Guide to macroalgae cultivation and use in the Baltic Sea Region

Tomasz Kulikowski (editor), Magdalena Jakubowska,
Joanna Krupska, Iwona Psuty, Olga Szulecka

National Marine Fisheries Research Institute
Gdynia, 2021

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provides a summary of the results of WP 4.1. and WP 4.2. GRASS project

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Explanation of abbreviations used in the publication

BSR - Baltic Sea Region
CAGR - compound annual growth rate
CAWI - Computer Assisted Web-Interview (method of quantitative consumer research)
EEZ - economic exclusive zone
FAO - Food and Agriculture Organization of the United Nations
GRASS - Growing algae sustainably in the Baltic Sea (international project, financed by Interreg Baltic Sea Region)
MAP - modified-atmosphere packaging
N - nitrogen
NMFRI - National Marine Fisheries Research Institute (in Polish: Morski Instytut Rybacki - Państwowy Instytut Badawczy)
P - phosphorus
RTE - ready-to-eat products
VAP - value-added products

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Summary

Asian countries produce the majority of the macroalgae biomass and also cultivate the greatest diversity of seaweed species. Although more than 200 species of macroalgae are exploited commercially, five genera represent approximately 98% of the world seaweed production. Macroalgae are commercially processed mainly for food products and production of hydrocolloids. However, due to the presence of various valuable compounds, which are suitable for e.g. pharmaceutical, biomedical or cosmetic industry, more and more new products are available on the market and additional ones are in the research phase.

In 2005-2015, the global production of seaweed doubled, but in 2016-2018 the dynamics of the development of seaweed production decreased significantly. The vast majority of production is made in Asia. Europe accounts for less than 0.1% of the world's seaweed cultivation. In the Baltic Sea Region, apart from the western waters on the border of the North Sea, only a few experimental farms are conducted. On a small commercial scale, the wild seaweed in the Baltic Sea is fished only in Estonia and Denmark (1.2.)

There is little documented evidence of seaweed consumption prior to the 20th century in the Baltic Sea Region. In the 20th century, consumption of seaweed spread to the Eastern Baltic Sea, along with the Soviet cuisine, into which seaweed was introduced by the Korean diaspora. In the last 3 decades, there has been a sharp increase in interest in seaweed throughout the Baltic Sea Region, due to the growing popularity of Far Eastern cuisine, mainly Japanese (sushi).

Currently, seaweed products are appearing more and more often on the market of the Baltic Sea Region - not only in Far East gastronomy, but also in the retail market (retail chains, specialist health food stores, less often - fish stores) - in the form of salads (loose and packed, in different flavors), dried products (including various snacks), as well as a number of innovative multi-ingredient products. There is also a wide availability of dietary supplements based on seaweed.

Seaweed products are quite commonly known to consumers in the Baltic Sea Region - due to studies conducted during GRASS project, 26% of consumers in the Baltic Sea Region have already eaten seaweed, but only as an ingredient of sushi, while nearly every fourth (23%) consumer has already tried seaweed also in other forms (e.g. salads, soups, snacks). As many as 34% of consumers declare that they "could try to eat" seaweed food products. Over 30% of consumers in the region believe that seaweed is food with particularly high pro-health values. Combining this data with the great interest of consumers in the region in products with guaranteed local (regional) origin, it must be determined that seaweed food products have great market potential.

Algae can constitute new sources of functional compounds for food chain but also could be useful in various industries, as valuable raw material for:

- cosmetics and cosmetology industry,
- medical and pharmaceutical industry,
- agriculture (fertilizers, bio-stimulants),
- biofuel production,
- many other industrial applications.

Seaweed is a raw material that, due to its numerous properties, is very versatile. Thanks to its high nutritional value (a rich source of proteins, essential amino acids and vitamins necessary for the proper functioning of the body), algae are widely used in food production. A diet rich in algae meets the needs for protein, essential amino acids, minerals and vitamins. As they are a source of elements, e.g. fiber, magnesium, zinc, calcium, potassium, iron, fluorine, phosphorus and copper, as well as folic acid and omega 3 acid, vitamins A, B, C, D, E are more and more commonly used in supplements (supplements with algae are recommended for various dysfunctions, e.g. an ingredient supporting slimming) and functional food. Algae, rich in elements, are eagerly used in the production of cosmetics, because they stimulate the reconstruction and protection of the epidermis, soothe irrita-

tions, and also have anti-allergic and anti-inflammatory properties. They have a cleansing, moisturizing and soothing effect, making them suitable for the care of dehydrated, acne and hypersensitive skin. In the cosmetics industry, they are also used in the production of preparations that accelerate skin healing, regenerate and rejuvenate. Algae is also used in pharmacy and laboratories, and for the production of biomaterials. Due to their anti-inflammatory, antioxidant, antibacterial, anticancer and antioxidant properties, algae can be used in the treatment of many diseases in the world, because there is a growing interest in natural pharmaceuticals, which are perceived as safer for humans. Algae as a renewable energy source, also represent a huge potential in the production of biofuels, and the rapidly advancing technology development makes them increasingly used in other technical and industrial products.

As macroalgae uptake naturally occurring nutrients, their cultivation sites may also provide environmental services - they can be used as a tool to combat eutrophication. The biogen content and the rate of their uptake vary between the macroalgae species and populations and depend on environmental conditions. Generally, growth rates and the nutrient uptake rates are higher in fast growing green macroalgae than slow-growing species like many red and brown seaweed. Based on the calculations, it is possible to remove 1.3-7.9 kg of nitrogen and 0.2-1.9 kg of phosphorus while harvesting 1 ton of Baltic macroalgae, depending on the species.

The macroalgae species that, according to their properties, content of valuable substances or abundance can be considered suitable for cultivation in the Baltic Proper and adjacent basins are: (1) red alga *Furcellaria lumbricalis* - the only species that was harvested on a commercial scale in the Baltic Sea to obtain polysaccharide furcellaran (gelling agent); (2) red alga *Ceramium tenuicorne* - this small, filamentous species contain many bioactive substances, can be utilised to produce agar and is rich in red pigment phycoerythrin; (3) brown alga *Fucus vesiculosus* that has been used as food and medicine for centuries is commercially harvested in few countries outside the BSR to obtain its structural polysaccharide fucoidan and can be also used as a source of alginic acid; (4) *Ulva intestinalis* - green alga that is very abundant on rocky bottoms along the Baltic coasts is suitable for human consumption and cultivated in Japan. For the Western Baltic/ Sweden, characterised with higher salinity, two Laminariales species are suitable for cultivation - *Laminaria digitata* and *Saccharina latissima* and they are/ can be utilised as high value food products or in alginate industry.

It should be emphasised that there are few different legal barriers but also opportunities for the cultivation and harvesting of macroalgae. The legal aspects can be divided to: (1) spatial conflicts and synergies with other users and maritime sectors resulting from Maritime Spatial Plans for BSR countries; (2) legal regulations directly related to the cultivation of marine organisms and resulting from the environmental law, usually connected to the necessity of obtaining few permissions from the relevant authorities; and (3) the regulations related to the usage of macroalgae as food and feed ingredients, connected mainly to the limits of harmful substances, food labeling and the introduction of novel species into the market.

As *Sacchcarina latissima* and *Laminaria digitata* are experimentally and commercially cultivated in Sweden and Denmark, the cultivation techniques, based mainly on the long-line technology, dedicated for these species exist and are well described in the literature. The experience in cultivation of macroalgae in the Baltic Proper and adjacent basins is limited to few experimental initiatives. Based on the findings from these initiatives and on the scientific literature, we assumed that sufficient knowledge exists to plan at least experimental farms of *Fucus vesiculosus* and *Ulva intestinalis* in the Baltic Sea. Based on the results from FucoSan project, we propose fucus farms which rely on vegetative fragments of thalli as a ‘seeding’ material, placed in the experimental infrastructure consisting of floating baskets and cultivated throughout the year. For *Ulva intestinalis* we suggest the farm based on the long-line technique - using lines with planted spores, suspended shallow below the water’s surface and located in the shallow coastal zone, most preferably in areas characterised with high nutrient concentration. Due to seasonality, it is possible to cultivate *U. intestinalis* 5-6 months per year.

Preliminary calculations show that the production of macroalgae in the south-east of the Baltic Sea: Poland, Latvia, Estonia is quite cost-intensive. Depending on the adopted input parameters, the production cost of 1 kg of fresh *Ulva* varies from 0.23 €/kg, with the optimistic assumption of efficiency of 87t/ha, up to 1.0 €/kg, assuming the pessimistic version of the yield of 9.8t / ha. The estimated unit cost of producing 1 kg of fresh *Fucus* is ca 2.34 €/kg.

Starting the cultivation of seaweed in the Baltic Sea Region, from the market point of view, would be a response to the growing consumer demand for new, pro-health products of aquatic origin, also in line with the trend of reduced demand for animal products. Production in the Region would make it possible to offer a local, ultra-fresh product. From a socio-economic point of view, local cultivation of seaweed would contribute to increasing added value in the Region (replacing imported products), promoting employment (including people leaving sea fishing) and better utilizing the potential of fish processing plants. From an environmental point of view, the cultivation of seaweed, especially fast-growing seaweed (like *U. intestinalis*), offers a unique opportunity to reduce water eutrophication while accumulating CO2.

The main problems and threats to the start of macroalgae cultivation in the main part of the Baltic Sea (except its western part) are: the inability to estimate the market absorption capacity for new species, practically absent in the food market of the Region (such as *U. intestinalis*); lack of proven in practice technologies for the cultivation of *U. intestinalis* and *F. vesiculosus* in Baltic conditions; legal and legislative barriers - especially for first market entrants; finally - the lack of public funding for the water-environmental services that will be provided by seaweed farms.

The following report synthetically collects the available knowledge about the production possibilities and the seaweed market in the Baltic Sea Region and was carried out as part of the GRASS project - Growing Algae Sustainably in the Baltic Sea.

1. Introduction

(Magdalena Jakubowska, Tomasz Kulikowski)

1.1. Basic characteristics of the world macroalgae production

Macroalgae have been used in human diets since very early times. Apart from direct consumption, seaweeds being rich in protein, dietary fibers and bioactive compounds may be also used as additives to enhance the nutritional quality of the food products. Some species are cultivated or harvested almost exclusively for direct human consumption, whereas other are industrially processed to extract various compounds. The main producing countries are China, Indonesia and the Philippines, which also cultivate the greatest diversity of seaweed species (FAO, 2018). The five genera – *Saccharina*, *Undaria*, *Porypia*, *Eucheuma*/*Kappaphycus* and *Gracilaria* – represent approximately 98% of the world's cultivated seaweed production (Buschmann et al., 2017; FAO, 2018; Ferdouse et al., 2018). In the seaweed industry 85% of its total market value is attributed to the food products followed by the production of hydrocolloids – carrageenan, alginate and agar (Nayar and Bott, 2014; Ferdouse et al., 2018). It has been assessed that more than 200 species of macroalgae are exploited commercially at various scales (Nayar and Bott, 2014). List of macroalgae species, which are most important on the market are presented in Tab. 1. More data concerning the global production of particular seaweed species and the processing of edible macroalgae are presented in:

Read also:
Moona Rahikainen, Global production of macroalgae and uses as food, dietary supplements and food additives

report available online:
https://www.submariner-network.eu/grass

Polysaccharides extracted from macroalgae contribute to 40% of the global hydrocolloid market (Ferdouse et al., 2018). They are commonly used as natural colloids and gelling agents, which thicken aqueous solutions and form gels in food products as well as in non-food industries (medicine, research, pharmaceuticals, cosmetics). Alginates are extracted from brown algae (class *Phaeophyceae*), whereas carrageenan and agar are derived from a number of red seaweed (division *Rhodophyta*). Some polysaccharides were named according to their biological source (Usov, 2011), for example furcellaran - commercially produced sulphated polysaccharide extracted from *Furcellaria lumbricalis* (Indergaard and Knutsen, 1990). While any brown seaweed could be used as a source of alginate, the actual chemical structure of this hydrocolloid varies among algae genera and species (McHugh, 2003). Similarly, agar and carra-

Fig. 1 Edible green algae — *Ulva* genus (photo source: 123rf.com)

geenan obtained from particular species may differ in quality (gelling ability) due to slight differences in chemical structure (Freile-Pelegrin and Murano, 2005; Imeson, 2009).

Algal extract-based products that improve plant growth and development have been already tested and applied in agriculture. Products available on the market include vitamins, amino acids, phytohormones, polysaccharides, micro and microelements or plant hormones and have a beneficial effect on, among others, cell division, plant growth and development, growth of fruits, the intensity of flowering resistance against diseases or stimulates the uptake of fertilizers from the soil (for review see Sharma et al., 2014 and Michalak and Chojnacka, 2016). The use of macroalgae in various industries was described in detail in chapter 2 (=>2. Macroalgae applications).

Tab. 1 Macroalgae species (green, brown and red) utilized commercially and their applications.

Species	Product/ usage
Undaria pinnatifida	human food (Wakame)[1, 2]
Saccharina japonica *(formerly Laminaria japonica)*	human food (Kombu) [1, 2]
Cladosiphon okamuranus	human food (Mozuku)[2, 3]
Alaria esculenta	human food[2, 3]
Eisenia bicyclis	human food (Arame)[4]
Sargassum fusiforme	human food (Hijiki)[1, 3] alginate[2]
Macrocystis pyrifera *Durvillea potatorum* *Ecklonia* spp. *Laminaria digitata* *Lessonia* spp.	alginate[1, 2]
Ascophyllum nodosum	alginate[2] products for agriculture (biostimulants, soil conditioners and fertilizers)[5, 6] animal feed[2, 7]
Laminaria digitata	products for agriculture (biostimulants)[5, 6]
Ecklonia maxima	products for agriculture (biostimulants), soil conditioners and fertilizers[5, 6]
Pyropia spp. *(formerly Porphyra)*	human food (Nori)[1, 2]
Palmaria palmata	human food[2, 3]
Gracilaria spp.	human food (Ogonori) [2, 3] agar[1, 2, 8, 9] animal feed (for abalone)[2, 10]
Gelidium spp.	agar[2, 8]
Gellidiela spp.	agar[2, 8]
Pterocladia capillacea, *Pterocladia lucida*	agar[2, 8]
Crassiphycus corneus	agar[11, 12]

Species	Product/ usage
Furcelaria lumbricalis	furcellaran[13, 14, 15]
Chondrus crispus	human food[2] carrageenan[16]
Eucheuma spp.	carrageenan[2, 17]
Kappaphycus alvarezii	carrageenan[1, 16, 18]
Gigartina spp.	carrageenan[2, 16]
Sarcothelia crispata	carrageenan[2]
Mazzaella laminaroides	carrageenan[2]
Monostroma latissimum *Ulva prolifera, Ulva intestinalis*	human food (Aonori)[2, 3]
Ulva lactuca	human food (Aosa)[3] animal feed (for abalone)[2, 10]
Caulerpa spp.	human food[2, 3]
Codium spp.	human food[3, 19]

1. Buschmann et al., 2017, **2.** McHugh et al., 2003, **3.** Zemke-White and Ohno, 1999, **4.** Naylor, 1976, **5.** Sharma et al., 2014, **6.** Michalak and Chojnacka, 2016, **7.** Algae, 2015, **8.** Armisen and Galatas, 1987, **9.** Marinho-Soriano and Bourret, 2005, **10.** FAO, 2016, **11.** Marinho-Soriano et al., 2001, **12.** Pereira-Pacheco et al., 2007, 1**3.** Laos and Ring, 2005, **14.** Chemical Book, 2017, **15.** EstAgar, 2020, **16.** Ferdouse et al., 2018, **17.** Imeson, 2009, **18.** Pereira and Yarish, 2008, **19.** Trowbridge, 1999

Besides products available on the market listed in Table 1, various compounds, suitable for pharmaceutical, biomedical or food-related applications have been identified and extracted from macroalgae (Alves et al., 2013; Leandro, 2020). In addition, whole algae extracts are gaining increasing interest due to their unique composition and possibilities of wide industrial applications (Michalak and Chojnacka, 2015; Leandro, 2020). Some compounds and extracts are already being commercially used, whereas other constitute patents or are in the research phase (Zemke-White and Ohno, 1999; Alves et al., 2013). Macroalgae are rich in, among others, amino-acids, proteins, lipids, carbohydrates, minerals, dietary fibers, polyunsaturated fatty acids as well as contain bioactive compounds which possess antibacterial, anti-viral, anti-fungal, anti-oxidative, anti-inflammatory, and antitumor properties, such as polyphenols, vitamins or pigments (Kumar et al., 2008; Michalak and Chojnacka, 2015; Parjikolaei et al., 2016). Few examples of biologically active compounds which can be extracted from various seaweed species are presented in Tab. 2. It should be kept in mind, however, that the structure and the biological activities of valuable compounds may be influenced by environmental factors, such as water temperature, salinity, concentration of nutrients, water dynamic or depth of immersion (Gupta and Abu-Ghannam, 2011). Also the extraction method and conditions (e.g. temperature, extraction time) strongly influence the composition of the obtained products (Wang et al., 2011; Michalak et al., 2015).

Fig. 2 Japanese terms for popular seaweed and seaweed products (*photo source:* 123rf.com)

Interestingly, the research carried out so far has indicated that macroalgae are also promising material for the production of biofuels. According to experimental data, seaweed from genus *Ulva*, due to their high growth rates and photosynthetic activity, high polysaccharide content and the absence of lignin (what facilitate hydrolysis and fermentation), are potentially suitable source for biofuel production, both bioethanol (Trivedi et al., 2013; Korzen et al., 2015; Li et al., 2016) and biogas (Bruhn et al., 2011; Saqib et al., 2013). Brown and red algae are also considered good candidates for a feedstock for large-scale and cost-effective production of biofuels (Adams et al., 2009; Wi et al., 2009; Hou et al., 2017).

Tab. 2 Examples of biologically active compounds which can be extracted from various green, brown and red macroalgae species.

Species	Compound	Properties/ activities/ usage
Undaria pinnatifida *Sargassum fusiforme*	phytosterols, phytol[1]	anti-diabetic, anti-cancer, anti-inflammatory, anti-oxidative
Undaria pinnatifida *Alaria esculenta* *Fucus vesiculosus* *Laminaria digitata*	fucoxanthin (pigment)[2, 3]	anti-cancer, anti-oxidative
Caulerpa racemose *Ulva prolifera* *Ascophyllum nodosum* *Pelvetia canaliculata* *Fucus spiralis*	phenolic compounds, polyphenols[4, 5, 6]	anti-oxidative
Ulva prolifera *Ecklonia cava*	polysaccharides[7, 8]	anti-oxidative anti-bacterial
Fucus vesiculosus *Fucus evanescen* *Ascophyllum nodosum* *Undaria pinnatifida*	fucoidan (polysaccharide)[9, 10, 11, 12, 13]	anticoagulant, antithrombotic, anti-inflammatory, anti-tumor, anti-viral
Laminaria spp.	laminarin (polysaccharide)[14]	antibacterial and anti-tumor
Eisenia bicyclis	fucosterol[15]	anti-inflammatory
Dictyota spp.	diterpenes[16, 17, 18]	anti-retroviral, cytotoxic

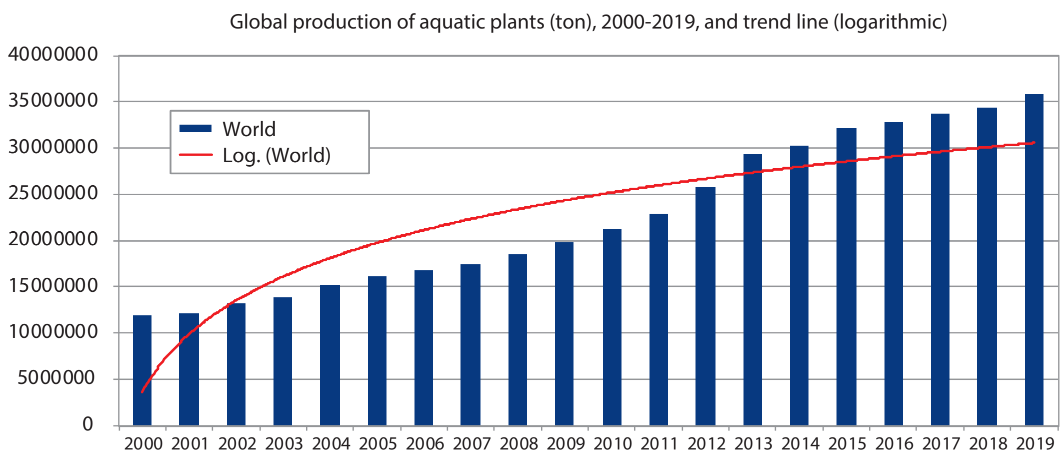
Species	Compound	Properties/ activities/ usage
Porypia yezoensis	R-phycoerythrin (pigment)[19]	fluorescent pigments, colorants (cosmetics, drinks, foods, paints), anti-cancer and anti-oxidative properties
Ulva prolifera	lectins[20]	biological roles in many cellular processes
Ulva spp.	ulvan (polysaccharide)[21, 22, 23]	antioxidant, anti-viral, anti-coagulant

1. Xiao et al., 2013, **2.** Piovan et al., 2013, **3.** Shannon et al., 2017, **4.** Li et al., 2012, **5.** Luo et al., 2010, **6.** Tierney et al., 2013, **7.** Wang et al., 2011, **8.** Lee et al., 2011, **9.** Rodriguez-Jasso et al., 2011, **10.** Merck, 2020, **11**. Alekseyenko et al., 2007, **12.** Marais et al., 2007, **13.** Lee et al., 2004, **14.** Gupta and Abu-Ghannam, 2011, **15.** Jung et al., 2013, **16.** Manzo et al., 2009, **17.** Pereira et al., 2004, **18.** Jongaramruong and Kongkam, 2007, **19.** Niu et al., 2010, **20.** Ambrosio et al., 2003, **21.** Lahaye et al., 2007, **22.** Alves et al., 2013, **23.** Rahimi et al., 2016

1.2. Trends in global and European macroalgae production

Global aquaculture production of seaweed doubled, from 14.7 million ton in 2005 up to 29.4 million tons in 2015. At the same time seaweed harvest from the wild dropped from 1.2 million tons in 2005 to 1.1 million tons in 2015 (Ferdouse et al., 2018). Due to other sources, the global production of farmed aquatic algae (mostly seaweeds), has experienced relatively low growth in the most recent years, and even fell by 0.7 percent in 2018. This change was mainly caused by the slow growth in the output of tropical seaweed species and reduced production in Southeast Asia, while seaweed farming production of temperate and coldwater species was still on the rise (SOFIA, 2020).

