	0.20	2.2	0.22	7.0	15	0.09	8.0	0.85
Meat Products[a]									
Beef, muscle	0.06	0.26	7.5	0.24	3.0	5.0	0.02	n.d.	0.48
Pork, muscle	0.90	0.23	5.0	0.57	2.5	2.0	6.0	n.d.	0.41
Chicken breast with skin	0.07	0.09	10	0.53	9.0	0.4	n.d.	n.d.	0.25
Reference Values[b]									
m	1.2	1.4	15	1.5	300	4.0	110	20	14
w	1.0	1.1	12	1.2			95		12

*values given in µg
[a](Souci et al., 2016) [b](German Nutrition Society, n.d.)
B_1 = Thiamin; B_2 = Riboflavin; B_3 = Nicotinamide; B_6 = Pyridoxin; B_9 = Folate; B_{12} = Cobalamin; A = Retinol equivalent; D= Vitamin D; E = Vitamin E activity; (m) = values for men; (w) = values for women; n.d. = not determined/no data

4 Discussion

4.1 Macroalgae: Implications for Public Health

4.1.1 Energy density and macronutrient profiles

Unhealthy diet is a modifiable behavioral risk factor involved in the development of non-communicable diseases (NCDs), a public health crisis killing 41 million people a year and accounting for 71% of deaths globally. Also referred to as chronic diseases, the major NCDs are cardiovascular diseases, cancers, chronic respiratory diseases, and diabetes. Four key physiological changes determine the metabolic risk factors which increase the probability for NCDs and include in order of significance: elevated blood pressure, overweight/obesity, hyperglycemia, and hyperlipidemia (World Health Organisation, 2018).

Macroalgae are generally characterized as having high fiber carbohydrate and low fat content, thus making them low-calorie foods (Fleurence, 2016, pp. 156–157). While this may not be seem relevant for undernourished populations such as in sub-Saharan Africa where the prevalence of undernourishment increased in 2016/2017 (FAO, 2018a, p. 2), average daily energy supply per person per day exceeds the minimum requirement of 1 950 kcal both in low- and middle-income as well as high-income countries, with 2 750 kcal/day and 3 350 kcal/day respectively (FAO, 2017, p. 85). However, adequate energy availability does not equal sufficient energy nor food intake and optimal health, a trend becoming more clear as high-energy, low nutrient-dense processed food heavy diets characterized by excessive amounts of saturated fat, salt, sugar, and preservatives are leading to a higher prevalence of NCDs (FAO, 2017, p. 85).

In the 13th Nutrition Report published by the German Nutrition Society in 2016, the overall prevalence of overweight (pre-obesity and obesity) in Germany was reported in 58.5% of men and 37.1% of women aged 18–65. With prevalence remaining high and increasing in some age groups, the German Nutrition Society states that “this comprehensive analysis shows very clearly, that urgent action is needed to overcome the obesity epidemic.” (German Nutrition Society, 2016, pp. 16–17).

Regarding energy imbalance as a fundamental criteria for weight gain, data from the German Nutrition Survey (NVS II) showed that energy density increased with more highly processed food consumption (German Nutrition Society, 2016, p. 32).

Energy density is similar among land-based vegetables and seaweed. Furthermore, there are various additional health-promoting aspects to vegetable consumption including dietary fiber, micronutrient content and phytochemicals, suggesting that seaweed consumption should not displace these foods in the diet. A possible strategy for implementing seaweed as a tool for lowering energy intake is by adding small amounts to cereal products like breads and pastas. Mahadevan summarizes several studies investigating the use of seaweed in bakery and cereal products where for example, powdered forms implemented up to 4% contributed to appetite management and increased crude fiber content without decreasing acceptability (Hall, Fairclough, Mahadevan, & Paxman, 2012, p. 383; Mahadevan, 2015, p. 351).

