



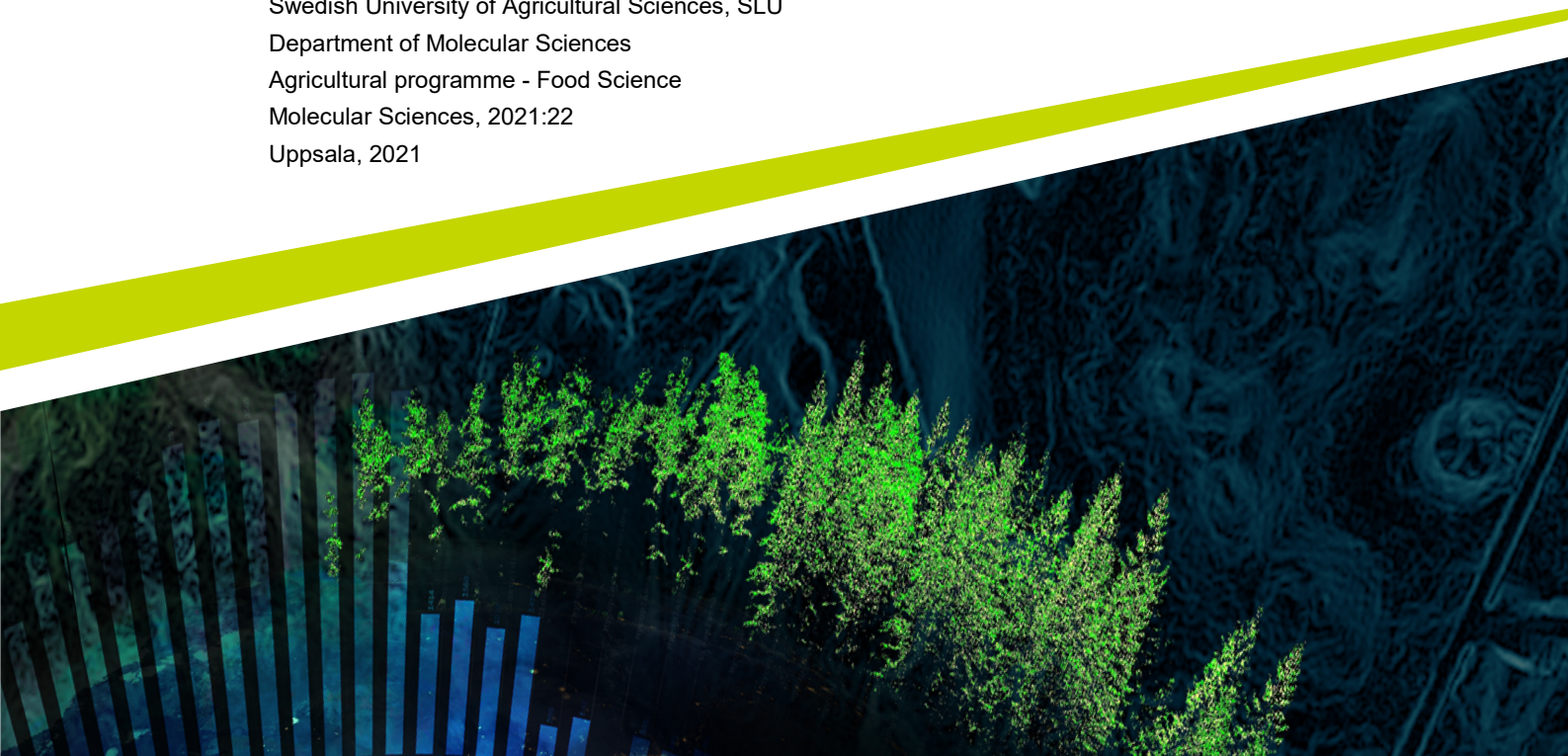
Seaweed as a future food

– a nutritional perspective with focus on seaweed aquaculture in Scandinavia

Sjögräs/tång som en framtida mat – ett näringsämnesmässigt perspektiv med fokus på sjögräsvattenbruk i Skandinavien

Robin Lukic

Individual project in Food Science • (15 hp)
Swedish University of Agricultural Sciences, SLU
Department of Molecular Sciences
Agricultural programme - Food Science
Molecular Sciences, 2021:22
Uppsala, 2021



Seaweed as a future food – a nutritional perspective with focus on seaweed aquaculture in Scandinavia

Sjögräs/tång som en framtida mat - ur ett näringsämnesmässigt perspektiv med fokus på sjögräsvattenbruk i Skandinavien

Robin Lukic

Supervisor: Sabine Samples, Swedish University of Agricultural Sciences,
Department of Molecular Sciences
Examiner: Jana Pickova, Swedish University of Agricultural Sciences, Department
of Molecular Sciences

Credits: (15 hp)
Level: (G2E)
Course title: Independent project in Food Science
Course code: EX0876
Programme/education: Agricultural Programme - Food Science
Course coordinating dept: Department of Molecular Sciences
Title of series: Molecular Sciences
Part number: 2021:22
Place of publication: Uppsala
Year of publication: 2021

Keywords: Edible seaweed, sugar kelp, Scandinavian seaweed aquaculture, nutrients, toxic metals, food processing, food safety regulation, IMTA

Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences

Publishing and archiving

Approved students' theses at SLU are published electronically. As a student, you have the copyright to your own work and need to approve the electronic publishing. If you check the box for **YES**, the full text (pdf file) and metadata will be visible and searchable online. If you check the box for **NO**, only the metadata and the abstract will be visible and searchable online. Nevertheless, when the document is uploaded it will still be archived as a digital file.

If you are more than one author you all need to agree on a decision. Read about SLU's publishing agreement here: <https://www.slu.se/en/subweb/library/publish-and-analyse/register-and-publish/agreement-for-publishing/>.

☒ YES, I/we hereby give permission to publish the present thesis in accordance with the SLU agreement regarding the transfer of the right to publish a work.

☐ NO, I/we do not give permission to publish the present work. The work will still be archived and its metadata and abstract will be visible and searchable.

Abstract

Edible seaweeds or macroalgae have been a staple food for many centuries in parts of East Asia and have recently started to gain attraction in Europe. Seaweed aquaculture is a well-established food production system in many East Asian countries but has only recently started in Scandinavia. In recent years there has been a growing seaweed cultivation industry in Norway and Denmark but less so in Sweden. The most cultivated species of seaweed in Scandinavia is sugar kelp, *Saccharina latissima*, followed by winged kelp, *Alaria esculenta*, both species are from the division of brown macroalgae.

Previous studies on edible seaweeds and seaweed aquaculture have shown beneficial health effects from consumption and positive ecological impact on marine flora and fauna near cultivation sites. Though, many of these aspects are not yet fully understood due to absence of proper assessment in science literature. There is much to be done about legislation, permits, and food safety regulations regarding seaweed production both on European Union and member state level.

Many edible seaweed species have high levels of sought-after nutrients and minerals. Some nutrients have less biological value due to their indigestibility, but there are promising food processing methods and techniques emerging. There is a concern regarding certain trace elements and toxic compounds that can be found in variable amounts in different seaweed species.

Seaweed is an extracting organism that can assimilate certain nutrients that cause eutrophication. Therefore, seaweed aquaculture could be a way of decreasing anthropogenic emissions from other aquaculture systems by merging them together, thereby creating integrated multitrophic aquaculture (IMTA).

There is an already established food market for seaweed-based products in parts of Europe that could be supplied with regional cultivated seaweed. Seaweed could soon become a staple food in Scandinavia.