Fig. 3 Global production of aquatic plants (ton), 2000-2019



Source: online database, FAO - Fisheries and Aquaculture Information and Statistics Branch - accessed 16/05/2021

According to the most recent data (FAO - Fisheries and Aquaculture Information and Statistics Branch - 16/05/2021) the total annual production of aquatic plants in 2019 amounted to 35.8 million tons. Production in Asia amounted in 2019 to 34.8 million tons (which is 97% of total global production), while production in Europe amounted to 0.3 million tons (0.8%). It included 1.1 million tons of capture (harvested) production, where Europe contributed to 26% production (0.3 million tons), and 34.7 million tons of aquaculture production (where Europe contributed less than 0.1% - only 11 500 tons).

European capture (harvested) production of seaweed were dominated in 2019 by Norway (163 080 tons, 61% of European production; mostly brown seaweed), followed by: France (51 300 tons, mostly brown seaweed), Ireland (29 500 tons, brown seaweed) and Iceland (17 533 tons, mostly brown seaweed). In the Baltic Sea Region the most important producer in 2019 was Estonia (60 tons, red seaweed). It should also be mentioned that capture production in the Russian Federation amounted to 8 968 tons (but not in the Baltic Sea Region). According to other data, of the European Commission's Knowledge Center for Bioeconomy, production size amounted in 2014 to 100 tons in Denmark and 500 tons in Estonia (Dos Santos, 2019). Estonian information showed that the maximum allowed the capture of red seaweed in Estonia amounting to 2000 tons (two licences), but the production dropped from ca. 450-550 tons in 2014-2016 to less than 70 tons in 2019 (in 2018 catches have not been made) (Kasuk 2020).

Aquaculture (farmed) production of aquatic plants (mostly seaweed) in 2019 in European countries amounted to ca. 11 500 tons. This information is somewhat misleading, as the production was dominated by the Russian Federation (10 573 tons, mainly in Far Eastern, not European, waters). 383 tons of aquatic plants were produced in France in 2019 (incl. 176 tons of seaweeds in marine waters). Due to FAO statistics, the aquaculture production of brown seaweed amounted in Denmark to 1800 tons in 2013, and then dropped to 100 tons in 2014-2016 and only 10-12 tons in 2017-2018 (for 2019 statistics shows 0 production).

In 2001 the global seaweed market value (production value) was estimated at almost US $ 6 billion of which food products for human consumption represented US $ 5 billion (FAO Guide 2003). In 2018 ex farm sale value of seaweed amounted to 13.1 billion USD (incl. brown seaweed - 6.8 billion USD; red seaweed - 6.3 billion USD and green seaweed - 33 million USD) (FAO Yearbook 2018, 2020). In 2016, 1 million tons of seaweed products were exported globally at an estimated value of 4 billion USD (Ferdouse et al., 2018).

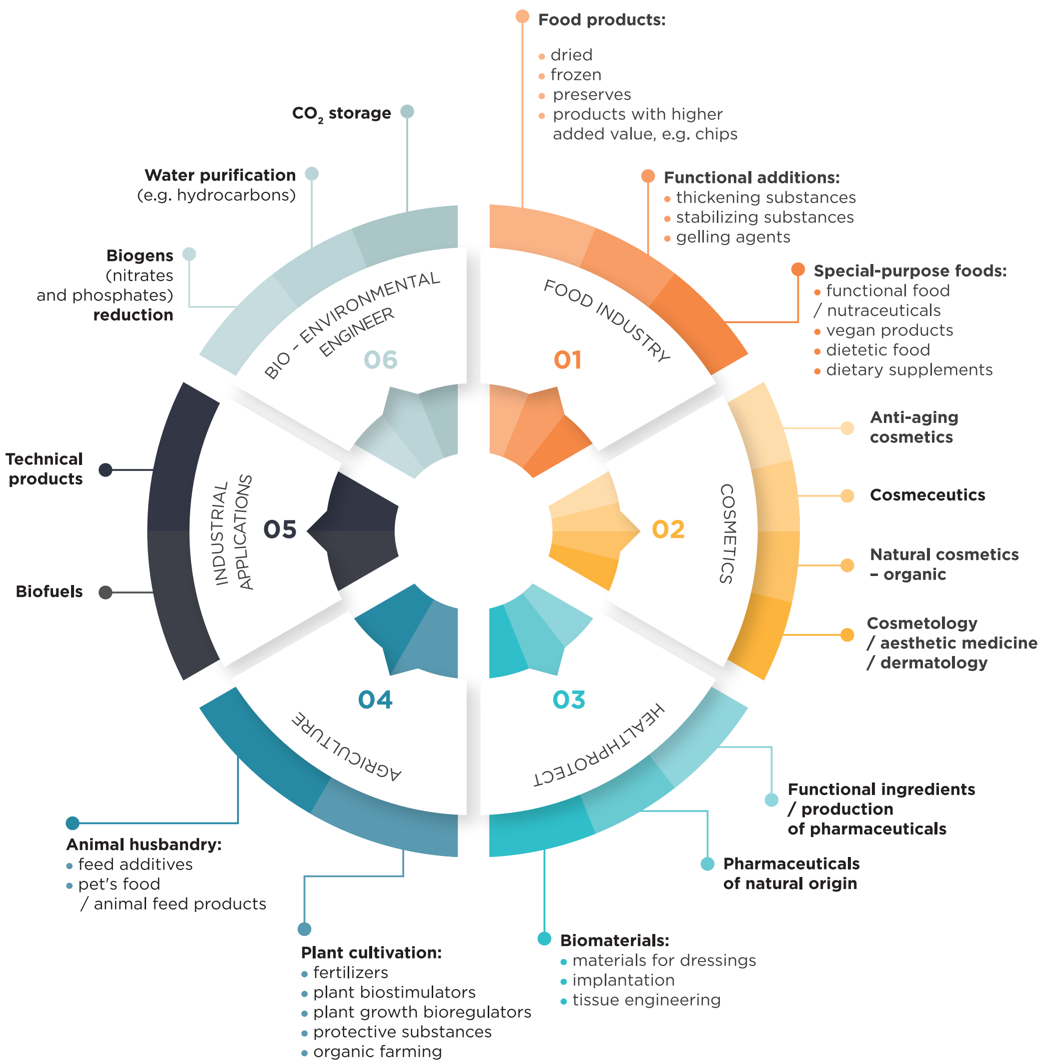
Commercial seaweed market size was valued at USD 59 billion (retail value) in 2019 and is estimated to exhibit more than 12% CAGR from 2020 to 2026. Increasing seaweed adoption for pharmaceutical & personal care products will escalate the revenue generation (Pulidindi, Prakash, 2020). In 2030 the European demand for seaweed is projected to reach between 3.0 and 9.3 billion euro across with the largest share of four segments: animal feed, food, biostimulants and bio-packaging (Seaweed for Europe, 2020).

2. Macroalgae applications

(Joanna Krupska, Iwona Psuty, Magdalena Jakubowska)

Algae are an efficient and sustainable source of biological processes and products. Due to the enormous species diversity of algae, products with an almost infinite number of possibilities can be produced, and their composition can be adapted by changing the breeding conditions. Additionally, the cultivation and use of seaweed can alleviate a number of major environmental problems today. Their effective use can help to tackle the problem of non-ecological processes and thus stimulate the bioeconomy and play an important role in shaping a more sustainable society and a cleaner and healthier environment. In addition, as algae are used more widely in commercial applications, the pressure on

Fig. 4. Current and potential use of macroalgae products (elaborated by J. Krupska / NMFRI)



terrestrial or non-renewable resources will decrease. By strategically placing production facilities, seaweed production can reduce ocean eutrophication as nutrients are taken up during growth and removed by the seaweed harvest (He et al., 2008). The use of seaweed, rather than fossil fuels, can contribute to climate change mitigation (Sustainable Energy Ireland, 2009; Dave et al., 2013). The use of seaweed as a livestock feed additive can reduce the import of soybeans, thus preventing deforestation in soy-producing countries, while the use in fish feed can reduce fish catches and solve the problem of over-exploitation of fish stocks (Wassef et al., 2005; Valente et al., 2006).

Algae are not only a rich source of various valuable substances, but above all a very important element of ecosystems. They serve as food for aquatic organisms (they are found at the beginning of most food chains in the aquatic ecosystem) and enrich water bodies with oxygen and regulate access to sunlight.

Thus, the cultivation of seaweed has great potential, firstly because of its positive environmental impact and sustainability strategies, as well as its extremely high nutritional value and content of commercially useful compounds.

Currently, consumers are looking for high quality products of natural origin. Algae and algae-derived products (algae extracts) may be one of them. Algae can constitute new sources of functional compounds that are already in use or could be useful in various industries, as for example:

- food industry,
- cosmetics and cosmetology industry,
- medical and pharmaceutical industry,
- agriculture,
- biofuel production,
- other industrial applications,
- environmental bioengineering.

2.1. Algae in the food industry

The most widespread use of algae is in the food industry. Marine algae are an excellent source of protein, vitamins, minerals and fatty acids, exogenous amino acids, as well as micro and macroelements, without posing a risk to human health, as confirmed by the Food Drug Administration (FDA) in 2012. Algae contain the following components: bromine, zinc, iodine, magnesium, manganese, copper, and iron. They occur in a particularly well assimilable form – as organometallic or complex compounds (Godlewska et al., 2014).

Algae are valuable to the food industry due to (Pielesz et al., 2010)

- high nutritional value (e. g. microelements easily assimilated by humans) used as a supplement to the daily diet,
- source of vitamins, proteins and exogenous amino acids to supplement the vegetarian diet,
- thickeners, stabilisers and gelling agents added to food products (e. g. agar, carrageenan or alginates are commonly used in the food industry as functional ingredients such as stabilisers),
- prebiotic properties of seaweed polysaccharides.

Fig. 5. Sushi consumption is the main driver for seaweed consumption in Europe. Sushi competition in the METRO market (Germany) in the picture (photo source: 123rf.com)

Food products

Despite the fact that eating macroalgae does not belong to the culinary tradition in the Baltic Sea Region (with minor historical exceptions – such as scarce sources regarding the time of the Vikings), marine algae are offered in various forms in the countries of the Baltic Sea region. Generally, the consumption of macroalgae in the Baltic Sea region is the result of four culinary trends: in the eastern part of the region, the influence of Russian cuisine (which assimilated macro-algae from the tradition of Korean minority cuisine in the 20th century), the growing popularity of Japanese cuisine (especially sushi) for three decades, the growing demand (especially in the last two decades) for foods with pro-health benefits such as superfoods, and finally the growing number of people following a vegetarian (vegan) diet and looking for alternatives for both seafood and vegetables (mostly in the Western part of the Region).

Nori is formed from various species of algae (Porphyra genus is the most commonly used algae), growing in temperate waters. These algae are shredded, dried, pressed into sheets and roasted. On one side they have a matt, rough surface, on the other side they are smooth and shiny. There are several types of nori: green, red, silver, gold, platinum and diamond. These names refer to their characteristics, e.g. thickness and brittleness (green are the thinnest and least gummy – the easiest to roll up; diamonds are the thickest) (Fleurence et.al., 2016)

Fig. 6 *Dried seaweed in form of nori (photo source: 123rf.com)*

In retail the most popular are dried seaweed. They can be easily purchased in leading supermarket chains in all countries of the region, health food stores. However, the largest selection of these products is in online shops. Among dried products, nori holds a special position. It is an essential ingredient of sushi, which is consumed all over the world, including all of the Baltic Sea countries. The special form of dried products with higher added value are: dried sprinkle snacks, seaweed chips and salt with dried seaweed powder. Raw material for most of dried seaweed products in Baltic Sea region retail are: *Porphyra spp*. (incl. *Porphyra yezoensis*. To a lesser extent: *Palmaria palmata*, *Undaria pinnatifida*, *Laminaria japonica*, *Ulva pertusa*, *Pyropia yezoensis* [source: GRASS retail surveys conducted in Denmark, Germany, Finland, Russia, Poland, Latvia, Lithuania]

Fig. 7. Seaweed salads in Riga Central Market (Latvia). The name of the product is „sea cabbage" (photo T. Kulikowski)

Algae for consumption can also be purchased in different forms and presentations, including chilled (loose or pre-packed) and frozen RTE (ready-to-eat) products. The most popular RTE products are salads from fresh (sea vegetable, sea spaghetti), cooked or grilled seaweed with different additional ingredients. The most common types of seaweed salad, taken from Japanese, are „wakame" and „chuka". Other RTE products include: ready meals (e. g. miso soup), fish products with the addition of seaweed (e. g. salted / marinated herring with

Fig. 8. Frozen wakame seaweed salads in a supermarket in Gdynia, Poland (photo T. Kulikowski)

Fig. 9. Seaweed chips, produced in Denmark (photo T. Kulikowski)

Fig. 10. Seaweed salads in a supermarket in Klaipeda, Lithuania (photo T. Kulikowski)

Fig. 11. Chilled wakame seaweed salads in a supermarket in Helsinki, Finland (photo T. Kulikowski)

the addition of seaweed salad). Raw material for most of dried seaweed products in Baltic Sea region retail are: *Undaria pinnatifida* and *Laminaria japonica*. To a lesser extent: *Furcellaria lumbricalis*, *Codium fragile*, *Phaeophyceae*, *Alaria esculenta*, *Himanthalia* (Ibidem).

Some higher added value products are also available on the market, eg. mayo, spaghetti with seaweed extract, instant miso soup (source: GRASS processor and wholesalers surveys conducted in Denmark, GRASS retail survey in Latvia).

In the foodservice sector, macroalgae are represented mostly in menus of ethnic cuisine bars and restaurants (incl. sushi-bars) and higher positioned restaurants with special (author's) cuisine, but rarely you can find products from macroalgae in restaurants with local seafood cuisine. For sushi (nori) *Porphyra umbilicalis*, *Porphyra tenera* and other species from the genus *Porphyra* are mostly used. Other important raw materials for Japanese cuisine dishes are: *Laminaria japonica* and *Laminaria saccharina*, which in the form of dried kombu, are used for the miso soup.

Despite the fact that the majority of sushi consumption falls on the food service, the popularity of retail packed sushi as well as home-made sushi ingredients is growing. Other sushi varieties that are becoming more and more popular in retail chains are also Korean „kimbap" and Hawaiian „poke".

Fig. 12. New snack on Polish seaside - herring with algae. "Przetwórnia" Restaurant in Kuźnica (photo T. Kulikowski)

Fig. 13. Trendy snack - poke, modeled on Hawaiian cuisine. One of the basic raw materials is seaweed (photo source: 123rf.com)

Food products for vegans

Algae as a source of vitamins, proteins and exogenous amino acids, as well as micro and macroelements are a valuable supplement to the vegetarian diet. Recently, due to the growing popularity of the vegan diet, there has also been an increase in demand for agar-agar (Callaway et al., 2015).

Algae are excellent substitutes for animal protein. Ingredients based on algae are used for „fish" and „meat" vegetarian products such as burgers, sausages, bacon, salmon, tuna. Algae, as a rich source of omega-3 acids, can also be a substitute for conventional oils, e.g. olive oil (Handbook of Algal, 2020).

read more:
Macroalgae as food in the Baltic Sea region:
(i) Health benefits and potential for food industry
(ii) Risks and food safety regulation

reports available online:
www.submariner-network.eu/grass

Functional food, supplements, nutraceuticals

Functional food is defined as food which has a beneficial effect on one or more target functions in the body, in addition to having an adequate nutritional effect, in a way that significantly improves health and well-being and/or reduces the risk of diseases. Nutraceutics are defined as a food or food products that provide health and medical benefits, including the prevention and treatment of a disease. These include compounds such as carotenoids and PUFA. The nutraceutical market is very

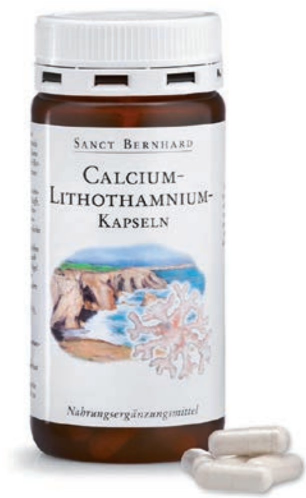
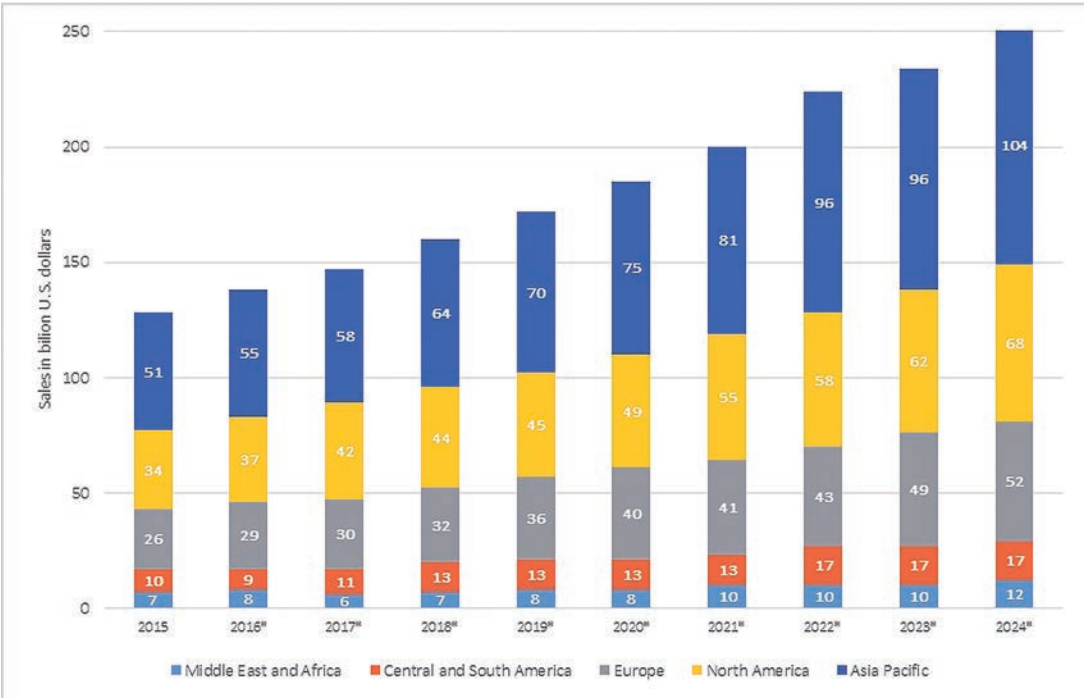


Fig. 14 An example of food supplement — calcium from macroalgae Lithothamnium calcareum, produced in Germany (photo source: producers catalogue)

attractive for many bioactive compounds derived from algae. Moreover, this is not limited to humans, and there is a significant market for pet food.

Fig. 15. Worldwide sales of functional food in 2015-2024 (USD billion)



Sales estimates. Figure source: Worldwide Sales of Functional Food (2017)

There are more and more dietary supplements and functional food that contain algae in their composition. Algae are rich in microelements: bromine, zinc, iodine, magnesium, manganese, copper, iron. They occur in a particularly well assimilable form – as organometallic or complex compounds (Godlewska et al. 2014). From the group of vitamins in algae, the following were identified: carotenoids, e. g. β-carotene (source of vitamin A), B vitamins (B1, B2, B5, B6, B12), and vitamins: E (tocopherol), C (ascorbic acid) and D (Wells M. et al., 2016).

Diet product/dietary supplement

Dietetic food

Agar as a substitute for gelatin has much less calories, swells in the stomach, giving a feeling of satiety. It contains large amounts of fibre, vitamins K, E and B6, folic acid and omega 3 acid.

Supplementation

From the group of vitamins in algae, the following were identified: carotenoids, e.g. β-carotene (source of vitamin A), B vitamins (B_1, B_2, B_5, B_6, B_{12}), and vitamins: E (tocopherol), C (ascorbic acid) and D (Wells M. et al., 2016).

„Agar-agar is the longest used colloid derived from plants. For more than 300 years it has been used as a food additive in the Far East and for more than 100 years in Western countries. It is completely safe. This confirms its longstanding application, as well as the opinions issued by FAO/WHO and FDA expert groups"
(Żyłowska-Mharrab, 2019)

Fig. 16 *Agar-agar (photo source: 123rf.com)*

2.2. Cosmetic industry

The broad spectrum of compounds derived from marine algae has played an important role in the development of cosmetic and pharmaceutical products. Cosmetics and creams based on algae provide the skin with nutrients, accelerate the regeneration of the epidermis, heal scars, make the skin tight and brighten up, show antiviral and antibacterial effects. Sugars found in algae have a strong moisturizing and protective effect. They stimulate blood and lymph microcirculation and metabolic processes in the cells. Lipids contribute to the restoration and protection of the epidermis. Numerous dyes have anti-free radical and anticancer properties. They show a photoprotective effect and delay ageing processes. Algae contain also polyphenols (indicating antioxidant and anti-inflammatory effects), biogenic compounds (acting antibacterial), natural dyes (protecting against UV damage), and vitamins (B1, B2, B5, B6, B12, C, E, A and D).