Macroalgae contain high amounts of carbohydrates, comprising up to 70% of dry weight in some species. Carbohydrate content is however primarily comprised of dietary fiber, consequently providing few digestible carbohydrates, indicating negligible glycemic load which may be less problematic than common high fiber foods such as brown rice and legumes that are accompanied with high amounts of starch (MacArtain et al., 2007, p. 537). There are many well-known health benefits attributed to high fiber intake, including promoting and maintaining healthy body weight, improving plasma lipid profiles, in turn reducing the risk of cardiovascular disease (CVD), minimizing the risks of hypertension, diabetes, and obesity. Soluble fiber has a high water-binding capacity, slows gastric emptying, and consequently nutrient absorption leading to increased feelings of satiety and improved glycemic control (Cornish et al., 2015, pp. 651–652; Rajapakse & Kim, 2011, pp. 23–26). Diets high in fiber are also associated with reducing the risk of colorectal cancer through various protective mechanisms involving the dilution of fecal carcinogens, binding of carcinogenic bile acids, increasing fecal bulk accelerating fecal transit time, and production of short-chain fatty acids (SFCA), which provide an important energy substrate for intestinal epithelial cells as well as promote anti-carcinogenic action (Holdt & Kraan, 2011, p. 557; Rajapakse & Kim, 2011, pp. 22, 24).

Soluble fibers found in macroalgae include agar, carrageenans, alginate, fucoidan, laminarin, porphyran, and ulvan, some of which have shown similar activities to soluble fibers in terrestrial plants (Rajapakse & Kim, 2011, p. 22; Wells et al., 2017, pp. 958–960). Laminarin and fucoidan, present in brown seaweeds such as *Laminaria* sp. and *Saccharina latissima*, have been shown to increase SCFA levels in the colon of pigs (Reilly et al., 2008, p. 1471). In a small human trial, sodium alginate had positive effects on fecal weight, water content, putrefactive products, bifidobacteria, and Enterobacteriaceae (Terada, Hara, & Mitsuoka, 1995, p. 262).

When evaluating the potential health benefits of a food product, protein, as the essential nutrient for growth, is a major factor of consideration. Protein content in macroalgae varies greatly across species and time of harvest. Red and green macroalgae often contain higher levels of protein in comparison to lower levels found in brown macroalgae (MacArtain et al., 2007, p. 540; Wells et al., 2017, p. 952). For example, *Palmaria palmata*, *Porphyra* sp. and *Ulva* sp. can contain up to 35%, 44%, and 50% protein of dry matter, respectively (Holdt & Kraan, 2011, p.

558). Perhaps more important than total protein content is protein quality. This is determined by assessing the presence and composition of essential amino acids (EAA), those which cannot be synthesized by the body and therefore must come from the diet. Of the 20 amino acids, 9 are considered essential for humans: histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine (Hoffman & Falvo, 2004, p. 119). The degree to which a dietary protein can be utilized to build human protein depends on the ratios of EAA, digestibility of the protein and the adequacy of the diet as a whole (Olu & Adediran, 2015, p. 704). Most species of macroalgae contain all EAA, with the first limiting AA described as tryptophan, while red species have lower levels of leucine and isoleucine and brown varieties with limited amounts of methionine and lysine (Dawczynski et al., 2007, p. 895). Tryptophan is also commonly the first limiting AA reported in plant proteins, followed by methionine and cysteine, threonine, and lysine (Young & Pellett, 1994, p. 1205S). While total protein amounts remain small in the context of maximum daily intake limited to 11g dry weight, several authors suggest that macroalgae show balanced amino acid profiles and could be a complementary source of protein for humans (Dawczynski et al., 2007, p. 898; Edavilakathil P. & Vinoj Kumar, 2007, p. 39; MacArtain et al., 2007, p. 541; Maehre et al., 2014, p. 3289).

Some macroalgae have a high proportion of total fatty acids as essential fatty acids (EFA). Essential fatty acids are PUFAs, which are roughly divided into two families, the linoleic acids, also called n-6 or omega 6 fatty acids, and the α-linolenic acids, also known as n-3 or omega 3 fatty acids. PUFAs play important roles in health and disease, and similar to essential amino acids, they cannot be synthesized by the body, but rather must be included in the diet. The most critical of the EFAs are eicosapentaenoic acid (EPA; 20:5 n-3) and docosahexaenoic acid (DHA; 22:6 n-3) as well as their precursors α-linolenic acid (ALA; 18:3 n-3) and docosapentaenoic acid (22:5 n-3) (Wells et al., 2017, p. 954). Involvement of further metabolites of EPA and DHA are well documented in providing various cardioprotective effects and have been shown in humans to possess hypotriglyceridemic, hypotensive, anti-arrhythmic, and antithrombotic properties, as well as improve arterial stiffness and endothelial function, increase insulin sensitivity and glycemic control, and improve blood lipid markers by increasing high-density lipoprotein (HDL) and low-density lipoprotein (LDL) particle size while decreasing blood triglyceride levels (Cottin, Sanders, & Hall, 2011, pp. 216–225).

