DIVISION BIOECONOMY AND HEALTH

Environmental and nutritional perspectives of algae

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Abstract

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Algae have gained increasing attention as promising food from both an environmental and nutritional perspective. However, current understanding is still limited. This report summarizes the status of knowledge for this emerging sector, focusing on micro- and macroalgae species most relevant for Europe (particularly Sweden). Environmental impacts, with focus on climate, are evaluated through literature reviews and analysis of existing life cycle assessments (LCAs), and nutritional potential in the form of data compilation and calculation of nutrient density scores. Overall, findings reveal that current data is incomplete and of poor representativeness. Most LCAs are not performed on commercial production, but at pilot or experimental scale, why often only indicative drivers for greenhouse gas emissions may be identified. For microalgae, there is a wide diversity of production systems in different conditions across the globe. Based on the data at hand, energy use is a key hotspot across most studies for this production, driven by the requirements of different types of systems and species, and to location. For macroalgae production, despite poor representativeness of especially green and red macroalgae, key aspects for minimizing greenhouse gas emissions are associated with energy consumption and use of materials for farming such as ropes. No LCA exists on wild harvested macroalgae, representing the largest production volume in Europe (>95%); large-scale wild harvest may also be associated with risks to ecosystems unless suitable management is enforced. Significant data gaps also exist in food composition databases regarding nutrient and heavy metal content in algae (e.g., vitamins and omega-3 fatty acids). When available, nutrient content was found to be highly variable within and across species, but overall, the evaluation of nutritional quality indicated that algae may be a considerable source of minerals and vitamin B12. The contribution of fiber and protein is generally minimal in a 5 g dry weight portion of macroalgae; microalgae may have higher protein content, and also fat. However, excessive amounts of iodine and several heavy metals may be represented even in very small amounts of unprocessed macroalgae. In summary, the suggested potential of farmed algae as a sustainable food resource is overall strengthened by its generally low carbon footprint during production compared to other food raw materials. However, more input data are needed to fill data gaps regarding both environmental impacts and nutrient quality, and effects from different processing, as well as improved understanding of nutrient and contaminant bioavailability. Pending further research, careful considerations of risks and benefits associated with algae production and consumption should be applied.

Key words: algae, carbon footprint, environmental impact, nutrition, contaminants

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Content

Preface

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Sammanfattning

Alger har under mer än 2000 år nyttjats som livsmedel, framför allt i östra och sydöstra Asien. Idag växer intresset för alger som resurseffektiv och hållbar naturtillgång även i Europa, bland annat inom kosmetika- och läkemedelsbranschen samt som biobränsle. Alltmer ljus riktas också mot algers potentiella roll i ett framtida hållbart livsmedelssystem, där de lyfts fram som ett icke-animaliskt, näringsmässigt lovande och miljömässigt hållbart alternativ till konventionellt producerade livsmedel från såväl hav som land. Men vad vet vi egentligen om alger, som för- och nackdelar med olika produktionssystem och skillnader mellan olika arter? I den här rapporten sammanställs den tillgängliga kunskapen om mikro- och makroalgers miljöpåverkan samt innehåll av näring och oönskade ämnen, med fokus på europeiska och framför allt svenska förhållanden.

Tillvägagångssättet har varit att samla in representativa data för så många arter och produktionssystem som möjligt med fokus på arter av högst relevans för svensk och europeisk produktion och konsumtion. För miljömässig utvärdering har datakällor huvudsakligen bestått av livscykelanalyser. För vildskördade alger, vilka dominerar den europeiska produktionsvolymen, saknas dock livscykelanalyser. För denna produktion fokuserar rapporten istället på vetenskapliga studier kring möjliga ekosystemeffekter från skördning. Rapporten presenterar även ett förenklat verktyg för att beräkna utsläppen av växthusgaser från odling av makroalger. För utvärdering av näringssammansättning samt eventuella innehåll av hälsoskadliga ämnen samlades data in via olika livsmedelsdatabaser. Denna data användes sedan för att utvärdera den näringsmässiga kvaliteten och innehållet av såväl önskade som oönskade ämnen.

Trots att dataluckorna för miljöpåverkan från flertalet produktionssystem var stora, kunde vissa trender identifieras. Dessa kan användas för att förstå i vilken del av produktionen det finns potential att optimera och därmed minska miljöavtrycket. För mikroalger visade sig klimatpåverkan variera stort, där energianvändningen för värmereglering och belysningen på odlingen utgjorde de största bidragen till utsläpp av växthusgaser. Eftersom behovet av uppvärmning och belysning varierar geografiskt, innebär det att val av plats för odlingen kan ha stor påverkan. Bland makroalgerna var det utmanande att hitta jämförbara och representativa data från livscykelanalyser av produktionen avseende arter, produktionsteknik, geografisk plats och skala som utvärderats – med undantag för brunalger där data från flera studier kunde harmoniseras vad gäller metodval för bättre förståelse. Övergripande indikerar resultaten att produktion av gröna makroalger verkar generera större utsläpp av växthusgaser per kilo än brun- och rödalger. Värt att understryka är dock att klimatavtrycket från produktion av samtliga makroalger är lågt jämfört med många andra typer av livsmedel.

Genomgången av litteratur kring miljöeffekter av att skörda vilda makroalger visade att det finns flera utmaningar kopplade till bristen på miljöövervakning, som gör det svårt att identifiera långsiktiga effekter av skörden. Något som dock konstaterades är att förekomsten av makroalger minskar, vilket huvudsakligen verkar vara en följd av klimatförändringar, men också en omfattande mekanisering av skördningen. Alger i kustzoner påverkas även av kumulativa effekter från mänskliga aktiviteter. Att mängden makroalger minskar kan i sin tur få ytterligare konsekvenser för marina ekosystem,

inklusive förlust av habitat, försämrad kolinlagring och ökning av främmande arter. För att bromsa och förebygga denna utveckling krävs, förutom miljöövervakning, en fungerande ekosystembaserad förvaltning av resursen.

Även vad gäller näringsaspekter identifierades stora dataluckor, men för de arter som kunde analyseras uppvisades stor variation i näringsinnehåll. För makroalger kunde det generellt konstateras att det största potentiella näringsbidraget utgörs av mineraler såsom magnesium, järn och selen, medan innehållet av fiber, fett och protein är generellt lågt i en portion. Mikroalger (*Chlorella* och *Spirulina*) visade högre halter protein och fett än makroalger, samt betydliga mängder koppar (*Spirulina*), järn och vitamin B12 (*Chlorella*). Vad gäller förekomst av oönskade ämnen är det svårt att dra generella slutsatsen eftersom innehållet kan vara starkt påverkat av exempelvis geografisk plats. En observation var dock att samtliga makroalger innehöll någon form av oönskat ämne, däribland tungmetallerna bly och kadmium. Dessutom visade sig en portion (5 g torrvikt) av den bruna makroalgen sockertång (*Saccharina latissima*) kunna innehålla halter av jod som kraftigt överstiger övre rekommenderade gränsvärden för hälsosamt intag om den inte processas. Baserat på detta blancheras sockertång vanligen idag.

Sammanfattningsvis kan man säga att mer livscykelanalyser av olika produktionssystem av alger behövs för evidens-baserad kartläggning av algers miljöpåverkan samt möjlighet till att optimera nuvarande produktionssystem. För makroalger, som har låg klimatpåverkan från produktionen men sällan konsumeras råa, är det dessutom motiverat att även inkludera senare led i kedjan för att studera klimatpåverkan från olika processteknologier och optimera dessa. Dessutom behövs kompletta data för alger kring innehåll av både önskade och oönskade ämnen, och en ökad förståelse för hur näringsinnehållet påverkas av olika förädlings- och tillagningsmetoder samt i vilken grad olika ämnen kan tas upp av kroppen. Först när både miljö- och näringsmässiga data finns att tillgå i större utsträckning kan algers potentiella roll i hållbara dieter utvärderas.

1 Background

With transition toward a less livestock-based diet being identified as key for a more sustainable food system (Poore and Nemecek 2018; Willett et al. 2019), increased interest for both traditional and novel non-animal-based foods is seen. Both micro- and macroalgae are suggested to have great potential as resource efficient food production systems (Parodi et al. 2018; Gephart et al. 2021). Around 10 000 algal species exist but few are commercially utilized (Mac Monagail et al. 2017). In Eastern and South-eastern Asia, macroalgae (or 'seaweeds') have been consumed for more than 2000 years and products are widely available, most frequently in a dried form (e.g., as seasoning, snacks, sushi wrap) or as "sea vegetables" (e.g., sold fresh, pickled/fermented, frozen, etc.). However, in the Western world, historically, macroalgae have mostly been used for non-food applications such as animal feed and agricultural fertilizer. Algae are still relatively uncommon in European diets, apart from primarily sushi, where algae products are often marketed as 'vegetables' or 'superfoods' of the sea today. Additional areas of use include biofuel, bioremediation, cosmetics, pharmaceutics, hydrocolloid production, bio-based materials, and as feed, fertilizers, and stimulants within agriculture.

Seaweeds represent about a third of global aquaculture production (120 million tonnes in 2019, FAO 2022) and are the largest taxonomic group of species farmed. In 2019, the global production volume of macroalgae was estimated to be around 36 million tonnes wet weight of which 97% was farmed (Cai 2021). Farming of macroalgae has thus seen a dramatic increase; in 1969, the total global production volume was only 2.2 million tonnes wet weight – of which half of the volume came from wild-harvest which has not increased since. There are however some uncertainties concerning global production volumes (e.g., see Porse and Rudolph 2017). The global production is today mainly based in Asia (>97% of volume).

Macroalgae are sorted into three groups based on their pigmentation (brown, red and green), where global aquaculture production today is dominated by red and brown ones while farming of green macroalgae is very limited (Table 1). Global microalgae production only contributed with 56 thousand tonnes in 2019, of which over 99% was based on cultivation of *Spirulina*, mainly in China (>97%). Overall, a large potential for expansion in production has been described both globally (Gentry et al. 2017; Costello et al. 2020), in the European Union (EC 2022) and in Sweden (Thomas et al. 2019; Hasselström et al. 2020). However, there are also important barriers to this expansion, related to e.g., need for technological development, regulatory hurdles, negative public perception of aquaculture establishment along coastlines and currently low consumption levels.

Table 1 Global farming of macroalgae (or seaweeds) by volume. Based on Cai (2021).

Type	Main species	Share
Red	*Kappaphycus/Eucheuma* spp. and *Gracilaria* spp. (both warm water) and *Porphyra* spp. (cold water)	>52%
Brown	*Laminaria* spp./*Saccharina* spp. and *Undaria* spp.	~47%
Green	*Caulerpa* spp.; *Monostroma nitidum*; *Enteromorpha/Ulva* spp.; *Capsosiphon fulvescens* and *Codium fragile*	<0.1%

Available data and comparisons indicate that seaweed farming generally provides a biomass at relatively benign environmental impacts from a Life Cycle Assessment (LCA) perspective (Gephart et al. 2021), despite comparing dried seaweeds with other seafood in fresh form. The increased number of scientific articles in this field improves the understanding of environmental impacts of different types of algae production systems. However, current coverage of LCAs in terms of species and production systems is patchy (e.g., Seghetta et al. 2017; Thomas et al. 2020; Porcelli et al. 2020). Although Gephart et al. (2021) took an approach that resulted in comparable results across species and species groups, discrepancies in methodological choices in LCA hinders robust comparisons of results across studies as well as interpretation and decision-making at a higher level (Ziegler et al. 2022). To date, no systematic review dedicated on LCAs of algae has been done that focuses on differences in environmental performance between algae species and production techniques and that identifies the main drivers of impacts.

Algae are also considered to be nutrient-dense foods (Parodi et al. 2018) and their content of e.g., iron and vitamin B12 is of special interest because intake of these nutrients is low in parts of the Nordic population (Amcoff et al. 2017), and content of these nutrients is generally limited in plant-based foods. Moreover, the scientific evidence for health benefits from algae consumption is still limited and considerable knowledge gaps exist in quantifying these benefits, as well as possible adverse health effects (Wells et al. 2017). In addition, recent studies have shown great variability in nutrient density across various types of seafoods (Hallström et al. 2019; Bianchi et al. 2022), but algae have so far not been evaluated from this perspective.

According to data available at FAO (FAO 2021; Cai et al. 2021), global macroalgae production currently grows at a 7-10% rate annually. Farming in the Nordic countries is now growing (Stévant et al. 2017). In Sweden, farming, harvesting and product development of algae is the basis for a new sector of primary food production, with a number of macroalgae startup companies emerging (e.g., Nordic Seafarm, Bohus Sea culture, Tångkullan, Ten Island Seafarm) and many larger food processing and retailing companies have a great interest in incorporating algae or "vegetarian seafood" in their products. Interest for increased utilization of algae is thus a strong trend in the food industry both in Sweden and rest of Europe, driven by the search for novel tasty and nutritious foods with low environmental impact (Thomas et al. 2020; Parodi et al. 2018). However, as described earlier, there is an overall limited understanding of both environmental and nutritional aspects of algae production and consumption. This calls for a synthesis of available literature to identify knowledge gaps and research needs to assist the industry in designing their production and product development.

1.1 Aim and specific objectives

The overall aim of this report is to synthesize findings from a project funded by Formas on available environmental and nutritional data and information on algae production and consumption and provide the larger picture of algae in sustainable diets. The focus is on species most relevant for Europe with emphasis on Sweden. The report summarizes the status of knowledge for an emerging sector to assist in optimization of production systems through:

- Finding and gathering representative LCA and nutritional data for as many species and production systems as possible.
- Identifying key environmental aspects to consider in developing algae aquaculture with a focus on greenhouse gas emissions.
- Developing a simplified tool for estimation of greenhouse gas emissions of macroalgae aquaculture.
- Calculating nutrient density for different algae species.
- Identifying potential toxicological risks of algae consumption.
- Identifying knowledge and data gaps in e.g., nutritional aspects where further research is needed.

2 Material and method

2.1 Literature reviews

Literature reviews were undertaken during 2020-2022 searching for Life Cycle Assessment (LCA) studies of algae production and data on nutritional content of algae. The methodology of each literature review is explained below.