Cosmetics with anti-aging properties

Algae extracts are mainly used in facial and skin care products, i. e.:

- anti-wrinkle creams,
- regeneration creams,
- skin softening products,
- anti-irritation products,
- sunscreens,
- hair care products.

Cosmeceuticals

Cosmeceutics are cosmetic products containing biologically active components with pharmaceutical properties (medical or drug-like benefits). The term „cosmeceutics" originates from the words cosmetics and pharmaceuticals.

Algae extracts have already been used as sources of cosmeceutics. Particular attention was paid to carotenoids and astaxanthin extracted from marine algae, which were studied for cosmeceutical purposes ((Pereira, 2020)).

Brown seaweed extract (containing fucoidan fractions) can be used in cosmetology as an activator of fibroblast proliferation in aesthetics-oriented treatments, for example, in anti-wrinkle treatments or in the prevention of skin aging without patent infringement.
The methanol extract from Corallina pilulifera algae has a strong antioxidant and a protective effect on the UVA-induced oxidative stress of human skin fibroblast cells. Macroalgal extract can be a potential source of natural anti-ageing compounds (Rudawska D., et.al., 2018; Alves A. et.al., 2020).

Fig. 17 *Seaweed use in cosmetology: algae mask (photo source: 123rf.com)*

Natural cosmetics

Natural cosmetics are products that are produced almost exclusively from natural substances. Natural raw materials are substances of plant, animal or mineral origin, as well as mixtures and reaction products between them. Only physical processes such as pressing, extraction (with water, ethanol, glycerine or carbonic acid), filtration, distillation, drying, etc. may be used in order to obtain and process them. In addition, enzymatic and microbiological processes which are used on naturally occurring unmodified enzymes and microorganisms are acceptable. Eco/bio/organic/natural cosmetics are much more expensive than traditional ones. The production of those cosmetics is associated with many requirements. They must meet strictly defined standards (Pereira, 2020; Alves et.al., 2020).

MAA extracted from Porphyra umbilicalis red algae has shown in vitro protective effects of DNA and vitality enhancing properties. Another compound, GSH, is an oxidant found in all macroalgae species. Some of them contain up to 3 mg GSH / 100 g biomass. Sometimes GSH is used orally as a skin bleaching agent. Macroalgal polysaccharides have many bioactivities that can have antioxidant, antibacterial, antiviral, anticancer, antithrombotic and other bioactive properties for use as pharmaceuticals and cosmeceutics. Laminaria saccharina extract contains proteins, vitamins, minerals and carbohydrates that regulate the activity of the sebaceous glands, and it has anti-inflammatory and healing properties. Other bioactive compounds are β-carotene, γ-linolenic acid, polysaccharides and amino acids. Lipids extracted from small green Nannochloropsis algae are used in cosmeceutics and skin care.

TARASÓL - The pioneering bio-marine liposomal sunscreen released to the skin upon sunlight exposure

A team of Taramar scientists has developed a method of making water-based skin care products using unique compounds that benefit the skin and body. The results of these studies indicate that Icelandic seaweed extracts stimulate the immune modulatory response and protect skin cells against the aging process. Taramar scientists have successfully developed a UV filter that is free from the harmful toxic chemicals found in most cosmetics on the market. At the same time, thanks to the NoTox ™ technology, they discovered safe and natural methods of preserving the functional properties of the bioactive seaweed molecules by blocking the growth of microorganisms. As a result,

Fig. 18 *Use in cosmetology: a seaweed wrap (photo source: 123rf.com)*

the UV filter developed under the TARASÓL project is devoid of typical preservatives, making it completely safe for the skin and the whole body. Seaweed's antioxidant and anti-inflammatory properties provide additional and clearly visible skin benefits. Researchers have observed that some organic compounds, such as collagen and vitamin C, do not readily cross the cell membrane. Therefore, they enclose the components of seaweed in liposomal carriers of substances that stabilize and release a bioactive UV filter when exposed to sunlight (Tarasol).

Aesthetic medicine and dermatology

Algae can also be used in cosmetic treatments as well as in aesthetic medicine and dermatology (Thomas et.al, 2019). Advantages of using algae in aesthetic medicine (Godlewska et.al., 2014):

- provide the skin with nutrients and protect it from adverse environmental factors,
- have the ability to cleanse, tighten the skin and brighten the complexion,
- protect against moisture loss, forming a protective layer on the skin,
- soothe irritation, heal scars, accelerate the regeneration of the epidermis by renewing it by granulation (wound granulation),
- support osmosis in the intercellular areas and cellular metabolism, thus preventing leg swelling and cellulite,
- improve blood circulation, reduce the tendency of blood vessels to burst, stimulate microcirculation, helping to eliminate circulatory disorders,
- iodine contained in algae mucous substances acts on the subcutaneous fatty tissue, which leads to regulation of sebaceous glands by removing excess fat (elimination of cellulite and support of weight loss),
- antibacterial properties, by inhibiting inflammation – show free radicals removal.

2.3 Medical industry / pharmacy

PHARMACY

Agar, carrageenan or alginates are commonly used in the pharmaceutical industry as functional components, such as stabilisers. It was also indicated that seaweed polysaccharides have prebiotic properties. Agar is also used in pharmaceuticals and laboratories (as a medium for microbiological cultures). In addition, agar can be applied externally, e.g. on sore joints (it has an anti-inflammatory effect). Traditionally, sodium alginate is used as a filling for tablets.

MEDICINE

Due to its anti-inflammatory, antioxidant, antibacterial, anticancer and slimming properties, algae can be used in the treatment of many diseases (Shu et al., 2013). They are successfully used for weight loss as well as for the treatment of: bronchitis, colds, chronic coughing, venereal diseases, hyperthyroidism, urethral fossa, and also as ointments and anaesthetics. Thanks to their anti-inflammatory, anticancer and antibacterial properties, they can be used in medicine, as there is a growing worldwide interest in pharmaceuticals of natural origin, which are perceived as more safe for humans (Boopathy, 2010).

Research on the antibacterial properties of algae extracts isolated off the coast of Jeddah, the Red Sea in Saudi Arabia was conducted. High activity of the extracts formed on the basis of biomass of the following species was found: Ulva reticulate, Caulerpaoccidentalis, Cladophora socialis, Dictyota ciliolatei, Gracilaria dendroides. Four algae extracts prepared in ethanol and chloroform contain active substances that may inhibit the growth of the bacteria examined (Staphylococcus aureus, Enterococcus faecalis, Escherichia coli and Pseudomonas aeruginosa), with the exception of C. occidentalis alcohol extract, which inhibited the growth of Enterococcus faecalis only. The aqueous extract of C. occidentalis did not show antibacterial properties against all studied bacteria. It is concluded that the extraction using ethanol and chloroform allows obtaining from the algae biomass substances with a strong bacterial growth inhibitory effect (Abdu-llah Al-Saif , et. al., 2014).

Rhodophyta are a potential source of new compounds that can be used to treat inflammation and relieve pain. The main feature of secondary metabolites derived from these organisms is the presence of halogens such as neorogioltriol - a tricyclic bromine diterpenoid isolated from Laurencia glandulifera. Neorogioltriol acts as an analgesic by blocking the activity of reaction mediators, through a mechanism dependent on the activation of opioid receptors and has anti-inflammatory properties that require inhibition of the transcription factor. Other halogen compounds such as vidalol A and B, bromophenol isolated from Vidalia obtusiloba have strong anti-inflammatory effects (Silva et.al., 2010].

Antibacterial and antiviral properties

In the last few years, increasing resistance of bacteria to antibiotics has been observed. Therefore, there is a tendency to search for and acquire new biologically active substances with antibacterial properties from natural sources.

Anti-inflammatory properties

Inflammation is a defensive reaction of the body aimed at counteracting harmful factors such as bacteria or viruses. In the treatment of diseases that can cause inflammation, nonsteroidal anti-inflammatory drugs (NSAIDs) are used, which cause a number of side effects. The most common is damage or irritation of the gastric mucosa. An alternative to these drugs appear to be products of natural origin that show anti-inflammatory and analgesic effects (Mirsha et al., 2015).

Diterpens – the Dictyotaceae algae family is capable of producing secondary metabolites such as diterpenes, derived from marine brown algae Dictyota ciliolata. They have an antiviral effect. For example, diterpenes extracted from Dictyota pfaffii and Dictyota menstrualis inhibited infection with the common herpes virus type 1 in Vero cells. Diterpenes from D. menstrualis were tested for HIV-1 (Chen et al., 2018).

Antioxidant properties

Antioxidants are compounds that counteract oxidation processes. Catabolic processes in living organisms produce free radicals which can damage, among others, the nucleic acids RNA and DNA.

Antioxidant activity has been reported in many types of marine algae including: Ahnfeltiopsis, Colpomenia, Gracilaria, Halymenia, Hydroclathrus, Laurencia, Padina, Polysiphonia and Turbinaria. Natural antioxidants can play an important role in various diseases and ageing processes. They have the ability to balance the harmful effects of oxidative processes in the body. They inhibit the chemical activity of free radicals (Mikołajczak, 2016).

Biomaterials

There are four types of alginate biomaterials produced: alginate fibres - fibres and nanofibres, active dressings, tissue engineering - structures used in tissue engineering, drug carriers - controlled drug dosing systems.

Currently, the main interest in the production of alginate fibres concerns their medical applications, mainly as modern dressing materials. Depending on the construction of the fibre material, many types of alginate fibres can be distinguished. These include alginic acid fibres, zinc alginate, copper alginate, sodium alginate, calcium alginate, calcium alginate with the addition of nanosilica (SiO_2), mixed fibres of Ca/Na and Ca/Zn alginates.

Modern constructions of biomaterials use tissue compatibility of alginates and their ability to biodegrade (Pielesz, 2010).

Fig. 19 Antimicrobial calcium alginate wound dressing, produced in Germany (photo source: producer's catalog)

A polymer naturally occurring in marine algae, i.e. alginic acid, does not dissolve in water, but swells very easily in an aqueous environment. After being extracted from algae, it is usually processed into the form of water-soluble sodium salts or very weakly soluble calcium salts. These alginates are formed into fibres and used, among others, to obtain absorbable dressings or surgical sutures. Biodegradable alginate fibres are for wound dressings and the production of implant materials.

Depending on the intended use, the following three types of biodegradable fibres were obtained and used for wound dressings: from copper alginate; calcium alginate containing nano-silver; and sodium alginate containing nano-silver.

The universal wound dressing is made from a mixture of fibres of copper alginate, calcium alginate and sodium alginate containing nano-silver. In addition to the specific effects of alginates, which include supporting wound healing, the presence of silver nanoparticles has increased the antibacterial properties of the wound dressing. Both types of nanocomposite fibres also differ in speed and ability to gel. Sodium alginate fibres are soluble in physiological fluids, allowing painless removal of the wound dressing, and calcium alginate fibres, with high sorption properties, absorb wound secretions. Due to the fact that copper alginate fibres are able to generate a negative static electrical charge, when in contact with the skin, it has a positive effect on the wound's surroundings, causing a reduction in pain sensation for patients.

Wound dressing is designed for skin lesions without exudate, e.g. bedsores or wounds at granulation stage. Calcium alginate fibres containing nano-silver are components of such multi-purpose wound dressings.

Algae intended for the production of implantable materials are polylactide nanofibres containing hydroxyapatite; calcium alginate fibres containing a ferromagnetic nanoadditive (Fe_3O_4); calcium alginate fibres containing nano-hydroxyapatite.

Marine algae are also used externally. They work well in the event of scratches or cuts, as they accelerate the healing process of wounds on the skin surface. Algae stimulate and intensify the process of the skin granulation, and thus rebuild the damaged epidermis.

2.4. Agriculture

Plant production

Marine algae have been qualified by scientists as a group of the most important living organisms that can be used on a large scale in plant cultivation. They are organisms rich in micro- and macroelements, necessary for plant growth.

Extracts obtained from algae have a set of plant hormones, thanks to which they show strong biostimulatory effects. The group of basic phytohormones identified in algae include: auxins, cytokinins, gibberellins, abscisic acid and ethylene. Auxins are responsible for the elongation growth of plant cells, apical dominance, root bud formation, cell division, plant movements and their aging. Cytokinins are involved in the regulation of cell division, thus affecting plant growth and dormancy. In addition, they inhibit the aging of plant tissues and play an important role in the transport of assimilates. The basic functions of gibberellins include induction of seed germination, growth regulation, interruption of the bud dormancy, and flowering and fruit set. Abscisic acid and ethylene inhibit growth, accelerate plant aging, and are responsible for plant responses to environmental stress factors. In addition, abscisic acid also participates in the regulation of seed germination (Tuhy, 2013).

Fig. 20 Plant stimulator, based on Ascophyllum nodosum concentrate (photo source: producer's catalog)

Products based on humic acids and algae are authorised for use in organic farming [Council Regulation (EEC) No 2092/91].

Algae extracts can be used in agriculture as fertilizers, plant biostimulators, plant growth bioregulators, protective substances.

Whole seaweed or purified polysaccharides can be supplemented with the diet of laboratory and farm animals. It has generally been observed that some macroalgae are eagerly eaten by cattle, sheep and pigs. This applies to the following species of algae: Fucus, Chorda laminaria, Alaria, Pelvetia, Ascophyllum, Rhodymenia, Laminaria digitata and Laminaria hyperborean (Kim 2014).

The future trend is the use of biologically active compounds contained in algae products to combat plant diseases caused by viruses and bacteria.

Algae as feed substances are listed in Commission Regulation (EU) No 68/2013 of 16 January 2013 on the catalogue of materials (OJ L 029, 30.1.2013, p. 1) (Algae are listed in Chapter 7. Other plants, algae and their by-products (items 7.1.1 to 7.1.6.).

Products for animals

Feed additives - no antibiotics
Animal feed

It is suggested that seaweed extracts can potentially be used as feed additives both to improve yield and to reduce pathogenic bacteria. From the literature review it can be concluded that the main attention is given to the use of brown macroalgae extracts (*Phaeophyta*) in pig nutrition.

Homogenized algae in mineral feed used in pig nutrition stabilize the gastric microflora and even reduce aggression and cannibalism. In cows, they stimulate rumen microorganisms, increase the amount of milk produced, reduce the number of somatic cells, prevent milk fever and facilitate subsequent calving. The studies proved that products rich in omega-3 and omega-6 fatty acids in the appropriate ratio, derived from edible algae, used in feeding of dairy cows, inhibited methane production. Honeycomb-like organisms of the genus Lithotamme promote the growth of bacteria in the rumen. When taken from the seabed, their calcified forms contain calcium that is better absorbed than that of fodder chalk. Freshwater macroalgae of the genera Ulva and Cladophora accumulate calcium and magnesium and can be supplements to these elements in animal nutrition. In goats, the rumen distribution of organic matter of macroalgae was recorded at 85% and its energy value was similar to that of medium quality hay. In fish farming in aquaculture, the use of algae has resulted in fish meat containing more protein and valuable nutrients such as taurine (biogenic amino acid), pigments (lutein and zeaxanthin), fats rich in omega-3 and omega-6 acids. Such farms produce salmon, trout, tuna, carp, shrimp and oysters. Algae provided in the larval stages of fish reduced mortality by 30% (Dorszewski, 2019).

The process of bioaccumulation of microelements by biomass from algae is used in feed supplementation. Livestock food should contain 8 basic microelements (Zn, Cu, Co, Mn, Mo, J, Fe, Se). Feed supplementation with inorganic salts is inefficient, and microelements from salts have low bioavailability in animal organisms. Elements (and proteins, unsaturated fatty acids or algae dyes) adsorbed by active biosorption are more effectively used by the consumer's body.

The main advantages of feeding animals with algae (mainly poultry, pigs, cattle) are (Chojnacka, 2012):

- improving weight gain and increasing fertility
- improving the functioning of the immune system (reducing the need for antibiotics)
- ensuring a higher concentration of beneficial compounds in meat, milk and eggs
- a source of highly digestible substances, vitamins, amino acids and proteins, micro and macro elements.

Recent studies have demonstrated that red macroalgasupplementation of beef cattle feed can reduce their enteric methane emissions up to 80% (Maia et al. 2016, Roque et al. 2021). These results suggest that red macroalgafeed supplements could significantly decrease the carbon footprint of ruminant livestock and increasing interest towards the red macroalgafeed supplements can be expected in the future (Rahikainen, 2021).

2.5. Industrial applications

Biofuel production

Algae can also be used for the production of biofuel. Algal biomass has many advantages: high growth rate, its vast potential to reduce greenhouse gas (GHG) emissions and climate change, and ability to store high amounts of lipids and carbohydrates. Algae can potentially reduce dependence on petroleum fuels and offset greenhouse gas emissions. In view of the increasing oil demand and the depleting oil reserves, the development of innovative techniques for the production of biofuels from novel renewable biomass feedstock sources are gaining importance all over the world. Aquatic biomass is considered a renewable energy source.

It is possible to produce ethanol from macroalgae (Goh and Lee 2010). Macroalgal biomass contains high amounts of sugars (at least 50%), which can be used in ethanol fuel production (Wi, 2009).

Macroalgae provides a promising bioethanol feedstock owing to their high biomass yield with a superior production relative to various terrestrial crops (John, et al. 2011).

The potential of macroalgae for ethanol production can be estimated based on the following postulations: a content carbohydrate 60% of dry weight and a 90% of conversion levels to ethanol through fermentation of 1 g of sugar can yield 0.4 g of ethanol. It will ideally give up 0.22 kg or 0.27 l ethanol from 1 kg dry weight of macroalgal biomass, equivalent to roughly 0.05 l ethanol per kg of wet weight (Kraan, 2010).

Optimal breeding conditions allow achieving a crop exceeding 100 t / ha / year. Other data show that algae can provide about 25,000 liters of oil per hectare, while rapeseed has a yield of 1,500 liters per hectare, sunflower 950 liters, and soybeans only 446 liters. Algae cultivation can become competitive in relation to traditional soil crops, also due to lower requirements for the area under cultivation (they have low nutritional requirements). Another advantage of using algae in biofuel production is that they are not competitors on the food market. In addition, biofuels obtained from algae biomass do not have sulfur compounds in their composition, therefore they do not show toxicity, and are distinguished by high biodegradability. One cannot ignore the fact that algae crops contribute to reducing the amount of carbon dioxide emitted into the atmosphere. In 2013, it was found that they are able to reduce greenhouse gas emissions by as much as 70%. Thanks to this property, algae can become an important weapon in the fight against global warming.

Algae are also a potential source of commercial biogas products, such as biohydrogen and biomethane that can be used as gas fuels or for electricity generation (Mussgnug et al., 2010). Hydrogen produced by macroalgae is a popular attraction in the renewable energy scenario. Current research has revealed that *Laminaria japonica* (brown alga) and *Gelidium amansii* (red alga) are both potential biomass sources for the production of biohydrogen by anaerobic fermentation (Park et al., 2011) Macroalgae can produce biohydrogen under specific conditions.

Other technical / industrial products

The gelling and viscosity properties of alginates are also used in the textile industry. They are characterized by high hydrophilicity, bind water and swell, so they are ideal thickeners in printing (Pielesz, 2010).

Some examples of unusual applications of alginates:

- plasticizers and sealants during fiber production;
- thickeners in reactive printing (high-viscosity CHT ALAINAT-SMT, low-viscosity CHT ALGINAT NV 10, liquid PRISULON AR-F 30);
- thickeners in shoe polish, used to cover the top layer of utility papers or as an additive in utility oils;
- fucus is used in the textile industry for fabric finishing and in the pharmaceutical and chemical industries in the manufacture of soaps, glue and plastic masses.
- a plastic substitute characterized by biodegradability and even shelf life
- „biopolymer nanocomposite" - a film of furcellaran, a sugar obtained from red algae invention; intelligent and active furcellaran-gelatin films (Jamróz E. et. al., 2019)
- objects with seaweed - pavilion made of kelp and rattan,
- natural (marinealgae based) red colorant which is healthy and has potentially skin rejuvenating properties;
- *F. lumbricalis* contains a red pigment, R-phycoerythrin, has laboratory applications in fluorescence-based detection, but requires a highly purified form for extraction (Estonian..., 2021).

"Recent innovations are expanding the use of seaweeds in the food sector to use in food packaging and production of single-use products like straws. Seaweed based bioplastics aim to be part of the solution to the global problem of ocean plastic litter. Seaweed plastics are degradable by marine bacteria and fungi and are thus an appealing solution to replace traditional plastics in food packages (https://rethink-plastic.com/, https://www.loliware.com/ (Rahikainen 2021)).

Fig. 21 *Biodegradable film based on furcelleran from red macroalgae, invented by Dr. Eng. Ewelina Jamróz and her team from the University of Agriculture in Krakow (photo source: E. Jamróz)*

2.6. Bio-environmental engineering

2.6.1. Biogen reduction in eutrophicated waters

(Magdalena Jakubowska)

As macroalgae uptake naturally occurring nutrients, cultivation sites have a huge potential to remove the excess of nitrogen and phosphorus from surrounding water and therefore may be used as a tool to combat eutrophication (Xiao et al., 2016). Theoretical amounts of nutrients that can be removed by harvesting 1 ton of Baltic macroalgae species, calculated based on their nitrogen and phosphorous content, are presented in Table 3.