Whereas the pre-cursor ALA can be found in plant foods such as flaxseeds and walnuts, and in more concentrated amounts in refined seed oils, humans have a limited ability to convert ALA into EPA, with estimates between 0.2–10%, and even lower in the case of DHA at 0.05–3.8% (Burdge & Calder, 2005, p. 591; Gerster, 1998, p. 170). This low conversion rate, which is more common in men, is reportedly lowered an additional 40–54% in diets high in linoleic acid (Gerster, 1998, p. 168). Gerster states, "It is therefore doubtful whether ALA (18:3n-3)-rich vegetable oils are a reliable source of EPA (20:5n-3) and DHA (22:6n-3) (Gerster, 1998, p. 162).

Theoretical values of EPA converted from high ALA plant foods were detailed in table 6 for comparison with actual EPA amounts in macroalgae. There are however, a few limitations in this comparison in that 1) total lipid content in the literature may include non-fatty acid lipids, 2) EPA conversion doesn't take into account other n-3 fatty acids present, and 3) the role of n-6 fatty acids present which compete for the same enzymes and therefore affect ALA conversion aren't factored in.

The German Nutrition Society recommends an n-6:n-3 ratio of 5:1, where n-6 FA represent 2.5% and n-3 FA comprise 0.5% of total energy intake, which for a 2000kcal/day energy requirement corresponds to 5.6 g n-6 and 1.1 g n-3 EFA (German Nutrition Society, n.d.-a). Moreover, the German Nutrition Society reports in their evidence-based guidelines for fat intake and diet-related disease prevention that the evidence for primary prevention of cardiovascular disease with long-chain n-3 FA is classified as probable, and applies to intake of up to 250 mg/day of EPA and DHA (Wolfram et al., 2015, p. 179). Highest amounts of EPA in macroalgae were identified in *Palmaria palmata* at about 35 mg per 8g of dry weight, suggesting daily consumption can contribute to 14% of overall recommended intake.

Lastly, PUFAs are sensitive molecules and easily prone to oxidation, which leads to a loss of shelf-life, consumer acceptability, functionality, safety, and nutritional value (Arab-Tehrany et al., 2012, p. 27). Nevertheless, this does not appear to be an issue in macroalgae as PUFA composition is normally determined after drying (MacArtain et al., 2007, p. 539).

4.1.2 Seaweeds as functional foods for nutrient deficiencies

In the 13th Nutrition Report published by the German Nutrition Society in 2016, some vitamins and minerals, including vitamin D, folate, sodium, potassium, and iodine, were selected for analysis with data from the German Health Interview and Examination Study for Adults (DEGS). The DEGS Study is a nationwide cross-sectional and longitudinal study carried out by the Robert Koch Institute (RKI) with the agenda of continuous health monitoring. The goal of the study is to regularly gather health information and provide representative data on the health status of adults in Germany between the ages of 18 and 79 (German Nutrition Society, 2016, p. 10).

4.1.2.1 Folate

In 2013, the German Nutrition Society together with corresponding organizations in Austria and Switzerland published new reference values for folate/folate equivalents, recommending 300 µg/day for adults. Folate belongs to the group of water-soluble B-vitamins and refers to a group of similar compounds with the same metabolic effects, and is, among other functions, involved in nucleotide synthesis and is fundamental for cell growth, division, and differentiation. Adequate supply is therefore of critical significance for pregnant and nursing mothers to ensure proper growth of the fetus and newborn child, where 550µg/day and 450µg is recommended respectively. Median folate concentrations were found in DEGS to be far above the lower limit for adequate supply, however, when WHO recommendations for women of reproductive age are considered, only 3% of those aged 18–29 and 4% of those 30–49 reached the recommended red-blood cell folate concentration of 400 ng/ml for maximum risk reduction of neural tube defect. On the other hand, the threshold value identified by the WHO cannot be accepted as a predictive measure, since the onset of neural tube defects are multi-factorial (Deutsche Gesellschaft für Ernährung, 2016, pp. 49–50). Some species of seaweed, including *Ascophyllum nodosum* and *Porphyra umbilicalis* contain extremely high amounts of folate per 8 g serving with 1216% and 334% of RDA respectively and imply that at least these species may be a logical prophylactic for folate deficiency as no tolerable upper limits for folate have been identified.