2.1.1 Microalgae

LCA studies of microalgae production systems have increasingly been published after 2011, though a handful of exploratory studies predate this (e.g. Kadam 2002; Aresta et al. 2005). A search on Web of Science in early 2022 (search terms "microalg* (Abstract) and "life cycle assessment" OR LCA (Abstract)" yielded 211 hits of which 153 were original articles and 37 were reviews, which have seen a steady increase in number to a peak of 37 publications per year in 2020. In terms of main focus of these publications, the Web of Science Categories analysis function suggests that these publications are dominated by Energy Fuels (92), Biotechnology Applied Microbiology (67) and Environmental Sciences (65) studies. Furthermore, based on 103 hits in a refined search for fuel OR bioenergy in abstract, the microalgae LCA literature largely focuses on the production of third generation (algae) biofuels. Some studies also target end-products such as protein powders for human or animal consumption (e.g., from spirulina), bioactive compounds (e.g., from *P. tricornutum*), biostimulants and biofertilisers (e.g., from *S. almeriensis*), or additives/ingredients such as astaxanthin (from *H. pluvialis*) and omega-3-rich oil.

Due to the great diversity of production systems and different purposes of end products, LCA outcomes of microalgae production systems can give very different results. Different methodological choices in the LCA modelling (e.g. system boundaries and functional unit) affects comparability across studies. The literature search however found one systematic review attempting to harmonize LCA results through applying the same methodological choices in the modelling (Schade & Meier 2019). It was therefore decided to use the results of this existing review to represent current knowledge on greenhouse gas emissions of microalgae production. Furthermore, given the diversity of species and production systems, the analysis was focused on literature available for the most important production volumes in Europe based on a recent overview of algae production in Europe (Araújo et al. 2021).

2.1.2 Macroalgae (farmed)

A systematic literature review was done for peer reviewed LCA studies of macroalgae production. An initial screening search was done in Scopus for original articles published up until end of year 2021 with the following search query: TITLE-ABS-KEY (macroalgae OR seaweed AND "life cycle analysis" OR "life cycle assessment" OR lca). This resulted in 58 articles that were further screened based on the content of title and abstract. A study was included in the analysis if:

- It was a LCA of a macroalgae production system destined for food, feed or energy; and
- It contained new, collected data on actual production of macroalgae (rather than being a theoretical study or a study re-using data).

This resulted in 10 papers, all on aquaculture, that were further assessed in terms importance to European production (Table 2). All 10 papers where further analysed in terms of results, at least qualitatively. For the studies where LCA transparency allowed (6 papers, five on brown and one on red macroalgae), available life cycle inventory data was extracted and recalculated using a defined methodological approach (Gephart et al. 2021). The recalculation required harmonization of functional unit (1 tonne fresh weight), system boundary (farm gate), allocation method (mass) and impact assessment (ReCiPe 2016 midpoint) methodology. Further details on this harmonization and full results of brown macroalgae are found in Thomas et al. (submitted). For red macroalgae, inventory data for long-line cultivation of *Gracilaria chilensis* in Chile was extracted from Aitken et al. (2014) and harmonized in the same way.

For green macroalgae, additional data collection came from Winqvist & Gillgren (2022), a master thesis including an LCA of a recently initiated sea-based farming in Sweden of the green algae *Ulva fenestrata*. This was a prospective LCA of a production system composed of an on-land hatchery and offshore cultivation using suspended lines. The study applied the same methodological choices as in Thomas et al. (submitted) and is supported by experimental data from a commercial scale *Saccharina latissima* producer located on the west coast of Sweden. The demonstration scale scenario (20 tonnes/year from 2 ha) was used in this report to indicatively compare outcomes with average results for brown and red seaweeds.

Table 2 LCA studies on macroalgae production analysed.

Reference	Country	Type of macroalgae	Production technology	Type of analysis
Aitken et al. (2014)	Chile	Brown (*Macrocystis pyrifera*), Red (*Gracilaria chilensis*)	Long-line cultivation (brown); sub-tidal bottom planting & long-line cultivation (2 scenarios; red)	Harmonized LCA
Brockmann et al. (2015)	France	Green (*Ulva sp.*)	Unclear but likely wild harvest followed by cultivation in land-based raceways	Qualitative
Helmes et al. (2018)	Portugal	Green (*Ulva sp.*)	Land-based IMTA	Qualitative
Langlois et al. (2012)	Europe	Brown (*Saccharina latissima*)	Long-line cultivation	Harmonized LCA
Pilicka et al. (2011)	Latvia	Green (*Ulva prolifera*)	Land-based ponds	Qualitative
Seghetta et al. (2017)	Denmark	Brown (*Saccharina latissima, Laminaria digitata*)	Long-line cultivation	Harmonized LCA (only for *Saccharina latissima*)
Slegers et al. (2021)	Norway	Brown (*Saccharina latissima*)	Long-line cultivation	Qualitative
Taelman et al. (2015)	Ireland and France	Brown (*Saccharina latissima*)	Long-line cultivation	Harmonized LCA
Thomas et al. (2021)	Sweden	Brown (*Saccharina latissima*)	Long-line cultivation	Harmonized LCA
Anand et al. (2018)	India	Red (*Gracilaria edulis*)	Bamboo rafts	Qualitative
Winqvist & Gillgren (2022)	Sweden	Green (*Ulva fenestrata)*	Long-line cultivation	Qualitative

All studies were screened for relevant environmental issues and key parameters driving impacts, including important knowledge and data gaps. The studies that could not be harmonized were qualitatively examined in terms of potential to fill in data gaps or indicate environmental performance for other production systems of importance to current algae production in Europe (Araújo et al. 2021). This entailed, for example, examination of key drivers behind impact, and how this may be affected by growth rate (for different species, seasons, regions) and production technology.

2.1.3 Macroalgae (wild-harvested)

Given the importance of wild harvest of macroalgae in Europe (Araújo et al. 2021), and the lack of LCAs identified for these production systems (Table 2), a separate literature screening was made. This was done with the objective to identify key environmental aspects to consider related to current macroalgae production based available literature on wild-harvest, thus only being able to summarize key findings related to potential ecological pressures. This literature search included peer-reviewed papers and reviews in English (titles, abstracts and keywords) and was performed in Scopus on February 3rd, 2022. The search query was: (alga OR algae OR algal OR macroalga* OR kelp* OR seaweed*) AND harvest* AND pressure OR impact) AND biodiversity. The narrow search is motivated by the aim to find papers explicitly reporting on impacts from seaweed harvesting on biodiversity (species abundance or distribution, ecosystem structure and function), not including the extensive literature on seaweed ecology in general. This search resulted in 43 papers for further analysis. Based on the inclusion criteria of papers covering i) harvested macroalgae in temperate regions; and ii) potential effects on biodiversity from harvesting; or iii) current status and trends of wild macroalgae, 8 papers were reviewed from this search. An additional 5 papers were included that the authors were aware of but did not appear in search hits, which resulted in a total of 13 papers that were summarized in the chapter Ecosystem effects from wild harvest.

2.2 Simplified tool

Based on the findings of the literature review and harmonization of results, an Excel-based tool for the estimation of greenhouse gas emissions of seaweed cultivation was developed, building on LCA-methodology. The structure of the tool should be able to be used by producers to estimate greenhouse gas emissions for farming of brown macroalgae using longlines in temperate regions, only based on a few, key input parameters. The tool was built using a hidden spreadsheet with background data from LCA databases for the production of materials and different types of energy used (e.g., electricity and fuel used on boats). The user needs to fill in material use for infrastructure in one sheet (where different materials may be chosen) and add the total amount of each material used in the farm as well as their expected lifetime. In a second sheet on maintenance, data needs to be filled in on the use of boats for maintenance for one year, as well as production (harvest). Greenhouse gas emissions per tonne produced is then automatically calculated in total for the farm and a specific time period, often a recent year, in a third sheet.

The tool was validated by entering the data from one published study (Thomas et al. 2021) and one unpublished dataset for seaweed farming to see how results aligned with a full LCA, i.e., if the tool was precise enough to give a rough indication of the climate impact of farmed seaweeds.

2.3 Nutritional composition from food composition databases

Food composition databases (FCDs) were searched to identify nutritional and toxicological data publicly available for the macro- and microalgae of interest (see list of species in Appendix 1). FCDs from Asian countries, as well as North America and Europe were identified from the INFOODS (2021) collection. Moreover, FCDs from universities and research institutes were assessed (i.e., Aquatic Food Composition Database compiled by the Harvard School of Medicine). Data on nutrient and heavy metal content was included if the algae description in the database was sufficiently clear to allow for the identification of genus and species (if not directly reported) and if presented as dried samples. Data that was only provided for fresh or process samples was excluded due to lack of information on water content. However, for two species of red macroalgae, data on heavy metals was only available for fresh weight but was included after adapting the portion size, as specified in the results section. Detail on the FCDs used is given in Appendix 1 alongside the nutrient content per 100 g dried algae biomass weight (DW).

The reason for gathering nutrient content for dry algae is that this is the prevalent form these products are found on the market. In the analysed FCDs, seaweed preparation modes other than "dried or freeze-dried" are present (i.e., baked algae) but no detail is usually provided on the preparation process, leading to the decision to exclude this data. As FCDs in most cases do not present water content, it is important to be aware that samples presented as "dried or freeze-dried" might not be 100% dry and also may differ in moisture depending on how drying was done and depending on surrounding humidity during storage.

2.4 Calculation of nutritional quality

The nutritional quality of algae was estimated as nutrient density based on the Nutrient Rich Foods (NRF) index, originally developed by Fulgoni et al. (2009). The index variant NRF11.3 was chosen for this study based on two considerations: the lack of comprehensive nutrient data does not allow the inclusion of more nutrients, and this index represents an optimized version of the base index (NRF9.3) which has been validated for the Swedish population (Strid et al. 2021; Bianchi et al. 2020). NRF11.3 is calculated with the following equation:

$$\text{Nutrient Rich Foods} = \sum_{i=1}^{x} \frac{Nutrient\ i}{DRI\ i} - \sum_{j=1}^{y} \frac{Nutrient\ j}{MRI\ j} \qquad \text{(Equation 1)}$$

where x indicates the number of nutrients to encourage and y the number of nutrients to limit, nutrient i/j describes the content of nutrient i or nutrient j per reference unit. *DRI* is the Dietary Reference Intake of the desirable nutrient i, and *MRI* is the Maximum Recommended Intake for the non-desirable nutrient j. NRF11.3 assigns a nutrient density score based on 11 nutrients (protein, dietary fibre, iron, folate, vitamins A, C, D, E, magnesium, calcium, potassium) whose intake is to be encouraged (qualitative nutrients), and three nutrients (saturated fat, added sugar, sodium) whose intake is to be limited (dis-qualitative nutrients). No added sugar is present in dried macro- and microalgae, and therefore this value was considered equal to zero in the calculation of the index. A mean of sex- and age-specific DRIs and MRIs for adults were taken from the Nordic Nutrition Recommendations (NNR) 2012 (NCM, 2014). When specific recommendations for fertile women existed (iron, folate), these were used. Nutrients included in NRF11.3, including DRIs and MRIs, are presented in Appendix 2.

A version of NRF11:3 was also calculated with the application of capping. Capping is used to avoid over-crediting nutrient contents that exceed their DRIs by rounding off their nutrient content per reference unit to 100% of DRI. Although earlier research suggests that capping might not be needed when comparing the nutritional quality of foods across food groups as it does not improve coherence with the dietary guidelines (Bianchi et al. 2020), the use of capping might be more justified when comparing foods within a specific food category, especially when containing nutrients in levels exceeding the DRI considerably (Bianchi et al. 2022). The NRF index was calculated for 5 g dry weight (DW), which is suggested as a reference amount for a portion of algae by the European Food Safety Authority (EFSA) and used in the CEVA database (CEVA 2021; Sá Monteiro et al. 2019).

Further, based on the DRIs, the percentage contribution to the recommended daily intake of individual nutrients was calculated for a portion of algae (5 g DW).

2.5 Components of concern for health

The content of heavy metals was obtained from the Norwegian Institute of Marine Research as this was considered to be the database with the overall most reliable measure units for these compounds based on e.g., consistency across records in magnitude of different contents. The potential toxicological risk of heavy metals was primarily assessed for a portion of seaweed (5 g DW or 50 g fresh weight for *Chondrus crispus* and *Porphyra umbilicalis*) by the percentage contribution to tolerable daily intake (%TDI). TDI is defined as one seventh of the tolerable weekly intake (TWI), where TWI estimates the amount per unit body weight of a potentially harmful substance that can be ingested weekly over a lifetime without risk of adverse health effects. If the TWI or TDI was not available, a benchmark dose lower confidence limits (BMDL) was used. BMDL is estimated when a tolerable intake cannot be determined. It represents the minimum dose that gives a clear, low-level health risk (usually in the range of 1-10% of a particular adverse health effect). If different BMDL were available for a specific substance, e.g., one for adults and one for children, the lowest level was used (EFSA, 2012; 2010; 2009a,b).

Furthermore, since the content of iodine per portion (5 g DW) exceeded DRI, this nutrient was also considered to represent a potential threat to health. The content of iodine per portion (5 g DW) was therefore assessed against the daily upper limits (UL) as defined by NNR (NCM 2014).

The values for ULs, TDIs, BMDLs are reported in the Appendix 3 (Table 4S).

3 Results

3.1 European algae production

A diversity of species and production methods are used to produce algae in Europe today, but the main volume comprise of wild harvest of the brown macroalgae *Laminaria* spp. (Table 3). Microalgae production is based on a range of different species and production systems, but mainly in different photobioreactors (71%); combined, this sector contributes with volumes over 182 tonnes (not all volumes are reported). Spirulina production amounts to 142 tonnes, mainly from ponds (83%). By volume, the most important other microalgae species are *Chlorella* spp. (~82 tonnes), *Haematococcus pluvialis* (~66 tonnes) and *Nannochloropsis* spp. (~21 tonnes), all in dry weight (DW).

Table 3 Most important algae species in Europe by production volume (>10 tonnes by either wild harvest or aquaculture) based on Araújo et al. 2021.*reported in dry weight (DW).

Type		Species	Aquaculture (t fresh weight, or companies in brackets)	Wild harvest (t, or companies in brackets)	Main production technology
Macroalgae	Brown	*Saccharina latissima*	376 (26)	n.a. (25)	unclear
		Laminaria spp.	n.a. (8)	209 772 (37)	wild harvest
		Ascophyllum nodosum	-	82 476 (24)	wild harvest
		Alaria esculenta	107 (16)	n.a.	aquaculture (?)
		Undaria pinnatifida	n.a. (10)	294 (22)	wild harvest
	Green	*Ulva* sp.	50 (10)	217 (38)	wild harvest
	Red	*Palmaria palmata*	n.a. (6)	455 (35)	wild harvest
		Chondrus crispus	n.a	186 (23)	wild harvest
Micro-algae		Spirulina	142* (222)	-	ponds
		Chlorella sp.	82*(30)	-	photobioreactors
		Haematococcus pluvialis	66* (17)	-	
		Nannochloropsis	21* (25)	-	

3.2 Overview of environmental differences

3.2.1 Microalgae

Overall, an analysis of results from available LCAs show that many different microalgae production systems exist today, each with strengths and weaknesses for instance related to scales (high or low productivity per m^2), operational costs, open- or closed-systems (contamination risk), using natural or artificial light, and different end-products such as food, feed, fuel or other. This variety of production systems reflects the wide range of conditions required for specific strains of microalgae to grow, but also the wide range of environments where microalgae production systems occur. In other words, the state of microalgae production is similar to that of agriculture: A wide range of species are being cultivated around the world in areas with sub-arctic to semi-desertic environmental conditions, using technologies ranging from industrial monoculture suited to rural landscapes to intensive aquaponics in urban/industrial areas.