Sammanfattning

Ätbara sjögräs eller makroalger har länge varit en basföda i delar av Ostasien under många århundraden och har nyligen börjat få ökande popularitet i Europa. Sjögräsvattenbruk är ett väl etablerat livsmedelsproduktionssystem i många Ostasiatiska länder men har bara nyligen börjat i Skandinavien. De senaste åren har det funnits en växande sjögräsodlingsindustri i Norge och Danmark men den är fortsatt liten i Sverige. Den mest odlade arten av sjögräs i Skandinavien är sockertång, *Saccharina latissima*, följt av havskål, *Alaria esculenta*, båda arter är från divisionen brunalger.

Tidigare studier av ätbara sjögräs och sjögräsvattenbruk har visat fördelaktiga hälsoeffekter från konsumering och positiv ekologisk inverkan på marina djur och växter nära odlingsplatser. Många av dessa effekter är inte helt kartlagda i forskningslitteraturen. Det finns mycket kvar att göra med lagstiftning, licens, och livsmedelssäkerhet kring sjögräsproduktion både på Europeisk Unions- och medlemsstatsnivå.

Många ätbara sjögräsarter har höga nivåer av eftertraktade näringsämnen och mineraler. Vissa näringsämnen har mindre biologiskt värde på grund av sin osmältbarhet i digestionssystemet, men det finns lovande livsmedelsmetod- och processtekniker på framfart. Det finns en oro angående vissa spårämnen och giftiga föreningar som kan finnas i varierande mängder hos olika sjögräsarter.

Sjögräs är en extraherande organism som kan assimilera vissa näringsämnen som orsakar övergödning. Därför kan sjögräsvattenbruk bli ett sätt att minska de mänskliga utsläppen från andra vattenbruk-produktionssystem genom sammanslagning med dom och därigenom skapa integrerad multitrofiskt vattenbruk (IMTA).

Det finns redan en etablerad livsmedelsmarknad för sjögräsbaserade produkter i delar av Europa som skulle kunna förses med regionalt närodlat sjögräs. Sjögräs kan snart bli en basföda i Skandinavien.

Keywords: Edible seaweed, sugar kelp, Scandinavian seaweed aquaculture, nutrients, toxic metals, food processing, food safety regulation, IMTA

Table of contents

1. Introduction.....	9
2. Method	11
3. Results and discussion	12
3.1. Biology, physiology, and ecology	12
3.2. Seaweed aquaculture	13
3.2.1. Sweden	14
3.2.2. Norway	14
3.2.3. Denmark	15
3.2.4. International context	16
3.3. Nutrients and toxic compounds in macroalgae	17
3.3.1. Carbohydrates	18
3.3.2. Proteins	19
3.3.3. Fatty acids.....	22
3.3.4. Minerals and vitamins	24
3.3.5. Toxic elements and compounds	27
3.3.6. Processing and reduction of unwanted mineral and toxic metal levels	29
4. Conclusion	31
References	32

1. Introduction

With words like sustainability and climate change arising more and more in people's consciousness, it will be important to renew our current food production systems and find new solutions to mitigate the anthropogenic imprint on our planet. By the year 2050 it is estimated that 9.7 billion people will need to be fed (UN 2019), and that the demand on food production will increase from 50 to 100% in total (FAO 2009; UN 2009; Forster 2015). One foodstuff that could be a part of our main diet is edible seaweed or kelp, as some seaweed species are called. Seaweeds are currently a staple food for millions of people in East Asia but has only recently started to gain attraction in other parts of the world, like Europe, as a nutritious and beneficial food (Radulovich 2015; Lozano Muñoz & Díaz 2020).

The introduction and popularization of certain Asian foods in Europe, i.e., Japanese food such as sushi during the last decades of the 20th century, has introduced edible seaweeds to “western” pallets in a broad degree. Japanese foodstuff such as ‘nori’, a red algae species from the genus *Porphyra* that has been dried and shaped into paper-thin sheets and is the main ingredient in ‘maki’ (sushi rolls) and ‘onigiri’ (rice balls wrapped in seaweed) (Rioux 2015; FAO 2020).

Seaweed is an aquatic plant like organisms that can also be called macroalgae, who use light and nutrients in sea water to achieve photosynthesis. The species of edible seaweeds can be categorized under three main divisions: green (*Chlorophyta*), red (*Rhodophyta*), and brown (*Phaeophyceae*) macroalgae (Lozano Muñoz & Díaz 2020). The three most cultivated seaweed species in the world in 2018 were *Saccharina japonica* (Japanese kelp, ‘kombu’, brown algae), *Euchema* and *Gracilaria* (red algae) species. Major producers of cultivated seaweed can be found in East Asia, mainly China, Indonesia, the Koreas, Japan, and the Philippines (FAO 2020).

Though many seaweed species are edible, few are a matter of interest regarding commercial viability and nutritional properties as a food for human consumption. In the European Union (EU), the main edible seaweed species that are cultivated are that of brown algae and is largely based on Chinese seaweed aquaculture methods. The most cultivated species in Europe is sugar kelp, *Saccharina latissima* (formerly *Laminaria latissima*), which falls under the division of brown algae. The species grow naturally in the arctic, subarctic, and temporal regions of the world and can be found in the coastal waters surrounding the Scandinavian peninsula.

This is one of the most promising brown algae species for cultivation on small or large scale in North Europe as they can grow relatively fast between autumn and spring and produce large yields (Campbell *et al.* 2019).

The purpose of this literature study is to investigate food related properties of edible seaweeds: nutrients, food safety, and quality parameters, with a focus on seaweed aquaculture in Scandinavia. This encompasses the western coastal waters surrounding Norway, Denmark, and Sweden. There are hundreds of edible seaweed species from all macroalgae divisions, but the focal edible seaweed species in this study will be sugar kelp, *S. latissima*.

2. Method

This literature study was accomplished by compiling and assessing the current research situation based on scientific literature on the subject. The study was conducted by using web-based search engines, i.e., Scopus, Web of Science, Science direct, and local university library (SLU Library) digital resources: scientific articles, publications, and reports. Example of keywords used in search engines: “Macroalgae”, “Edible seaweed”, “Sugar kelp”, “Nutrients”, “Food safety”, “Seaweed biology”, “Seaweed aquaculture”, “Seaweed cultivation”, “Seaweed cultivation in Scandinavia”.

There was also personal correspondence conducted with various agency/authority work staff through e-mail.

3. Results and discussion

3.1. Biology, physiology, and ecology

Seaweeds are autotrophic organisms that live submerged in shallow to deeper waters. They use sunlight, inorganic nutrients, and dissolved gases from their surrounding water habitat to conduct photosynthesis and synthesize organic matter. The depth at which seaweeds can grow is determined by the availability of light and appropriate substrata they can attach to. Seaweeds do not have roots or stems; they form large multicellular structures called 'thallus' who constitute the main "body" or biomass of the organism. Instead, they have some organ like features, i.e., a holdfast. In sugar kelp, the holdfast is located on the base of the long blade like structure. The holdfast able sugar kelp to attach on submerged rocks or cliffs. Sugar kelp and other seaweeds can assimilate nutrients or compounds from their surroundings throughout their whole biomass (Redmond *et al.* 2013; Radulovich 2015).

Some species of edible brown algae, like kelp, grow naturally in the northern hemisphere. The factors that suit these species are cold waters with high salinity. Their growth period usually lasts between autumn and spring. The lifecycle of kelps and other seaweeds consists of two life stages: one diploid and one haploid. The long, large and visible sugar kelp individual is called a sporophyte and constitutes the diploid life stage. The mature sporophyte releases microscopic meiospores that mark the beginning of the haploid life stage. The meiospore cells undergo germination and develop into either male or female gametophytes that later form sperm and egg cells. After fertilization of an female gametophyte egg by an algae sperm, a zygote develops and subsequently grows into a sporophyte individual, thereby completing the lifecycle (Redmond *et al.* 2013).