4.1.2.2 Sodium

Sodium is found in high concentrations in macroalgae, with up to 560 mg/8g serving in the case of wakame, more than six times higher than that of mangold. Sodium intake as determined in DEGS, found that 93% of males and 90% of females in Germany consume more than 1500 mg/day as recommended by German, Austrian and Swiss Nutrition Societies (Deutsche Gesellschaft für Ernährung, 2016, p. 53). While the WHO recommends consumption less than 2000 mg/day and the American Heart Association similar to the D-A-CH reference value is set at 1500 mg/day, the Health and Medicine Division (HMD), formerly the Institute of Medicine of the National Academies of Science, Engineering and Medicine in the United States, cites inconclusive and conflicting data in stating that it remains unclear if sodium reduction to less than 2.3 g/day has positive or negative impacts on cardiovascular health. For this reason as well, the European Food Safety Administration (EFSA) has not asserted a tolerable upper intake level for sodium intake (Deutsche Gesellschaft für Ernährung, 2016, p. 55). As evident by these statements from the former IOM and EFSA, the topic of adequate sodium intake is complex and not completely understood, and therefore won’t be addressed in this paper.

4.1.2.3 Iodine

Macroalgae contain the highest concentrations of iodine found in food. Iodine is a trace element of the halogen group and indispensable for life as an important component of thyroid hormones, which require iodine for synthesis. Thyroid hormones are involved in growth, osteogenesis (bone growth), metabolism, and brain development. Recommended iodine intake varies depending on the country and the status of iodine sufficiency in the population. Whereas Asian nations and USA, for example, are amply supplied with iodine, iodine intake is not sufficient in Germany. Chronic iodine deficiency can lead to thyroid nodules in the thyroid gland, especially in seniors. In people with iodine deficiency sudden iodine intake, for example via excessive macroalgae consumption, can cause iodine-induced hyperthyroidism and result with life-threatening impacts on metabolism. Conversely, in the case of a properly functioning thyroid gland, long-term excessive intake of iodine inhibits the synthesis of thyroid hormones, triggering iodine-induced hypothyroidism leading to goiter, a swelling of the thyroid gland (BfR, 2007, p. 1). The German Nutrition Society reports that while iodine intake has increased in recent years, roughly 30% of adults remain at risk for iodine deficiency, and that health-related action is needed (Deutsche Gesellschaft für Ernährung, 2016, pp. 63–64). Under such circumstances, the supplementation of iodine through macroalgae appears logical, although not without potential hazards. The Federal Institute for Risk Assessment states that while healthy adults with adequate thyroid iodine levels can tolerate 1000–2000 µg of iodine per day without side-effects, the upper tolerable limit (UL) is much lower in populations that have been exposed to iodine deficiency in the past. To ensure the protection of these particularly susceptible consumers, the German Nutrition Society recommends that iodine intake should not exceed 500µg per day (BfR, 2007, p. 4). With highly varying amounts found in macroalgae, values over 110 times exceeding the UL were found in some species of *Laminaria*. On the other side of the spectrum, as little as 136µg and 168µg were reported in *Porphyra* and *Ulva* species respectively, which fall under the UL into an acceptable range. Moreover, post-harvesting processing techniques such as washing, dehydration, rehydration, and boiling have been shown to reduce iodine content by 75% in the brown seaweed *Alaria esculenta*, whereas iodine was reduced by 32% and 14% in *Palmaria palmata* and *Ulva intestinalis* respectively (Nitschke & Stengel, 2016, p. 3532).