The harmonization of LCAs in Schade and Meier (2019) included four studies investigating pilot scale production in open raceway ponds (ORP) and photobioreactor (PBR) in the Netherlands and Singapore of *Nannochloropsis* sp., lab-scale production (ORP) in the USA of *Scenedesmus dimorphus* and lab-scale production (PBR indoor and outdoor) in Spain of *Heterosigma akashiwo, Alexandrium minutum and Karlodinium veneficum*. No commercial scale production, nor *Spirulina* production was included which limits opportunities for reporting on representative greenhouse gas emissions of European production (Table 4).

Table 4 Percentage of producers using different production systems for microalgae and Spirulina (based on Araújo et al. 2021) and harmonized LCA results (based on Schade and Meier 2019).

Type	Production system	Percentage of European production volume	CO_2e range (in kg/kg dry mass)
Spirulina	Ponds	83	-
	Photobioreactors	17	-
	Fermentors	-	-
Microalgae, other	Ponds	19	220–3100
	Photobioreactors	71	7–2100
	Fermentors	10	-

Although no commercial scale production was evaluated, Schade and Meier (2019) report that the greenhouse gas emissions of microalgae grown in PBRs is highly connected to seasons and location. Colder locations require higher energy input for temperature management (especially for heating during winter) than warmer locations. This results in a span of 160–2100 kg CO_2e/kg dried microalgae mass (dependent of season) in the Netherlands. In warmer climates (Spain in this study), a lower carbon footprint of ~200 kg CO_2e/kg dried microalgae mass is achieved when growing indoors. This can be further reduced by placing the PBR outside, eliminating the need for artificial lighting, down to 7–22 kg CO_2e/kg dried microalgae mass.

When growing microalgae in an ORP, effects of seasonality are also seen. This is connected to the heating required during colder months. Dutch ORP-grown microalgae are associated with a carbon footprint of 220–3100 kg CO_2e/kg dried microalgae mass depending on season, i.e., overall, slightly higher than PBRs. ORP farms in warmer climates are however very effective with a carbon footprint of <10 kg CO_2e/kg dried microalgae mass; water use due to high evaporation is the biggest contributor.

In summary it can be said that Schade and Meier (2019) show that energy use for temperature management at the farm or lighting gives the biggest contribution to the carbon footprint of both growing systems and that location of farm is important for microalgae farming.

3.2.2 Macroalgae

There is no LCA available on wild harvest of macroalgae which represent a major data gap from a European perspective in terms of coverage of main production volumes (Table 5).

Table 5 Number of LCAs identified for the species and production systems. Shaded cells (grey) indicate production systems existing in Europe that have not been studied.

Type	Species	Aquaculture (t)	Wild harvest (t)	Total number of LCAs
Brown	*Saccharina latissima*	376	n.a.	5
	Laminaria sp.	n.a.	209 772	-
	Ascophyllum nodosum	-	82 476	-
	Alaria esculenta	107	n.a.	-
	Undaria pinnatifida	n.a.	294	-
Green	*Ulva* sp.	50	217	4
Red	*Palmaria palmata*	n.a.	455	-
	Chondrus crispus	n.a	186	-

For brown macroalgae, several LCAs on farming are however found. Through harmonization of methodological choices and recalculation, farming of *Saccharina latissima* was found to be associated with a mean estimate of around 114 kg CO_2e/tonne fresh weight, with a standard deviation of 63 kg CO_2e (Thomas et al. submitted). The consumption of diesel by boats primarily during maintenance and harvest operations is the main driver for greenhouse gas emissions (mean ≈55%). Use of plastic materials such as buoys and ropes are the main drivers of cultivation stage (≈29%), while the nursery had the lowest contribution (mean ≈15%) primarily linked to electricity consumption. Differences between systems are likely driven by large differences in material inputs, e.g. electricity, plastics, concrete and metals. Although several studies exist, the representativeness of this data for current commercial-scale farming of *Saccharina latissima* in Europe is uncertain, since the LCAs were performed while the production was still at pilot scale.

For green macroalgae, *Ulva* spp. production systems in Europe today are rather small scale, with ten companies producing 50 tonnes (Araujo et al. 2021). Based on the master thesis on a recent start up in Sweden, the estimated GHG emissions of *Ulva* production was 271 kg CO_2e/tonne fresh weight (Winqvist & Gillgren, 2022). The system included two land-based activities (spore preparation and seeding) and two sea-based (cultivation and harvest). A dominance analysis suggested that the main hotspots for greenhouse gas emissions, in terms of processes, were the cultivation (45%) followed by the spore preparation (30%). Components that contributed the most were carrying lines, seeding lines and buoys (non-electricity driven), as well as the seawater pump (electricity-driven), with use of diesel, gasoline and plastics being the most contributing materials. The spore preparation accounted for approximately 78% of the total energy demand. This LCA was however performed on a pilot scale production coastal production outside of Sweden and is thus not representative for commercial scale aquaculture production in Europe which may often be based on land or in ponds. A few additional LCAs of *Ulva* spp. production were identified in the literature search: wild harvest followed by land-based grow out in raceway tanks (Brockmann et al. 2015), land-based Integrated Multi-Trophic Aquaculture (IMTA; Helmes et al. 2018), and ponds connected to wastewater treatment plant (Pilicka et al. 2011). However, in these cases the intended biomass applications were bioethanol, lactic acid and methane, respectively, and may not be suitable for food purposes. Uncertainties in estimates are also high due to the prospective nature of the data also for these studies, and further transparency in inventory data is needed to be able to harmonize methods and compare the different systems.

For red macroalgae, no LCA was found comprising production of the species important to Europe. However, drivers for greenhouse gas emissions for Chilean farming of *Gracilaria chilensis* are found in Aitken et al. (2014). LCAs of two cultivation techniques were investigated, bottom-planting (pre-nursed seaweed thalli are planted directly into the seabed) and long-line cultivation (thalli are attached to off-shore ropes). For the long-line scenario, hot spots for greenhouse gas emissions came from preparation (~54%) followed by cultivation (~37%). The dominant contribution comes from production of materials needed for these stages, such as polyamide ropes and concrete blocks, as well as infrastructure (shed for preparation and barge for cultivation). Harvesting was the least impactful stage (~8%). A different pattern was identified for the bottom-planting scenario, with harvesting being the hotspot of the process (~65%). The predominant contributor in this stage is diesel, followed by aluminium required for production of the harvesting vessel. Preparation (~19%) and cultivation (~17%) was associated with smaller contributions to the overall carbon footprint. Drivers for greenhouse gas emissions for Indian production of *Gracilaria edulis* may also be found in Anand et al. (2018). In the commercial scale but low-tech system (bamboo rafts, no hatchery), more than 80% of the impact came from plastic components (nets and ropes) and plastic extrusion (based on the electricity production mix in India).

In summary, indicative magnitudes of greenhouse gas emissions in the current literature for different macroalgae of relevance to Europe are 271 CO_2e/tonne for green and 114±63 kg CO_2e/tonne for brown macroalgae respectively. For farming of red macroalgae in other regions of the world, and indicative value of ~35 kg CO_2e/tonne fresh weight was found for long-line cultivation. These values represent snapshots in different times, includes prospective data and pilot production, and are influenced by data availability and modelling thereof, as well as of different technologies and geographies – thus not fully comparable and may certainly not be representative for a highly diverse production sector. Based on the data at hand, it suggests that green seaweeds are more GHG emission intensive to produce than others, which may be a result of either true differences between seaweed groups based on e.g., lower yield per similar input of infrastructure, less optimised systems for green seaweeds today or the prospective data of these systems. However, at the stage of production, all seaweeds studied here have relatively small carbon footprints compared to many other foods.

3.2.2.1 Ecosystem effects from wild harvest

Kelp forests (brown macroalgae) are fundamental components in the production, biodiversity and functioning of coastal ecosystems, by supporting complex food webs and providing food, shelter and habitats for several marine species (Araújo et al. 2016). They support primary production, function as both sinks and sources of carbon and prevent coastline erosion as well as sedimentation by reducing tidal surge and waves (Mineur et al. 2015; Mac Monogail et al. 2017). Brown macroalgae (Laminariales and Tilopteridales) are the dominant seaweed species along the European coastline, but abundance and distribution differ geographically. Identifying large-scale trends thus remains challenging due to lack of baselines and quantitative datasets in combination with spatial variability (Araújo et al. 2016; Mineur et al. 2015).

Lack of baseline data from insufficient monitoring generally hinders detection of large-scale effects from harvesting (Mineur et al. 2015). However, there is a tendency of decreasing abundance with exception of some populations in specific areas around France, Germany, Norway and Svalbard (Araújo et al. 2016). Araújo and colleagues (2016) identified global warming as the dominant stressor, combined with effects from overfishing causing cascading effects on seaweed predator abundance, and pollution. Local stressors such as water turbidity, diseases and kelp harvesting are also adding to impacts. According to Monagail et al. (2017), the ecological impacts of wild seaweed harvesting can be assumed extra notable in Europe where the production has undergone extensive mechanization. The dominant production country, Norway, launched its first dedicated 'seaweed trawler' in 1969. From capability to operate in shallow waters and with increasing hull capacity, these boats have facilitated a high exploitation rate through effective mechanical removal, which generally causes more harm to seafloor habitats than traditional harvesting by hand.

The following risks from wild harvesting of seaweed have been identified:

- Overall, impacts depend on aspects such as target species and geographical area, where e.g. removal of seaweed species forming canopies, such as kelp species, generally causes most severe ecosystem level impact (Lotze et al. 2019).
- Harvesting may negatively affect the macroalgae resource itself in the form of decreased density and skewed population mixes. The regenerative and recovering

capacity of wild cut seaweeds stocks depends on the techniques used and the extent of harvesting (Monagail et al. 2017), but even removal by hand can affect the extent and structure of seaweeds, which makes cutting height and time intervals between harvest crucial (Lotze et al. 2019).

- There may also be negative effects on species that depend on the habitats and functions offered by macroalgae, where e.g. kelp trawling (*Laminaria hyperborea*) in the Norwegian archipelago has been shown to change the structure and habitat function, and decrease the abundance of several other species groups including fish (Norderhaug et al. 2020).
- Harvesting can result in structural changes of seaweed beds, which in turn can impact the primary and secondary production, the shoreline buffering and filtering functions, and the capacity to store carbon and nutrients in the seaweed (Lotze et al. 2019).
- Harvesting may increase the abundance of unwanted seaweed species such as opportunistic turf algae (Monagail et al. 2017; Lotze et al., 2019), as well as favor introduction of new species (Mineur et al. 2015). In Europe, for instance, invasive species such as *Sargassum muticum* has proven hampered the growth of *Laminaria digitata* and other canopy forming algae, by shading and monopolizing space.
- Continued wild harvesting of seaweed may be hampered by distributional shifts caused by climate change, which may make different species more vulnerable for harvesting (Norderhaug et al., 2020). Risks for decline and even local extinction have been identified for a number of European native kelp species, such as *L. digitata*, *L. hyperborea*, *Saccharina latissima* and *Saccorhiza polyschides* (Monagail et al., 2017). Further reductions of *L. digitata* and *L. hyperborea* have been predicted by modelling studies (Raybaud et al. 2013; Assis et al. 2016).

The scientific literature emphasizes the importance of quantifying European seaweed resources, to generate accurate baseline data for sustainable management (Monagail et al., 2017; Hamilton et al., 2022). Furthermore, it is repeatedly stressed that these resources require an ecosystem-based management, characterized by the precautionary principle, considering the multiple ecosystem services provided. Hamilton and colleagues (2022) underlines that such management, combined with continuous (annual/sub-annual) monitoring, is of extra relevance considering the relatively short lifespans (1-7 years) of key canopy-forming kelp species, making them respond rapidly to changing conditions. Additionally, as a result of growing nearshore, seaweeds are subject to several impacts from human activities. This strengthens the importance of monitoring and addressing cumulative impacts even further.

According to Lotze and colleagues (2019), management plans and regulations of seaweed harvesting, if they exist, often lack an ecosystem approach considering, for instance, cumulative effects on species that may depend on the targeted seaweed. Implemented plans generally lack detail and rather focus on the regeneration of the seaweed resource itself, and/or regulations concerning specific gear types, licenses, quotas, temporal, spatial restrictions, etc. Evaluation of effects of different management plans has shown that territorial user rights and marine protected areas are more beneficial for conservation of kelp than regional management plans (Gonzáles-Roca et al. 2021), and co-management approaches has been proven successful in many regions (Hamilton et al. 2022). Education and communication between industry and responsible government agencies is essential, as highlighted by Monagail and colleagues (2017). Successful examples of management initiatives include seaweed harvester apprenticeship programs, offering training in sustainable harvesting and development of good practice guides for seaweed producers.

Another outlook for the European kelp-market is increased establishment of cultivation sites for macroalgae, which potentially could unburden wild stocks in terms of ecological impact. Through its habitat providing function, several species could benefit from such initiatives. According to Corrigan and colleagues (2021) however, the ecological and economic value of this provisioning function is still unquantified, which inhabit incentives for farmers to apply an ecosystem approach in designing cultivation sites. Barrento and colleagues (2016) add that farming lacking sustainable management can result in loss of genetic diversity. In response to this risk, they developed a germplasm bank aiming to preserve genetic diversity of the giant kelp *Macrocystis pyrifera*. The storage of gametophytes was proven successful, and the authors stress the need to recognize genetic resource management as a resource insurance.

3.3 Simplified tool

The input options were found to be sufficient regarding material choice, dimensions, and available life lengths. When using inventory data from Thomas et al. (2021), the Excel tool returned a carbon footprint of 66 kg CO_2 eq./ton fresh weight seaweed, 10% higher than the results presented in the original article. Using inventory data from the unpublished study on seaweed farming, the excel tool derived at a carbon footprint 10% lower than the results from a more extensive analysis performed previously. Following the same reasoning as for Thomas et al. (2021), ±10% is deemed an acceptable variation for a simplified tool.