The water zones in which the kelp inhabits are termed as littoral and benthic zones. The littoral zone is the body of water close to the coastline and the benthic zone is the closest water level above the seabed. *S. latissima* can grow close to the water surface down to 50 meters in depth depending on certain conditions, i.e., light radiation. The species grows optimally in water temperatures between 10 to 15 °C. The main "blade" structure, thallus, of sugar kelp is shaped in a way that makes it

able to stay elongated and withstand dynamic water forces (Redmond *et al.* 2013). In one study on environmental impact by sugar kelp aquaculture, where a cultivation site was compared to several wild kelp locations, the seaweed aquaculture site caused minimal impact on the benthic environment. It had beneficial effects as well, i.e., drawing local fauna and other seaweed species to the cultivation site (Visch *et al.* 2020). There are also risks associated with seaweed cultivation, where a possibility of genetic interaction by other unwanted seaweed species can occur. These unwanted species can eventually become invasive. There is an famous example of such an occurrence from France in the 1980's where an imported seaweed species spread uncontrollably (Campbell *et al.* 2019). Though, many of these ecological interactions between seaweed aquaculture sites and a local marine environment are poorly understood (Visch *et al.* 2020), it may be of value to conduct further research on environmental impact from kelp to procure vital data for future seaweed aquaculture expansion in Scandinavia.

3.2. Seaweed aquaculture

Most cultivated seaweed is germinated on land in special facilities, sometimes called “hatcheries”, where the young sporophytes are grown and seeded onto an appropriate substratum: ropes, nets, or lines in water containers. This process can be controlled by adapting the conditions in the “hatcheries”, i.e., irradiance and salinity, to fit the biological needs of the species at hand. It takes about a month for young sporophytes to grow to a sufficient size. The young sporophytes attach to the seeding substrate and are submerged in sea water at their cultivation site where the remaining growth cycle can occur. Important factors that determine growth and quality of seaweeds are water salinity, irradiance, season, and interactions from potential parasites, such as the epiphyte bryozoa (Redmond *et al.* 2013; Stévant *et al.* 2017c; Campbell *et al.* 2019).

Sugar kelp is seeded in autumn and harvested in spring to gain maximal growth and avoid interactions with conditions associated with warmer temperatures during the summer months, such as damage from other marine organisms or other types of fouling (Campbell *et al.* 2019).

3.2.1. Sweden

There is no official statistic on Swedish seaweed aquaculture production according to The Swedish Board of Agriculture (Jordbruksverket)¹ and the Central Bureau of Statistics (Statistiska Centralbyrån)². The few seaweed aquaculture operators that do exist are included in the overall statistics for all domestic aquaculture producers, which is dominated by fish aquaculture. There is no specific data available on total biomass production of seaweed because of company confidentiality.

The few operators that are present have not been operating for long. The first commercial seaweed aquaculture productions were only started in the mid 2010's, stating the difficulty of gaining permits and licensing to produce seaweed in Sweden today (Lindstedt 2019). One such operator is Nordic SeaFarm, a Swedish company based in Gothenburg. They are currently one of the few commercial edible seaweed producers in Sweden and have their cultivation site in Tanumshede near Strömstad on the west coast close to Norway. The company cultivates sugar kelp and sells it in blanched or dried form (Nordic-SeaFarm 2021).

There is a large potential for further expansion of Swedish seaweed aquaculture. The suitable area for new possible cultivations on the Swedish west coast was estimated to around 500 km² in one study using GIS-MCDA (Geographical Information System and Multi-Criteria Decision Analysis) method. The main concerns regarding these projected areas revolved around the usage of coastal area by other operators, i.e., marine or tourism industries, and potential hazards such as oil spills from shipping traffic. These and other parameters must be considered if plans for new seaweed aquaculture locations are made, as every site will have its own unique conditions (Thomas *et al.* 2019).

In a Swedish context, seaweed can still be seen as a novel food or exotic ingredient. Most Swedes probably encounter their first edible seaweed abroad or through various East Asian cuisines in domestic restaurants. With the ongoing “green food” trend and concerns on climate change that have arisen in the last decade, seaweed could become an attractive novel food source in Sweden soon.

3.2.2. Norway

In 2020, there were 93 seaweed aquaculture sites, divided among 25 seaweed aquaculture operators in Norway according to the Directorate of Fisheries (Fiskeridirektoratet). The domestic output of harvested cultivated macroalgae was 185 metric tons in 2020, of which 96 tons were *S. latissima*, and 88 tons were winged kelp, *Alaria esculenta* (Fiskeridirektoratet 2021).

¹ Johann Penner, Fisheries Coordinator, the Business Development Unit, The Swedish Board of Agriculture, e-mail correspondence, 2021-04-22.

² Martina Kielen, Statistician, Unit for Agricultural and Energy Statistics
Department of Regions and the Environment, Central Bureau of Statistics, e-mail correspondence, 2021-04-23.

Since Norway is the largest producer of seafood in Europe (FAO 2020), the seaweed aquaculture has a large potential of being merged into integrated multi-trophic aquaculture (IMTA); a type of aquaculture that includes different types of marine organisms, i.e., fish, shellfish, or crustaceans, who are cultivated together with seaweed. In IMTA, nutrient leakage from other aquaculture, i.e., salmon farming, is assimilated with the seaweed biomass to minimize eutrophication. Most of the seaweed cultivation sites in Norway are monoculture, with one or more seaweed species being cultivated, and few are IMTA (Stévant *et al.* 2017c).

There are challenges regarding the expansion of Norwegian seaweed aquaculture because it occupies a large coastal area that can interfere with other industries. Therefore, it has been suggested that the cultivation sites are moved further out towards the sea. This creates new obstacles in terms of infrastructure, weather, and water dynamics if the aquaculture area is further away from the mainland. Another difficulty is the geography of Norway, the current cultivation sites are spread across a large distance which makes processing and transport an issue regarding the fast microbial degradation of harvested seaweed (Stévant *et al.* 2017c; Campbell *et al.* 2019).

3.2.3. Denmark

In 2019, the aquaculture production of *S. latissima* (Danish: Sukkertang) was less than 0.5 metric tons according to the Danish Fisheries Agency (Fiskeristyrelsen). There were no statistics on other cultivated seaweed species except for sugar kelp. The amount of total harvested sugar kelp is confidential due to their being three or less operators in Denmark in 2019. In 2018, the production of sugar kelp was 12 metric tons. Furthermore, there is no listed seaweed production before 2017 in the official statistics (Fiskeristyrelsen 2020a) (Fiskeristyrelsen 2020b) (Fiskeristyrelsen 2019).

Common seaweed-based food products in Denmark are seaweed pesto, snacks, salad, and spice mixes. Denmark has a well-established industry on carbohydrate extraction from algal sources, i.e., carrageenan and agar, aimed at the food production market with several world leading companies that have facilities and factories locally and abroad (FAO 2018).

Currently, there are some organizations that are working on promoting edible seaweed to the broad public, i.e., Danish Seaweed Organization (<http://www.danish-seaweed.org/>), as well as informing and helping individuals or groups to start cultivating seaweed. One such organization is Ocean Harvest (Danish: Havshøst), who is a member organization that encourages local inhabitants to conduct regenerative aquaculture in their communities through cultivating blue mussels, oysters, and seaweed together. The organization has built a few floating cultivation platforms that can be placed in close vicinity to harbors or other infrastructure. The cultivation itself is conducted by placing ropes or lines

beneath and around the edges of the platform, where the organisms can latch onto the structure. Currently, there are only a few of these locations and platforms (Havhøst 2021). This could be seen as a kind of “lightweight” IMTA that deals with smaller local cultivation sites which are primarily focused on private individuals and communities.

3.2.4. International context

The world production of cultivated aquatic algae was estimated to 32.4 million metric tons (live weight) in 2018, of which 11.4 million tons were *S. japonica* (Japanese kelp). The three largest producing countries in 2018 were China (18.5 million tons), Indonesia (9.3 million tons), and South Korea (1.7 million tons) (FAO 2020).