4.1.3 Heavy metal toxicity

Algae are recognized for their ability to bioaccumulate heavy metals which may be detrimental to health, including aluminum, arsenic, cadmium, copper, lead, and mercury (BVL, 2015, pp. 4–6). Whereas this may be a beneficial tool in mitigating environmental pollution in contaminated waters, it can pose certain threats when considering seaweed as a viable food source. In the 2013 Food Monitoring Report by the Federal Office for Consumer Protection and Food Safety (BVL), 41 samples of macroalgae were analyzed for heavy metal content, of which 63.4% (n=26) originated from non-EU countries. The average values of arsenic, cadmium and mercury identified by BVL can be seen in table 18 in comparison with average values determined by Maehre et al. in ten macroalgae species harvested in northern Norway.

Table 18: Heavy metal content in macroalgae

Reference	Unit	Arsenic	Cadmium	Mercury
BVL[a]	µg/100g	3090	172	n.d.
	µg/8g	247.2	13.76	n.d.
Maehre et al.[b]	µg/100g	2775	102.43	11.16
	µg/8g	222	8.19	0.928
TWI[c]	µg/kg body weight		2.5	1.3

*values given as µg/kg body weight/week
[a](BVL, 2015) [b](Maehre et al., 2014, p. 3288) [c]TWI = tolerable weekly intake

In both cases, the heavy metal content of tested algae did not exceed the limits set by the AO/WHO Joint Expert Committee on Food Additives (JECFA) or European Food Safety Administration (EFSA) for a 70kg male or 60kg female for cadmium or mercury. The provisional tolerable weekly intake (PTWI) established for arsenic by WHO in 1989 and set at 15µg/kg body weight has since been removed with no new PTWI in place. In assessing arsenic levels there are some differentiating factors to consider. Firstly, absolute arsenic content is typically measured. There are over 50 arsenic compounds present in fish, seafood, and algae, of which most are usually present in the form of organic compounds and considered less toxic than inorganic arsenic. Secondly, of the few brown algae that store inorganic arsenic, up to 90% that may be present has been shown to be removed through cooking (Wells et al., 2017, pp. 967–968).

4.2 Bivalves: Risks and Opportunities

4.2.1 Macronutrient quality

Bivalves have lower EAA concentrations than the most common sources of meat globally: beef, pork, and poultry (FAO, 2014). Nevertheless, all EAAs are present. While the limiting amino acid in all analyzed proteins was tryptophan, with lowest relative amounts in oysters, clams had the highest amino acid score with a better profile than beef, pork, and chicken, indicating high protein quality. Identifying the limiting amino acid forms the basis of protein quality evaluation. The limiting amino acid is the essential amino which is found in lowest amount relative to the same amino acid in a reference pattern of essential amino acids as defined by the FAO/WHO in 1989, which has evolved since then (Schaafsma, 2000, p. 1865S). There are many methods in assessing protein quality, the most current method developed and recommended by the FAO/UN being the digestible indispensable amino acid score (DIAAS). The DIAAS combines amino acid composition with digestibility to determine protein quality where the lowest amino acid score (that of the limiting EAA) is multiplied with the true fecal crude protein digestibility factor (Huang, Wang, Sivendiran, & Bohrer, 2018, p. 1,4). However, determining the digestibility of common foods is expensive and no data for the digestibility of the bivalves described here were found, which limits the accuracy of protein quality comparison.

As illustrated in table 14, bivalves contain substantially higher amounts of n-3 polyunsaturated fatty acids than conventional meat products, corresponding to low n-6:n-3 ratios of less than 0.5 whereas opposite proportions in conventional meat products are reflected in higher n-6:n-3 ratios, up to 4.9 in the case of chicken breast, with skin. While a ratio of 5:1 is considered by European authorities as beneficial to health, estimates as high as 10–20:1 in favor of n-6 fatty acids have been reported (German Nutrition Society, n.d.-b; Simopoulos, 2011, p. 10). Conventional meat products exacerbate this problem as large-scale animal production relies on feed rich in n-6 fat, resulting in higher n-6 fat content in the end product (Simopoulos, 2011, p. 10). As previously discussed, EPA and DHA are indicated in a variety of physiological activities beneficial to health which can play a role in reducing risk of NCDs.