Using this tool[1], increased understanding is gained about what matters most for greenhouse gas emissions of this kind of production, and to facilitate for seaweed farmers who want to start collecting data to be able to follow up on the climate performance of their production. Furthermore, it allows the user to explore the impact of different material and management choices and can be used to facilitate a change to more climate efficient farming practises.

3.4 Overview of nutrient content

Nutrient data was completely missing in the used FCDs for a number of species of interest and the analysis could only be performed for a subset of the species (Appendix 1.1 and Table 1S). For the included algae, nutrient content collected from FCDs was however often incomplete, with one or more nutrients missing, which limits the assessment of the nutritional quality of these products.

When available, data on nutrient content presents a large variability within (for a limited number of species where data is available from more than one FCD) and across algae species and subspecies (Tables 2S a-d in Appendix).

The contribution to the nutrient daily recommended intake per 5 g portion indicates that micro- and macroalgae can be regarded as a considerable source of minerals and, in some

[1] Available at https://www.ri.se/en/what-we-do/projects/the-role-of-algae-in-a-sustainable-food-system-environment-and-nutrition

cases, of vitamin B12 (Figure 1). A portion of the green macroalgae *Ulva* spp. provides a high nutritional contribution of magnesium (all analysed species), iron (*Ulva rigida* and *Ulva* spp.), selenium (*U. fenestrata*, *U. intestinalis*, *U. rigida*) and vitamin B12 (*Ulva* spp.*)*. Brown macroalgae generally show lower mineral and vitamin contribution, with exception of *Alaria esculenta* providing more than 20% of the DRI for iron, and *Saccharina latissima* providing 27% of the DRI for selenium. Red macroalgae contain some iron (*Gracilaria* spp. 15% DRI, *Porphyra umbilicalis* 17% DRI and *Porphyra* spp. 15% DRI), and are particularly interesting for the high selenium (*Gracilaria gracilis*, 47% of DRI and *Gracilaria* spp. 18% respectively) and vitamin B12 (*Porphyra* spp., 68% of DRI, *Palmaria palmata* 18% and *Chondrus crispus* 17% respectively). The microalgae *Chlorella* is rich in iron (52% of DRI) and vitamin B12 (64% of DRI), whilst *Spirulina* only contributes as a significant source of copper on a portion basis (34% of DRI). Besides vitamin B12 (Figure 1), other vitamin contribution of interest is vitamin E in *Ulva lactuca* (16% of DRI per portion) and folate in *Chlorella* (22% of DRI per portion). Iodine is the only nutrient that exceeds DRI for a 5 g portion, with values up to 18 times the DRI (*Laminaria digitata*), and therefore was assessed in relation to the daily tolerable intake (Figure 2).

None of the algae included in this study provide meaningful amounts of protein or fibre per portion, which would have been the case if we had considered the content per 100 g of dry algae; then e.g., fibre values exceed 100% DRI in most cases (data not shown, refer to content per 100 g provided in Tables 2S a-d). Mean fibre contribution to DRI ranged between 4.2 to 9.5% per portion for macroalgae (data not shown). Mean protein contribution ranged between 0.5 to 1.1% DRI per portion for macroalgae and was slightly higher in the microalgae *Chlorella* (2.7% DRI) and in *Spirulina* (3.3% DRI). Contribution of total and saturated fat was negligible (<1% MRI per portion), whilst data for omega-3 fatty acids was largely missing in the analysed FCDs.

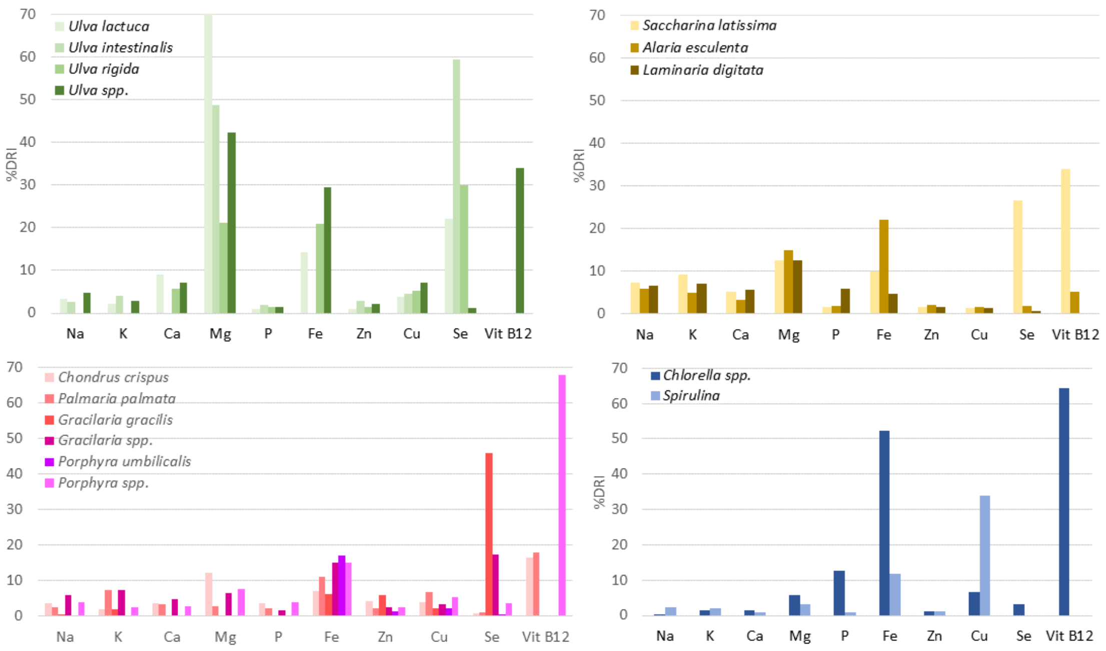

Figure 1. Mineral and vitamin content expressed as % DRI for a portion of 5 g DW* of the analysed green, brown, red macroalgae and microalgae. *Data are based on mean values per dried algae biomass weight. Median values were also calculated when possible

(not available for data from CEVA) and are presented in Appendix 1 Tables 2S a-d. For most nutrients mean and median values were identical. Nutrient content, and the deriving % DRI, present very large variation. Ranges (min-max) are provided in Appendix 1, Tables 2S a-d.

3.5 Nutrient density

Due to data gaps, NRF11:3 could only be calculated for six species: *Alaria esculenta, Chondrus crispus*, *Palmaria palmata*, *Porphyra spp., Saccharina latissima*, *Ulva* spp. (Table 5). In the case of *Laminaria digitata* only data for folate was missing and, as its contribution to the nutrient density was not expected to impact results drastically, the corresponding nutrient density was calculated and is shown in Table 5. For other macroalgae and for the microalgae *Chlorella* and *Spirulina*, more than one nutrient was missing and therefore NRF values are not presented.

Green macroalgae *Ulva* spp. showed the highest nutrient density per portion whilst *Laminaria digitata* showed the lowest value. However, within brown and red macroalgae nutrient density values are very close, and do not present the large variation that has been observed among seafood in a broader context (Bianchi et al. 2022). Across species, magnesium and iron gave the highest contribution to the NRF score (data not shown).

Table 5. Ranking of macroalgae based on the nutrient density score NRF11:3* per portion (5 g DW).

Macroalgae	NRF11:3/5g DW
*Ulva spp. (*green seaweed*)*	0.93
*Alaria esculenta (*brown seaweed*)*	0.64
*Palmaria palmata (*red seaweed*)*	0.44
*Saccharina latissima (*brown seaweed*)*	0.41
*Porphyra spp. (*red seaweed*)*	0.39
*Chondrus crispus (*red seaweed*)*	0.35
*Laminaria digitata (*brown seaweed*)*	0.31[a]

[a]Based on 10 qualitative nutrients, the value for folate is missing.

*The application of capping when NRF11:3 is calculated per portion is irrelevant, as none of the 11 qualitative nutrients exceed the DRI values.

3.6 Substances of toxicological concern

The content of heavy metals per 100 g DW for green, brown and red macroalgae is presented in the Appendix 3 (Table 5S). For two species (*Chondrus crispus* and *Porphyra umbilicalis*) data are presented per fresh weight (FW) since data for dried weight was missing. Heavy metal content for *Chlorella* and *Spirulina* were not available. In order to show the potentially harmful impact of heavy metals intake from macroalgae, data are also presented as contribution to the TDI per portion (Table 6 and Table 7). The content of inorganic arsenic (iAs) measured in wild-harvested *Laminaria digitata* is of particular concern as it is more than three times higher than the TDI, per portion. Although much lower, even *Alaria esculenta* reports a higher contribution of iAs when harvested as compared to cultivated (17.1 and 1.4 %TDI respectively). No other heavy metals exceed the TDI, but for cadmium and lead mean values are reported close to or exceeding 15% TDI, which is not a negligible risk for health if macroalgae would be consumed frequently.

Since the contribution of iodine per portion (5 g DW) exceeds 100% of DRI for some of the analysed macroalgae, iodine is also considered of toxicological concern. Considering that the TDI for this mineral corresponds to the upper level (UL) of 600 μg per day (NCM, 2014 and EFSA, 2018), only dried unprocessed *Ulva* and *Porphyra* can be regarded as "safe" sources of iodine (Figure 2 and Table 6S). Brown macroalgae, *Saccharina latissima* and *Laminaria digitata*, as well as the red macroalgae *Gracilaria spp*. are considerably exceeding the daily safe level of intake for this nutrient (Figure 2 and Table 6S). No iodine content was available for *Chlorella* and *Spirulina* from the screened FCDs.

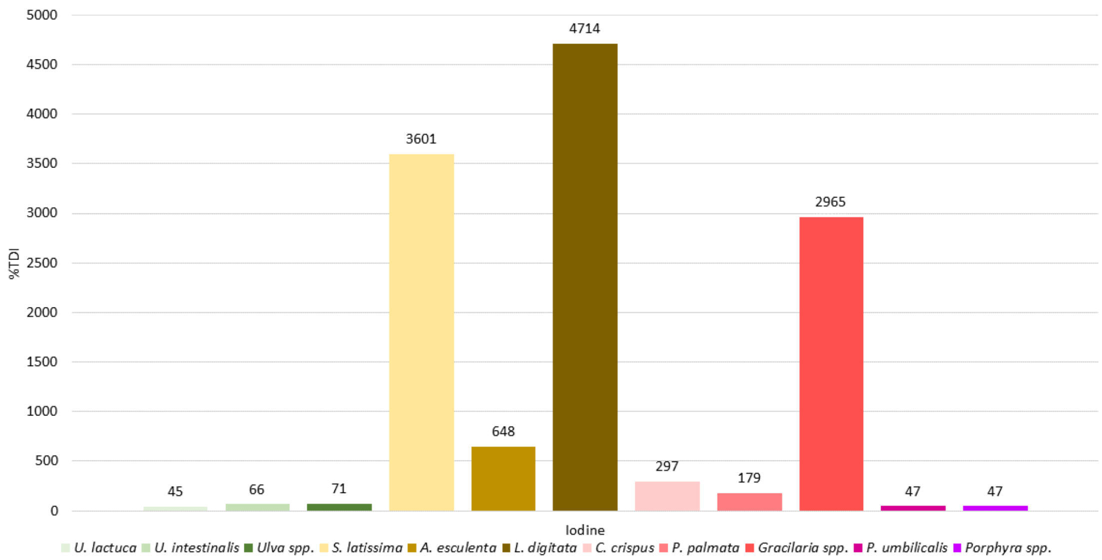

Figure 2. Percentage contribution to the upper level (%UL) of iodine for dried unprocessed macroalgae per portion (5 g DW)*. *Reference value for upper level presented in Appendix 3 (Table 4S). Data are mean values. Median values were also calculated when possible (not available for data from CEVA) and are presented in Appendix 3 Table 6S, together with ranges (min-max).

Table 6. Percentage contribution to tolerable daily intake (%TDI) of heavy metals for dried unprocessed macroalgae per portion (5 g DW)*. All values presented are obtained from the Norwegian Institute of Marine Research.

Green macroalgae

	***Ulva lactuca* (wild-harvest)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**
iAs (% TDI)	9.4	9.4	1	9.4	9.4
Cd (% TDI)	3.6	3.6	1	3.6	3.6
iHg (% TDI)[1]	n.d.	n.d.	1	n.d.	n.d.
meHg (% TDI)[1]	n.d.	n.d.	1	n.d.	n.d.
Pb (% TDI)	14.4	14.4	1	14.4	14.4

Brown macroalgae

	***Saccharina latissima* (wild-harvest)**					***Saccharina latissima* (cultivated)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
iAs (% TDI)	5.5	4.6	6	1.3	14.1	1.3	1.2	4	0.8	2.0
Cd (% TDI)	16.6	7.5	6	2.7	54.7	11.1	9.3	4	6.0	20.1
iHg (% TDI)[1]	n.d.	u.l.d.	6	u.l.d.	0	n.d.	u.l.d.	4	u.l.d.	u.l.d.
meHg (% TDI)[1]	n.d.	u.l.d.	6	u.l.d.	0	n.d.	u.l.d.	4	u.l.d.	u.l.d.
Pb (% TDI)	n.d.	u.l.d.	6	u.l.d.	6.1	n.d.	u.l.d.	4	u.l.d.	3.3

	***Alaria esculenta* (wild-harvest)**					***Alaria esculenta* (cultivated)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
iAs (% TDI)	17.1	5.4	5	0.5	58.3	1.4	1.4	2	0.8	2.1
Cd (% TDI)	20.1	20.1	1	20.1	20.1	23.7	23.7	2	18.2	29.2
iHg (% TDI)[1]	n.d.	u.l.d	1	u.l.d	u.l.d	n.d.	u.l.d	2	u.l.d	u.l.d
meHg (% TDI)[1]	n.d.	u.l.d	1	u.l.d	u.l.d	n.d.	u.l.d	2	u.l.d	u.l.d
Pb (% TDI)	n.d.	u.l.d.	1	u.l.d.	u.l.d.	n.d.	u.l.d.	2	u.l.d.	u.l.d.

	Brown macroalgae					**Red macroalgae**				
	***Laminaria digitata* (wild-harvest)**					***Palmaria palmata* (wild-harvest)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
iAs (% TDI)	329.6	242.2	8	1.9	784.8	5.2	5.2	2	0.8	9.6
Cd (% TDI)	8.9	8.9	7	3.6	15.7	6.6	6.2	3	2.6	11.1
iHg (% TDI)[1]	0.4	0.2	7	u.l.d	1	n.d.	u.l.d	3	u.l.d	0
meHg (% TDI)[1]	1.2	0.5	7	u.l.d	2	n.d.	u.l.d	3	u.l.d	0
Pb (% TDI)	1.2	0.4	7	u.l.d.	0.6	n.d.	u.l.d.	3	u.l.d.	3.5

*Refence values for TDI presented in Appendix 3 (Table 4S). No reference values for TDI available for total arsenic (only for iAs) and total mercury (only for iHg and MeHg). [1]Percentage of TDI is calculated by assuming the 100% of total mercury is either iHg or MeHg. n.d.: not determined; u.l.d.: under level of detection. Number refers to data points used for the calculation of mean and median.