In context, no EU member states were included in the listed countries of aquatic algae producers. The only European country that is listed is the Russian Federation (4500 tons). The unlisted producers were cataloged under “Other producers”, with a total production output of 21000 tons (FAO 2020), which we can assume includes some European countries. This issue also became clear with certain official statistics from FAO, as they were unspecific regarding production volume by individual EU member states or other European non-EU countries. Comparatively, European operators are behind other international operators in production quantity and volume. The huge scale of seaweed aquaculture in top producing East Asian countries can be linked to tradition, cuisine, and long-time experience of cultivating macroalgae. For now, it remains a small industry in Europe.

Though, seaweed has been gaining attention as an organic foodstuff in some parts of Europe (FAO 2018), and could be seen as an alternative or complementary food source when compared to carbon emissions from conventional plant production. Seaweed aquaculture does not require the use of fertilizers or pesticides and is relatively easy to grow under the right circumstances (Visch *et al.* 2020). This could make it a more attractive foodstuff in Europe, if seen from a climate conscious point of view.

The current challenges of large scale seaweed aquafarming in North Europe revolve around economic viability (Stévant *et al.* 2017c), technical hurdles (Campbell *et al.* 2019), and potential environmental issues (Visch *et al.* 2020). Regarding seaweed-based food products, it would be cumbersome to compete with other non-European producers as they already have a well-established foothold on the European food market, not to mention a large part of the whole world market on seaweed.

A reoccurring problem throughout this study was finding credible information or data regarding edible seaweed in Scandinavia, to estimate the general attitude towards seaweed aquaculture and status of seaweed as a foodstuff. It could be that seaweed is not yet a well-established standalone food item on the Scandinavian

food market, but more popular within certain demographics. Furthermore, there was limited data on seaweed cultivation in some of the Nordic countries.

3.3. Nutrients and toxic compounds in macroalgae

In many East and Southeast Asian countries, seaweed has been and still is an important source of essential nutrients in their basic diet. Before introduction to “western” eating habits, i.e., consumption of dairy, bread, and processed meat products, seaweed could cover some of the required nutrient intake (Dawczynski *et al.* 2007; Martins *et al.* 2013). Edible seaweeds have an immense variation in nutrients depending on cultivation site, season, and species. Like many other aquatic and terrestrial organisms, they contain proteins, lipids, minerals, vitamins, and carbohydrates (Holdt & Kraan 2011).

There are many suggested health benefits of the nutrients that can be found in seaweeds. Most previous studies on edible seaweed have dealt with *in vitro* and *in vivo* animal subjects. Therefore, the potential health benefits of individual compounds or nutrients are hard to definitively claim as proven in humans. Yet, certain subgroups of nutrients, i.e., polyunsaturated fatty acids (PUFA) and dietary fibers, have unique qualities associated to them. They are beneficial for human health if consumed on a regular basis in a moderate amount (Holdt & Kraan 2011; Brown *et al.* 2014; Tanna & Mishra 2019).

In one study on the correlation between diet and disease in a population in Japan, it was shown that when most of the population ate seaweed daily, generally less of them experience chronic diseases that are associated with “western” style diets and habits. It was also noted that after some individuals adopted a “western” lifestyle by either moving or changing their diet, the number of total cases of chronic diseases increased (Brown *et al.* 2014).

Eating seaweed may not yet be seen as a given part of an ordinary diet in Scandinavia. This potential negative attitude towards seaweed as a food could dishearten new consumers to adopt it. Therefore, it is important to make a strong case on why more people in Scandinavia and Europe should eat seaweeds.

3.3.1. Carbohydrates

Macroalgae contain the polysaccharides cellulose, agar, alginate, and carrageenan, and smaller mono and-disaccharides, i.e., mannitol and sucrose. These carbohydrates can be found in variable percentages depending on seaweed species (Holdt & Kraan 2011; Rioux 2015). Agar, alginate, and carrageenan are important thickening and gelling agents in foodstuff, i.e., ice creams and desserts, and can be applied to other fields such as medicine (Tanna & Mishra 2019). Several species of seaweed are solely harvested to extract polysaccharides such as carrageenan, i.e., the red algae Irish moss (*Chondrus crispus*) (FAO 2018).

Brown seaweeds have in general a larger percentage of alginate compared to other seaweed divisions and contain specific polysaccharides such as fucoidans and laminaran in a higher degree than other macroalgae. Alginate is bound in salt form as alginic acid and can make up to 47 % in DW in some brown seaweeds and has hydrocolloid properties. Fucoidans are composed of L-fucose and sulphate groups and can range from 10 to 20% in DW in several brown algae. Laminaran is only found in higher levels in the cell walls of *Laminaria* and *Saccharina* species. Many of these carbohydrates are indigestible by humans and are considered dietary fibers. They can also interfere with the absorption of other nutrients, i.e., proteins. (Tanna & Mishra 2019). This is due to the chemical composition of the cell walls in seaweeds, but particularly in brown algae cell walls; which have a higher presence of these individual polysaccharides (Holdt & Kraan 2011; Harrysson *et al.* 2018).

According to the Nordic Nutrition Recommendations (NNR) 2012, carbohydrates are classified as: glycemic carbohydrates, dietary fibers, and added sugars, i.e., sucrose. The recommended intake for glycemic carbohydrates is 130g/daily for adults and children over the age of 1, dietary fiber is 25-32 g/daily, and added sugars 10% of total energy intake (E%). Though, 52-53 E% is recommended as total carbohydrate intake (Nordic-Council-of-Ministers 2014). Many of the carbohydrates found in macroalgae are considered dietary fibers and can therefore contribute to the total intake of fibers, whereas seaweeds are not a replacement for other carbohydrate rich foodstuff, i.e., rice, wheat, or potatoes.

Seaweed polysaccharides have displayed several health beneficial properties such as anticoagulatory, antiviral, antioxidant, and antitumor activities (Tanna & Mishra 2019). The unique chemical properties of exclusive seaweed polysaccharides are and can be applied in many different types of food utilizations. One could be serving as a substituent ingredient in foodstuff that needs to be replaced to meet individual preferences, such as: ethical, religious, or allergenic requirements. An example is vegan caviar, or kelp caviar, which is an imitation product of fish roe eggs made from sugar kelp or kelp extracts. Another example is replacing gelatin, which is derived from animal origin, for agar in candy or other confectionaries, like that of Japanese sweets and desserts (Rioux 2015).

3.3.2. Proteins

The overall protein content is usually lower in brown algae compared to red and green algae. Red algae species have the highest recorded protein concentrations (Holdt & Kraan 2011). The protein in sugar kelp is relatively high compared to other brown seaweeds, 15% in DW (Bruhn *et al.* 2019), some sources cite 7.5 % in DW (Stévant *et al.* 2018), and others up to 21% in DW (Holdt & Kraan 2011). Some kelp species contain all essential amino acids (EAA): cysteine (Cys), leucine (Leu), isoleucine (Ile), phenylalanine (Phe), methionine (Met), valine (Val), threonine (Thr), and tryptophan (Trp). Not all EAA can be found in sugar kelp, but those who are present constitute approximately 40% of the total amino acid (AA) content per gram kelp protein. Depending on protein extracting method different values of peptides or free AA will appear (Table 1) (Harrysson *et al.* 2018).

The recommended intake of protein is approximately 1g / kg body weight / day for adults, 10 to 20 E%, and slightly higher for the elderly, 15 to 20 E% (Nordic-Council-of-Ministers 2014). A protein score is defined by how much of the total protein content consist of EAA, in mg AA/g protein, according to WTO/FAO/UNU (WHO 2007). The protein score of *S. latissima* can range from 17 to 100% (Stévant *et al.* 2018). This gives further credibility for seaweed as a good addition to our general diet in Europe and other parts of the world, specially were protein or EAA deficiency can be found.