Tab. 3 The total nitrogen and phosphorus content in Baltic macroalgae and theoretical values of nutrient removal by macroalgae harvesting.

	Mean dry weight (DW) content	N content (% DW)	P content (%DW)	Nutrient removed by harvesting of 1 ton of fresh macroalgae
Saccharina latissima	15.1%[1]	0.8 - 2.2[1] 1.81[9]	0.32[9]	1.3 - 3.3 kg N 0.5 kg P
Laminaria digitata	15.5%[1]	1.0 - 2.5[1]		1.55 – 3.9 kg N
Fucus vesiculosus	22.5%[2]	1.0 - 3.5[8]	0.39 - 0.75[8]	2.25 - 7.9 kg N 1.0 - 1.9 kg P
Ulva inestinalis	12.5%[4]	2.89[3] 1.48 - 4.07[7] ~1.5 - 5.5[5] 1.85[6]	0.23[3] 0.30 - 0.56[7] ~0.15 - 0.60[5]	1.8 - 5.1 kg N 0.2 - 0.7 kg P

	Mean dry weight (DW) content	N content (% DW)	P content (%DW)	Nutrient removed by harvesting of 1 ton of fresh macroalgae
Furcellaria lumbricalis	19.0%[10]	2.89 [9]	0.15[9]	5.5 kg N 0.3 kg P
Ceramium tenuicorne	12.6[11*]	3.03[3]	0.27[3]	3.8 kg N 0.3 kg P

1. Schiener et al., 2015, **2.** Catarino et al., 2018, **3.** Suutari et al., 2017, **4.** Ruangchuay et al., 2012, **5.** Fong et al., 2004, **6.** Barr and Rose, 2003 **7.** Björnsäter and Wheeler, 1990 **8.** Pedersen and Borum, 1996. **9.** Kornfeldt, 1982, **10.** Indergaard and Knutsen, 1990, **11.** Marsham et al., 2007.
*data for *Ceramium sp*. ranges of values - depending on the conditions, mainly nutrient concentrations

The nutrient content in macroalgae, especially nitrogen, is strongly related to that of seawater, thus varying through the year (Kornfeldt, 1982) and among macroalgae populations (Barr and Rees, 2003). Moreover, not only environmental nutrients concentrations but also their ratios (N:P) in surrounding water determine their content in algae (Björnsäter and Wheeler, 1990). Also, other factors like light intensity or salinity may affect the nutrient uptake of macroalgae (Kornfeldt, 1982). For example, *Ceramium tenuicorne* from the Baltic Sea can utilize very high nutrient levels, however, with decreasing efficiency towards the low salinity (Bergström and Kautsky, 2005).

Nutrient requirements, thus the nutrient uptake per biomass and time are much higher for fast-growing green macroalgae than slow-growing species like many red and brown seaweed (Pedersen and Borum, 1996). Therefore, green algae seem to be the most suitable for cultivations intended for nutrient removal. According to Kruk-Dowgiałło and Dubrawski (1998) *U. intestinalis* can remove 4.7 to 14.1 g of nitrogen in 24 hours from the water per 1 m^2 of net substratum in cultivation located close to the discharge of the wastewater. It should be kept in mind, however, that in many coastal ecosystems nutrient limitation for algae may occur, especially in summer, and thus such fast growing algae may suffer from the nutrient limitation much more than perennial species (Pedersen and Borum, 1996). Contrary to fast-growing algae, the perennial species may accumulate nitrates and phosphates to sustain growth during periods when less nutrients are available (Wallentinus, 1984). Although the nutrient content in red and brown algae may be high, they are characterized with relatively low growth rates, thus their production would probably affect the nutrients content in the surrounding water to a lesser extent than the farming site of green algae.

2.6.2. CO_2 capture

(Iwona Psuty)

Carbon dioxide (CO_2) is the greatest contributor to greenhouse gas emissions and is also responsible for causing ocean acidification. The global average atmospheric carbon dioxide concentration has increased from 277 ppm (pre industrial level) to 407 ppm (in 2018). The rapid increase in CO_2 concentration is having severe impacts on global climate patterns. Over 40% of anthropogenic CO_2 emissions dissolve into the oceans which slows the rise in the atmospheric level (Friedlingstein et al., 2019), but ocean acidification is considered one of the main threats to marine biodiversity (Riebesell et al., 2000). Given the severity of these impacts, mitigation of CO_2 emissions is of great importance.

Direct air carbon dioxide capture and storage technologies have been developed (Keith et al., 2018), however carbon sequestration through seaweed photosynthesis represents an alternative, more "natural" solution to removing CO_2 from the atmosphere. Seaweeds are ranked among the most efficient photosynthetic organisms on earth. They need nutrients and inorganic carbon to grow. The source of inorganic carbon is air-born CO_2 that dissolves into seawater.

The main processes providing climate mitigation are carbon assimilation by growing seaweed and carbon retention in soil. Actual seaweed global aquaculture production makes only a small contribution to capturing CO_2. The upper limit of the potential, based on 2014 data, is estimated at 0,68 Tg C per year (2,48 mln tons of CO_2) (Duarte et al., 2017). This estimate was based on the assumption that dry weight constitutes 10% of the fresh production weight and the average carbon content of seaweed is 24.8% of dry weight.

Considering the species that can be farmed in the Baltic Sea, growing and harvesting 1 ton of wet weight of macroalgae means capturing 140 to 220 kg CO_2 (Table 1). However, it should be emphasized that the carbon content would be different depending on the growth stage of the macroalgae and the physico-chemical conditions at the site.

Tab. 4 Estimated amounts of CO_2 capture by growth and harvesting of 1 ton of macroalgae

	Dry matter content (DW)	Average total carbon content	CO_2 capture from 1 t of fresh weight FW (kg)
Saccharina latissima	15.10%[1]	26.20%[1]	140
Laminaria digitata	15.50%[1]	29.20%[1]	170
Fucus vesiculosus	16.00%[2]	36.90%[3]	220
Ulva intestinalis	12.50%[4]	35.00%[5]	160

1. (Schiener et al. 2015) 2. (Catarino et al. 2018) 3. (Balina et al. 2016) 4. (Ruangchuay et al. 2012) 5. (Gubelit et al. 2015)

The seaweed cultivations can produce between 20 and 150 tons FW per hectare per year, depending on cultivated species, cultivation configurations and seasonal fluctuations (Kerrison et al., 2015). For *Saccharina latissima* potential production in the Oosterschelde estuary was assessed by van Oirschot et al. (2017) based on the growth rates of experimental seaweed farms in the Netherlands, Sweden, Ireland and France at the level of 72 (single layer design) to 108 (dual layer) tons per hectare per year. However, the yield obtained from a 0.5 ha experimental farm on the Swedish west coast was only 22.6 - 27.6 ton FW/ha (Pechsiri et al., 2016). Based on data collected during 10 years of field experiences on a 2 ha farm (Hasselström et al., 2020) it was estimated that the average yield was 18.7 with a range from 17.5 to 35.1 ton FW/ha.

Data on the growth rate of *Fucus vesiculosus* and *Fucus serratus* at an experimental cultivation from the Kiel fjord in the Western Baltic Sea (Meichssner et al., 2020) suggests that the productivity of the farm can reach 50 tons FW/ha under optimal conditions. A similar level of maximum yields of 50-80 ton FW/ha, depending on the location of the cultivation site, results from an experiment on the growth of *Ulva* spp carried out in 1995 in the Puck Bay (Kruk-Dowgiałło and Dubrawski, 1998).

Considering the results above, Table 2 shows the estimated values of absorbed CO_2 by cultivation and harvest of 1 hectare of sea surface area for different species of macroalgae under optimal conditions in the Baltic Sea.

Tab. 5 Estimated amounts of $C0_2$ capture by seaweed cultivation per hectare of sea area under conservative and optimistic scenarios

	Biomass yield (ton FW/ha)	CO_2 capture (t)
Saccharina latissima	20	2.90
	50	7.24
Laminaria digitata	20	3.31
	50	8.28
Fucus vesiculosus	20	4.32
	50	10.80
Ulva inestinalis	20	3.20
	50	8.01

2.6.3. CO_2 reduction through biofuel production

(Iwona Psuty)

The production of seaweed biofuel in the context of reducing CO_2 emissions is economically, energetically and technically challenging. In addition, any successful process appears to require both a method of preserving the seaweed for continuous feedstock availability and a method exploiting the entire biomass at a commercial scale (Milledge and Harvey 2016). But the attractiveness of the seaweed biorefinery concept is not based on the production of bioenergy itself but on the integration of different biomass conversion processes to produce energy and value added products into a single facility. This in turn reduces the cost of fuel production with the maximum utilization of the biomass (Balina et al., 2017). Design of a biorefinery, which will generate sustainable food, fuels and chemicals with reduced CO_2 emission is a complex task and is largely influenced by local raw material supplies, advances in multiple technologies and socio-economic conditions. A stepwise approach to maximizing the benefits from seaweed would include to sequentially extract high-value molecules used in the food, pharma or biotech industries, such as bioactive sulphated polysaccharides, pigments, and antioxidants and then convert—after extraction of carbohydrates for the hydrocolloid industry or for biofuels production—the lower value residue to protein concentrates with value in the feed industry (Duarte et al., 2017).

Fig. 22a Jet fuel produced from seaweed by Honeywell's Green Jet Fuel (photo source: producer / licence type CC BY-SA 3.0)

Another dimension of seaweed cultivation is the use of the maritime space. Calculations of the area required for seaweed aquaculture to supply 60% of the transportation fuel vary broadly, from <1% of the economic exclusive zone (EEZ) for Norway, to 10% of the Dutch EEZ and about twice of the German EEZ (Fernand et al. 2017). In the case of Israel, achieving the national target reduction in greenhouse gas emissions (26% compared to 2005 emissions) by replacing fossil fuels with bioethanol would require as much as 71% of the national EEZ (Chemodanov et al., 2017). Sea space is a limited resource for many countries. Its use for seaweed aquaculture may result in a change in CO_2 emissions from other sources (e.g. related to the shipping). According to calculations by Duarte et al., the CO_2 sequestration secured by offshore wind farms is 12,500 tonnes CO_2 km^2 a $year^{-1}$, while the potential CO_2 sequestration intensity by seaweed farms is about 1,500 CO_2 km^2 a $year^{-1}$. However, seaweed can be planned in areas already occupied by wind farms and in areas where they are not possible to construct.

2.6.4. CO_2 emissions mitigation future potentials

(Iwona Psuty)

Seaweed aquaculture can mitigate CO_2 emissions in other ways than the biofuel production:

- Macroalgae are as well considered as promising sustainable alternatives to conventional terrestrial animal feed resources. The advantages include high growth rate, potential cultivation in saltwater, and no occupation of arable land (Øverland et al. 2019).
- The addition of macroalgae to animal feed can inhibit microbial methanogenesis e.g. (Brooke et al. 2020; Machado et al. 2014). In vitro experiments showed that fermentation of seaweed, simulating that of ruminant digestion, substantially reduced methane emissions (Maia et al., 2016). When incubated with meadow hay, *Ulva* sp. (among other species), decreased methane production to 55% of the control fermentation.
- Soil amelioration by nutrient-rich seaweed biochar or seaweed compost are reported as factors to increase productivity of agricultural crops (Roberts et al., 2015) (Cole et al., 2016). Agriculture is responsible for about 26% of greenhouse gas emissions (Poore and Nemecek, 2018), resulting in intense emissions associated with the production and application of industrial fertilizers and emissions from cattle. Use of seaweed biochar or compost would reduce greenhouse gases emissions involved in mineral fertilizer production.
- Seaweed is a highly potential source for renewable biopolymers and the development of biocompatible and environmentally friendly materials (Jumaidin et al., 2018).

[1] The CO_2 emissions avoided per unit area by offshore wind farms were derived by dividing the CO_2 avoidance of wind farms by the area occupied by the farms, corrected for a 2% lifecycle CO_2 emissions over a nominal 20 year life span of the turbines (Martínez et al., 2009). The calculations were based on data for the Sandbanks offshore wind farms (Germany, 21 turbines in 61 km^2) and for the LINCS offshore wind farms (UK, 83 turbines in 35 km^2).

3. Macroalgae food market

(Tomasz Kulikowski, Olga Szulecka)

3.1. Consumption traditions in BSR

During the GRASS project, the NMFRI has obtained reliable information on the long-standing tradition of the safe consumption (within the meaning of Regulation (EU) 2015/2283) of a few seaweed products in the Eastern Baltic Sea Region, covering at least three countries: Estonia, Latvia and Lithuania:

- seaweed in a form of salad and dried seaweed from genera *Laminaria* (called „sea cabbage"),
- sweet jelly based on furcellaran produced from genera *Furcellaria*.

The first is *sea kelps,* known on the market as *„sea cabbage"* (rus. *морская капуста*, lit. *jūros kopūstai*, lat. *jūras kāposti*, est. *merikapsas*). These are various products from macroalgae species: *Laminaria japonica*, *L. digitata*, *L. saccharina*. The most important form is chilled, pasteurized or sterilized salad *(Morskaja Kapusta, 2020)*.

Fig. 22b Sea cabbage salad from Estonian market, 2020 (photo source: producer's catalog)

Fig. 23 Sea cabbage salad from Latvia, 2014 (photo source: producer's catalog)

Fig. 24 Sea cabbage salad from Lithuania, 2020, (photo T. Kulikowski)

Fig. 25 Sea cabbage salad from Latvia, sold "by weight" on Riga Central Market, 2012 (photo source: 123rf.com)

The tradition of consuming these products dates back to the beginning of the 20th century and has been documented also in the scientific literature for the entire former Soviet Union (Song, 2016), thus also in the area of the present-day Estonia, Lithuania and Latvia**.** These products (sea cabbage salad) are constantly present on markets. During the GRASS project, photographs were taken of these products, sold by weight and packaged, in Lithuania, Latvia and Estonia (see Fig. 22-25). During interviews with sellers, they confirmed that these products have been on the market at least since the 1970s.

In the Soviet Union, thus also in the area of the present-day Estonia, Lithuania and Latvia, the consumption of *Laminariae* algae in the form of a dried product (used, among others, as an addition to soups) was also known. This also applied to the species *Laminaria thalli* (Fig. 26a). This product (dried seaweed) is also constantly present on the markets of Estonia, Latvia and Lithuania, but is currently offered as a product associated with Far Eastern cuisine, not traditional cuisine.

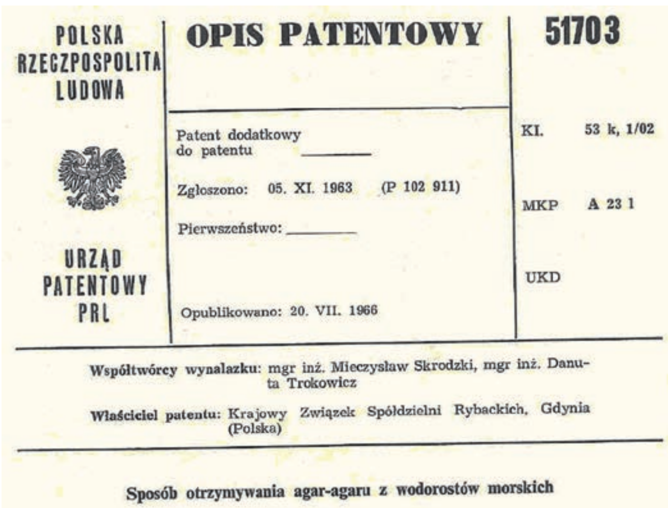
Fig. 26a Packages of dried sea cabbage from the Soviet Union, 1977 (photo source: http://foto.a-le.ru/?p=1564)

The consumption of agar-agar from *Furcellaria*, now correctly referred as "Furcellaran" (other names: *Baltic agar, Black Carrageen, Crúba préacháin, Danish agar, Escad, Forma minor, Forma tenuior, Furcellaran, Furgin, Leaba phortáin, Ostsee-agar*), is well documented for Estonia, from 1966 (Möller, Georg 2020). This gelling agent is used for production of jelly confection for decades (at least 50 years) in Kalev factory.

"NOSTALGIC FLAVOURS – A RECIPE FROM 1966
The slightly sour berry-flavoured jelly confection Mary has been on Kalev's production list for decades. The jelly contains apple puree and the jellifier Estagar, obtained from the Baltic Sea red algae Furcellaria, and this is what makes Kalev's jelly candies unique. Mary is coated with a glaze of real chocolate. A perfect treat for sweet tooths who appreciate the combination of sour jelly with a delicious chocolate glaze" (Kalev, 2020).

Fig. 26b *Sour berry-flavoured jelly confection from Kalev company in Estonia (photo source: Möller, Georg 2020)*

For the Polish market - no documentation was found regarding the direct consumption of seaweed (fresh or processed). Instead, records were found for the production (from years 1963 to 1974) of a substance called that time agar-agar produced from macroalgae *Furcellaria* genus.



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Sposób otrzymywania agar-agaru z wodorostów morskich

Fig. 27 Copy of the title page of the patent description for the production of agar-agar from *Furcellaria* seaweed - Poland, 1963 (photo source: Jakubowska 2020)

3.2. Legal aspects of macroalgae use in food industry

3.2.1. European legislation about novel foods

The requirements for novel foods are currently established in Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods, amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001 (Reg. (EU) 2015/2283).

Familiarize yourself with the following legal acts:
Commission Implementing Regulation (EU) 2017/2470 of 20 December 2017 establishing the Union list of novel foods in accordance with Regulation (EU) 2015/2283 of the European Parliament and of the Council on novel foods (OJ L 351, 30.12.2017, p. 72–201, with later amendments).
Commission Regulation (EU) No 231/2012 of 9 March 2012 laying down specifications for food additives listed in Annexes II and III to Regulation (EC) No 1333/2008 of the European Parliament and of the Council (OJ L 83, 22.3.2012, p. 1–295, with later amendments).
Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives (OJ L 354, 31.12.2008, p. 16–33, with later amendments).
Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods, amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001 (OJ L 327, 11.12.2015, p. 1–22, with later amendments).

In accordance with the document (Reg. (EC) 2015/2283) novel food means any *food that was not used for human consumption to a significant degree within the Union before 15 May 1997, irrespective of the dates of accession of Member States to the Union, and that falls under at least one of the following categories* mentioned in Reg. (EU) 2015/2283. One of the categories is food consisting of, isolated from or produced from microorganisms, fungi or algae. That means that the food consisting of algae which were not used for human consumption within the EU significantly before 15 May 1997 will be declared as novel food if it is included in the list contained in Commission Implementing Regulation (EU) 2017/2470 of 20 December 2017 establishing the Union list of novel foods under Regulation (EU) 2015/2283 of the European Parliament and of the Council on novel foods (Reg. (EC) 2015/2283).

In accordance with Regulation (EU) 2015/2283 the novel foods can be authorised by the Commission only and included in the Union list if they comply with the following conditions:

1. *the food does not, on the basis of the scientific evidence available, pose a safety risk to human health;*
2. *the intended use of the food does not mislead the consumer, especially when the food is intended to replace another food and there is a significant change in the nutritional value;*
3. *where the food is intended to replace another food, it does not differ from that food in such a way that its normal consumption would be nutritionally disadvantageous for the consumer.*

The application for authorisation of placing on the UE market of novel foods can be started either on the Commission's initiative or following an application to the Commission by an applicant and shall include:

a) the name and address of the applicant;
b) the name and description of the novel food;
c) the description of the production process(es);
d) the detailed composition of the novel food;
e) scientific evidence demonstrating that the novel food does not pose a safety risk to human health;
f) where appropriate, the analysis method(s);
g) a proposal for the conditions of intended use and for specific labelling requirements which do not mislead the consumer or a verifiable justification why those elements are not necessary (Reg. (EC) 2015/2283).

The list of novel foods presented in Reg. (EU) 2017/2470 contained for every item particular information: name of novel food, the condition under which the novel food may be used (specified food category, maximum levels), additional specific labelling requirements, other requirements and new criteria – data protection. Also the list includes the full description and characteristic/composition, content of heavy metals and microbiological criteria (Reg. (EU) 2017/2470).

The novel foods from algae or microalgae placed on the list in Reg. (EU) 2017/2470 are e.g. *Odonella aurita* microalgae, *Schizochytrium* sp. oil rich in DHA and EPA, *Schizochytrium* sp. (ATCC PTA-9695) oil, *Schizochytrium* sp. oil, *Schizochytrium* sp. (T18) oil, dried *Tetraselmis chuii* microalgae, algal oil from the microalgae *Ulkenia* sp., Astaxanthin-rich oleoresin from *Haematococcus pluvialis* algae.

3.2.2. Rules for the use of seaweed-based food additives in the food industry

According to Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives, the following additives produced from algae are established as additives other than colours and sweeteners (Table 6). They can be used in food products. The specific maximum level for those additives for most of the food products is quantum satis, which shall mean that no maximum numerical level is specified and substances shall be used in accordance with good manufacturing practice, at a level not higher than is necessary to achieve the intended purpose and provided the consumer is not misled (Reg. (EC) No 1333/2008).

However there are the food products when the maximum level of mentioned additives is strictly established e.g. jam, jellies and marmalades and sweetened chestnut purée as defined by Directive 2001/113/EC (maximum level – 10 000 mg/l or mg/kg), processed cereal-based foods and baby foods for infants and young children as defined by Directive 2006/125/EC but only for desserts and puddings (maximum level - 500 mg/l or mg/kg), dietary foods for infants for special medicinal purposes and special formulae for infants and also for dietary foods for babies and young children for special medicinal purposes as defined in Directive 1999/21/EC (of E 410 – 1000 mg/l or mg/kg and E 405 – 200 mg/l).