4.2.2 Supplementing vegetarian and vegan diets

4.2.2.1 Vitamin B_{12}

Vegetarian and vegan diets are also the most environmentally friendly diets, however there are potential risks for nutrient deficiencies including vitamin B_{12}, iron, and zinc (Deutsche Gesellschaft für Ernährung, 2016, pp. 93–94; FAO, 2017, p. 86). Vitamin B_{12} is found almost exclusively in animal products, while iron and zinc bioavailability is limited in plant sources. Bivalves are rich sources of these micronutrients, with soft-shelled clam supplying more than 38 times of RDA. While B_{12} absorption is limited by several factors, including but not limited to intrinsic factor present in the gut, the body has a high capacity to store B_{12}, up to several years depending on initial storage levels, suggesting that only periodic bivalve consumption may suffice to maintain adequate vitamin B_{12} storage levels (Institute of Medicine, 1998, p. 2).

4.2.2.2 Iron

Iron is a nutrient of concern, especially among women of reproductive age who are at higher risk of iron-deficiency due to iron loss via menstruation and require more iron than men. Waldmann et al. concluded in the German Vegan Study that 40% of vegan women aged under 40 and 12% of those over 50 were iron-deficient, recommending those that follow a vegan diet regularly check iron status and in the occurrence of deficiency should supplement with highly bioavailable iron. Furthermore, the authors advise strict monitoring of iron supplementation as elevated levels are associated with higher of cardiovascular disease and cancer (Waldmann, Koschizke, Leitzmann, & Hahn, 2004, pp. 107–108). Bivalve consumption in this situation could be an economical alternative, allowing the consumer to forego medical testing and costs for supplements.

4.2.2.3 Zinc

As diets shift more towards plant-based food sources, the prevalence of zinc deficiency can also be expected to increase, which is already estimated at 25% worldwide. Highly bioavailable forms of zinc are found in red meat, but as was shown in table 16, in bivalves as well, especially oysters. Furthermore, increased grain consumption also limits zinc bioavailability, as phytates found in grains bind zinc and prevent absorption. Zinc is a crucial micronutrient involved in numerous biological activities as a cofactor, catalyzing over 100 enzymes and influencing cell metabolism, intracellular signaling, transport, protein synthesis, as well as playing a role in antioxidant activity, behavioral and cognitive function, and maintaining a healthy immune system (Jung, Spira, Steinhagen-Thiessen, Demuth, & Norman, 2016, pp. 1–2). Additionally, zinc deficiency has also been associated with depression in older people, a condition affecting an estimated 350 million people globally and expected to rise (Jung et al., 2016, p. 1,3).

4.2.2.4 Vitamin D

Not limited to just vegetarians and vegans, vitamin D is another nutrient of concern, as reported by the German Nutrition Society on the basis of data provided by DEGS. Measured through serum concentrations of 25-hydroxyvitamin D, vitamin D_3 is synthesized in the skin of humans when exposed to certain wavelengths of UVB radiation, which due to the latitudinal location of Germany, is only of adequate intensity for vitamin D synthesis between March and October (Deutsche Gesellschaft für Ernährung, 2016, p. 45). The German Nutrition Society recommends optimal levels of vitamin D of at least 50nmol/l serum concentration of 25-hydroxyvitamin D, of which 61.7% of men and 61.4% of women of DEGS failed to reach (Deutsche Gesellschaft für Ernährung, 2016, p. 43; German Nutrition Society, n.d.-b). While endogenous vitamin D synthesis can provide 80–90% of recommended supply, improving vitamin D through nutrition is advised in the case of deficiency before turning to supplementation (Deutsche Gesellschaft für Ernährung, 2016, p. 42). In this case, oysters may be of significance in avoiding vitamin D deficiency, especially for vegans. Vitamin D is found only in fatty fish, beef liver, eggs and dairy products, enriched margarine, and some mushrooms (Deutsche Gesellschaft für Ernährung, 2012). A 100g serving of oysters provides 8µg, 40% of the estimated AI of 20µg in the event of deficient endogenous synthesis.

4.2.3 Allergens

About 0.1% of Europeans display allergic reactions to crustaceans and/or to mollusks in allergy provocation tests, with higher prevalence in Scandinavian countries, Portugal and Spain where larger amounts of seafood are consumed. The main allergens in mollusks that are responsible for triggering allergic reactions are referred to as tropomyosins, which are heat-stabile proteins and therefore are not destroyed in cooking. Symptoms can range from mild to severe reactions with tingling in the face to anaphylactic shock with difficulty breathing and circulatory collapse (Zuberbier, 2016).