Table 1. List of 20 chosen AA including EAA and non-EAA in some *Laminaria* and *Saccharina* sp. Content of some AA values may vary depending on analytic method.

Amino acids	<i>Laminaria</i> and <i>Saccharina</i> sp. (% of total nitrogen (N), DW)	Unit (% AA of total protein N)	<i>S. latissima</i> (Lowry method, dried)	Unit (% AA total protein N)	<i>S. latissima</i> (Osnes and Mohr method, dried at 25 °C)	Unit (mg AA/g protein)
EAA						
Leucine (Leu)	8.70-9.20	%	7.60	%	89.30	mg/g
Phenylalanine (Phe)	5.70-6.20	%	5.00	%	63.70	mg/g
Lysine (Lys)	6.50-7.30	%	n.d.		59.20	mg/g
Valine (Val)	6.90	%	5.60	%	53.10	mg/g
Isoleucine (Ile)	5.50-5.80	%	5.10	%	49.80	mg/g
Threonine (Thr)	4.60-5.00	%	3.80	%	40.90	mg/g
Methionine (Met)	1.90-2.20	%	1.30	%	24.10	mg/g
Histidine (His)	2.30-2.40	%	2.40	%	21.60	mg/g
Tryptophan (Trp)	n.d.		n.d.		n.d.	mg/g
Non-EAA						
Glycine (Gly)	6.50-7.00	%	10.00	%	50.80	mg/g
Alanine (Ala)	8.00-9.00	%	7.70	%	117.90	mg/g
Serine (Ser)	3.80-3.90	%	3.80	%	58.90	mg/g
Cysteine (Cys)	0.60-1.30	%	3.30	%	29.70	mg/g
Proline (Pro)	4.80-4.90	%	4.90	%	46.80	mg/g
Tyrosine (Tyr)	4.00-4.30	%	3.70	%	27.20	mg/g

Aspartic acid (Asp)	9.60-9.80	%	8.30	%	90.00 ^b	mg/g
Glutamic acid (Glu)	11.00-13.00	%	7.50	%	120.00 ^a	mg/g
Asparagine (Asn)	n.d.		1.50	%	90.00 ^b	mg/g
Glutamine (Gln)	n.d.		n.d.		120.00 ^a	mg/g
Arginine (Arg)	5.00-5.90	%	4.70	%	51.80	mg/g

^acombined value for Glu + Gln, ^bcombined values for Asp + Asn. No data = n.d. Table references: (Holdt & Kraan 2011; Harrysson *et al.* 2018; Stévant *et al.* 2018)

One hurdle that decreases our ability to digest proteins from kelp is the high content of polysaccharides found in brown algae cell walls. For other seaweed divisions, the situation is different. Multiple *in vitro* studies have shown that species of red and green macroalgae contain proteins that can be digested by common digestive enzymes (Holdt & Kraan 2011; Stévant *et al.* 2018; Tanna & Mishra 2019). A possible solution to increase protein digestibility from brown algae is to investigate and develop different protein extraction and food processing methods. These can be applied during postharvest processing to increase the protein bioavailability in the end food product (Pangestuti 2015; Shekar 2015; Harrysson *et al.* 2018).

Examples of food processing methods are fermentation, milling, cooking, maceration or drying. In two separate reports on food processing of *S. latissima*, one on fermentation and one on the effects of drying at different temperatures, it was shown that none of the methods reduced the protein content in the kelp. Though, the biological value of protein from sugar kelp was not analyzed (Stévant *et al.* 2018; Bruhn *et al.* 2019). In another study on protein extracts from *S. latissima* and two other red and green algae species, the amount of extracted protein depended upon which extraction method was used. The most successful extraction method was the pH-shift method, it gave the highest protein concentration for all three species, including *S. latissima*: total AA 40% in DW in the pH-shift method extract compared to crude sample 10% in DW (Harrysson *et al.* 2018).

Depending on which type of seaweed-based product that is needed, some of the previously mentioned methods can be applied. Though, the focus in the earlier cited studies has been on total protein content after processing or extraction, and not on biological value of protein. It could be argued that the protein extraction described in Harrysson *et al.* 2018 would possibly increase the total amount of available AA that can be absorbed in the human gastrointestinal system.

3.3.3. Fatty acids

The consumption of omega (ω)-3 and ω -6 PUFA on a regularly basis has long been attested crucial for human health and wellbeing since two of these ω -3 and ω -6 PUFA are essential fatty acids (EFA): C18:2 ω -6 (linoleic acid) and C18:3 ω -3 (α -linolenic acid). To ensure these fatty acids (FA) are a part of a general diet within the population, it is encouraged to consume fatty fish or other nutrient supplements that contain ω -3 and ω -6 PUFA. A low ω -6/ ω -3 ratio, preferably 5:1, is considered the optimal healthy fat ratio intake of these PUFA. In “western” countries, there is an excess of ω -6 PUFA consumption in the general diet, between 15:1 and 20:1, that is linked to various chronic diseases (Martins *et al.* 2013; Nordic-Council-of-Ministers 2014; Hamid 2015).

Lipid content in most brown algae and the other seaweed divisions is commonly low (Stévant *et al.* 2018). In one study on cultivated Swedish macroalgae of red,

green, and brown algae, the percentage of total lipid content in crude samples were between 2.0 – 2.5% in DW (Harrysson *et al.* 2018), while some previous values for multiple seaweeds are up to 4.5% in DW (Holdt & Kraan 2011). The lipid profile of *S. latissima* consisted mainly of four FA; C16:0 (Palmitic acid), C18:4 ω -3 (Stearidonic acid), C20:4 ω -6 (Arachidonic acid), and C20:5 ω -3 (Eicosapentaenoic acid, EPA) (Table 2). They made up approximately 68% of the total lipid profile of crude sugar kelp sample in DW (Harrysson *et al.* 2018). Previous lipid values from earlier works on lipid profiles of brown seaweed genus *Laminaria* and *Saccharina* mostly concur with the profile presented in the Swedish study, with the slight exceptions on single monounsaturated fatty acids (MUFA) and PUFA (Dawczynski *et al.* 2007; Holdt & Kraan 2011; Harrysson *et al.* 2018).

Table 2. List of chosen FA in *Laminaria* and *Saccharina* species compared with FA profile of *S. latissimi* (% of total fat).

EFA/FA	Common name	<i>Laminaria</i> and <i>Saccharina</i> species	<i>S. latissima</i>
C18:2 ω -6	Linoleic acid	n.d.	5.80
C18:3 ω -3	α -linolenic acid	0.80-3.90	8.50
C16:0	Palmitic acid	23.00-36.00	16.80
C18:4 ω -3	Stearidonic acid	1.00-3.90	18.40
C20:4 ω -6	Arachidonic acid	11.00-12.00	14.10
C20:5 ω -3	EPA	5.40-16.00	18.90

No data = n.d. Table references: (Holdt & Kraan 2011; Harrysson *et al.* 2018)

For adults and children above 2 years of age, the total fat intake should be between 25 – 45% of total E%, of this 2/3 should be of cis-MUFA and cis-PUFA (Nordic-Council-of-Ministers 2014). Sugar kelp has a lower ω -6/ ω -3 ratio, around 1:2, and more ω -3 compared to ω -6 PUFA. Though, the lipid profile on ω -3 and ω -6 PUFA was incomplete with some FA listed as not detectable (Harrysson *et al.* 2018). Overall, other brown algae species have a low ω -6/ ω -3 ratio, but this varies greatly (Dawczynski *et al.* 2007).

Since a very small percentage of sugar kelp in DW consists of fat, it cannot be a sole replacement for E% of fat. It should rather be a complimentary intake, because the proportion of PUFA is greater than MUFA in total fat amount, and it could be a valuable source of both MUFA and PUFA even if the total amount of fat in one serving is small. Direct consumption of edible seaweed could be a complementary

source ω -3 and ω -6 PUFA if they can be processed in a way that makes them digestible.