Tab. 6 Additives produced from algae established as other the colours and sweeteners

No	E-number	Name of food additive
1	E 400	Alginic acid
2	E 401	Sodium alginate
3	E 402	Potassium alginate
4	E 403	Ammonium alginate
5	E 404	Calcium alginate
6	E 405	Propane-1,2-diol alginate
7	E 406	Agar
8	E 407	Carrageenan
9	E 407a	Processed euchema seaweed

Source: Elaborated on the basis of Reg. (EC) No 1333/2008.

Algae can be also used as the colours - additive E 160a (iv) Algal carotens,, which is produced from strains of the algae *Dunaliella salina*. Beta-carotene is extracted using an essential oil. Additive E 160a is a food colour authorised at quantum satis and can be used for particular types of food listed in Tab. 7.

Tab. 7 Types of food, where E 160a can be used as colours

No	Type of food	Maximum level (mg/l or mg/kg as appropriate)	Restrictions
1	Ripened cheese	*quantum satis*	Only ripened orange, yellow and broken-white cheese
2	Processed cheese	*quantum satis*	-
3	Cheese products (excluding desserts)	*quantum satis*	Only ripened orange, yellow and broken-white products
4	Fats and oils essentially free from water (excluding anhydrous milkfat)	*quantum satis*	Only fats
5	Butter and concentrated butter and butter oil and anhydrous milkfat	*quantum satis*	Except butter from sheep and goats milk
6	Other fat and oil emulsions including spreads as defined by Council Regulation (EC) No 1234/2007 and liquid emulsions	*quantum satis*	-
7	Dried fruits and vegetables	*quantum satis*	Only preserves of red fruits
8	Fruits and vegetables in vinegar, oil, or brine	*quantum satis*	Only preserves of red fruits Only vegetables (excluding olives)
9	Canned or bottled fruits and vegetables	*quantum satis*	Only preserves of red fruits

No	Type of food	Maximum level (mg/l or mg/kg as appropriate)	Restrictions
10	Fruits and vegetables preparations excluding compote	*quantum satis*	Only preserves of red fruits Only seaweed based fish roe analogues
11	Jam, jellies and marmalades and sweetened chestnut purée as defined by Directive 2001/113/EC	*quantum satis*	Except chestnut purée
12	Processed potato products	*quantum satis*	Only dried potato granules and flakes
13	Breakfast cereals	*quantum satis*	Only extruded puffed and or fruit-flavoured breakfast cereals
14	Non-heat-treated meat products	20	Only sausages
15	Heat-treated meat products	20	Only sausages, pâtés and terrines
16	Processed fish and fishery products including molluscs and crustaceans	*quantum satis*	Only fish paste and crustaceans paste Only pre-cooked crustacean Only smoked fish

Source: Elaborated on the basis of Reg. (EC) No 1333/2008.

Commission Regulation (EU) No 231/2012 of 9 March 2012 laying down specifications for food additives listed in Annexes II and III to Regulation (EC) No 1333/2008 of the European Parliament and of the Council, presents the necessary specification for all the additives also E 400-407a and E 160a (iv). The regulation includes for each additive: chemical definition and other chemical information e.g. einecs, chemical name, chemical formula, molecular weight and assay, description, identification (also pH requirements) and also important information of purity (e.g. loss in drying, the content of arsenic, lead, mercury, cadmium) and microbiological criteria (total plate count, yeast and moulds, *Echerichia coli* and *Salmonella* spp.). Fulfilment of mentioned criteria led to use that additive for food purposes (Reg. (EU) No 231/2012).

3.2.3. European seaweed contaminants legislation

The seaweeds and products derived from seaweed as a part of foodstuffs have to fulfil the European Union regulations concerning the safety of food also in the field of contaminants.

The maximum levels of arsenic, cadmium, lead, tin and mercury for various foodstuffs are established under Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. However, under this regulation, only the limits of cadmium for food supplements consisting exclusively or mainly of dried seaweed or products derived from seaweed, are established at the level of 3.0 mg/kg wet weight. The limits of lead and mercury for all food supplements are established respectively at the level of 3.0 mg/kg and 0.1 mg/kg wet weight. The maximum level applies to the food supplements as sold. There is no other specific regulation for seaweeds or halophytes in this document (Reg. (EC) No 1881/2006).

The level of mercury for algae and prokaryotic organisms was established at the default level of 0.01 mg/kg under Regulation (EC) No 396/2005 (Reg. (EC) No 396/2005).

An upper limit for iodine intake was established in 2006 by the European Food Safety Authority and accounts for 600 μg/day for adults. The limits for children and teenagers are presented in table 8 (EFSA, 2006). In accordance with the high level of iodine in seaweed the European Commision recommends the monitoring of metals and iodine in seaweed, halophytes and products based on seaweed (Rec. (UE) 2018/464).

Tab. 8 Tolerable Upper Intake Level for Iodine

Age (years)	Tolerable Upper Intake Level (UL) for Iodine (µg per day)
1-3	200
4-6	250
7-10	300
11-14	450
15-17	500

Source: EFSA (2006).

The algal products, especially dried products are considered iodine-rich and can lead to dangerously excessive iodine intakes if such products contain more than 20 mg iodine/kg dry matter and the exposed population lives in an area of endemic iodine deficiency.

Seaweeds, according to the available occurrence data, contain significant concentrations of arsenic, cadmium, iodine, lead and mercury. The contribution of seaweeds to the consumption habits of consumers in the EU is increasing. Therefore it is necessary to assess whether the contribution of arsenic, cadmium, iodine, lead and mercury from seaweeds requires the setting of maximum levels for arsenic, cadmium and lead for these commodities or a revision of the maximum residue levels for mercury for algae and prokaryotic organisms. It is also necessary to assess if another action needs to be taken concerning exposure to iodine from these products (Rec. (EC) 2018/464).

For food additives based on seaweed, specifications are laid down in the annexes to Commission Regulation (EU) No 231/2012 (Reg. (EU) No 231/2012). However, for some additives from seaweeds e.g. agar E 406, EFSA recommended a review of toxic element contamination levels to confirm its food safety. Moreover, it is necessary to assess the exposure to arsenic, cadmium, iodine, lead and mercury in seaweed- and algae-based food additives should be assessed.

Maximum levels of arsenic, lead, cadmium and mercury in the feed are established under Directive 2002/32/EC of the European Parliament and of the Council. Certain seaweed species are used as feed therefore the metal content of these species should also be investigated (Rec. (EC) 2018/464, Dir. 2002/32/EC).

The maximum residue levels of pesticides in plants for food and feed purposes were established in Regulation (EC) No 396/2005. This Regulation is often changed, therefore to be sure that the product complies with the provisions of this regulation, it is necessary to check it frequently. The algae and prokaryotic organisms have the code number 0290000 which makes this document easier to search. The maximum residue level for most pesticides in algae prokaryotic organisms amounts 0.01-0.1 (mg/kg).

3.2.4. Labelling legislation of the seaweeds

In accordance with Annex I of Reg. (EU) No 1379/2013 the seaweeds and other algae are classified as fishery and aquaculture products and are covered by the common organisation of the market in fishery and aquaculture products.

Therefore seaweeds and other algae have to be properly labelled not only in accordance with art. 9 of Reg. (EU) No 1169/2011, but also art. 35 of Reg. (EU) No 1379/2013.

Article 9 of Reg. (EU) No 1169/2011 requires that the following particulars shall be mandatory for the labelling of the products:

(a) the name of the food;

(b) the list of ingredients;

(c) any ingredient or processing aid listed in Annex II (of the reg.) or derived from a substance or product listed in Annex II causing allergies or intolerances used in the manufacture or preparation of a food and still present in the finished product, even if in an altered form;

(d) the quantity of certain ingredients or categories of ingredients;

(e) the net quantity of the food;

(f) the date of minimum durability or the 'use by' date;

(g) any special storage conditions and/or conditions of use;

(h) the name or business name and address of the food business operator referred to in Article 8(1) of the Reg.;

(i) the country of origin or place of provenance where provided for in Article 26 of the reg.;

(j) instructions for use where it would be difficult to make appropriate.

The other mandatory information which must be labelled on the seaweed or other algae, in accordance with article 35 of Reg. (EU) No 1379/2013 are the following:

(a) the commercial designation of the species and its scientific name;

(b) the production method, in particular by the following words '... caught ...' or '... caught in freshwater ...' or '... farmed ...';

(c) the area where the product was caught or farmed, and the category of fishing gear used in capture of fisheries, as laid down in the first column of Annex III to this Regulation;

(d) whether the product has been defrosted;

(e) the date of minimum durability, where appropriate.

The information about the defrosting of the product shall not apply to:

(a) ingredients present in the final product;

(b) foods for which freezing is a technologically necessary step in the production process;

(c) fishery and aquaculture products previously frozen for health safety purposes, in accordance with Annex III, Section VIII, of Regulation (EC) No 853/2004;

(d) fishery and aquaculture products which have been defrosted before the process of smoking, salting, cooking, pickling, drying or a combination of any of those processes.

Summarising the seaweeds and other algae have to be labelled not only as other food products but also as the fishery or aquaculture products, therefore the information about the production methods or scientific name are necessary for the next step in the supply chain and for the consumers.

3.3. Algae certification systems

The producers of all kinds of food placed on the European Union market have to fulfil the requirements established in many regulations. Two most general regulations which must be fulfilled by the entities in the plant supply chains are Reg. (EC) No 178/2002 (General Food Law) (Reg. (EC) No 178/2002) and Reg. (EC) No 852/2004 (Hygiene of Foodstuffs) (Reg. (EC) No 852/2004). It is no less important to comply with the requirements concerning, for example, microbiological criteria for foodstuffs written in Reg. (EC) No 2073/2005 or Reg. (EC) No 1881/2006 about contaminants (Reg. (EC) No 2073; Reg. (EC) No 1881/2006).

According to the European Union legislation (Reg. (EC) No 852/2004), the implementation of the HACCP system is required by every entity in the food supply chain (except the primary production). However, the seaweed or seaweed product producers can fulfil the additional requirements contained in various voluntary and private international standards e.g. ISO or CEN standard, MSC – Marine Stewardship Council or ASC – Aquaculture Stewardship Council, Friends of the Sea, GLOBALG.A.P., organic.

FAO

In 2011 the Technical Guidelines on Aquaculture Certification was prepared by FAO – Food and Agriculture Organization of the United Nations (FAO, 2011). These guidelines, according to the document, *provide guidance for the development, organization and implementation of credible aquaculture certification schemes*. The document presents 13 principles which must be fulfilled by the aquaculture certification schemes. One of the principles requires that *the aquaculture certification scheme should recognize that any person or entity undertaking aquaculture activities is obliged to comply with all national laws and regulations*. The other presents the statement that an aquaculture *certification scheme should be developed based on the best scientific evidence available, also taking into account traditional knowledge, provided that its validity can be objectively verified* (FAO, 2011). The document includes the minimum substantive criteria for food safety, animal health and welfare, environmental integrity and socio-economic aspects conceded with aquaculture. In addition, it presents the institutional and procedural requirements for establishing and implementing credible aquaculture certification schemes and special considerations for the implementation. Moreover, the document contains the list of terms and definitions connected with certification and accreditation.

ISO standards

Currently, there is no specific ISO standard for seaweed or algae certification. The standards connected directly to algae refers to environmental conditions e.g. water quality, and specifies methods for determining the inhibition of growth of algae by substances and mixtures contained in water or waste water (ISO, 2021).

However, the producers of seaweed and seaweed products for human consumption can implement the requirements of standards connected with quality, food safety or environmental management, and certify their systems according to the following standards:

- ISO 9001:2015 Quality management systems — Requirements,
- ISO 22000:2018 Food safety management systems — Requirements for any organization in the food chain,
- ISO 14001:2015 Environmental management systems — Requirements with guidance for use (ISO, 2021).

CEN

In March 2020 the European Committee for Standardization (CEN) released the first European standard for algae and algae products: EN 17399:2020 Algae and algae products – Terms and definitions. The document defines the terms related to functions, products, and properties of algae and algae products (CEN, 2021). It has also set up a foundation for regulations that can ease the entrance of algae into various markets (Algaebiomass, 2021a). According to that standard algae are regarded as a functional group of organisms consisting of microalgae, macroalgae, cyanobacteria and Labyrinthulomycetes (CEN, 2021).

This standard has been developed because of the growing market for algae and algae products and could represent an important milestone for establishing common baselines for a European seaweed industry and market.

ASC-MSC

ASC-MSC Certification standards version 1.0 was published on 22 November 2017 and the document became effective on 30 April 2018. Currently, version 1.01 is in force (ASC, 2021b). It is a joint Aquaculture Stewardship Council (ASC) and Marine Stewardship Council (MSC) certification for sustainable seaweed production.

The standard covers the certification for both marine and freshwater algae and also includes requirements for both macroalgae and microalgae.

The ASC-MSC certified seaweed producer ensures that their operations are sustainable by:

- Maintaining sustainable wild populations
- Minimising environmental impacts
- Ensure effective management
- Promoting social responsibility
- Strengthening community relations and interaction (ASC, 2021d).

The standard requires fulfilling 31 indicators organized in 5 core principles.

According to sustainable wild populations, producers have to confirm that harvesting and farming of seaweeds maintain the productive capacity of the wild seaweed populations and their sustainable use.

The principle "Environmental impact" describes the requirements about habitats, ecosystem structure and function, ETP and other species, waste management and pollution control, management of pest and diseases, energy efficiency, translocations and introduction of alien species. The principle "Effective management" includes requirements about legal and/or customary framework, decision-making processes, as well as compliance and enforcement. Also according to the "Social responsibility" principle all the *harvesting and farming activity have to operate in a social responsible manner including fulfilment of requirements about child labour, health, safety and insurance, fair and safety wages, working hours, and environmental and social training*. The 5th core principle of the ASC-MSC seaweed standard "Community relations and interactions" harvesting and farming activities have to be operated in a way that minimises negative impacts on neighbours, respects rights and cultures, and benefits communities (ASC, 2018).

Each of the 31 performance indicator can be assessed by the auditor as:

- Your operation meets global best practice.
- Your operation meets the acceptable level of practice but requires improvements to reach the global best practice.
- The acceptable level of practice is not met.

The certification will be awarded if the operation meets the global best practice for all performance indicators or meets the global best practice for most applicable performance indicators and some improvements are required. Depending on the type of production system used by the seaweed entity, the total number of performance indicators that can require improvements will vary (to a maximum of 8) (ASC, 2021c). The ASC-MSC seaweed standard is prepared not only for individual certification but also for group or multi-side assessment (ASC, 2018). The certified entities can label their certified products the ASC or MSC or joint label logo. The proper logo use depends on the production location and type and also the linkage to the wild stocks. A product carrying the ASC and/or MSC labels may contain 5% of non-certified seaweed in the total seaweed content (ASC, 2021a). The standard prepared in the English language was translated into Japanese, Korean and Bahasa language used in Indonesia (ASC, 2021b).

Currently, two production units are under assessment, five seaweed operations have already got certified (ASC, 2021b). One of them is the Dutch biotechnology company which became in January 2021 the first microalgae oil producer certified according to that standard (MSC, 2021). These microalgae are mostly cultivated for fish feed purposes. The ASC-MSC certified seaweed operations produce the following seaweed species: *Schizochytrium* spp., *Hizikia fusiformis*, *Saccharina japonica*, *Euglena* spp, *Chlorella* spp, *Undaria pinnatifida* (ASC, 2021a).

In June 2021 nine seaweed suppliers (mostly Asian) were certified according to the ASC-MSC seaweed standard, however one certificate was cancelled before the expiry date. (ASC, 2021b).

GLOBALG.A.P.

The Global GAP standard is dedicated to farmed animals and harvested plants. Version 5.4. of the standard was established in July 2020. In accordance with the Aquaculture module requirements, from April 2020, not only finfish, crustaceans or molluscs can be certified but also seaweed, including marine macro-algae: brown, red, or green. However, currently only *Caulerpa lentillifera* (Sea Grape/

Moai Caviar), *Ulva lactuca* (Sea Lettuce) and *Saccharina latissima* (Sugar Kelp/Royal Kombu) can be certified according to the GLOBALG.A.P. standard (GLOBALG.A.P., 2020a).

The seaweed producers have to fulfil the requirements established in the All Farm Base module and Aquaculture module.

The All Farm Base module includes requirements from the following areas: site history and site management, record keeping and internal self-assessment/internal inspection, hygiene, workers' health, safety and welfare, subcontractors, waste and pollution management, recycling and re-use, conservation, complaints, recall/withdraw procedure, food defence, logo use, traceability and segregation, mass balance, food safety policy declaration, food fraud mitigation, non-conforming products and GLOBALG.A.P. status (GLOBALG.A.P., 2020c).

The Aquaculture module, established previously for fish crustaceans or molluscs module include the requirements for site management, reproduction, chemical compounds, occupational, health and safety, fish welfare, management and husbandry at all points of the production chain, sampling and testing, feed management, pest control, environmental and biodiversity management, water usage and disposal, harvesting and post-harvesting operations, holding and crowding facilities, slaughter activities, depuration, postharvest – mass balance and traceability and also social criteria (GLOBALG.A.P., 2020c). Not all of them will be suitable for seaweed and have to adapt to the special seaweed cultivation. The requirements of the GLOBALG.A.P. are divided into Major Must and Minor Must level. To obtain GLOBALG.A.P. certification, the auditor has to confirm 100% compliance with all applicable Major must and QMS control points and also 95% compliance with minor must control points. The certified products can be then labelled GLOBALG.A.P. logo (GLOBALG.A.P., 2020b).

Friend of the Sea

Friend of the Sea is a non-governmental organisation founded in 2007 which certifies and promotes certified products from sustainable fisheries and aquaculture in order to conserve marine habitat and its resources (FotS, 2021). Friend of the Sea has created a certification program for products from both fishing and sustainable aquaculture. Audits must be carried out by independent certification bodies that ensure that the product conforms to the sustainability requirements.

The certified products can be labelled the Friend of the Sea logo.

The Friend of the Sea has prepared the Certification Criteria Checklist for Seaweed Products, for which the last update was in 2014, as well as the standard for sustainable seaweed both from harvesting and farming. The core criteria of the Friend of the Sea sustainable seaweed certification are:

- No impact on critical habitat
- Water monitoring
- Chemicals and hazardous substances
- Energy management
- Social accountability
- Traceability (FotS, 2021).

The certification criteria include the essential and important requirements which are mandatory for certification and recommendations which must be verified and reported by the auditor, however they are not mandatory for certification. The essential requirements are mandatory for certification.

Organic

The requirements for organic production were established in Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91. That document establishes common objectives and principles to underpin the rules set out under this Regulation concerning:

(a) all stages of production, preparation and distribution of organic products and their control;

(b) the use of indications referring to organic production in labelling and advertising (Reg. (EC) No 834/2007).

The regulation applies to the following products originating from agriculture, including aquaculture:

- *live or unprocessed agricultural products;*
- *processed agricultural products for use as food;*
- *feed;*
- *vegetative propagating material and seeds for cultivation*;

when such products are placed on the market or are intended to be placed on the market (Reg. (EC) No 834/2007). The regulation established the terms and definitions conceded with organic production and marker e.g. organic production which *means the use of the production method compliant with the rules established in this Regulation, at all stages of production, preparation and distribution.*

Detailed rules for implementation of the Reg. (EC) No 834/2007 was established in the Commission Regulation (EC) No 889/2008 of 5 September 2008 laying down detailed rules for the implementation of Council Regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control (Reg. (EC) No 889/2008).

However Reg. (EC) No 834/2007 is valid till 31 of December 2021 because it has been repealed by Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007 which shall apply from 1 January 2022. The products produced before 1.1.2022 in accordance with the Council Regulation (EC) No 834/2007 may be placed on the market after that date until stocks are exhausted (Reg. (EU) 2018/848).

The articles of Regulation (EU) 2018/848 precise the requirements for all the products, however part III (points 1 and 2) of Annex II include requirements for organic algae production.

Point 1 established the general requirements for both algae and aquaculture animals production. In accordance with point 1.1., part III, annex II *operations shall be situated in locations that are not subject to contamination with products or substances not authorised for use in organic production, or with pollutants that would compromise the organic nature of the products* (Reg. (EU) 2018/848).

All the operators producing algae or aquaculture animals should provide a sustainable management plan proportionate to the production unit. In accordance with point 1.6. *the plan shall be updated annually and shall detail the environmental effects of the operation and the environmental monitoring to be undertaken, and shall list the measures to be taken to minimise negative impacts on the surrounding aquatic and terrestrial environments, including, where applicable, nutrient discharge into the environment per production cycle or per annum. The plan shall record the surveillance and repair of technical equipment* (Reg. (EU) 2018/848).

Point 2 was dedicated to algae and also to phytoplankton production. It includes the requirements for conversion period for production units, production rules for algae, algae cultivation, and for sustainable collection of wild algae.

In accordance with point 2.2.1 the collection of wild algae and parts thereof is considered as organic production provided that:

(a) the growing areas are suitable from a health point of view and are of high ecological status as defined by Directive 2000/60/EC, or are of equivalent quality to:

— the production zones classed as A and B in Regulation (EC) No 854/2004 of the European Parliament and of the Council (1), until 13 December 2019, or

— the corresponding classification areas set out in the implementing acts adopted by the Commission in accordance with Article 18(8) of Regulation (EU) 2017/625, from 14 December 2019;

(b) the collection does not significantly affect the stability of the natural ecosystem or the maintenance of the species in the collection area (Reg. (EU) 2018/848).