Table 7. Percentage contribution to tolerable daily intake (%TDI) of heavy metals for unprocessed red macroalgae *Chondrus crispus* and *Porphyra umbilicalis*. Values are expressed for fresh unprocessed macroalgae per 50 g portion, which corresponds approximately to 5 g DW. No water content was available to make an accurate conversion fresh weight to DW. Values obtained from the Norwegian Institute of Marine Research.

	***Chondrus crispus* (wild-harvest)**					***Porphyra umbilicalis* (wild-harvest)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
iAs (% TDI)	16.6	16.6	1	16.6	16.6	0.9	0.9	3	0.8	0.9
Cd (% TDI)	7.7	7.7	1	7.7	7.7	12.6	12.6	4	8.6	17.0
iHg (% TDI) [1]	0.2	0.2	1	0.2	0.2	n.d.	u.l.d.	4	u.l.d.	u.l.d.
meHg (% TDI) [1]	0.7	0.7	1	0.7	0.7	n.d.	u.l.d.	4	u.l.d.	u.l.d.
Pb (% TDI)	16.6	16.6	1	16.6	16.6	n.d.	u.l.d.	4	u.l.d.	11.2

*Refence values for TDI presented in Appendix 3 (Table 4S). No reference values for TDI available for total arsenic (only for iAs) and total mercury (only for iHg and MeHg). [1]Percentage of TDI is calculated by assuming the 100% of total mercury is either iHg or MeHg. n.d.: not determined; u.l.d.: under level of detection. Number refers to data points used for the calculation of mean and median.

4 Discussion

4.1 Main findings

This report set out to generate a unique data set on environmental and nutritional aspects of algae production and consumption, an objective that has been met alongside identification of considerable knowledge gaps.

From an environmental perspective, the European production differs from global production in terms of production methods, i.e., being dominated by wild harvest of seaweeds – a production technique for which public LCA data is still lacking. Representativeness of available LCAs is thus overall poor for current production systems, both from not covering wild-harvested macroalgae and the fact that most studies on farmed algae were done on systems at pilot scale. Nevertheless, key aspects to consider for minimizing carbon footprints in developing aquaculture for macroalgae are efficient transport at sea, use of ropes and buoys during cultivation and electricity consumption in the hatchery. Improvement options are therefore found in use of cleaner energy sources, minimizing use of materials, selecting materials that are climate-efficient and recycle them after their lifetime is reached and smart location of farm at sea. For microalgae aquaculture, a wide range in carbon footprint may be observed based on pilot studies. Based on the data at hand, location of production is important since heating requirements and light conditions affect the carbon footprint. For wild-harvest of macroalgae, development of ecosystem-based approaches to management is needed.

In terms of nutritional value, significant data gaps only allowed the evaluation of nutritional quality for a subset of species of interest, indicating the need for a better representation of algae in FCDs. Based on available data, the nutrient content per 5 g portion indicates that macro- and microalgae may be a considerable source of minerals and, in some cases, of vitamin B12. On the contrary, the contribution to the dietary intake of one portion of dried macroalgae of 5 g is minimal for protein and fat, and very low for fibre. Nevertheless, the suggested small portion of macroalgae can contain harmful amounts of the mineral iodine and of several contaminants such as the heavy metals inorganic arsenic, lead and cadmium. Therefore, a careful consideration of risks and benefits associated with algae consumption should be done when introducing algae in the dietary advice, as well as continuous product development towards safe algae-based food ingredients.

Although green seaweed production was here found to be associated with 5-10 times higher GHG emissions than red and brown seaweeds (at around 300 and 30 kg CO_2e/tonne fresh weight, respectively), all systems represent very low-GHG emission seafoods per kg. Dried seaweed has higher emissions than fresh, even without including the processing, just from the reduced mass. Still, even in dried format, seaweeds have been found to have lower emissions than any other type of seafood, an average of 1086 kg CO_2e/tonne dry seaweed (Gephart et al. 2021). In addition, their land and freshwater use is zero, as opposed to many farmed species that depend on manufactured feeds, and they take up more nitrogen and phosphorous than is emitted in their production.

4.2 Nutritional aspects – which role may algae play in diets?

A crucial point in the assessment of the nutritional value of algae for human consumption is their role in the diet. It has been extensively discussed whether macroalgae should be seen as a protein, a carbohydrate, a vegetable, a salad or even as herbs, and thereby what comparisons with other foods are justified. In Asia, where macroalgae consumption is widespread, macroalgae products destined for direct human consumption can be found in many different forms, but dried is the most common one (FAO and WHO 2022). To analyse a realistic contribution of algae to the human diet, we chose to look at the nutrient content per portion (5 g of dry macroalgae, based on EFSA). For macroalgae, this corresponds approximately to 30-40 g of fresh product which relates to a commonly consumed portion of salad. The same portion size (5 g DW) was applied to the microalgae *Chlorella* and *Spirulina*. Considering the relatively small size of the suggested portion, dried macro- and microalgae provide a relatively low protein contribution to the diet (up to 1.1% DRI for macroalgae, and 2.7 and 3.3% DRI for *Chlorella* and *Spirulina*, respectively) and therefore challenges the idea that algae per se (but not protein-enriched extracts, for example) should be seen as a protein source in the diet. It is however likely that this can change, given successful recent studies where the protein content of green macroalgae, e.g. *U. fenestrata,* was increased up to 4-fold following cultivation in presence of nutrient rich food process waters (Stedt et al. 2022a;b;c).

There are different methodological approaches for collecting nutrient data: compilation from original studies based on literature review or use of data available from food composition databases (FCDs). A literature review of studies containing a nutritional characterization of macroalgae was conducted as part of this project and led to a separate publication (Jacobsen et al. 2023). In this report we only present results based on the second approach. The starting point for both methods, however, was compiling a list of algae of interest for production and consumption in Europe. As shown in the Appendix 1, the screened FCDs only partially covered the composition of macroalgae, and almost no data was present for microalgae, except for *Chlorella* and *Spirulina*. More data is available in international FCDs for species that are traditionally part of the Asian diets. Even when available, nutrient data presents several gaps, and very limited or no details are provided on the area of origin, production and preparation methods, sampling and analysis procedures. Only for some databases (i.e. Harvard Aquatic Food database) clear references to the original studies are available.

The nutritional quality of algae was assessed both by looking at the mere nutrient content in a dry sample and by estimating the nutrient density based on the use of a nutrition quality score commonly used in nutritional LCA (McLauren et al. 2021). The index used in this study is a variant of the NRF score (11.3) which has been shown to better relate the nutritional quality of food products to the Swedish dietary guidelines for healthy eating (Bianchi et al. 2020). However, it could be argued that the two additional nutrients in NRF11.3 (as compared to the base version of this score, NRF9.3), vitamin D and folate, might not be particularly relevant for most algae. Other minerals and vitamins more abundant in algae could instead be integrated in the score (i.e., selenium, vitamin B12). However, due to the lack of data from FCDs this was not possible to apply. A broader approach has been used in Jacobsen et al. (2023) where a more comprehensive nutrient density score, including 21 qualitative nutrients has been applied (even including iodine). When comparing results for NRF11.3 of *Ulva* spp. and *Saccharina latissima* obtained from FCDs versus literature review (Jacobsen et al. 2023), similar results are found.

Overall, algae can be said to theoretically be good sources of minerals and some vitamins. However, bioavailability of nutrients or any variation in the nutrient content due to post-harvest processing or home preparation cannot be captured in the methods and results presented here. Green macroalgae (*Ulva* spp.) has the highest mineral content, with *U. lactuca* being particularly rich in magnesium *U. intestinalis* in selenium respectively. The microalgae *Chlorella*, on the contrary, has a high content of vitamin B12 and iron. Brown and red macroalgae are less rich in nutrients, but still contain considerable amounts of, for example, selenium as is seen in the red macroalgae *Gracilaria gracilis*. As highlighted above, the mere nutrient content per dried algae product does not necessarily predict its degree of absorption and utilisation by the human body. Other factors, such as the presence of the active form in the case of vitamin B12 (active vs. non-active) or the bioavailability of vitamins and minerals (particularly relevant for vitamin B12 and iron) are key factors to address. This is even more important considering that macroalgae are attractive foods to be consumed as part of vegan or vegetarian diets, in which content and/or bioavailability of vitamins and minerals plays a crucial role for the nutritional adequacy of the diet. More studies are also needed on the effect of different processing techniques on nutrient bioavailability.

To further investigate the impact of algae consumption to human health, a literature review of randomized controlled trials was also conducted within the project this report has been produced within (Trigo et al., 2023). This review found limited but favourable evidence for the effects of seaweed intake on blood glucose metabolism, blood pressure, anthropometric measures, markers of oxidative stress, and to a lesser extent blood lipids. However, the authors also acknowledged the importance of designing more clinical trials aiming at a lower risk of bias (Trigo et al. 2023).

4.3 Toxicological concerns

Heavy metals and iodine content are of concern for the consumption of macroalgae. Content of e.g., iodine, varies not only between species, but may also be affected by e.g., location or season (Roleda et al. 2018). As the dataset for heavy metals from FCDs is particularly limited, no conclusions can be drawn on the toxicity of consuming macroalgae as dried unprocessed samples. The unusually high content of inorganic arsenic in *Laminaria digitata* could, for example, be sporadic and caused by harvesting in a contaminated area. Nevertheless, almost all the macroalgae showed some content of major contaminants such as cadmium and lead.

A portion of 5 g of dried macroalgae contains between 45 and 4700% of daily level for safe consumption of iodine. *Saccharina latissima* contains 3600% of the UL of iodine, a content which is in line with what has been observed from the literature (Jacobsen et al. 2023). A recent report from the Nordic Council of Ministers presents the content of heavy metals and iodine in a larger number of macroalgae species cultivated in north Europe, confirming that key compounds of concern are cadmium, arsenic and iodine (NCM 2023), although with a very high variability among and within species. Very little is known about the bioavailability of iodine in macroalgae, especially from human studies, which calls for the need of more randomized controlled clinical trials (Blikra et al. 2022). However, it is regarded as being generally high (NCM 2023) requesting even greater attention to the safety of macroalgae consumption. This uncertainty and the large variability of iodine content in macroalgae is also at the base of the advice from the Swedish Food Agency to pregnant and lactating women which calls for precaution in the consumption of algae-based products (Swedish Food Agency, 2023). For some of the macroalgae (i.e., *S. latissima*) the thermal processing of blanching before commercialisation is a necessary practice to reduce the iodine content in the product (Trigo et al. 2023). In the analysed FCDs, however, no data is available for blanched macroalgae samples.

4.4 The full value chain perspective

This report has focused on the production of algae and thus not considered the full value chain perspective. Macroalgae biomass can degrade rapidly after harvest and be at risk of microbial decomposition and loss of sensory properties such as taste and odour (Barbier et al. 2019). For all foods, preservation allows to stabilize and prolong shelf life of products, but it usually comes at a high energy and environmental cost (Boye and Arcand 2013; Menon et al. 2020; Adnouni et al. 2023). The literature assessing environmental pressures of different methods for post-harvest preservation of macroalgae destined for direct human consumption however appears to be scarce. Based on five LCAs and one material and substance flow analysis, some insights may be provided (Table 6). Although these studies vary in LCA methodology and products assessed, they all refer to products based on long-line farming of the brown algae *S. latissima* and include key production processes such as cultivation at sea, harvest and post-harvest drying. In each study, the products were in the form of dried biomass or protein concentrate from dried *S. latissima* but it was not explicitly mentioned if they were suitable for direct human consumption.

Table 6 Studies on processing of *S. latissima* biomass.

Reference	Functional unit and end product (based on *S. latissima*)	Drying method	Contribution to energy use from drying (%)	Contribution to GHG emissions from drying (%)
Ekman-Nilsson et al. (2022)	1 kg dry weight for further processing (e.g., alginate)	No details on drying method, based on commercial production.	-	75%
Thomas et al. (2021)	1 tonne fresh weight, prior to preservation (not specified)	Air cabinet, modelled from Ecoinvent data.	77%	43%
Koesling et al. (2021)	1 kg of crude protein extracted from dried biomass (aquafeed ingredient)	No details provided.	66%	60%
Halfdanarson et al. (2019)	1 tonne protein concentrate extracted from dried biomass (aquafeed ingredient)	No details provided.	-	65%
Philis et al. (2018)	2 tonnes of protein concentrate extracted from dried biomass (aquafeed ingredient)	Steam drying, based on Hortimare (Holland) and literature.	84%	-
van Oirschot et al. (2017)	1 tonne of protein from dried biomass (suitable for further processing)	Thermal drying (based on a maize drying process in the Ecoinvent database).	77%	75%

Drying algae by other means than the sun, the latter being common practice in e.g., Asia, requires high energy use due to the high moisture content of the harvested biomass. The reviewed literature suggests that a moisture content of around 20% should be obtained after the drying processes – i.e., reduced from a pre-drying moisture content of 80-85%. The specific moisture extraction rate, or the amount of energy required to extract 1 kg of water from the biomass, has been identified as a main hotspot (Thomas et al. 2021; van Oirschot et al. 2017). In the four studies that estimated the cumulative energy demand (MJ) of different production systems, drying was consequently the most energy demanding, accounting for between 66 to 84% of the total energy demand (Table 6). The drying process is thus perhaps not surprisingly also the biggest contributor to greenhouse gas emissions, ranging between approximately 43 to 75% of the total greenhouse gas emissions. The greenhouse gas emissions are however dependent on energy source (Koesling et al. 2021), where each drying process used different energy sources in the studies.