As discussed earlier in 3.3.2. about protein extraction methods, the pH shift method that amounted to the highest protein concentration among the studied seaweed species, also concentrated the total FA content; from 2 to 3% in DW in *S. latissima* (Harrysson *et al.* 2018). This suggests that some extraction methods could be applied in postharvest food processing of sugar kelp or other seaweeds to make more of the FA content available for nutrient uptake.

3.3.4. Minerals and vitamins

Seaweeds contain a larger amount of minerals compared to most of the terrestrial plants. In brown algae these macro minerals, trace elements and toxic metals are as follow; Macro minerals: sodium (Na), potassium (K), nitrogen (N), phosphor (P), iodine (I), calcium (Ca), and magnesium (Mg). Trace elements: chromium (Cr), manganese (Mn), iron (Fe), copper (Cu), selenium (Se), and zinc (Zn). Toxic metals: cadmium (Cd), mercury (Hg), lead (Pb), arsenic (As), inorganic arsenic (iAs), and aluminum (Al) (Stévant *et al.* 2017a; Bruhn *et al.* 2019; Lozano Muñoz & Díaz 2020).

The amount of these minerals and trace elements varies depending on species and where they are cultivated or harvested in the wild, seen in (Table 3). Many of these elements are vital for normal physiological function in humans and other animals, but some are of concern regarding recommended daily intake (RDI) set by authorities. Particularly the iodine levels in brown algae species, which can be several times above RDI (Table 3) (Stévant *et al.* 2017a; Stévant *et al.* 2017b; Bruhn *et al.* 2019; Lozano Muñoz & Díaz 2020)

The recommended daily intake of iodine is 150 μ g/d for adults above 18 years of age, both female and male (Table 3) (Nordic-Council-of-Ministers 2014). Several other species of brown algae have concentrations of iodine per g in DW well above RDI and this is consistent throughout the brown algae division with some exceptions (Lozano Muñoz & Díaz 2020). The main obstacle regarding edible seaweed in general is the vast richness of minerals in percentage in DW and the potential presence of toxic metals. This limits the amount of kelp to be eaten in one serving. Because of this, the consumers need to be informed and it may require the industry to process postharvest seaweed, i.e., soaking, boiling, or blanching, to reduce these minerals in the food product.

Table 3. List of chosen macro-minerals and trace elements from two brown seaweed species along with RDI and AR (Average Requirement per day) from NNR 2012 and EFSA.

Mineral/Trace element	<i>S. japonica</i> (DW)	<i>S. latissima</i> (DW)	Unit	RDI adult female	AR adult female	RDI adult male	AR adult male
Iodine (I)	2.00	0.23 - 2.60	mg/g	150 µg	n.d.	150 µg	n.d.
Sodium (Na)	12.70	23.00	mg/g	2.0-2.4 g	2.00 g	2.00-2.40 g	2.00 g
Potassium (K)	96.30	69.90	mg/g	3.10-3.50 g	n.d.	3.5 g	n.d.
Zinc (Zn)	18.00	58.30	µg/g	7.50 ^a -12.70 ^b g	6.20 ^a -10.20 ^b mg	9.40 ^a -16.30 ^b mg	7.50 ^a -12.70 ^b mg
Iron (Fe)	80.00	40 -293	µg/g	11.00 ^c -16.00 ^d mg	6.00 ^c -7.00 ^d mg	9.00-11.00 mg	6.00-7.00 mg

^a phytate intake lower limit, ^b phytate intake upper limit, ^c postmenopausal women, ^d premenopausal women. No data = n.d. Table references: (Nordic-Council-of-Ministers 2014; Bruhn et al. 2019; Lozano Muñoz & Díaz 2020; EFSA 2021)

Vitamins are found in many forms and are defined according to their bioactive capability in human physiology. The vitamin groups who are generally found in all seaweeds are A, B, C, and E. Brown seaweeds have higher concentrations of vitamin E than other seaweed classes. The color and hue in seaweeds, algae, and plants is due to several groups of pigments, and one of these pigments are carotenoids; a broad class of molecules who are tetraterpenes and functions as light sensitive component in photosynthesis. There are many variants of carotenoids that have vitamin function. In brown seaweeds β -carotene, which has pro-vitamin A activity, is present. Other carotenoids that have vitamin function are tocopherols which have vitamin E activity and can be found in both brown and other seaweed divisions. Particularly, α -tocopherol is present in many *Saccharina* species (Holdt & Kraan 2011; Hamid 2015). RDI for vitamin A is 900 $\mu\text{g/d}$ for men, and 700 $\mu\text{g/d}$ for women. While RDI for vitamin E is 10 mg/d for men and 8 mg/d for women (Nordic-Council-of-Ministers 2014).

When searching for specific recommendations set by the Swedish National Food Administration (Livsmedelsverket) on edible seaweed, there was not any detailed or specific information about RDI on their official webpage³. There are no results when searching on keywords like “seaweed”, “sugar kelp”, “nori”, or “kombu” in the agency’s nutritional database⁴. The exception is the search-word for “kelp” (Swedish: tång) which has two listed kelp caviar (Swedish: tångkaviar) products in their database. Therefore, it is important that the package of the seaweed-based product provides sufficient information regarding certain macro-minerals and trace elements, especially when they are not a regular food item.

Consuming edible seaweeds can be a good and stable source of some vital minerals and vitamins. Still, in many parts of the world there are problems regarding nutrient deficiencies. This includes regions of Europe and revolves around iodine deficiency. Despite some EU and non-EU countries fortifying table salt with iodine in Europe, the problem remains, especially in the countries that do not have a regulation on fortified table salt (Stévant *et al.* 2017a; Lozano Muñoz & Díaz 2020). The introduction of seaweed in daily diet in these places could firstly mitigate iodine deficiency and secondly other mineral shortages if there are any within these populations.

³ <https://www.livsmedelsverket.se/>

⁴ <https://www7.slv.se/SokNaringsinnehall>

3.3.5. Toxic elements and compounds

Seaweed is an extracting organism and can accumulate several toxic compounds from the environment that may have harmful effects on humans (Lozano Muñoz & Díaz 2020). With an increased seaweed production, there will be some points of concern regarding certain macro-minerals, trace elements, and other toxic substances that could be present in variable amounts. Depending on species, season, and closeness to other industries near cultivation sites, the hazards could be hard to ascertain giving the immense biological variability in the organism and the unique environmental settings around each aquaculture spot (Campbell *et al.* 2019; Thomas *et al.* 2019). The issue becomes more complex with compounds that cannot be extracted or excluded with simple methods.

One potential hazard toward seaweed aquaculture is its proximity to the coastline where other industries also operate. Accidental leakages, emissions, or spills of various organic or in-organic compounds could make seaweed inconsumable or harmful (Thomas *et al.* 2019; Lozano Muñoz & Díaz 2020). In one study on fermented sugar kelp by Bruhn *et al.* 2019, none of the metals Cd, As, Pb, and Hg were above or at thresholds set by EU regulation (Bruhn *et al.* 2019). As for regular consumption of postharvest soaked sugar kelp, a low to moderate consumption does not exceed weekly tolerable intake of Cd and values of iAs set by EFSA. The main concern, as previously discussed, focuses on the excessive iodine content in brown seaweeds (Stévant *et al.* 2017a).

Levels of toxic metals found in chosen seaweed along with maximum allowed levels in EU and France can be viewed in (Table 4). Many of the regulations from EU on toxic metals in food do not specify seaweed except for a few. The French Agency for Food, Environmental and occupational Health & Safety (ANSES) have their own recommendations regarding some of the toxic metals that can be found in seaweed (ANSES 2017).

Table 4. List of chosen toxic metals found in two species of brown algae and maximum levels of toxic metals allowed in seaweed in EU and recommendation by ANSES.