The requirements of algae cultivation depend on the place of that process. In accordance with point 2.3.1 of part III annex II *algae culture at sea shall only utilise nutrients naturally occurring in the environment, or from organic aquaculture animal production, preferably located nearby as part of a polyculture system* (Reg. (EU) 2018/848). But in facilities on land where external nutrient sources are used, in accordance with point 2.3.2 of part III annex II *the nutrient levels in the effluent water shall* *be verifiably the same, or lower, than the inflowing water. Only nutrients of plant or mineral origin authorised pursuant to Article 24 for use in organic production may be used* (Reg. (EU) 2018/848).

The requirements for organic algae production include also the area of sustainable collection of wild algae. In accordance with point 2.4.3 of part III annex II *collection shall be carried out in such a way that the amounts collected do not cause a significant impact on the state of the aquatic environment. Measures such as collection technique, minimum sizes, ages, reproductive cycles or size of remaining algae shall be taken to ensure that algae can regenerate and to ensure that by-catches are prevented* (Reg. (EU) 2018/848).

Chapter V of Reg. (EU) 2018/848 presents the requirements for certification. In accordance with art. 36, the certificate of organic production can be granted not only to particular operators but also to group operators.

Article 33 of Reg. (EU) 2018/848 defines that organic production logo of the European Union may be used in the labelling, presentation and advertising of products which comply with Regulation (EU) 2018/848.

Algae Biomass Organization

In 2017 the Algae Biomass Organization set the document titled Industrial Algae Measurements, version 8.0. which established the set of minimum descriptive parameters and metrics required to fully characterize the economic, sustainability, and environmental inputs and outputs of an aquatic biomass processing operation e.g. volumetric productivity, areal productivity, culture density, specific energy consumption, water consumption for cultivation (Algaebiomass, 2021b). The document consists of 7 chapters:

1: State-of-the-Art algal Product and Operations Measurements,
2: Life Cycle and Techno-Economic Analysis for the Uniform Definition of Algal Operations
3: Regulations and Policy on Algal Production Operations
4: Use of Wastewater in Algal Cultivation
5: Regulatory and Process Considerations for Marketing Algal-Based Food, Feed, and Supplements
6: Regulatory Considerations and Standards for Algal Biofuels
7: Open and Closed Algal Cultivation Systems (Algaebiomass, 2021b).

The Algae Biomass Organization presents the position that the voluntary adoption of a uniform common language and methodology will accelerate and allow the industry to grow (Algaebiomass, 2021b).

In summary, it should be noted that the growing market for both the sale of algae and algae products as well as the cultivation of these plants have led to the development of certification systems that make it possible to certify these products and their production. Products with an internationally recognised logo ensure full traceability of the supply chain and confirm, for example, proper management of the cultivation and processing stage or compliance with high environmental conditions.

4. Consumer attitude

(Tomasz Kulikowski)

4.1. Methodology of consumer research

The dedicated studies were conducted by IMAS International for National Marine Fisheries Research Institute in October 2019 in 8 countries/regions: Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Denmark and Northern Germany (Schleswig-Holstein, Mecklenburg-Vorpommern, Hamburg). The study was conducted using the CAWI (Computer Assisted Web-Interviews) method on a group of 2,040 respondents.

Equal numbers of respondents (n = 252-258) in individual countries/regions have been selected in order to obtain data that can be compared across regions. At 95% confidence level, the estimated amount of statistical error of the study was +/-3,1 percentage points.

The aim of the study was to answer the following questions: how many consumers in each country consume seaweed, how many of them consume seaweed in a form other than sushi, how many consumers are willing to include seaweed in their diet, what is the opinion about the health properties of seaweed, how many consumers use cosmetics with seaweed, how many are interested in such cosmetics, whether seaweed is treated as a substitute for seafood or vegetables, whether consumers expect locally produced seafood, how consumers assess the environmental condition of the Baltic Sea as a place of food production.

4.2. Research results

The percentage of consumers who do not buy seafood

It is worth noting that almost 14% of respondents do not buy seafood in general. It is also worth emphasizing that the younger the group of respondents, the greater the percentage of people who do not buy seafood. This can be seen as a major threat to the consumption of seafood in the future (33% of respondents aged 18-24 and 20% of respondents aged 25-34, do not buy seafood).

When analyzing the answers in geographical terms, the highest percentage of people who do not buy fish at all is in Germany (19%), Estonia (18%) and Denmark (17%). Poland is on the other extreme, where although the consumption of seafood is not high per person (what we know from statistical data [EUMOFA, 2020]), it is however common (only 6% of consumers do not buy fish at all).

High percentage of people declaring that they do not buy seafood among young consumers in the Baltic Sea Region is a big threat to the future of the fish market, but not necessarily to the seaweed market. First, we do not fully know whether seaweed is perceived as seafood. Second, many people who say they do not eat fish are vegans / vegetarians. For them, seaweed may be an alternative to seafood. This, however, would require in-depth research.

Tab. 9 The percentage of consumers who do not buy seafood at all in the various age groups of respondents

	Age					
	18-24	25-34	35-44	45-54	55-59	60+
I do not buy any seafood products	33.0%	19.7%	13.2%	12.2%	7.4%	6.8%

Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Fig. 28 The percentage of consumers who do not buy seafood at all in the various age groups of respondents

Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Product origin

Respondents were asked what origin of the seafood they prefer, as long as they buy any kind of seafood, and if its origin is at all significant.

Over 20% of the respondents declared that they buy seafood but do not pay special attention to its origin. Such people are relatively the most numerous (above 25%) in: Latvia and Lithuania. However, this attitude is not typical (under 16%) of the Danes, Finns and Germans for whom, as we can see, the origin is important.

Baltic Sea as the origin of seafood is specially preferred in Poland (32%), Latvia (26%) and Northern Germany (31%). In Sweden 19% consumer prefer the Baltic Sea (it is worth emphasizing that 34% of consumers prefer fish “originating in the Nordic sea”) – similar situation is in Denmark (20% - Baltic Sea, 26% - “Nordic sea”) and Estonia (18% - Baltic, 35% - “Nordic sea”). A large group of consumers simply declares that they are looking for products manufactured in their country. The most ethnocentric are: Finland (48%), Denmark (40%), Estonia (37%), Poland (37%) and Latvia (36%). The lowest - Germany (27%) and Lithuania (28%).

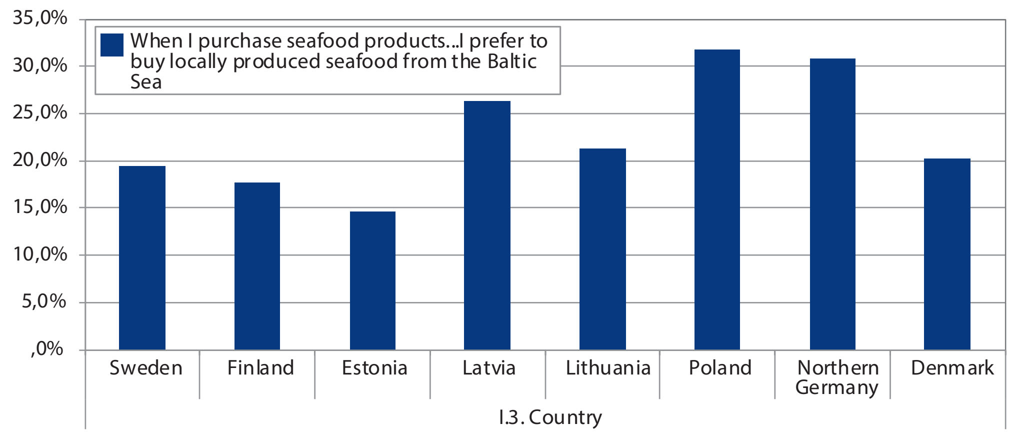
An important observation from the point of view of the GRASS project is that while the majority of consumers prefer the seafood to come from local, regional or at least European sources, the Baltic Sea origin is preferred by less than a quarter of consumers. This marks the future direction of the promotion for seaweed producers in the Baltic Sea Region. The keywords are “local origin” or (in the case of the Northern Region) “Nordic sea / Nordic origin”.

Tab. 10 Percentage of consumers who prefer: Baltic or Nordic seafood origin, depending on the respondent's region / country of residence

	Total	I.3. Country / Region							
	Total	Sweden	Finland	Estonia	Latvia	Lithuania	Poland	Northern Germany	Denmark
When I purchase seafood products...I prefer to buy locally produced seafood from the Baltic Sea	22.7%	19.4%	17.6%	14.6%	26.4%	21.3%	31.7%	30.8%	20.2%

Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Fig. 29 Percentage of consumers who prefer: Baltic or Nordic seafood origin, depending on the respondent's region / country of residence



Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

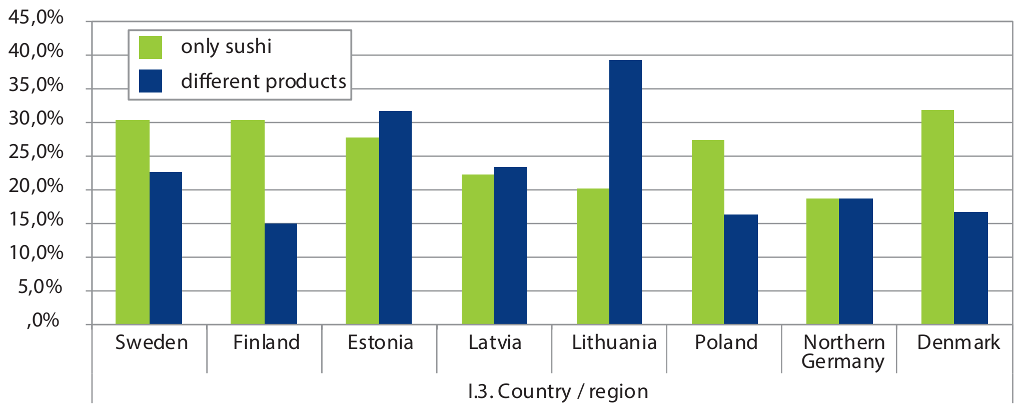
Product knowledge - seaweed consumption

In the scale of the entire survey, more than half of the respondents never ate seaweed or were unable to answer this question.

26% of respondents in the Baltic Sea Region have already eaten seaweed, but only as an ingredient of sushi, while nearly every fourth (23%) consumer has already tried seaweed also in other forms (e.g. salads, soups, snacks). In total, 49% of the Baltic consumers have experienced (food) contact with any form of seaweed. The highest percentages of consumers who have eaten any seaweed product are found in Estonia (59%), Lithuania (59%) and Sweden (53%). On the other hand, the highest percentage of consumers who ate seaweed products other than sushi lives in: Lithuania (39%), Estonia (32%), Latvia (23%) and Sweden (23%).

Interestingly, while contact with seaweed in the form of sushi is slightly more common among consumers <35 years old, the experience with consuming seaweed in the form of a different form is even more common at the age of over 35 years. It should therefore be noted that some seaweed products (sushi, snacks) are part of the "food trends" among younger generations of consumers, while others belong to the canon of traditional cuisine (especially in Estonia, Latvia and Lithuania, where salad called "sea cabbage" is consumed mostly by older generations of consumers).

Fig. 30 Percentage of consumers who have eaten seafood - only in a form of sushi or also in other forms, depending on the respondent's region / country of residence



Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Tab. 11 Percentage of consumers who have eaten seafood - only in a form of sushi or also in other forms, depending on the respondent's age

	I.3. Country / region							
	Sweden	Finland	Estonia	Latvia	Lithuania	Poland	Northern Germany	Denmark
only sushi	30.2%	30.2%	27.7%	22.1%	20.2%	27.4%	18.6%	31.8%
different products	22.5%	14.9%	31.6%	23.3%	39.1%	16.3%	18.6%	16.7%

Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

The openness to try seaweed

As many as 34% of consumers declare that they "could try to eat" seaweed food products. This is a very large development potential for the future market of edible seaweed products. The potential of such new consumers, who can be acquired in the near future, is particularly high among people aged 45-59. This may be due to the fact that at this age people are interested in health-promoting products, as shown by other research results (ProHealth 2017).

In terms of geography, the consumers are open to buying seaweed in the future in: Finland (as much as 45%), Latvia (37%), Denmark (35%), Germany (34%). The smallest number - in Poland (28%) - but it still has large purchasing potential.

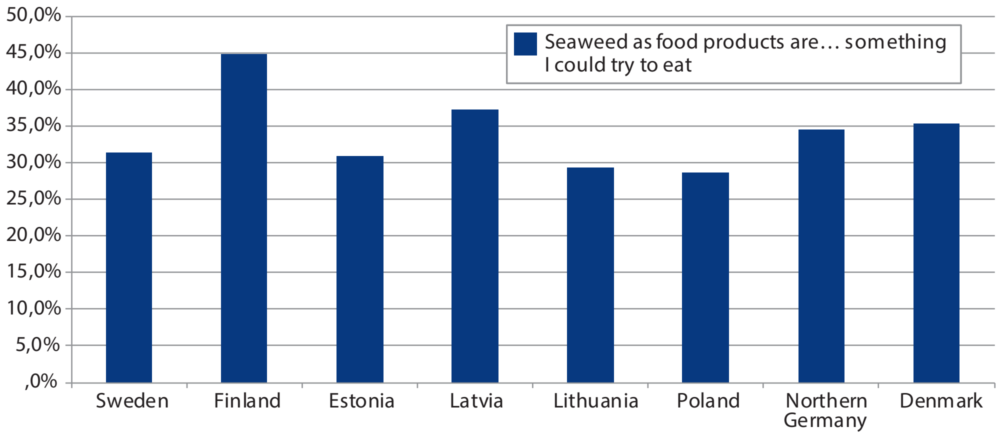
It is also worth noting that many consumers are interested in trying seaweed-based dietary supplements. In the scale of the entire Baltic Sea region, it is 23% of consumers. Particular interest in trying seaweed-based supplements is in Lithuania (32%) and Finland (31%). The Swedes are the most skeptical (rational?) towards supplements - here only 15% of consumers are interested in such products. It is similar with the Danes (19%).

Tab. 12 Percentage of consumers open to try seaweed products in the future

	I.3. Country / Region							
	Sweden	Finland	Estonia	Latvia	Lithuania	Poland	Northern Germany	Denmark
Seaweed as food products are… something I could try to eat	31.4%	44.7%	30.8%	37.2%	29.2%	28.6%	34.4%	35.3%

Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Fig. 31 Percentage of consumers open to try seaweed products in the future



Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Recognition of seaweed healthy values

Over 30% of consumers in the region believe that seaweed is food with particularly high pro-health values. This is fantastic news for producers and distributors, providing the basis for building a large market. The awareness of the high health benefits of seaweed is particularly high among consumers over 45 years of age. On the other hand, communication with the youngest consumers must be improved, here the percentage of indications of such advantages of seaweed is much lower. Women are more likely to believe that seaweed has health benefits, which could help define the future target audience of seaweed products.

Fig. 32. Seaweed is recognised as healthy and trendy food product. Women in Russia consuming seaweed salad (photo source: 123rf.com)

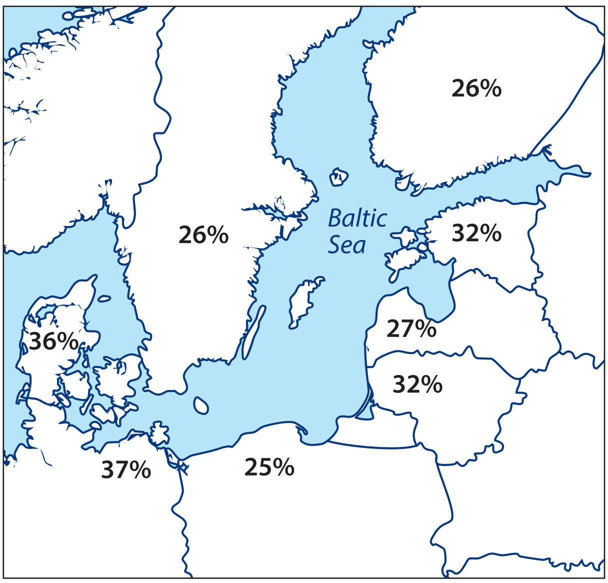
Particularly convinced of the pro-health values of seaweed are the inhabitants of: Northern Germany (37%), Denmark (36%), Estonia (32%) and Lithuania (32%). In other countries of the region approximately 25% of consumers believe that seaweed is a product of particular health value.

Tab. 13 The percentage of consumers who consider seaweed food products to be very healthy

	I.3. Country / region							
	Sweden	Finland	Estonia	Latvia	Lithuania	Poland	Northern Germany	Denmark
Seaweed as food products are... something that are very healthy	26.0%	25.9%	32.4%	26.7%	32.0%	25.4%	36.8%	36.0%

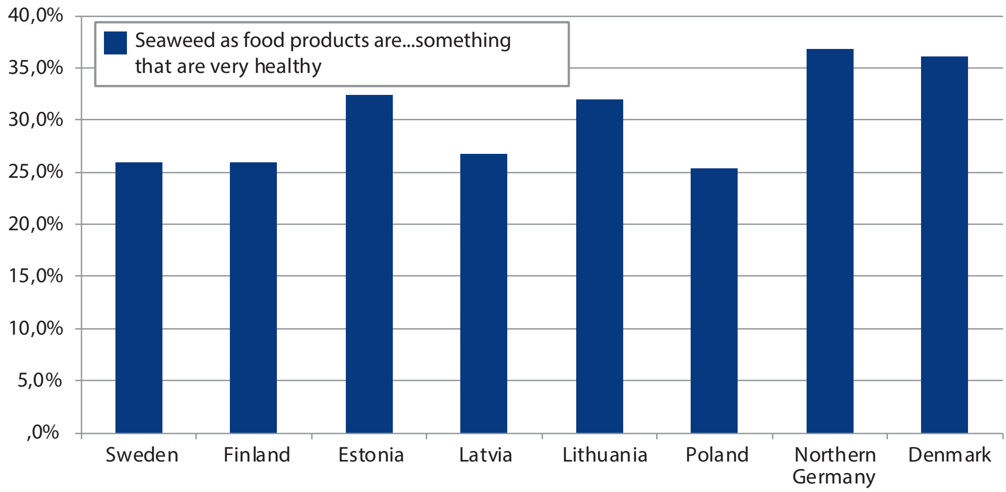
Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Fig. 33 Map showing the percentage of consumers who consider seaweed food products to be very healthy



Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Fig. 34 The percentage of consumers who consider seaweed food products to be very healthy



Source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Interest in cosmetics from seaweed

The Baltic Sea Region market offers a wide range of cosmetics containing seaweed. This was noticed by consumers. Every fourth respondent (25%) believes that these products are very healthy for the skin, and 11% declare they like to use them. Almost 46% of consumers (with a statistically significant majority of women) are willing to try a seaweed cosmetic in the future. Especially Polish and German consumers are especially enthusiasts of seaweed cosmetics.

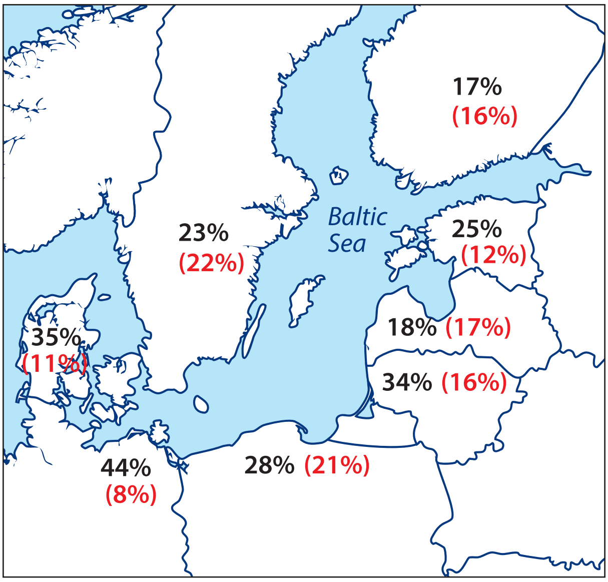
Consumer perception of the health quality of products from the Baltic Sea

At the end of the study, respondents were asked about their assessment of the environmental condition of the Baltic Sea as a place where seafood, including seaweed, is produced. The structure of the answer to this question partially explains why so few consumers in the survey indicated the Baltic Sea as their preferred origin for seafood.

Although more than 40% of respondents indicated that the Baltic Sea is an interesting location for the production of food alternatives to imported products, already 34% of consumers believe that Baltic food should be consumed “with caution”, and 15% even believe that seafood from the Baltic Sea is polluted / unhealthy. Concerns about the condition of the Baltic Sea environment and the safety of seafood from the Baltic Sea are expressed by consumers in all countries of the region, but especially in Sweden and Poland.

Consumers are very polarized in their opinions on the safe consumption of fish from the Baltic Sea. In general, only those consumers who consider the Baltic Sea as a source of high-quality, safe products are the target audience for future local edible seaweed production. It is positive that a greater percentage of people who consider the Baltic Sea seafood a high-quality and safe product is among younger consumers.

Fig. 35 Map showing percentage of consumers in individual countries recognizing seafood (including seaweed) from the Baltic Sea as good quality local food (green) ver. consumers recognizing the Baltic food products as polluted / unhealthy (red)



source: CAWI study conducted in the countries of the Baltic Sea Region by IMAS International for NMFRI, 2019, n = 2040

Tab. 14 Percentage of consumers in individual countries recognizing seafood (including seaweed) from the Baltic Sea as good quality local food

	Total	I.1. Age					
	Total	18-24	25-34	35-44	45-54	55-59	60+
Seafood (including seaweed) from Baltic Sea are… good quality local food	28.0%	30.5%	31.8%	26.6%	27.2%	28.0%	26.4%

Summary of consumer research results

It should be noted that seaweed has a positive image among consumers in the Baltic Sea Region. Half of the consumers have already seen this product and have tried it. Every tenth inhabitant of the region declares that they like this product, and every third believes that it is a product of high pro-health value. Among people who have not yet eaten seaweed - most declare openness and that they could try it. Consumers are also positive about seaweed cosmetics. This positive image of seaweed is mainly due to the media, including social media - where you can find mostly (or almost exclusively) positive information about seaweed. In this perspective, as well as taking into account the growing percentage of vegetarians, seaweed is an alternative to other seafood (fish, crustaceans, molluscs) for many consumers, and an interesting and pro-health supplement to the diet for others.