4.2.4 Environmental contaminants

Heavy metals that can bioaccumulate in bivalves are cause for concern in dietary implementation and include arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), and mercury (Hg) (Prato et al., 2019, p. 154). In a literary review and analysis of eight bivalve species Prato et al. determined provisional tolerable weekly intake (PTWI), total hazard quotient (THQ), and hazard index (HI) values to assess the risks and benefits of select species of mussels, clams, scallops, and oysters finding that no health risks were present in regards to heavy metal content in *M.*

galloprovincialis (mussel), *R. philippinarum* (clam), *and O. edulis* (oyster). Conversely, they identified relatively high HI in *F. glaber* (mussel), *M. barbatus* (mussel), *S. marginatus* (razor clam), *M. varia* (scallop), and *V. verrucose* (clam), stating that fishermen, and more importantly, their children and pregnant or lactating women should be aware of their consumption of these species. Several factors can affect metal concentrations and accumulation capacity between species such as physiological state, biotic factors (age, size, sex), genetic traits, abiotic factors (water salinity, pH, temperature, and dissolved oxygen), the chemical forms of the metals, and area contamination (Prato et al., 2019, pp. 160–162). In the 2013 Food Monitoring Report by the BVL elevated levels of heavy metals were identified in blue mussels as seen in table 19, however none of the samples analyzed exceeded the maximum levels as fixed by the Regulation (EC) No. 1881/2006 set by the European Union (BVL, 2015, pp. 13–16).

Table 19: Heavy metals in blue mussels (Mytilus sp.)

	Aluminum	Lead	Arsenic	Copper	Cadmium	Nickel	Mercury
Blue mussels	29	0.176	1.90	1.38	0.159	n.d.	0.018
PTWI	n.d.	1.5	n.d.	n.d.	1.0	n.d.	0.5

*Values given as mean mg/kg
(BVL, 2015, pp. 40–49)
PTWI = provisional tolerable weekly intake in mg/kg body weight

Dioxins and dioxin-like polychlorinated biphenyls (PCBs) as well as polycyclic aromatic hydrocarbons such as Benzo(a)pyrene are additional environmental contaminants that can be found in animal products and can potentially bio-accumulate in fish and bivalves. They comprise large groups of organic compounds resulting from industrial chemicals, combustion byproducts, and certain herbicides (Umweltbundesamt, 2013). Shellfish can also be contaminated with human pathogenic bacteria and viruses, mainly bacteria of the genus *Vibrio*, noroviruses, and hepatitis viruses. While vibrios can cause diarrhea and vomiting, noroviruses can cause gastroenteritis and hepatitis A and E infection. Marine biotoxins are another group of potentially dangerous substances known to be found in bivalves. Originating from algae and consumed by bivalves, they comprise three groups: paralytic shellfish poison (PSP), amnesic shellfish poison (ASP), and a group of lipophilic toxins including diarrhoetic shellfish poison (DSP) (Bundesinstitut für Risikobewertung, n.d.).

According to O'Mahoney, the various potential hazards regarding marine biotoxins from bivalve consumption are well-recognized by the European Union and that "the molluscan food-chain benefits from some of the most proactive, diligent, and comprehensive food safety controls of any food product (O'Mahony, 2018, p. 25)."

5 Conclusion

Seaweeds have several nutritional properties which are of relevance in regards to promoting health and preventing NCDs. They have been shown to be high in essential vitamins and minerals, especially iodine, and contain all the essential amino acids as well as healthy polyunsaturated fats not found in terrestrial plants. Although relative amounts of EPA are high in seaweeds, they do not suffice to fulfill dietary recommendations, but nonetheless may contribute to a balanced diet. High fiber and low calorie content suggest they may be useful in combating excessive energy intake leading to overweight and obesity. Major causes of concern remain elevated iodine levels which may cause acute hyperthyroidism in deficient individuals, and conversely trigger hypothyroidism long-term in healthy individuals. Brown seaweed of the genus *Laminaria* tend to have the highest levels of iodine, whereas lower levels have been detected in the red algae *Porphyra* and green algae *Ulva* which fall under tolerable upper intake levels. Iodine levels can be reduced further by cooking, but more studies need to be completed for verification and to ensure food safety. Overall, varieties of *Porphyra* show more preferable characteristics than other macroalgae, including high percentage of carbohydrate as fiber, highest relative amounts of essential amino acids and total n-3-fatty acids, low sodium content, high amounts of zinc, and lowest concentrations of iodine.