Toxic metal	<i>S. japonica</i> (DW)	<i>S. latissima</i> (DW)	Unit	EU Max levels (wet weight)	Unit	French max levels (DW)	Unit
Mercury (Hg)	0.40	0.01-0.02	µg/g	n.d.		0.10	mg/kg
Lead (Pb)	n.d.	0.26	µg/g	0.10	mg/kg	5.00	mg/kg
Arsenic (As)	116	38.30-76.20	µg/g	n.d.		n.d.	
In-organic arsenic (iAs)	1.44	n.d.	µg/g	n.d.		3.00	mg/kg
Cadmium (Cd)	0.02	0.68-2.80	µg/g	3.00	mg/kg	0.50	mg/kg

No data = n.d. Table references: (EU 2006; ANSES 2017; Bruhn *et al.* 2019; Monteiro 2019; Lozano Muñoz & Díaz 2020)

EU and local regulations in Scandinavian countries are not yet fully suited for seaweed aquaculture operation, except for some wayward initiatives from authorities, i.e., recent developments in Denmark regarding permits for aquaculture. In Sweden, it took several years for different seaweed ventures to gain necessary permit from local authorities, and the first commercial cultivations in Norway only started in 2014 (Stévant *et al.* 2017c; Lindstedt 2019; Havhøst 2021). This highlights the infancy of European seaweed cultivation and the investigatory actions that need to be taken to ensure food safety and adapt current regulations around it.

3.3.6. Processing and reduction of unwanted mineral and toxic metal levels

There are many possible ways of processing seaweed after harvest. Some of these methods include soaking, washing, and drying. The purpose is to decrease or remove the potential toxic compounds or undesired macro-mineral levels without altering the chemical-physical food properties of the seaweed. Some of the vital macro-minerals in sugar kelp exceed RDI and mandate pretreatment, and in some cases processing of the kelp before consumption. These amounts are manageable if the kelp is treated accordingly: washing, soaking in fresh water, boiling, or blanching (Shekar 2015; Stévant *et al.* 2017a; Stévant *et al.* 2018; Bruhn *et al.* 2019; Lozano Muñoz & Díaz 2020)

Some of the toxic metals of concern in brown seaweeds are Cd and iAs. These were the subject of a study on cultivated brown algae *S. latissima* and *A. esculenta* harvested from an aquaculture on the northwestern coast of France. The algae were subjected to different post-harvest soaking methods; sea water (SW), fresh water (FW), fresh warm water (WW), and hypersaline fresh water (0.5, 1.0, and 2.0 M NaCl). Levels of Cd in both pre-treated sugar kelp samples were found to be exceeding regional RDI set by ANSES (Table 4), but iAs was not found to be above threshold levels. The Cd level in *A. esculenta* was reduced to an acceptable level after soaking in hypersaline waters. Moderate (3.3 g) and large (12.5 g) servings of dried *S. latissima* and *A. esculenta* daily does not pose a significant health concern with consumers if consumption levels do not exceed a moderate amount (Stévant *et al.* 2017a).

Soaking post-harvested kelp in SW, FW, WW, boiling or blanching may reduce unwanted levels of both macro-minerals and toxic metals, depending on the type of soaking treatment. Soaking *S. latissima* in warm fresh water and *A. esculenta* in hypersaline fresh water reduced levels of Cd and iodine respectively, but at cost of the physical-chemical properties of the kelps. This includes loss of essential minerals, bioactive compounds, and color change. Furthermore, the authors

recommended future studies on which type of soaking method is better when applied in a broader food production context (Stévant *et al.* 2017a). Another method of reducing undesirable amounts of minerals could be through fermentation. It has been shown in one study on fermented *S. latissima* that the fermentation process reduced amounts of Cd and Hg by as much as 1/3 compared to fresh sugar kelp. Though, Pb and As were not reduced by the fermentation process (Bruhn *et al.* 2019). Other similar or different food processing techniques will need to be implemented to ensure a safe consumable food product (Stévant *et al.* 2017a).

4. Conclusion

Seaweeds could be a larger part of our general diet both in Scandinavia and Europe. Many species of edible seaweed contain high values of sought-after nutrients. There have been many positive health effects observed in earlier studies on edible seaweeds, but there have not been many *in vivo* studies conducted on humans. Therefore, health claims of seaweed-based foodstuff should be presented in a moderate way. There are many promising food processing techniques that could enhance the biological value of certain nutrients that are limited by indigestibility. Seaweed polysaccharides are already used as gelling and thickening agents in the food industry and have been for a long time, likewise different nutrient groups also have their unique chemical-physical properties that could be applied in novel food products and other fields as well. Seaweed farming could be one way of reducing anthropogenic emissions from current food production systems if managed and monitored correctly. There is a potential of upscaling IMTA and merging existing aquaculture infrastructure with seaweed cultivation. The environmental impact from seaweed aquaculture is not yet fully understood but there has been promising positive ecological effects observed in some studies. Seaweed cultivation is on the rise in Denmark and Norway, the same cannot be said about Sweden. There are still many hurdles regarding current legislation from authorities both on EU and state level that are not suited for seaweed cultivation and food safety issues, particularly threshold levels for toxic metals and seaweed aquaculture permits. There is an established food market for Asian cuisine in Scandinavia that already includes some seaweed-based foodstuffs. Seaweeds are an important staple food for many peoples in other parts of the world and could soon become one in Scandinavia and the rest of Europe.

References

- ANSES (2017). *Opinion of the French Agency for Food, Environmental and Occupational Health & Safety on "maximum cadmium levels for seaweed intended for human consumption"*. <https://www.anses.fr/en/system/files/ERCA2017SA0070EN.pdf>.
- Brown, E.M., Allsopp, P.J., Magee, P.J., Gill, C.I.R., Nitecki, S., Strain, C.R. & McSorley, E.M. (2014). Seaweed and human health. *Nutrition Reviews*, 72(3), 205-216. <https://doi.org/10.1111/nure.12091>
- Bruhn, A., Brynning, G., Johansen, A., Lindegaard, M.S., Sveigaard, H.H., Aarup, B., Fonager, L., Andersen, L.L., Rasmussen, M.B., Larsen, M.M., Elsser-Gravesen, D. & Børsting, M.E. (2019). Fermentation of sugar kelp (*Saccharina latissima*)—effects on sensory properties, and content of minerals and metals. *Journal of Applied Phycology*, 31(5), 3175-3187. <https://doi.org/10.1007/s10811-019-01827-4>
- Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., Hughes, A.D. & Stanley, M. (2019). The Environmental Risks Associated With the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps. *Frontiers in Marine Science*, 6. <https://doi.org/10.3389/fmars.2019.00107>
- Dawczynski, C., Schubert, R. & Jahreis, G. (2007). Amino acids, fatty acids, and dietary fibre in edible seaweed products. *Food Chemistry*, 103(3), 891-899. <https://doi.org/10.1016/j.foodchem.2006.09.041>
- EFSA (2021). *DRV Finder*. <https://efsa.gitlab.io/multimedia/drvs/index.htm>
- EU (2006). Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs (Text with EEA relevance). *Official Journal of the European Union*. <http://data.europa.eu/eli/reg/2006/1881/oj>
- FAO (2009). *Global agriculture towards 2050*. Rome.
- FAO (2018). *The global status of seaweed production, trade, and utilization*. (Globefish Research Programme). Rome: FAO.
- FAO (2020). *The State of World Fisheries and Aquaculture 2020*. (Sustainability in action 978-92-5-132692-3). Rome. <https://doi.org/10.4060/ca9229en>
- Fiskeridirektoratet (2021). *Algae*. <https://www.fiskeridir.no/English/Aquaculture/Statistics/Algae>
- Fiskeristyrelsen (2019). *Nettoproduktion fordelt på arter, ekskl. overførsel til andre danske anlæg*. https://fiskeristatistik.fiskeristyrelsen.dk/stat/Akvakultur_tab/prod_art_18_ex.html