5. Macroalgae market size in BSR

(Tomasz Kulikowski)

5.1. Local production

According to different data collected in the GRASS project in BSR we have: 2 producers in Sweden (West Coast - aquaculture), 2 producers in Estonia (harvesting), 10 producers in Denmark (West Coast - mostly aquaculture) and 2 companies in Germany (aquaculture).

According to The European Commission's Knowledge Center for Bioeconomy production size (in the years 2014-2016) were ca. 100 ton in Denmark and ca. 500 tons in Estonia (Dos Santos 2019). The data are probably too optimistic, as due to the latest sources, production in Estonia dropped from ca. 450-550 tons in 2014-2016 to less than 70 tons in 2019 (in 2018 catches have not been made) (Kasuk 2020).

Fig. 36 Macroalgae harvesting in Estonia (photo source: Kärt Lehis / Vetik oü)

According to FAO data, in Denmark during 2011-2015, seven licences were issued for seaweed farming (largest for 1 sq.km). The commercial production based on *Saccharina latissima* and in pilot installations *Palmaria palmata* and *Fucus vesiculosus* is farmed. Aquaculture production increased in Denmark from 1 ton in 2009 to 10 tons in 2014. App. 20 companies are involved in seaweed harvest, mostly for local markets. According to The European Commission's Knowledge Center for Bioeconomy production size is 100 ton in Denmark (FAO 2018; Dos Santos 2019). Due to FAO statistics, aquaculture production of brown seaweed amounted in Denmark to 1800 tons in 2013, and then dropped to 100 tons in 2014-2016 and only 10-12 tons in 2017-2018 (for 2019 statistics shows 0 production). Here, in turn, the data may be affected by reporting errors.

Regardless of the discrepancy in the statistics, production in the BSR is negligible and does not meet even 1% of the demand for seaweed.

5.2. Import

Almost 100% macroalgae raw material supply in the BSR EU-countries come from import (intra-community deliveries and import from third countries). Foreign trade statistics are not very precise for macroalgae products. International customs codes (HS / CN codes) allow distinguishing the following product groups in statistics:

- Seaweeds and other algae — fit for human consumption (12 12 21);
- Seaweeds and other algae — others (121229);
- Agar-agar (130231);
- Carrageenan (13 02 32 90);
- Alginic acid, its salts and esters (39 13 10).

Unfortunately many companies import seaweed products, especially processed food, under other codes, e.g. nori and seaweed snacks are imported under codes: 20 08 99 (seasoned laver), 21 06 90 (other food preparations, not elsewhere specified or included) etc. Some products are declared as seaweed under a detailed CN code 20 08 99 99 90 (products manufactured on the basis of seaweed and other algae prepared or preserved by processes not provided for in Chapter 12) - however, public statistics do not allow for such a detailed analysis (CN 10). This, unfortunately, makes all market estimates undervalued, and the size of the market is significantly larger than the official statistics show.

Tab. 15 Seaweed products import volume to the BSE EU-countries

	Import volume (2020), ton			
	Edible seaweed	Other seaweed	Agar-agar	Alginates
Denmark	387	7 436	58	629
Germany	1 324	1 107	475	1 913
Estonia	49	0	1	9
Latvia	42	74	5	3
Lithuania	217	0	40	42
Poland	137	1 435	234	479
Finland	56	77	0	32
Sweden	193	228	5	89
BSR	2 405	10 358	817	3 196

Source of data: Eurostat (database last update 30.04.2021)

Tab. 16 Seaweed products import value to BSE EU-countries

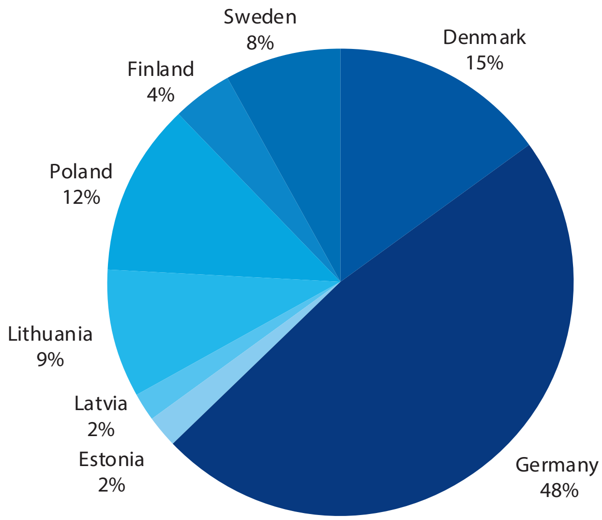
	Import value (2020), euro			
	Edible seaweed	Other seaweed	Agar-agar	Alginates
Denmark	2 541 759	7 235 044	1 859 790	8 754 248
Germany	8 377 270	1 601 033	8 329 969	15 244 740
Estonia	366 196	1 636	33 584	88 533
Latvia	281 312	59 799	214 672	19 710
Lithuania	1 512 175	178 892	755 776	241 068
Poland	2 048 831	930 160	3 213 992	4 983 143
Finland	720 385	204 962	296 683	450 366
Sweden	1 292 110	876 437	127 105	1 508 046
BSR	17 140 038	11 087 963	14 831 571	31 289 854

Source of data: Eurostat (database last update 30.04.2021)

Fig. 37 Seaweed snacks imported from Asia in Latvian supermarket, Riga, February 2020 (photo: T. Kulikowski)

Edible seaweed (code 12 12 21) imports to EU Baltic Sea Region countries, estimated on the basis of Eurostat data, amounted to 2 400 tons or 17 million euro in 2020. In the last 5 years, 44% increase in import of edible (fresh, frozen, dried, processed) seaweed in terms of value was observed. The main importers in 2020 were: Germany (1 100 tons), Sweden (286 tons) and Denmark (214 tons).

Fig. 38 Importers of edible seaweed among the BSR EU-countries, by value



Source: own elaboration, based on Eurostat-Comex data

Tab. 17 Changes in the level of edible seaweed imports to the EU countries in the BSR region

	Change in import value [2020/2016]
Estonia	+453%
Lithuania	+389%
Germany	+70%
Denmark	+60%
Finland	+6%
Sweden	+1%
Latvia	-8%
Poland	-22%

Source: own elaboration, based on Eurostat-Comex data

The average price for imported seaweed products in section 12 12, amounted in 2019 to 2188 euro per 1 ton, but in section 12 12 21 (seaweed fit for human consumption) average price amounted to 8 048 euro per 1 ton. This suggests that dried seaweed with the highest unit price has a significant share in this group of imported products.

Describing the BSR, it is important to mention the significant import of seaweed to Belarus and the Russian Federation. The data from Russia could not be included in the Baltic Sea region market, as these data relate to the entire territory of the Russian Federation. Import of seaweed to the Russian Federation amounted to 2 238 tons with a value of 25.2 million euro. In 2019 Belarus imported 841 tons of seaweed with the value of 2.2 million euro. [source: EUMOFA International Trade Database, accessed: 21.04.2020]

Although agar-agar has many substitutes, it is still an important product on the market. The countries of the EU Baltic Sea region imported 829 tons of agar-agar in 2020. The value of this import was

EUR 15.0 million. The main importers were: Germany (474 tons) and Poland (234). The import volume of agar-agar decreased during 2017-2019 by 22%. At the same time the import of other mucilages and thickeners derived from vegetable products (CN code 130239) increased.

The average price of the imported agar-agar amounted to 17 300 euro per 1 ton, which is 12% less than the average from years 2017-2018.

Fig. 39 Baltic Region EU countries imported ca. 1 000 tons of agar annually in 2018-2020 (photo source: 123rf.com)

In 2020 BSR EU countries imported 3 735 tons of alginic acid, its salts and esters. The value amounted to 56.0 million euro. The main importers of aginates, were in 2020: Germany (1913 tons), Denmark (629 tons) and Poland (479 tons). The average price of alginates amounted to 9 800 euro per 1 ton in 2020; the price was stable in the period 2017-2020.

Based only on official data for the codes explicitly describing imported products as seaweed and seaweed products, the average value of imports to the EU countries of the BSR region was 47 million euro in the last 5 years. Remember, however, that this is an underestimated value, as significant amounts of seaweed products are imported under different codes that prevent unequivocal identification.

6. Macroalgae species suitable for BSR farming, harvesting and beach-casting

(Magdalena Jakubowska)

6.1. Macroalage species

Baltic Proper and adjacent basins

Fucus vesiculosus

Brown alga *Fucus vesiculosus* has been used as food and medicine for centuries, mainly in Asian countries (Stansbury et al., 2011). It is a common source of fucoidan - sulfated polysaccharide, which possesses anti-oxidative, immunostimulating, anti-tumor, anti-inflammatory, antibacterial, antiviral and

Fig. 40 Brown algae from *Fucus vesiculosus* species on a beach, Hel Peninsula, Poland (photo: T. Kulikowski)

anticoagulant activity (Fitton, 2011). Fucoidan extracted from this species is commercially available (Nishino et al., 2014; Merck, 2020). Also due to high content of fucoxanthin and polyphenols, extracts from *F. vesiculosus* show very high anti-oxidative activity (Jimenez-Escrig et al., 2001; Diaz-Rubio, et al. 2009). Additionally, *F. vesiculosus* is a source of iodine in many food supplements (Restani et al., 2008). Species is also used for alginate production in Ireland (Peteiro, 2018). *F. vesiculosus* is commercially harvested in Ireland (Wild Irish Seaweeds, 2020), France (Mesnildrey et al., 2012), Spain (Gallardo et al., 1990), Canada (Nova Scotia Fisherman, 2020) and the United States (Maine Coast Sea Vegetables, 2020). It has never been commercially harvested but recently few pilot initiatives to farm this species in the Baltic Sea have been performed (FucoSan, 2020; Meichssner et al., 2020; Origin by Ocean, 2020). In the Baltic Sea it is widespread on hard substratum and often dominates within shallow macroalgal communities (Torn et al., 2006). As the species is sensitive to environmental changes, during the last few decades the decline in its depth have been observed, which was related to increasing eutrophication and competition with fast-growing filamentous macroalgae (Kautsky et al., 1986; Råberg et al., 2005; Torn et al., 2006; Graiff et al., 2015). Moreover, decreases in abundance or even local disappearance have been reported in many areas, but in some regions signs of recovery have been observed (Pliński et al., 1992; Berger et al., 2004).

Ulva intestinalis

Ulva intestinalis is green algae widely distributed in littoral zones around the world, characterized with broad salinity tolerance (Reed and Russel, 1979). It is also the principal macroalga growing on rocky bottoms along the Baltic coasts. However, the unattached form which creates floating mats is also present and often dominates the coastal biomass (Bäck et al., 2000). *U. intestinalis* efficiently uptakes nitrogen in response to its high concentration, thus massively occurs in eutrophicated areas, mainly in summer (Bäck et al., 2000; Fong et al., 2004). Moreover, it tolerates the variety of environmental conditions, seasonal changes and, due to its unique photosynthetic performance (ability to uptake HCO_3^-), it also inhabits areas characterized by conditions that are unfavorable for the other algae (Bäck et al., 2000; Bjork et al., 2004). Species belonging to *Ulva* genus are economically valuable and suitable for human consumption as they are rich in minerals, essential amino acids and hemicellulose (Aguilera-Morales et al., 2005). They also contain high levels of sulphated polysaccharides, which exhibit anti-oxidant and immunomodulatory activity, thus might be used as complementary medicine or functional foods (Peasura et al., 2016). Despite the fact that many species of *Ulva* genus are utilized as food or in medicine by Asian countries, *U. intestinalis* is still rarely consumed by humans (Zem-

Fig. 41 Green algae from *Ulva intestinalis* species in the Bay of Puck, Poland (photo: M. Jakubowska)

ke-White and Ohno, 1999). It is, however, cultivated in Japan (Ohno and Critchley, 1993; McHugh et al., 2003). In Thailand *U. intestinalis* has been used as a feed and a bio-filter in aquaculture, especially in earthen-pond co-cultures with giant tiger prawns (Ruangchuay et al., 2012). Experimental research conducted so far indicated that species is also suitable for the cultivation in laboratory/ recirculating systems (Ruangchuay et al., 2012; Balina et al., 2017). The experimental cultivations of *U. intestinalis* were also carried out in the natural environment - in the Gulf of Finland and in the Puck Bay, near the discharges from the sewage treatment plants, in order to increase the population of this algae and to remove the excess of nutrients from water (Kovaltchouk, 1996; Kruk-Dowgiałło and Dubrawski, 1998). Great effectiveness and very high yield (up to 82000 kg fresh weight per hectare from May to September) was obtained, especially when artificial substrate was used.

Furcellaria lumbricalis

Red alga *Furcellaria lumbricalis* is the only macroalgae species in the Baltic Sea that was harvested on a commercial scale (Weinberger et al., 2020). The commercial value of this slow growing perennial algae is related to the gelling properties of its structural polysaccharide - furcellaran. It was initially regarded as agar but further studies revealed that it is a different, unique polysaccharide, more similar to kappa and beta carrageenans (Bird et al., 1991) and with the gelling properties intermediate between carrageenan and agar (Laos and Ring, 2005). *F. lumbricalis* has attached and unattached (loose lying/ aegagropila) thallus forms, which represent two distinctive ecotypes (Austin, 1960; Martin et al., 2006). The unattached form, which reproduces only vegetatively (Austin 1960; Bird et al. 1991), was abundant in Danish (Kattegat), Polish (Puck Bay) and Estonian (Kassari Bay) waters and harvested for furcellaran production since mid-1900s (Austin, 1960; Trokowicz and Skrodzki, 1963, 1964; Ślesińska, 1977; Martin et al., 2006). Outside the BSR area, *F. lumbricalis* has been commercially harvested in Canada in 1970s-1990's (Bird et al., 1991). Unfortunately, in 1970s-1980s the populations of this species have been severely reduced due to eutrophication in the Puck Bay (Pliński and Florczyk, 1984; Kruk-Dowgiałło, 1991) or intensive harvesting in Kattegat (Weinberger et al., 2020). Nowadays due to great abundance of this species in Kassari Bay, Estonia is the only country which exploits *F. lumbricalis* on a commercial scale for the furcellaran production and recently for the development of industrial-scale phycoerythrin production for the cosmetic industry (Kersen et al., 2009; EstAgar, 2020; Vetik, 2021). Since 2011 *F. lumbricalis* stocks in Estonia have remained stable, amounting to 110-120·10^3 tons of wet biomass and occupying the area of 170-180 km^2 (Martin et al. 2006). Currently, harvesting of *F. lumbricalis* stocks by bottom trawling is limited to 2000 tons of wet weight per year (Paalme

Fig. 42 Red algae from *Furcellaria lumbricalis* species from the Bay of Puck, Poland (photo: M. Jakubowska)

2017). Additionally, beach deposits of both loose-lying and attached *F. lumbricalis* are collected for commercial utilization (Paalme, 2017). Despite the fact that the attached form has considerably higher furcellaran content (Kersen et al., 2017 after Tuvikene et al., 2010) is characterized by lower growth rate (Martin et al., 2006) and has never been commercially harvested. The species is not commercially cultivated, however, in Estonia several pilot projects have been initiated to develop cultivation techniques for both unattached and attached forms, to assess the environmental impact of different cultivation methods (Kersen et al., 2017; Weinberger et al. 2020) and to enhance the production of pigments from unattached forms by rearing in land-based systems (EUROFISH Magazine, 2021). Also in Poland a program which aimed to reintroduce *F. lumbricalis* to the Puck Bay was developed in 1990s, laboratory and in-situ experiments were performed and recommendations concerning cultivation were made (Ciszewski et al., 1992; Kruk-Dowgiałło and Ciszewski, 1994).

Ceramium tenuicorne

Small, filamentous red alga *Ceramium tenuicorne* is widely distributed in the Baltic sea. It tolerates low salinity, down to 2-3 PSU, moreover, it presents a high level of local adaptability and exhibits local ecotypes within different regions (Bergström et al., 2003; Bergström and Kautsky, 2005). It is an ecologically dominant species in the northern Baltic Sea (Bergström et al., 2003). It grows directly on the substrate, as an epiphyte on other algae or a loose-lying form in drifting algal mats (Bergström and Bergström, 1999; Bäck and Likolammi, 2004). *C. tenuicorne* is sensitive to various contaminants and it is abundant in different areas, therefore its growth inhibition has been proposed a toxicity test for chemicals and water effluents (Eklund, 2017). Red phycobiliprotein - phycoerythrin is the most abundant (70%) pigment in this species (Bäck and Likolammi, 2004). Due to content of bioactive substances such as phytol, but also to synergistic effects among components, extracts from species belonging to Ceramium genera are proved to have anti-bacterial and anti-viral activities (Serkedjieva, 2004; Cortés et al., 2014; Bazes et al., 2016). Ceramium species were occasionally used as a source of agar in Japan (Turvey and Williams, 1976; Dumitriu, 2004; Sudha et al., 2014). *C. tenuicorne* or any other Ceramium species has never been commercially harvested or cultivated in the BSR area. However, recently in Estonia the land-based cultivation technologies dedicated to rearing *C. tenuicorne*, in order to extract phycoerythrin, are under development as harvesting of this species from the natural environment is difficult (EUROFISH Magazine, 2021).

Other species:

Studies carried out so far indicated that extracts from species belonging to genera Polysiphonia, *Ulva* and *Cladophora* from the Baltic Sea, due to high lipid concentration and content of polyphenols, micro- and macroelements, have high potential to be applied in agriculture as biostimulants (Michalak et al., 2015; Godlewska et al., 2016, Michalak et al., 2017a). Additionally, extracts from the Baltic *Ulva prolifera* possess anti-oxidative properties and slight antibacterial activity, thus may be potentially used in the food, cosmetic and pharmaceutical industries (Michalak et al., 2017b). Baltic algae can be also co-composted with other natural material in order to produce fertilizer. Research carried out by Michalak et al. (2016, 2017c) indicated that the addition of *Fucus* sp. as well as the mixture of *Cladophora* sp. and *Ulva* sp. to compost and compost extract contributed to the increase in plant growth. Compost from seaweeds can find several applications, for example, as an alternative to conventional fertilizers. Moreover, the mentioned research on the Baltic green algae (Michalak et al., 2017c) indicated that not only drifting algal biomass, but also algae collected from the beach have a positive impact on the compost. Similarly, research carried out by Filipkowska et al. (2008) indicated that biomass of the Baltic beach-cast algae (dominant species: *Cladophora* sp., *Ulva* spp., *Pilayella littoralis* and *Ceramium* spp.) may be utilized as fertilizer. In addition to the possibility of production of valuable products as fertilizers, the utilization of macroalgae accumulated on the beach may reduce the high cost of beach cleaning, thus bringing benefits from an economical point of view. Also brown algae from Ectocarpales order (*Pylaiella littoralis* and *Ectocarpus siliculosus* might be commercially utilized as they are suitable for harvesting and after drying and homogenization may be used as organic fertilizer or as ingredient of animal feed (Ciszewski et al., 1992; Kruk-Dowgiałło and Ciszewski, 1994). Current research also indicated that algae washed-up on the shore (beach wrack) in different areas of the Baltic Sea (various species) can be used for the production of soil improvements and fertilisers, bio-coal, compost material and biogas (CONTRA, 2021).

West Baltic/Sweden

Laminaria digitata* and *Saccharina latissima

Laminariales are known to tolerate broad salinity range but their occurrence in the Baltic Sea is limited to two species - *Laminaria digitata* and *Saccharina latissima* (formerly *Laminaria saccharina*), which can be found only in the Kattegat (Nielsen et al., 2016). *L. digitata* grows in the upper sublittoral zone on the hard substratum, mainly in wave-exposed sites, while *S. latissima* also grows in the upper sublittoral, but usually below *L. digitata* as it requires more sheltered conditions (McHugh et al., 2003). *L. digitata* is the main raw material for the alginate industry in France (Kain and Dawes, 1987). It is also harvested for alginate in Ireland and Iceland and for food in Ireland (Munda et al., 1987; Zemke-White and Ohno, 1999). As *S. latissima* often grows in close association with *L. digitata*, it is often harvested at the same time (McHugh, 2003). *S. latissima* is commercially processed for food in Ireland, Alaska and Canada (Zemke-White and Ohno, 1999). Various forms of experimental and commercial cultivations, including multitrophic aquaculture, of *S. latissima* have been conducted in Spain and Norway but also in Germany, Sweden and Denmark (Buck and Buchholz, 2004; Peteiro, et al. 2006; Handå et al., 2013; Marinho et al., 2015; Seafarm, 2020; Nordic SeaFarm, 2021), therefore it is the only sea-based commercially cultivated macroalgae species in the BSR area.

Fig. 43 Algae of the genus *Laminaria* (photo source: 123rf.com)

Potential applications of Baltic macroalgae and of their particular compounds have been summarised in Tab. 18.