In conclusion, post-harvest drying may contribute significantly to the total energy demand and greenhouse gas emissions of macroalgae production systems and therefore should be given particular attention when evaluating the environmental impact of macroalgae products. However, drying may also decrease the total impact from a full value chain perspective since it can contribute to reducing energy demand for transport, packaging and storage (Bosona and Gebresenbet 2018) and prolong shelf-life. Furthermore, the drying methods in the reviewed studies are generally not explained in detail, making it difficult to compare them and identify how representative they are of currently available energy-efficient technologies (i.e. as described in Adnouni et al. 2023; Menon et al. 2020; Hnin et al. 2018). Only Thomas et al. (2022) compares different preservation methods and suggests that hang-drying and ensiling are better options than air cabinet drying and freeze-drying with regards to energy consumption and associated emissions. Furthermore, the reviewed studies do not mention how the selected drying processes can affect nutrient retention and organoleptic properties, nor if they can play a role regarding potential food safety hazards (e.g., iodine and heavy metal content). There seems however to be a growing body of literature discussing how processing methods can affect quality, both for direct human consumption usages (e.g., Løvdal and Skipnes 2022; Lytou et al. 2021; Choi et al. 2012) as well as other usages like hydrocolloids extraction, protein extraction or biofuels (e.g., Trigo et al. 2023; Adams et al. 2021; Gomez et al. 2020; Albers et al. 2021). However, with regard to direct human consumption purposes, there is a lack of studies assessing both quality retention and environmental impacts of macroalgae processing. Further investigations are also needed on cost-effectiveness of different preservation systems as well as consumer preferences regarding end products (Wendin and Undeland 2020).

4.5 Global and future outlook including research gaps

This report has taken a European perspective to algae production and identified many important knowledge gaps. Currently, most of current European production is used for indirect food consumption (alginate extraction) or non-food usages. Europe produced less than 1% of global production volume of macroalgae in 2019, while China and Indonesia accounted for 57% and 28%, respectively. Norway however represents the 3rd most important producer of wild-harvested macroalgae in the world (after Chile and China), and although marginal in terms of production volumes, algae production in Europe is widespread across countries (see Araujo et al. 2021 for an overview and main characteristics). There is thus both a diversity in production (countries, species, production technology and applications of biomass) as well as a high concentration of production – but regardless, few LCAs are found.

Although algae are increasingly discussed as a potentially nutritious and environmentally friendly source of food, the current consumption and prospective demand as food appears to be poorly documented (Mendes et al. 2022). Hornborg et al. (2021) estimated a total consumption of 156 tonnes of aquatic plants in Sweden in 2019, which at about 10 million inhabitants, makes consumption per adult per day negligible. However, the data at hand for the estimate was highly uncertain. Data on Swedish production had to be collected directly from the largest producer for the purpose, as no official data collection had been initiated on Swedish production. Furthermore, official statistics on imports and exports merges different algae products into one volume, with thus contain both dried, fresh and processed algae. Despite these uncertainties, the Swedish consumption is very low compared to Japan, where Vellinga et al. (2021) reported an average daily intake by adults of 1.7 g DW (or 8 g wet weight). Thus, there is in theory room for increased consumption which would benefit conditions for production in Sweden.

Based on insights gained from Araujo et al. (2021) and FAO (2021), the expansion potential is uncertain for European algae production for human consumption. Currently, there is a discrepancy between what we produce in Europe (mainly brown macroalgae) compared to what we eat – 60% of the consumed algae in Europe is red algae *Porphyra* (Nori, notably used in sushi rolls) of which 99% is imported from Asia (Mendes et al. 2022). Furthermore, the total reported European production of macroalgae has declined compared to the 1990s. This may be due to dependence of wild stocks, where the slight increase in farmed production has so far not compensated for the decrease in wild harvest. However, the number of companies have increased, with about a third being based on aquaculture (Araujo et al. 2021). Roughly a third (36%) of all production companies uses the biomass for direct human consumption, but it is unclear what this implies in terms of share of volume produced; most companies seem to be characterized by small-scale production and niche markets. To this end, Europe currently has a trade deficit of EUR 52 millions in 2018 for macroalgae food products (Mendes et al. 2022).

There are thus both opportunities and challenges for increased production and consumption of algae in Europe. On one hand, interest is on the rise to develop cultivation capacities along the Atlantic coastline catalysed by the EU's 2012 calls for Bioeconomy and Blue Growth strategies and the more recent EU Blue Economy Report 2020 (EC, 2020) and perhaps most strongly in the recent EU communication Towards a strong and sustainable EU algae sector (EC 2022). On the other hand, the current primary production is small and facing multiple barriers: legislative (e.g., complex regulations); political (e.g., lack of national policy/strategy and social acceptance/public support) and commercialization (e.g., production costs, consumer habit inertia, EU novel food legislation). More research is needed to better understand potential risks, both environmental (e.g., carrying capacity of local ecosystems) and food safety-related (e.g., heavy metals and iodine,) of an increased production/consumption. There may also be competition for the future algal biomass production between direct human consumption usages and the current interest for hydrocolloid extraction and non-food use by the European industry. These industries are currently major importers of macroalgae and the demand is expected to grow (FAO and WHO 2022; Camarena-Gomez et al. 2022; Mendes et al. 2022; Cai et al. 2021; Barbier et al. 2019; Albers et al. 2021). To prevent that one trade restricts the other from expanding, multiple product production from macroalgae in smart biorefinery sequences should be further explored (Wahlström et al. 2018; Baghel et al. 2023; Torres et al. 2019; Balina et al. 2017). This would allow several commercially relevant ingredients as e.g., food proteins, flavour extracts, selected bioactive substances and hydrocolloids to be produced in a cascading approach from the same inlet biomass.

On a global level, the expansion potential of marine aquaculture in terms of availability of biologically suitable areas is enormous. Based on an analysis of Gentry and colleagues (2017), less than 0.015% of global ocean area would be required to produce seaweed at the scale of the total volume of global fisheries. It is concluded that availability of suitable areas will not be the limiting factor for the development of marine aquaculture, but that economic, social and governance aspects in each region will shape future development.

Finally, related to the potential of algae from a climate perspective, an intense discussion has been going on recently regarding the effect of macroalgae farming on global carbon flows. Sinking the biomass to the deep ocean has been suggested as a greenhouse gas mitigation solution (e.g. Froehlich et al. 2019). However, two very recent reviews (Troell et al. 2022; Hasselström & Thomas 2022), both conclude that there is not yet sufficient knowledge about the carbon exchange between seaweeds, the surrounding water, and the atmosphere on the short and long term – i.e., it is not yet possible to reliable account for carbon uptake in a quantitative way. To little is known about how the global carbon cycle is affected by harvesting both wild and farmed macroalgae through ecosystem interactions and on what time perspectives. They also conclude that how seaweeds are used is central to the argument as the main way macroalgae can mitigate emissions is by replacing more impactful products, e.g., as food or food ingredients. In the midst of this ongoing debate, rather strong policy statements are however being made, pushing seaweed farming forward as a climate solution (Teasdale et al. 2022). However, when assessing the environmental impacts of macroalgae production, careful attention needs to be paid to if and how carbon sequestration/uptake should or should not affect greenhouse gas emission accounting. With current understanding, it is not advisable to account for carbon sequestration in greenhouse gas emission accounting of macroalgae production systems; the main emission reduction potential rather comes from replacing other emission-intensive materials with macroalgae.

5 Conclusions

What can we say about environmental performance of macroalgae? This report has found that:

- For brown macroalgae, harmonized LCA results of farming in different countries indicate large variability in performance. The data covers different production sites for farming of an important brown macroalgae from a global and European perspective, i.e., having fair representativeness, but productions are on pilot scale and may thus have improved their performance over time. Furthermore, European production is dominated by wild harvest which has not been evaluated by LCAs.
- For green macroalgae production, there are indications of production having higher carbon footprint compared to brown algae, but the information reported on here is based on a master thesis with prospective data. Representativeness is also poor, since *Ulva* spp. is not the dominating species in terms of global production volume of green macroalgae. Nearly 100% of current *Ulva* spp. production is farmed in South Africa and mainly used for abalone feed.
- For red macroalgae, no LCAs was found for the species of importance to Europe. However, Chilean and Indian farming of *Gracilaria* could indicatively be reported on, of which India is a minor global producer but Chile is the 3rd largest

producer. Still, in terms of representativeness, Chile only contributes with 0.6% of global production due to China's dominance (95%).

- The environmental performance of microalgae is highly variable and influenced by location, since light conditions and heating requirements are important drivers. The studies included here were not at commercial scale, thus having poor representativeness.

Based on the limited data at hand, more LCAs with primary data from commercial producers are needed for improved understanding of drivers behind impacts in different production systems, and how they may vary between locations, cultivation season, species and designs. In particular, input data for wild-harvest production is fully lacking. For farmed macroalgae, a future development option of the simplified tool would be to be able to cover more species and production systems, which requires improved LCA understanding of the systems. Furthermore, for the current tool, it may be beneficial to include use of alternative fuels (e.g., electricity, ethanol, hydrogen, methane) as an input option during maintenance operations.

In terms of nutritional value, this report has found that:

- Data available in food composition databases present significant gaps for nutrients, heavy metals and influencing parameters (e.g., cultivation, processing) of algae.
- The nutritional quality of unprocessed algae, as well as iodine and heavy metals content, differs between species examined. This has important implications for dietary advice.
- Amongst the species investigated, green macroalgae *Ulva* spp. shows the highest nutrient density per portion whilst *Laminaria digitata* the lowest value respectively. A portion of *Ulva* spp. provides a high nutritional contribution of magnesium, iron and vitamin B12.
- Brown macroalgae generally show lower mineral and vitamin contribution, relative to green macroalgae, although differences between species and individual nutrients exist. To provide examples, the red macroalgae *Porphyra* spp. exhibits the highest contents of vitamin B12, whereas the green macroalgae *Ulva intestinalis* has the highest content of magnesium and selenium.
- Of the two microalgae assessed, *Chlorella* contains high amounts of iron and vitamin B12, whilst *Spirulina* mainly contributes as a source of copper on a portion basis.
- Even with a limited portion that is suggested for a safe consumption (5 g dried biomass), macroalgae may in general represent a good source of minerals, such as magnesium, selenium and iron, and to some extent vitamin B12, but contribute minimally to protein and fiber intake, whilst still posing concern for iodine and heavy metal content if consumed unprocessed.

Overall, there are gaps to be filled in terms of nutritional characterization and data availability in FCDs, where data on vitamins is especially lacking. Furthermore, there is need for more and robust bioavailability assessments in order to understand the potential benefits and risks of algae in the human diet.

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Appendix 1 Nutritional composition of algae

Food Composition Databases

FCD were searched for the nutrient content for the following species and subspecies:

- Macroalgae: *Alaria esculenta*, *Chondrus crispus*, *Codium tomentosum*, *Gracilaria gracilis*, *Laminaria digitata*, *Palmaria palmata*, *Porphyra umbilicalis*, *Saccharina latissima*, *Ulva fenestrata*, *Ulva intestinalis*, *Ulva rigida*.
- Microalgae: *Chlorella spp.*, *Dunaliella salina*, *Haematococcus pluvialis*, *Isochrysis galbana*, *Nannochloropsis*, *Phaeodactylum tricornutum*, *Porphyridium spp.*, *Scenedesmus spp.*, *Schizochytrium*, *Spirulina spp.*, *Tetraselmis spp.*

Several FCD provided nutrient content for a subset of the searched species. For several screened species, no nutrition composition was found (Table 1S).

Table 1S: Algae species for which nutrition composition data was available and corresponding FCD.

Species/subspecies of interest		CIQUAL	Harvard	Nutrition File	CEVA	Korea	Marine Res. Inst.
Taxonomic name	**Common English name**						
Alaria esculenta	Atlantic wakame/winged kelp	X			X		X
Chondrus crispus	Carragheen moss	X	X		X		
Gracilaria gracilis	Gracilaria seaweeds		X				
Gracilaria spp.	Gracilaria				X		
Laminaria digitata	Oarweed	X	X		X		X
Palmaria palmata	Dulse	X	X		X		X
Porphyra umbilicalis	Pink laver		X				
Porphyra spp.	Laver				X		
Saccharina latissima	Sugar kelp	X			X		
Ulva fenestrata	Sea lettuce		X			X	X
Ulva intestinalis	Gut weed		X				X
Ulva rigida	Sea lettuce		X				
Ulva spp.	Sea lettuce	X			X		
Chlorella spp.	Chlorella				X	X	
Spirulina spp.	Spirulina			X			

Included databases:

[1]Anses. 2020. Ciqual French food composition table. https://ciqual.anses.fr/

[2]Golden, C.D., Koehn, J.Z., Vaitla, B., DeSisto, C., Kelahan, H., Manning, K., Fiorella, K.J., Kjellevold, M., Thilsted, S.H., 2021b. Aquatic Food Composition Database. Harvard Dataverse, V2. https://doi.org/https://doi.org/10.7910/DVN/KI0NYM

[3]Health Canada, Canadian Nutrient File, version 2015. [WWW Document]. URL https://www.canada.ca/en/health-canada/services/food-nutrition/healthy-eating/nutrient-data.html (accessed November 2021)

[4]CEVA, 2021. Nutritional data sheets on algae [WWW Document]. CEVA. URL https://www.ceva-algues.com/en/document/nutritional-data-sheets-on-algae/ (accessed November 2021).

[5]National Institute of Agricultural Sciences, Korean Standard Food Composition Table, 9th revision, [WWW Document]. URL http://koreanfood.rda.go.kr/eng/fctFoodSrchEng/engMain

[6]Norwegian Institute of Marine Research, Norway. URL https://sjomatdata.hi.no (accessed November 2021 and January 2023).

Nutrient composition per 100 g

Nutrient content obtained from FCD in Table 1S was compiled and is presented in Tables 2S a-d per 100 g DW. Data was included if a clear definition of the species was provided in the FCD. Only nutrient content related to "dried or freeze-dried" algae was retrieved. Further assumptions were made as specified below:

- Protein content was included if obtained from nitrogen with the use of a known multiplication factor. If the method for the determination of protein was not provided, the corresponding value was excluded.
- Total dietary fibre was calculated as the sum of soluble and insoluble fibre when only these contents were available.
- Vitamin A was included if provided as retinol activity equivalents (RAE). When the content of beta-carotene was present in the FCD, the corresponding RAE were obtained as µg beta-carotene/12.
- If not specified, the content of niacin was assumed to be expressed as Niacin Equivalents (NE).

Table 2Sa. Nutrient content per 100 g DW of the green macroalgae *Ulva spp.*.