Bivalves as a staple food source present many challenges. They contain high-quality protein and essential fatty-acids, as well as vitamins D and B_{12}, iron, and zinc, all critical nutrients at risk for deficiency in the framework of a plant-based diet. On the other hand, allergies, rare earth elements, marine biotoxins, and environmental contaminants pose certain risks for moderate to high consumption, and may limit large-scale bivalve cultivation to climate remediation and sequestering roles short-term or in highly contaminated waters until new technologies for extraction of toxic compounds are developed or ocean environments are restored.

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Appendix

1 Amino Acid Scores

	Mussel		Clam		Oyster	
crude protein/100g	10.5		10.5		9	
	mg/100g	mg/g CP	mg/100g	mg/g CP	mg/100g	mg/g CP
Alanine	550	52.4	1080	102.9	750	83.3
Arginine	730	69.5	870	82.9	680	75.6
Aspartic acid	1100	104.8	1180	112.4	1030	114.4
Cystine	160	15.2	140	13.3	150	16.7
Glutamic acid	1370	130.5	1700	161.9	1580	175.6
Glycine	500	47.6	1050	100.0	800	88.9
Histidine	240	22.9	230	21.9	210	23.3
Isoleucine	470	44.8	580	55.2	540	60.0
Leucine	760	72.4	760	72.4	820	91.1
Lysine	780	74.3	980	93.3	720	80.0
Methionine	270	25.7	310	29.5	260	28.9
Phenylalanine	410	39.0	420	40.0	420	46.7
Proline	410	39.0	470	44.8	570	63.3
Serine	500	47.6	600	57.1	510	56.7
Threonine	460	43.8	580	55.2	480	53.3
Tryptophan	120	11.4	160	15.2	80	8.9
Tyrosine	410	39.0	530	50.5	330	36.7
Valine	610	58.1	590	56.2	520	57.8
AAS		1.6		2.2		1.3

	Beef		Pork		Poultry	
crude protein/100g	22		22		22.2	
	mg/100g	mg/g CP	mg/100g	mg/g CP	mg/100g	mg/g CP
Alanine	1690	76.8	1530	69.5	1610	72.5
Arginine	1540	70.0	1530	69.5	1550	69.8
Aspartic acid	2340	106.4	2430	110.5	2530	114.0
Cystine	280	12.7	310	14.1	330	14.9
Glutamic acid	4130	187.7	3910	177.7	4120	185.6
Glycine	1560	70.9	1420	64.5	1560	70.3
Histidine	850	38.6	990	45.0	680	30.6
Isoleucine	1250	56.8	1270	57.7	1430	64.4
Leucine	1950	88.6	1920	87.3	1980	89.2
Lysine	2310	105.0	2200	100.0	2270	102.3
Methionine	650	29.5	720	32.7	710	32.0
Phenylalanine	1060	48.2	980	44.5	1010	45.5
Proline	1280	58.2	1210	55.0	1180	53.2
Serine	1140	51.8	1120	50.9	1020	45.9
threonine	1150	52.3	1250	56.8	1120	50.5
Tryptophan	290	13.2	310	14.1	310	14.0
Tyrosine	890	40.5	910	41.4	850	38.3
Valine	1320	60.0	1420	64.5	1320	59.5
AAS		1.9		2.0		2.0

2 Reference Pattern

Amino Acid	mg/g crude protein (CP)
Isoleucine	25
Leucine	55
Lysine	51
Methionine + Cysteine (SAA)	25
Phenylalanine + Tyrosine	47
Threonine	27
Tryptophan	7
Valine	32
Histidine	18
Total	287

Affidavit

I hereby declare that I have written the present work independently and without outside help and that I have only used the specified resources. Parts taken verbatim or according to their meaning from other works are marked with acknowledgement of the source.

Hamburg, 28.02.2019

Douglas Armour

Eidesstattliche Erklärung

Ich versichere, dass ich vorliegende Arbeit ohne fremde Hilfe selbständig verfasst und nur die angegebenen Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quelle kenntlich gemacht.

Douglas Armour