- Fiskeristyrelsen (2020a). *Produktion i tons fordelt på regioner, anlægstype og arter*.
https://fiskeristatistik.fiskeristyrelsen.dk/stat/Akvakultur_tab/prod_reg_ma_engde_19.html
- Fiskeristyrelsen (2020b). *Nettoproduktion fordelt på arter, ekskl. overførsel til andre danske anlæg*.
https://fiskeristatistik.fiskeristyrelsen.dk/stat/Akvakultur_tab/prod_art_19_ex.html
- Forster, J., Radulovich, Ricardo. (2015). Seaweed and food security. In: Tiwari, B.K. & Troy, D.J. (eds) *Seaweed sustainability : food and non-food applications*
 London, UK: Elsevier Science. 289-313.
- Hamid, N., Ma, Qianli., Boulom, Sayvisene., Liu, Tingting., Zheng, Zihui., Balbas, Jessica., Robertson, John. (2015). Seaweed minor constituents. In: Tiwari, B.K. & Troy, D.J. (eds) *Seaweed sustainability: food and non-food applications*. London, UK: Elsevier Science. 193-242.
- Harrysson, H., Hayes, M., Eimer, F., Carlsson, N.-G., Toth, G.B. & Undeland, I. (2018). Production of protein extracts from Swedish red, green, and brown seaweeds, *Porphyra umbilicalis* Kützinger, *Ulva lactuca* Linnaeus, and *Saccharina latissima* (Linnaeus) J. V. Lamouroux using three different methods. *Journal of Applied Phycology*, 30(6), 3565-3580.
<https://doi.org/10.1007/s10811-018-1481-7>
- Havhøst (2021). *In English*. <https://www.xn--havhst-eya.dk/in-english/>
- Holdt, S.L. & Kraan, S. (2011). Bioactive compounds in seaweed: functional food applications and legislation. *Journal of Applied Phycology*, 23(3), 543-597.
<https://doi.org/10.1007/s10811-010-9632-5>
- Lindstedt, J. (2019). *Alger kan bli storindustri i svenska hav*.
<https://www.nyteknik.se/innovation/alger-kan-bli-storindustri-i-svenska-hav-6965074>
- Lozano Muñoz, I. & Díaz, N.F. (2020). Minerals in edible seaweed: health benefits and food safety issues. *Critical Reviews in Food Science and Nutrition*, 1-16. <https://doi.org/10.1080/10408398.2020.1844637>
- Martins, D.A., Custódio, L., Barreira, L., Pereira, H., Ben-Hamadou, R., Varela, J. & Abu-Salah, K.M. (2013). Alternative sources of n-3 long-chain polyunsaturated fatty acids in marine microalgae. *Marine drugs*, 11(7), 2259-2281. <https://doi.org/10.3390/md11072259>
- Monteiro, M.S., Sloth, J., Holdt, S., Hansen, M. (2019). Analysis and risk assessment of Seaweed. *EFSA Journal*, 17(S2).
<https://doi.org/https://doi.org/10.2903/j.efsa.2019.e170915>
- Nordic-Council-of-Ministers (2014). *Nordic Nutrition Recommendations 2012 Integrating nutrition and physical activity*.
- Nordic-SeaFarm (2021). *Våra tångodlingar*.
<https://www.nordicseafarm.com/nordic-seafarm#odling>
- Pangestuti, R., Kim, Se-Kwon. (2015). Seaweed proteins, peptides, and amino acids. In: Brijesh, K.T., Declan, J. Troy. (ed.) *Seaweed sustainability : food and non-food applications*. London, UK: Elsevier Science. 125-140.
- Radulovich, R., Neori, Amir., Valderrama, Diego., Reddy, C.R.K., Cronin, Holly., Forster, John. (2015). Farming of seaweeds. In: Tiwari, B.K. & Troy, D.J.

- (eds) *Seaweed sustainability : food and non-food applications*. London, UK: Elsevier Science.
- Redmond, S., Green-Gavrielidis, L., Yarish, C., Kim, J. & Neefus, C. (2013). *New England Seaweed Culture Handbook: Nursery Systems*.
- Rioux, L.-E., Turgeon, Sylvie L. (2015). Seaweed carbohydrates. In: Tiwari, B.K. & Troy, D.J. (eds) *Seaweed sustainability : food and non-food applications*. London, UK: Elsevier Science. 141-192.
- Shekar, U.K., Álvarez, Carlos., Brijesh, K. Tiwari., O'Donnel, P. Colm. (2015). Processing of seaweeds. In: Tiwari, B.K. & Troy, D.J. (eds) *Seaweed sustainability : food and non-food applications*. London, UK: Elsevier Science. 61-78.
- Stévant, P., Indergård, E., Ólafsdóttir, A., Marfaing, H., Larssen, W.E., Fleurence, J., Roleda, M.Y., Rustad, T., Slizyte, R. & Nordtvedt, T.S. (2018). Effects of drying on the nutrient content and physico-chemical and sensory characteristics of the edible kelp *Saccharina latissima*. *Journal of Applied Phycology*, 30(4), 2587-2599. <https://doi.org/10.1007/s10811-018-1451-0>
- Stévant, P., Marfaing, H., Duinker, A., Fleurence, J., Rustad, T., Sandbakken, I. & Chapman, A. (2017a). Biomass soaking treatments to reduce potentially undesirable compounds in the edible seaweeds sugar kelp (*Saccharina latissima*) and winged kelp (*Alaria esculenta*) and health risk estimation for human consumption. *Journal of Applied Phycology*, 30(3), 2047-2060. <https://doi.org/10.1007/s10811-017-1343-8>
- Stévant, P., Marfaing, H., Rustad, T., Sandbakken, I., Fleurence, J. & Chapman, A. (2017b). Nutritional value of the kelps *Alaria esculenta* and *Saccharina latissima* and effects of short-term storage on biomass quality. *Journal of Applied Phycology*, 29(5), 2417-2426. <https://doi.org/10.1007/s10811-017-1126-2>
- Stévant, P., Rebours, C. & Chapman, A. (2017c). Seaweed aquaculture in Norway: recent industrial developments and future perspectives. *Aquaculture International*, 25(4), 1373-1390. <https://doi.org/10.1007/s10499-017-0120-7>
- Tanna, B. & Mishra, A. (2019). Nutraceutical Potential of Seaweed Polysaccharides: Structure, Bioactivity, Safety, and Toxicity. *Compr Rev Food Sci Food Saf*, 18(3), 817-831. <https://doi.org/10.1111/1541-4337.12441>
- Thomas, J.-B.E., Ramos, F.S. & Gröndahl, F. (2019). Identifying Suitable Sites for Macroalgae Cultivation on the Swedish West Coast. *Coastal Management*, 47(1), 88-106. <https://doi.org/10.1080/08920753.2019.1540906>
- UN (2009). *Food Production Must Double by 2050 to Meet Demand from World's Growing Population, Innovative Strategies Needed to Combat Hunger, Experts Tell Second Committee*. <https://www.un.org/press/en/2009/gaef3242.doc.htm>
- UN (2019). *World population prospects 2019*. <https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html>
- Visch, W., Kononets, M., Hall, P.O.J., Nylund, G.M. & Pavia, H. (2020). Environmental impact of kelp (*Saccharina latissima*) aquaculture. *Marine*

Pollution Bulletin, 155, 110962.
<https://doi.org/https://doi.org/10.1016/j.marpolbul.2020.110962>
WHO (2007). *Protein and amino acid requirements in human nutrition report of a joint WHO/FAO/UNU expert consultation*. (WHO technical report series ; 935). Geneva: World Health Organization.
<https://ebookcentral.proquest.com/lib/slub-ebooks/reader.action?docID=305231#>