		Ulva lactuca						*Ulva intestinalis*						*Ulva rigida*						*Ulva spp.*				
		Mean	Median	n	Min	Max	Sources	Mean	Median	n	Min	Max	Sources	Mean	Median	n	Min	Max	Sources	Mean	n	Min	Max	Sources
Energy	kcal	179.7	179.7	2	129.0	230.3	2, 5													203				4
Protein	g	14.8	14.4	10	7.1	20.1	2, 5	15.5	16.4	3	10.6	19.5	2	18.6	18.6	1	18.6	18.6	2	15.7	163	1.1	28.8	4
Lipid, total	g	0.5	0.5	1	0.5	0.0	5													1.9	92	0.0	9.2	4
Fatty acid, saturated	g	0.0	0.0	3	0.0	0.0	2													0.5	15	0.1	1.9	4
Dietary fiber, soluble	g	20.5	20.5	1	20.5	20.5	2	32.45	32.45	2	25.3	39.6	2											
Dietary fiber, insoluble	g	34.5	34.5	1	34.5	34.5	2	22.6	24.3	1	22.6	22.6	2											
Dietary fiber, total	g																			33.5	23	10.5	53.3	4
Carbohydrate, total	g	40.1	40.1	1	40.1	40.1	2																	
Sodium	mg	1603.4	807.5	6	351.7	5730.0	2	1205.3	1205.3	2	698.7	1711.9	2							2250	72	88	8151	4
Potassium	mg	1452.7	558.5	6	100.0	5040.0	2	2631.3	2631.3	2	2456.8	2805.8	2							1960	64	150	5461	4
Calcium	mg	1456.5	1207.5	6	490.0	3216.0	2, 5							898.6	223	5	156	2630	2	1134	79	44	5109	4
Magnesium	mg	5602.5	3125.0	4	2660.0	13500.0	2	3066.8	3066.8	2	2018.3	4115.2	2	1328	1038.5	6	613	2617	2	2663	56	150	6606	4
Phosphorus	mg	122.00	122.00	2	50.00	50.00	2, 5	219	219	1	219	219	2	160	160	1	160	160	2	173	54	26	458	4
Iron	mg	34.27	27.70	11	8.70	119.70	2, 5							50.12	43.07	6	29.39	97.30	2	70.9	101	0	510	4
Zinc	mg	1.36	1.08	10	0.65	3.19	2	4.59	1.50	3	1.40	10.87	2	2.45	1.38	13	0.80	11.67	2	3.4	47	0.1	16.6	4
Copper	mg	0.68	0.50	9	0.20	1.83	2	0.83	0.70	3	0.60	1.20	2	0.92	0.63	7	0.10	3.40	2	1.3	38	0	5.5	4
Manganese	mg	1.97	1.45	6	0.86	4.80	2	5.76	5.76	1	5.76	5.76	2	2.37	1.03	7	0.55	6.30	2	5.6	27	0.1	42.2	4
Iodine	µg	5350.0	5350.0	2	4400.0	6300.0	2	7900.0	7900.0	1	7900.0	7900.0	2							8500	45	700	26400	4
Selenium	µg	242.50	16.20	7	0.00	1600.00	2	654.00	654.00	1	654.00	654.00	2	329.17	360.00	3	230.00	397.50	2	12.2	21	0.9	70.5	4
Chromium	µg	0.12	0.10	7	0.05	0.30	2	1.57	1.57	1	1.57	1.57	2	0.57	0.02	5	0.00	2.29	2	404.5	24	0	2420	4
Molybdenum	µg							0.03	0.03	1	0.03	0.03	2	0.18	0.18	2	0.04	0.33	2	176.5	6	3	280	4
RAE	µg																			180	2	160	190	4
Vitamin D	µg																			1.29	6	0.62	1.9	4
alpha-Tocopherol	mg	29.10	29.10	1	29.10	29.10	2	0.83	0.83	1	0.83	0.83	2							2.46	14	0.3	10.38	4
Vitamin K	µg	0.22	0.22	1	0.22	0.22	2													18	4	8	29	4
Thiamin	mg	0.04	0.04	1	0.04	0.04	5													0.1	16	0	0.4	4
Riboflavin	mg	0.39	0.39	1	0.39	0.39	5													0.2	11	0	0.5	4
Niacin	mg	11.40	11.40	1	11.40	11.40	5													5.8	10	1.1	10.6	4
Vitamin B-6	mg																			0.3	4	0	0.2	4
Vitamin B-12	µg																			13.6	7	1.1	74.6	4
Folate	µg																			102.3	9	8.8	279.7	4
Pantothenic acid	mg																			0.15	1	0.15	0.15	4
Ascorbic acid	mg																			68.9	35	0	264.2	4

Table 2Sb. Nutrient content per 100 g DW of brown macroalgae species.

		Saccharina latissima						*Alaria esculenta*						*Laminaria digitata*					
		Mean	Median	n	Min	Max	Sources	Mean	Median	n	Min	Max	Sources	Mean	Median	n	Min	Max	Sources
Energy	kcal	204.5	204.5	2	204.0	205.0	1, 4	194.5	194.5	2	187	202	1, 4	214	214	2	211	217	1, 4
Protein	g	10.1	10.1	2	9.9	10.3	1, 4 (60)	12.3	12.3	2	12.2	12.3	1, 4 (28)	9.2	9.2	2	8.9	9.5	1, 4 (40)
Lipid, total	g	1.2	1.2	2	1.1	1.4	1, 4 (16)	1.515	1.515	2	1.5	1.53	1, 4 (9)	1.065	1.065	2	1	1.13	1, 4 (12)
Fatty acid, saturated	g	0.2	0.2	2	0.2	0.3	1, 4 (10)	0.31	0.31	1	0.31	0.31	1, 4 (3)	0.15	0.15	2	0.15	0.15	1, 4 (1)
Dietary fiber, total	g	29.8	29.8	2	29.3	30.2	1, 4 (10)	45.1	42.9	3	42.9	49.5	1, 4 (4), 6	35.25	35.25	2	33.2	37.3	1, 4 (8)
Carbohydrate, total	g	23.4	23.4	2	23.1	23.6	1, 4	10.96	13.3	3	6.28	13.3	1, 4, 6	24.25	24.25	2	22.9	25.6	1, 4
Sodium	mg	3465.5	3465.5	2	3301.0	3630.0	1, 4 (17)	2786	2786	2	1920	3652	1, 4 (7)	3180.5	3180.5	2	3150	3211	1, 4 (20)
Potassium	mg	6081.0	6081.0	2	5912.0	6250.0	1, 4 (16)	3245	3245	2	2180	4310	1, 4 (7)	4614.5	4614.5	2	4590	4639	1, 4 (20)
Calcium	mg	819.5	819.5	2	801.0	838.0	1, 4 (23)	502.0	502.0	2	233.0	771.0	1, 4 (8)	882.5	882.5	2	847	918	1, 4 (32)
Magnesium	mg	791.50	791.50	2	749.00	834.00	1, 4 (26)	931	931	1	931	931	1, 4 (4)	785	785	2	770	800	1, 4 (20)
Phosphorus	mg	191.00	191.00	2	174.00	208.00	1, 4 (20)	221.5	221.5	2	220	223	1, 4 (14)	688.50	688.50	2	520.00	857.00	1, 4 (6)
Iron	mg	23.60	23.60	2	23.10	24.10	1, 4 (34)	53.05	53.05	2	44.60	61.50	1, 4 (7)	11.02	9.90	7	5.60	17.60	1, 2, 4 (39)
Zinc	mg	2.30	2.30	2	2.30	2.30	1, 4 (27)	3.34	2.78	4	2.09	5.70	1, 4 (6), 6	2.34	1.20	7	0.82	5.00	1, 2, 4 (41)
Copper	mg	0.24	0.24	1	0.24	0.24	1, 4 (27)	0.27	0.27	2	0.24	0.30	1, 4 (5)	0.25	0.19	7	0.07	0.50	1, 2, 4 (40)
Manganese	mg	1.0	1.0	2	1.0	1.0	1, 4 (32)	2.0	2.0	2	1.9	2.1	1, 4 (7)	0.42	0.40	7	0.33	0.52	1, 2, 4 (36)
Iodine	µg	375500	375500	2	341000	410000	1, 4 (64)	77700	60600	4	34600	155000	1, 4 (25), 6	565714	486000	8	334000	######	1, 2, 4 (53), 6
Selenium	µg	292.90	292.90	2	64.80	521.00	1, 4 (10)	18.70	18.70	2	12.00	25.40	4 (5), 6	5.85	5.85	2	5.60	6.10	6
Chromium	µg							209.90	209.90	1	209.90	209.90	4 (7)	21.38	0.03	7	0.02	112.20	2, 4 (21), 6
Molybdenum	µg	54.10	54.10	1	54.10	54.10	1, 4 (10)	47.7	47.7	1	47.7	47.7	4 (4)	4.60	0.003	6	0.003	23	2, 4 (9)
RAE	µg	50.00	50.00	1	50.00	50.00	1, 4 (1)	800		4	83	1333	4*	0.02		1	0.02	0.02	4
Vitamin D	µg	1.29	1.29	2	1.28	1.30	1, 4 (1)							2.29	2.29	2	2.27	2.30	1, 4 (1)
alpha-Tocopherol	mg	2.44	2.44	2	0.57	4.30	1, 4 (9)	3.1		3	1.8	5.3	4	0.31	0.31	2	0.30	0.32	1, 4 (3)
Vitamin K	µg							498.1		2	220.4	871	4						
Thiamin	mg	0.27	0.27	2	0.10	0.44	1, 4 (8)	0.01		2	0.01	0.02	4						
Riboflavin	mg	0.22	0.22	2	0.10	0.34	1, 4 (8)	0.08		2	0.08	0.09	4						
Niacin	mg	2.1	2.1	1	2.1	2.1	1, 4 (7)	4.0		2	2.8	6.0	4	3.02	3.02	2	3.00	3.03	1, 4 (6)
Vitamin B-6	mg	0.2	0.2	1	0.2	0.2	1, 4 (6)	0.1		2	0.1	0.2	4						
Vitamin B-12	µg	2.6	2.6	1	2.6	2.6	1, 4 (7)	2		2	1.3	3.0	4						
Folate	µg	164	164	1	164	164	1, 4 (7)	429.2		2	379.1	561.5	4						
Ascorbic acid	mg	21.5	21.5	2	11.4	31.6	1, 4 (19)	65		2	0.0	142.5	4	5.56	5.56	2	0.02	11.10	1, 4 (3)

*calculated from β-carotene

Table 2Sc. Nutrient content per 100 g DW of red macroalgae species.

		Chondrus crispus						*Palmaria palmata*						*Gracilaria gracilis*						*Gracilaria spp.*				
		Mean	Median	n	Min	Max	Sources	Mean	Median	n	Min	Max	Sources	Mean	Median	n	Min	Max	Sources	Mean	n	Min	Max	Sources
Energy	kcal	224.5	224.5	2	215.0	234.0	1, 4	224	224	2	221	227	1, 4							232				4
Protein	g	16.7	16.7	2	16.6	16.7	1, 4 (28)	17.1	17.1	2	16.9	17.2	1, 4 (86)	10.9	10.9	1	10.9	10.9	2	17.8	28	0.6	40.5	4
Lipid, total	g	2.1	2.1	2	1.9	2.3	1, 4 (10)	1.315	1.315	2	1.3	1.33	1, 4 (45)	0.19	0.19	1	0.19	0.19	2	1.8	42	0	21	4
Fatty acid, saturated	g	0.1	0.1	2	0.1	0.2	1, 4 (5)	0.26	0.26	1	0.26	0.26	1, 4 (6)	0.12	0.12	1	0.12	0.12		0.14	2	0.06	0.23	4
Dietary fiber, total	g	33.1	33.1	2	30.6	35.5	1, 4 (3)	28.6	28.6	2	28	29.2	1, 4 (13)							25.4	5	9.4	35.8	4
Carbohydrate, total	g	18.3	18.3	2	15.0	21.5	1, 4	21.7	21.7	2	20.8	22.6	1, 4	63.1	63.1	1	63.1	63.1	2	23.4				4
Sodium	mg	1787.1	2070.0	3	2.2	3289.0	1, 2, 4 (5)	1255.0	1660.0	3	232.0	1873.0	1, 2, 4 (32)	290.9	290.9	1	290.9	290.9	2	2856.0	8	932.0	5023.0	4
Potassium	mg	1292.5	1570.0	3	3.4	2304.0	1, 2, 4 (5)	4863.7	6810.0	3	762.0	7019.0	1, 2, 4 (34)	1380.4	1380.4	1	1380.4	1380.4	2	4977.0	9	243.0	10243.0	4
Calcium	mg	586.5	586.5	2	362.0	811.0	1, 4 (5)	562.0	562.0	2	547.0	577.0	1, 4 (28)							770.0	9	180.0	2259.0	4
Magnesium	mg	780.9	1112.0	3	0.8	1230.0	1, 2, 4 (17)	176.0	241.0	3	23.0	264.0	1, 2, 4 (37)							420.0	17	171.0	1143.0	4
Phosphorus	mg	454.5	454.5	2	159.0	750.0	1, 4 (3)	265.0	265.0	2	250.0	280.0	1, 4 (20)							221.0	4	117.0	362.0	4
Iron	mg	17.2	18.1	3	12.4	21.1	1, 2, 4 (17)	26.5	29.3	3	15.5	34.8	1, 2, 4 (35)	15.20	15.20	1	15.20	15.20	2	36.0	20	3.3	189.9	4
Zinc	mg	6.75	7.00	3	5.39	7.86	1, 2, 4 (16)	3.57	4.00	3	2.55	4.17	1, 2, 4 (25)	9	9	1	9	9	2	4	18	2	12	4
Copper	mg	0.70	0.45	3	0.40	1.25	1, 2, 4 (14)	1.22	1.10	3	1.00	1.55	1, 2, 4 (27)	0.39	0.39	1	0.39	0.39	2	0.60	17	0.00	3.10	4
Manganese	mg	2.96	3.30	3	1.47	4.10	1, 2, 4 (4)	7.90	9.00	3	2.60	12.10	1, 2, 4 (20)	16.33	16.33	1	16.33	16.33	2	32.00	4	3.70	101.70	4
Iodine	µg	35675	32950	4	29600	47200	1, 2, 4 (9)	21450	22850	4	7600	32500	1, 2, 4 (29), 6							355.8	18	8.50	763.6	4
Selenium	µg	8.18	8.18	2	3.35	13.00	1, 4 (3)	11.12	9.4	3	8.95	15	1, 4 (9), 6	505.7	505.7	1	505.7	505.7	2	192.7	3	6.30	558.1	4
Chromium	µg	124.90	124.90	1	124.90	124.90	1, 4 (13)	399.7		20		3400	4	0.28	0.28	1	0.28	0.28	2	279.5	9	80.0	620.0	4
Molybdenum	µg							41.6		4	6	83	4	0.05	0.05	1	0.05	0.0472	2	144.0	1	144.0	144.0	4
RAE	µg	14.19	14.19	2	0.13	28.25	1, 4 (1)	1112.5	1112.5	2	916.7	1308.3	1*, 4 (1)							0.16	1	0.16	0.16	4
Vitamin D	µg	0.00	0.00	1	0.00	0.00	1	0.92	0.92	2	0.90	0.93	1, 4 (1)											
alpha-Tocopherol	mg	3.50	3.50	1	3.50	3.50	1, 4 (2)	3.78	3.78	2	3.45	4.10	1, 4 (10)							0.9	2	0.4	1.3	4
Vitamin K	µg	153	153	1	153	153	1, 4 (2)	443.50	443.50	2	420.00	467.00	1, 4 (8)											
Thiamin	mg	0.04	0.04	2	0	0.071	1, 4 (1)	0.29	0.29	2	0.20	0.37	1, 4 (10)											
Riboflavin	mg	1.17	1.17	2	0.1	2.23	1, 4 (1)	0.39	0.39	2	0.30	0.48	1, 4 (10)											
Niacin	mg	2.42	2.42	2	2	2.84	1, 4 (1)	3.96	3.96	2	3.60	4.31	1, 4 (14)											
Vitamin B-6	mg	0.37	0.37	2	0.33	0.4	1, 4 (1)	0.11	0.11	2	0.01	0.20	1, 4 (6)											
Vitamin B-12	µg	6.62	6.62	2	1	12.24	2, 4 (2)	7.21	7.21	2	4.60	9.81	1, 4 (7)											
Folate	µg	141.9	141.9	1	141.9	141.9	1, 4 (2)	193.65	193.65	2	92.00	295.30	1, 4 (9)											
Pantothenic acid	mg	0.84	0.84	1	0.84	0.84	1	0.40	0.40	2	0.40	0.40	1, 4 (1)											
Ascorbic acid	mg	43.25	53.84	3	14.30	61.60	1, 2, 4 (3)	65.25	65.25	2	46.90	83.60	1, 4 (13)							27.2	7	2.3	56.6	4

*calculated from β-carotene

Cont.

		Porphyra umbilicalis						*Porphyra spp*				
		Mean	Median	n	Min	Max	Sources	Mean	n	Min	Max	Sources
Energy	kcal							257				4
Protein	g							30.2	109	9.8	44.3	4
Lipid, total	g							1.8	43	0.2	8.3	4
Fatty acid, saturated	g							0.5	3	0.3	0.8	4
Dietary fiber, total	g							36.8	20	24.6	55.4	4
Carbohydrate, total	g							11.7				4
Sodium	mg							1900	39	112	6120	4
Potassium	mg							1762	40	168	3265.0	4
Calcium	mg							440.0	45	3	4478.0	4
Magnesium	mg							480.0	49	5	1903.0	4
Phosphorus	mg							491.0	21	139	801.0	4
Iron	mg	40.93	33.00	3	11.40	78.40	2	36.4	64	5.8	278.0	4
Zinc	mg	2.15	2.24	3	1.94	2.28	2	4	46	0.2	10	4
Copper	mg	0.43	0.42	3	0.39	0.49	2	1.00	42	0.3	3.50	4
Manganese	mg	1.82	1.91	3	1.33	2.23	2	3.90	32	1.5	9.30	4
Iodine	µg	5600.0	5600.0	1	5600.0	5600.0	2	5600.0	23	500	21500.0	4
Selenium	µg	5.50	2.00	3	1.10	13.40	2	41.1	19	4	186.6	4
Chromium	µg	0.09	0.08	3	0.05	0.15	2	150.7	28	8	460.0	4
Molybdenum	µg							27	15	0	103	4
RAE	µg							0.06	2	0	0.11	4
Vitamin D	µg							0.6	1	0.6	0.6	4
alpha-Tocopherol	mg							3.1	5	0.9	8.7	4
Vitamin K	µg							225.0	1	225.0	225.0	4
Thiamin	mg							0.5	10	0	1.20	4
Riboflavin	mg							1.8	10	0.2	3.60	4
Niacin	mg							6.3	8	2.4	10.30	4
Vitamin B-6	mg							0.5	2	0.1	1.00	4
Vitamin B-12	µg							27.2	4	3.92	54.70	4
Folate	µg							31.8	4	0	61.90	4
Pantothenic acid	mg							0.25	1	0.25	0.25	4
Ascorbic acid	mg							63.9	21	1.4	244.4	4

Table 2Sd. Nutrient content per 100 g DW of two species of microalgae.

		Chlorella spp.					*Spirulina spp.*	
		Mean	n	Min	Max	Sources		Sources
Energy	kcal	297.5	2	174	421	4, 5	290	3
Protein	g	46.9	2	45.3	48.5	4 (25), 5	57	3
Lipid, total	g	9.3	2	7.2	11.4	4 (17), 5	7.7	3
Fatty acid, saturated	g	1.8	5	1.57	2.1	4		
Dietary fiber, total	g						3.6	3
Carbohydrate, total	g	28.3	2	25.7	30.9	4, 5	23.9	3
Sodium	mg	115.0	7	17	481.0	4	1048.0	3
Potassium	mg	1038.0	8	824.0	1396.0	4	1363.0	3
Calcium	mg	244.5	2	117.0	372.0	4 (8), 5	120.0	3
Magnesium	mg	358.0	7	269.0	438.0	4	195.0	3
Phosphorus	mg	1521.5	2	1507.0	1536.0	4 (5), 5	118.0	3
Iron	mg	125.4	2	73.4	177.4	4 (8), 5	28.5	3
Zinc	mg	2.0	6	1.0	2.7	4	2.00	3
Copper	mg	1.20	6	0.30	3.10	4	6.10	3
Manganese	mg	8.20	6	3.90	17.30	4	1.90	3
Selenium	µg	36.1	2	4.80	67.4	4	7.20	3
Chromium	µg	305.7	4	240.7	375.5	4		
Molybdenum	µg	50.10	2	23.10	77.0	4		
RAE	µg	21.90	3	8.00	46.2	4	29.00	3
Vitamin D	µg						0.00	3
alpha-Tocopherol	mg	22	2	22	22	4	5.00	3
Vitamin K	µg	1348	1	1348	1348	4	25.50	3
Thiamin	mg	1.10	8	0.10	1.70	4	2.38	3
Riboflavin	mg	4.00	8	2.90	5.50	4	3.67	3
Niacin	mg	24.20	1	15.80	31.20	4	12.82	3
Niacin equivalents	mg						28.30	3
Vitamin B-6	mg	1.60	8	0.10	2.30	4	0.36	3
Vitamin B-12	µg	25.80	1	25.80	25.80	4	0.00	3
Folate	µg	1540.5	3	1155.4	2310.7	4	94	3
Pantothenic acid	mg	5.87	6	1.78	21.28	4		
Ascorbic acid	mg	75.6	5	13.1	279.2	4		

Appendix 2 Nutrient density score NRF11.3

Table 3S. Nutrients included in the nutrient density score NRF11:3 and their reference values, based on Nordic Nutrition Recommendation (NCM, 2014)*.

Qualitative nutrients	9.3	DRI
Protein (g)	✓	87 [a)]
Fibre (g)	✓	30
Vitamin A (retinol equivalents)	✓	800
Vitamin C (mg)	✓	75
Vitamin E (mg)	✓	9
Calcium (mg)	✓	800
Iron (mg)	✓	12 [b)]
Potassium (g)	✓	3.3
Magnesium (mg)	✓	315
Vitamin D (µg)	✓	10
Folate (µg)	✓	350 [b)]
Thiamine (mg)		1.1
Riboflavin (mg)		1.3
Omega-3 fatty acids (g)		2.7 [c)]
Niacin (niacin equivalents)		15
Vitamin B6 (mg)		1.2
Vitamin B12 (µg)		2
Phosphorus (mg)		600
Iodine (µg)		150
Selenium (µg)		50
Zinc (mg)		7
Disqualitative nutrients		**MRI**
Saturated fat (g)	✓	27 [d)]
Sodium (g)	✓	2.4
Added sugar (g)	✓	

NRF: Nutrient Rich Foods index; DRI: Dietary Reference Intake; MRI: Maximum Recommended Intake; E%: energy percent; RE: retinol equivalents; NE: niacin equivalents.

* Average values for men and women aged 31–60 years with an average level of physical activity (9900 kJ/day). [a)] Based on 15 E%; [b)] Highest value for fertile women used to calculate average for women and men; [c)] Based on 1 E%; [d)] Based on 10 E%

Appendix 3 Substances of toxicological concern

Table 4S. Threshold values for heavy metals and iodine.

Potentially toxic substances	Limit	Threshold value	Reference
Inorganic arsenic (iAs)	BMDL01*	0.3 µg /kg BW and day	EFSA (2009[b])
Cadmium (Cd)	TWI	2.5 µg /kg BW and week	EFSA (2009[a])
Lead (Pb)	BMDL01#	0.5 µg /kg BW and day	EFSA (2010)
Inorganic mercury (iHg)	TWI	4 µg /kg BW and week	EFSA (2012)
Methylmercury (MeHg)	TWI	1.3 µg /kg BW and week	EFSA (2012)
Iodine (I)	UL	600 µg per day	NCM (2014)

BMDL: benchmark dose lower confidence limits; BW: body weight; TWI: tolerable weekly intake; UL: upper limit.
* This threshold represents a 1% additional risk for lung cancer in adults. A higher threshold of 8 µg arsenic per kg BW and day is defined based on 1% additional risk for cancer in lung, skin and bladder, and skin changes.
# This threshold represents a 1% additional risk for developmental neurotoxicity in small children. Higher thresholds for adults are defined based on risk for kidney disease and blood pressure (15 ug/day).

Table 5S. Content of heavy metals for dried unprocessed green, brown and red macroalgae, expressed per 100 g DW or 100 g FW (for *Chondrus crispus* and *Porphyra umbilicalis*)*.

Green Seaweed										
	***Ulva lactuca* (wild-harvest)**									
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**					
As (µg/100g DW)	610.0	610.0	1	610	610					
Cd (µg/100g DW)	20.0	20.0	1	20	20					
Hg (µg/100g DW)	n.d.	n.d.		n.d.	n.d.					
iAs (µg/100g DW)	42.0	42.0	1	42	42					
Pb (µg/100g DW)	110.0	110.0	1	110	110					
Brown Seaweed										
	***Saccharina latissima* (wild-harvest)**					***Saccharina latissima* (cultivated)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
As (µg/100g DW)	5150.0	4950.0	6	3800	7100	12900.0	12000.0	5	8700	19000
Cd (µg/100g DW)	91.0	41.0	6	15	300	61.0	51.0	4	33	110
Hg (µg/100g DW)	n.d.	u.l.d.		u.l.d.	0.9	n.d.	u.l.d.		u.l.d.	u.l.d.
iAs (µg/100g DW)	24.6	20.5	6	5.9	63	5.7	5.4	4	3.4	8.7
Pb (µg/100g DW)	n.d.	u.l.d.		u.l.d.	47	n.d.	u.l.d.		u.l.d.	25
	***Alaria esculenta* (wild-harvest)**					***Alaria esculenta* (cultivated)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
As (µg/100g DW)	4800.0	4800.0	1	4800	4800	4100.0	4100.0	2.0	3800	4400
Cd (µg/100g DW)	110.0	110.00	1	110	110	130.0	130.00	2.0	100	160
Hg (µg/100g DW)	n.d.	u.l.d		u.l.d	u.l.d	n.d.	u.l.d		u.l.d	u.l.d
iAs (µg/100g DW)	76.1	24.0	5	2	260	6.4	6.4	2.0	3	9.3
Pb (µg/100g DW)	n.d.	u.l.d.		u.l.d.	u.l.d.	n.d.	u.l.d.		u.l.d.	u.l.d.
Red Seaweed										
	***Laminaria digitata* (wild-harvest)**					***Palmaria palmata* (wild-harvest)**				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
As (µg/100g DW)	8790.0	7800.0	7	5500	16000	1080.0	1200.0	3	730	1300
Cd (µg/100g DW)	49.0	49.0	7	20	86	36.0	34.00	3	14	61
Hg (µg/100g DW)	3.3	1.5	7	u.l.d.	6.7	n.d.	u.l.d.		u.l.d.	0.4
iAs (µg/100g DW)	1470.0	1080.0	8	8	3500	23.2	23.200	2	4	43
Pb (µg/100g DW)	9.3	3.3	7	u.l.d.	4.4	n.d.	u.l.d.		u.l.d.	27
	Chondrus crispus (wild-harvest)					***Porphyra umbilicalis (wild-harvest)***				
	MEAN	**MEDIAN**	**number**	**MIN**	**MAX**	**MEAN**	**MEDIAN**	**number**	**MIN**	**MAX**
As (µg/100g FW)	440.0	440.0	1	440	440	502.0	470.0	4	200	870
Cd (µg/100g FW)	4.2	4.2	1	4	4.2	6.9	6.9	4	5	9.3
Hg (µg/100g FW)	0.2	0.2	1	0	0.2	n.d.	u.l.d.		u.l.d.	u.l.d.
iAs (µg/100g FW)	7.4	7.4	1	7	7.4	0.4	0.4	3	0	0.41
Pb (µg/100g FW)	12.0	12.0	1	12	12	n.d.	4.4		u.l.d.	8.6

*All data obtained from the Institute of Marine Research, Norway, accessed January 2023.

Table 6S. Content of iodine for dried unprocessed green, brown and red macroalgae, expressed as µg per 5g DW and as % UL per 5g DW.

	µg/5g DW						%UL/5g DW				
	MEAN	MEDIAN	number	MIN	MAX	Sources	MEAN	MEDIAN	number	MIN	MAX
Alaria esculenta	3885.0	3030.0	4	1730.0	7750	1,4,6	647.5	505.0	4	288.3	1292
Chondrus crispus	1783.8	1647.5	4	1480.0	2360	1, 2 (2), 4 (9)	297.3	274.6	4	246.7	393
Gracilaria spp.	17790.0	n.a.	18	425.0	38180	4	2965.0	0.0	18	70.8	6363
Laminaria digitata	28285.7	24300.0	8	16700.0	51015.0	1, 2 (4), 4 (53), 6	4714.3	4050.0	8	2783.3	8502.5
Palmaria palmata	1072.5	1142.5	4	380.0	1625.0	1, 2, 4 (29), 6	178.8	190.4	4	63.3	270.8
Porphyra spp.	280.0	n.a.	23	25.0	1075.0	4	46.7	0.0	23	4.2	179.2
Porphyra umbilicalis	280.0	280.0	1	280.0	280.0	2	46.7	46.7	1	46.7	46.7
Saccharina latissima	21607.1	20500.0	7	12500.0	30650.0	1, 2 (3), 4 (64), 6 (2)	3601.2	3416.7	7	2083.3	5108.3
U. intestinalis	395.0	395.0	1	395.0	395.0	2	65.8	65.8	1	65.8	65.8
Ulva lactuca	267.5	267.5	2	220.0	315.0	2, 6	44.6	44.6	2	36.7	52.5
Ulva spp.	425.0	n.a.	45	35.0	1320	4	70.8	n.d.	45	5.8	220

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