Tab. 18 Valuable substances which can be extracted from Baltic macroalgae and their potential uses

Species	Valuable compound	Properties/ potential application
Furcellaria lumbricalis	furcellaran (40-50% DW[1]/ 19% - unattached form, 32% - attached[2]	gelling agent
	pigments: - R-phycoerythrin (0.13-0.42%[3, 4]) - allophycocyanin (0.07-0.12%[3])	fluorescent pigments, colorants (cosmetics, drinks, foods, paints), anti-cancer and anti-oxidative properties
	pigments: - lutein (28.6 µg g^{-1} DW[5]) - zeaxanthin (86.8 µg g^{-1} DW[5]) - beta-carotene (28.6 µg g^{-1} DW[5])	food, animal feed, cosmetics, anti-oxidative properties
	phenolic compounds (3.25% DW[a, 6])	anti-oxidative properties
Ceramium tenuicorne	pigments: - phycocyanin (up to 0.3 mg g^{-1} FW[7]) - phycoerythrin (up to 3 mg g^{-1} FW[7]) - R- phycoerythrin (up to 1.58%[4])	fluorescent pigments, colorants (cosmetics, drinks, foods, paints), anti-cancer and anti-oxidative properties
	Other Ceramium species agar/ agar-type polysaccharide (*C. rubrum, C. boydenii, C. pacificum*)[8, 9, 10]	gelling agent
	mycosporine-like amino acids (MMAs) (*Ceramium* spp.)[11, 12, 13]	anti-oxidative and anti-desiccant properties, protection against x-rays
	extracts from *C. rubrum*[14, 15]	anti-viral, anti-bacterial and anti-fungal activities
	extract from *C. virgatum*[16]	anti-bacterial
	extract from *C. botryocarpum*[17]	anti-fouling properties
Fucus vesiculosus	alginic acid (15[b, 18]/22-26% DW[e, 19])	gelling agent (textile industry, medical products)
	fucoidan (16.5 – 18.2%[c, 20])	anti-viral, anti-oxidative, anti-inflammatory, anticoagulant, antitumor, antithrombotic activity
	laminarin (3.5% DW[b, 18]) mannitol (12% DW[b, 18]/ 4-7% DW[d, 21])	antibacterial activity pharmacy, food (sweetener)
	pigments: - fucoxanthin (101.0 µg g^{-1} DW[5]) - violaxanthin (76.8 µg g^{-1} DW[5]) - beta carotene (42.8 µg g^{-1} DW[5])	anti-cancer, anti-oxidative properties, food, animal feed, cosmetic
	polyphenols[22, 23]	anti-viral properties
	iodine (0.05% DW [b, 18]/276 µg g^{-1} [d, 24]	pharmacy (weight reduction, stimulation of thyroid)

Species	Valuable compound	Properties/ potential application
Ulva intestinalis	edible seaweed (Aonori)[25, 26]	human food
	sulphated polysaccharides[27, 28]/ ulvan (8%[29])	anti-oxidative, immunomodulatory activities
	extracts[30, 31, 32, 33]	anti-bacterial, anti-protozoal, anti-oxidative activities
	extract/ liquid fertilizer[34]	fertilizers/ biostimulants for plants
	potential bioenergy resource[35, 36]	
Laminaria digitata	alginic acid (21-35[f, 19]/18-26% DW[h, 37])	gelling agent (textile industry, medical products)
	mannitol (12.8-24.4[38]/19.4% DW [g, 40])	pharmacy, food (sweetener)
	laminarin (6.7% DW[g, 39])	antibacterial activity
	fucoxanthin (0.16-0.49 mg g^{-1} DW[38])	anti-cancer, anti-oxidative properties
	extract[16]	anti-bacterial activity
	extracts[40, 41]	products for agriculture (biostimulants)
Saccharina latissima	edible seaweed[26]	human food
	alginic acid (21-27% DW[f, 19])	gelling agent (textile industry, medical products)
	mannitol (4.9-21.8[38]/ 18.6% DW[g, 39])	pharmacy, food (sweetener)
	laminarin (8.2%[g, 39])	antibacterial activity
	fucoxanthin (0.16-0.59 mg g^{-1} DW[38])	anti-cancer, anti-oxidative

Values for algae outside the BSR area:

a - values for *F. lumbricalis* from Atlantic cost (France), **b** - values for *F. vesiculosus* from Atlantic cost (Scotland) and Iceland coast respectively), **c** - values for *F. vesiculosus* from Atlantic cost (Portugal), **d** - values for *F. vesiculosus* from Atlantic cost (US), **e** - values for *F. vesiculosus* from the North Sea, **f** - values for *F. vesiculosus* and *L. digitata* from Iceland coast , **g** - values for *L. digitata* and *S. latissima* from Atlantic cost (Scotland), **h** - values for *L. digitata* from Atlantic cost (UK)

1. Czapke, 1963, **2.** Tuvikene et al., 2010, **3.** Saluri et al., 2019, **4.** Saluri et al., 2020, **5.** Bianchi et al., 1997. **6.** Zubia et al., 2009, **7.** Back and Likolammi 2004, **8.** Turvey and Williams, 1976, **9.** Hirase and Araki, 1961, **10.** Matsuhiro, 1982, **11.** Karsten et al., 1998, **12.** Serban et al., 2016, **13.** Pandey et al., 2017, **14.** Serkedjieva, 2004, **15.** Cortés et al., 2014, **16.** Dubber and Harder, 2008, **17.** Bazes et al., 2016, **18.** Black, 1949, **19.** Munda 1987, **20.** Rodriguez-Jasso et al., 2011, **21.** Munda and Hudnik 1988, **22.** Ragan and Jensen, 1978, **23.** Beress et al., 1993, **24.** Teas et al., 2004, **25.** Ohno and Critchley, 1993, **26.** Zemke-White and Ohno, 1999, **27.** Peasura et al., 2015, **28.** Peasura et al., 2016, **29.** Rahimi et al., 2016, **30.** Spavieri et al., 2010, **31.** Abdel-Khaliq et al., 2014, **32.** Berber et al., 2015, **33.** Srikong et al. 2017, **34.** Mathur et al. 2015, **35.** Kim et al., 2014, **36.** Sabunas et al., 2017, **37.** Peteiro, 2018, **38.** Nielsen et al., 2016, **39.** Schiener et al., 2015, **40.** Sharma et al., 2014, **41.** Michalak and Chojnacka, 2016

6.2. Substitutability

***Ulva intestinalis* <=> *Ulva lactuca*, *Ulva prolifera*, other *Ulva* species**

Despite the fact that *U. intestinalis* is cultivated and, due to its nutritional content, consumed in Japan, *U. lactuca* and *U. prolifera* are more popular species for production of nutritionally valuable food (Aguilera-Morales et al., 2005). *U. intestinalis* has similar content of lipids, carbohydrates, macro- and microelements, essential amino acids and even higher content of protein and dietary fibers than *U. lactuca* (Akköz et al., 2011; Benjama and Masniyom, 2011; Pereira, 2011; Tabarasa, et al. 2012;

Abdel-Khaliq et al., 2014). The main difference between these two species is their morphology. The thalli of *U. intestinalis* are thin and monostromatic (having the cells in a single layer), while *U. lactuca* forms distromatic blades. However, the Aosa algae (*U. lactuca*) are usually sold dried and grinded, thus the thallus morphology should not affect the market value.

***Fucus vesiculosus* <=> *Ascophylum nodosum*, *Saccharina latissima*, *Laminaria* spp.**

F. vesiculosus has similar content of alginic acid to *Ascophylum nodosum*, *Sachcarina latissima*, and some Laminaria species, which are commercially utilized to produce this polysaccharide (Munda, 1987; Peteiro, 2018). Nevertheless, alginates from *Fucus* species, including the Baltic *F. vesiculosus*, are characterized with lower viscosity, thus produce lower-strength gels comparing to e.g., alginates from Laminaria species (Truus et al., 2001; Catarino et al., 2018). On the other hand, it was recently shown that sodium alginate, obtained from the *F. vesiculosus* from the Barents Sea using optimized technology, is highly viscous and has similar quality to commercial sodium alginate from Laminaria species (Sokolan et al., 2019). Therefore, it seems that the possibility of using Baltic *F. vesiculosus* as a source of commercial alginate requires further research on the extraction technology.

Ceramium tenuicorne* <=> *Gracilaria* spp, other agarophytes; *Porphyra tenera*, *Gastroclonium coulterii

Studies revealed that agar-type polysaccharides extracted from Ceramium species have different chemical structures than agars obtained from other red algae (Hirase and Araki, 1961; Turvey and Williams, 1976; Miller, 2003). In addition, slight differences between various Ceramium taxa were observed (Matsuhiro, 1982; Miller and Blunt, 2002). Few Ceramium species were harvested along the coast of northern Japan and used as a source of agar, but rather occasionally (Turvey and Williams, 1976; Sudha et al., 2014; Dumitriu, 2004). Agar obtained from Ceramium species was described as easy melting, firm and elastic, and characterized by higher viscoelasticity parameters than agar obtained from Gracilaria or Gelidium species and other commercial agars (Dumitriu, 2004). Therefore, to find out if Baltic *C. teniucorne* might be a good substitute for commercially produced agars (from Gellidium and Gelladiella) detailed research on the content, chemical structure and parameters of its polysaccharides is required. Recent studies revealed that R-phycoerythrin can be extracted from *C. tenuicorne* (Saluri et al., 2020). This red fluorescent protein pigment, which is commercially available and used for fluorescent conjugation (e.g., in histochemistry and flow cytometry) is usually extracted from other red macroalgae - *Porphyra tenera* or *Gastroclonium coulterii* (Thermo Fisher Scientific, 2021).

Laminaria digitata*, *Sachcarina latissim*a <=> *Saccharina japonica

Saccharina japonica is massively cultivated in Japan, China and Korea. It is used mainly as a high value food product, and only surplus production is utilized in the alginate industry (McHugh, 2003). Despite the fact that the scale of *L. digitata* and *S. latissima* processing is limited compared to Asian *S. japonica*, the European Laminariales might be regarded as a substitute for *S. japonica*. *S. latissima* and *L. digitata* have similar nutritional value and alginate content to *S. japonica* (Honya et al., 1993; Jurković et al., 1995; Nielsen et al., 2016). Moreover, the methods of cultivation of both species in the BSR area are still under development, thus massive cultivation might be a matter of time.

7. Basic information on legal and spatial aspects of seaweed cultivation

(Magdalena Jakubowska)

Maritime Spatial Planning has been adopted as an instrument supporting the EU coastal countries in achieving aims set in the integrated maritime management strategy (European Parliament, 2014). Therefore in each country from the Baltic Sea Region, the spatial conflicts between different users and between the users and the environment have been identified. Aquaculture, including macroalgae farming, is usually not allowed in areas designated for e.g. military defense, shipping, underwater heritage, port infrastructure, marine tourism or MPAs. On the other hand, some synergies between macroalgae cultivation and other activities, such as offshore wind energy or fish aquaculture have been identified. Detailed data including maps showing relationships between macroalgae cultivation and other maritime sectors in few study cases (BSR countries) are presented in GRASS Maps illustrating MSP approach to best available sites for macroalgae cultivation and harvesting in the Baltic Sea.

Read also:
Maps illustrating MSP approach to best available sites for macroalgae cultivation and harvesting in the Baltic Sea

https://www.submariner-network.eu/grass

In most of the Baltic countries there are currently no specific legal regulations regarding the cultivation and harvesting of macroalgae. To cultivate seaweed, the general aquaculture permit procedures as well as the environmental and water laws usually apply, and the licensing process is long and complicated. In most BSR countries it is necessary to obtain a few different permits from the relevant ministries, maritime administration or water management board, and in some cases to obtain the decision on environmental conditions. Therefore, further improvement and clarification of the rules related to permits for macroalgae cultivation and harvesting is necessary. The European and national rules applying to macroalgae cultivation and harvesting are described in details in the GRASS Report on European and National Regulations on Seaweed Cultivation and Harvesting.

Read also:
Report on European and National Regulations on Seaweed Cultivation
and Harvesting

https://www.submariner-network.eu/grass

The macroalgae usage as food and feed ingredients is also under various regulations in terms of the limits of harmful substances, food labeling and the introduction of novel species into the market. In the EU countries the food law is regulated mainly by the Regulation No 178/2002 of the European Parliament and of the Council of 28 January 2002 (European Commission, 2002), which has been implemented in BSR countries by their national authorities. Some aspects related to the macroalgae requirements for novel food were summarized in chapter 3 (=>3.2. Legal aspects of macroalgae use in the food industry). The EU policy framework that regulates the use of macroalgae as food and feed in the EU member countries has been described in details in the GRASS report Macroalgae as food and feed ingredients in the Baltic Sea region - regulation by the European Union.

Read also:
Macroalgae as food and feed ingredients in the Baltic Sea region - regulation by the European Union

https://www.submariner-network.eu/grass

8. Cultivation technology, harvesting, postharvest treatment

(Magdalena Jakubowska, Olga Szulecka)

8.1. Cultivation technology and harvesting

As both experimental and commercial farms of *Sacchcarina latissima* and, in lesser extent, *Laminaria digitata* exist in Sweden and Denmark much is already known about the cultivation techniques dedicated for these species (KOSTERALG, 2020; SEAFARM, 2020; Thomas et al., 2020; Boderskov et al., 2021). Also the production costs and revenue have been estimated for *S. latissima* (Hasselström et al., 2020). More information concerning the production of Laminariales in the Baltic Sea is presented in GRASS report A manual on the efficient production methods of macroalgae farming in the Baltic Sea Region.

Read also:
A manual on the efficient production methods of macroalgae farming in the Baltic Sea Region.

https://www.submariner-network.eu/grass

Despite the fact that four species have been suggested as suitable for cultivation in the Baltic Proper and adjacent basins (=> Chapter 6), the data related to the possibility of farming *Ceramium tenuicorne* and *Furcellaria lumbricalis* are scanty as the technology dedicated to the cultivation of these species has not been invented or sufficiently tested yet. The information which can be derived from the literature is not sufficient to be upscaled to commercial production and to be the basis of the business plan. Therefore, in our calculations for the business planning we decided to concentrate on two species, *Ulva intestinalis* and *Fucus vesiculosus*. Although both experimental (Lignell and Pedersén, 1986; Haglund and Pedersén, 1988) as well as commercial (Meeresalgenland UG, pers. comm) initiatives to cultivate *Ulva* and *Fucus* species on land - in tanks or flow-through systems, have been carried out in the BSR area, the available data concerning farming of these species directly in the Baltic Sea are limited to scientific experiments. However, the data are sufficient to be the base of business planning calculations.

Fucus vesiculosus

In the case of *Fucus vesiculosus*, commercial farms exist neither in the Baltic nor anywhere else. The products offered on the market originate mainly from the biomass harvested from the environment. However, some experimental initiatives related to the cultivation of this species have been implemented. The pilot cultivation has been performed during implementation of FucoSan project (Interreg Deutschland-Danmark) in the Kiel Fjord, Germany. The chosen cultivation method did not rely on the typical seeding material (gametes or spores), but the adult individuals were collected from the field once and the vegetative fragments of thalli were cut and put in the floating baskets (covered with plastic mesh and attached to plastic pipes), where they grow throughout the year (FucoSan, 2020; Meichssner et al. 2020). The experiments show that the growth rate of *F. vesiculosus* is suitable for commercial farming and that under optimal conditions it is possible to obtain the annual yield of 50 tons of fresh weight per hectare (FucoSan, 2020). Also in Finland the experiment on *Fucus* farming in co-location with the fish farm was carried out in 2020 in Finland, however the results of this project are not yet available (Origin by Ocean, 2020).

While considering the cultivation of *Fucus vesiculosus*, two potential problems should be taken into account. Firstly, despite the fact that the occurrence of asexual populations of *F. vesiculosus* is limited in the Baltic Sea (Tatarenkov et al., 2005), it is better to concentrate on them, as in case of the possibility to profitably cultivate sexually reproducing *Fucus*, more research is needed. According to the research performed so far, it is possible to obtain *Fucus* gametes in laboratory or hatchery and thus to cultivate sexually reproducing *Fucus* using the long-lines technique (Balina et al., 2018; Mikkelsen, 2019). The process of reproduction includes the collection of adults or just their reproduction organs from the environment, induction of gametes release, and after fertilization rearing of the sporophytes in the laboratory or hatchery for some time. One *Fucus* individual can produce a million gametes (Knight and Parke, 1950). Unfortunately, the survival of small sporophytes in the field as well as in the laboratory is low (Serrao et al., 1999; Al-Janabi, 2016; Mikkelsen, 2019). The problem with low survival rate may be theoretically solved by the dense seeding of spores on the lines or by the longer rearing of sporophytes in the hatchery but more research is necessary. However, other issues related to the cultivation of sexual *Fucus* populations make the potential yield lower and thus the business less profitable than in case of vegetatively reproducing algae. The change from germling to adult individuals which can be harvested can take even up to 2 years (Al Janabi, 2016). Moreover, during the implementation of the FucoSan project it was revealed that the production and subsequent degeneration of reproductive organs significantly reduce the harvestable biomass (FucoSan, 2020). The second identified problem, which concerns both sexual and asexual *Fucus* populations, is fouling, mainly by invertebrates, what make the harvested biomass not suitable for the further processing and commercial usage. The study confirmed that there are solutions to reduce the biomass of epiphytes in a way not significantly reducing the *Fucus* biomass, either by regular desiccation (exposure to air) or rinsing with freshwater (FucoSan, 2020; Meichssner et al. 2020; Meichssner pers. comm.).

Taking into account the above mentioned facts and considerations, we decided to make an attempt to create a business plan only for vegetative *F. vesiculosus*, basing mainly on the data from experiments performed in the Kiel Fjord (FucoSan, 2020; Meichssner et al. 2020; Meichssner pers. comm). We assumed the annual yield equal to 5 kg of fresh weight per one cage (1 m x 1 m). Based on the results from the FucoSan project it is theoretically possible to obtain 50 tons of fresh mass from hectare per year but this approach assumes that the farm area is densely filled with cages. Therefore, the annual yield may vary depending on the harvesting technique e.g. necessary space for the harvesting boat. Therefore, we assumed the annual harvest equal to 10 tons of fresh *Fucus* weight per hectare. As coping with epiphytes by desiccation or rinsing of *Fucus* biomass in a small-scale experimental farm may be performed manually, e.g. from the boat, for an industrial-scale farm the technology dedicated to the elevation of the cultivation structures should be developed. Moreover, there is a lack of knowledge if the scale of fouling in other parts of the Baltic Sea, characterized with lower salinity is as problematic as in the Kiel Fjord. Therefore we decided not to include the desiccation process in our business planning.

Ulva intestinalis

Ulva intestinalis is commercially cultivated in Japan. Mature fronds are collected from the environment to obtain spores, which are then seeded on nets and transferred to growing areas (seed collection areas) and, when juveniles are 1-2 cm, to the target culture grounds, where they grow during whole year and are harvested 2-3 times in each of two periods (Ohno and Critchley, 1993). Although, in Europe some attempts to cultivate various *Ulva* species in the environment as well as in the land-based system have been carried out (KOSTERALG, 2020; Meeresalgenland UG, pers. comm), trials with *U. intestinalis* are limited mainly to the laboratory research (Balina et al., 2017; Sabunas et al., 2017). Therefore, no technology dedicated to the commercial cultivation of this species in Baltic Sea has been established yet. However, two field experiments connected with cultivation of *U. intestinalis* in BSR were performed - one in the Gulf of Finland (Russian part) and one in Puck Bay (Poland). Their aim was to assess the macroalgae potential to remove the excessive nutrients to counteract eutrophication (Kovaltchouk, 1996; Kruk-Dowgiałło and Dubrawski, 1998). *U. intestinalis* was cultivated using constructions with horizontally situated ropes with previously implemented *Ulva* spores, located in the shallow coastal areas. Both experimental cultivation sites were located in the close vicinity of the wastewater treatment outflow, i.e. in areas characterized with very high nutrient concentrations. Based on the obtained results it has been calculated that it is possible to obtain between 62 and 87 tons of fresh weight per hectare in one cultivation season (May - October) (Kovaltchouk, 1996).

Fig. 44 Farming of *Ulva* macroalgae in tanks (photo source: 123rf.com)

While planning the commercial investment, it should be considered that in the BSR, due to seasonality, it is possible to cultivate *U. intestinalis* only 5-6 months per year. Although it seems most reasonable to cultivate *U. intestinalis* in highly eutrophicated coastal zones to obtain high yield and to use its potential to remove the nutrient excess, it should be also kept in mind that in many areas the possible intensive growth of *U. intestinalis* may be limited by the nutrients availability. There are numerous studies on the reproduction of *Ulva* species, including *Ulva intestinalis*, which indicate that there is available technique for the zoospores obtaining (Kim and Lee, 1996; Ruangchuay et al., 2012; Li et al., 2014). It might be therefore assumed that the establishment of commercial hatchery should not be problematic. However, according to the recent findings, the seeding efficiency of *U. intestinalis* is lower compared to other *Ulva* species like *U. lactuca* or *U. linza* and further research concerning this issue is required (Kotta, pers. obs.).

Based on the parameters and result of experiments performed in the Gulf of Finland and in the Puck Bay, we made calculations for *U. intestinalis* planted on 5 mm ropes placed horizontally at a distance of one meter from each other, suspended shallow below the water's surface and located in the shallow coastal zone. As the annual yield equal to 62-87 tons of wet weight per hectare may be obtained only in highly eutrophicated areas, we performed a few various scenarios, including business planning for areas where *Ulva* growth may be limited by the availability of nutrients. For the calculations of the investment costs we also used the estimations made for *Ulva* cultivation using long-lines technique, located in the North Sea (Van den Burg, 2013).

8.2. Postharvest treatment

The seaweeds can be harvested manually using small boats or mechanically using harvester vessels. After manual harvesting seaweeds are mostly placed in plastic boxes while after the mechanical harvesting, the seaweeds are transported into bags or nets onto tracks to the factories (Kadam et al., 2015a).

The seaweeds (e.g. *Ulva lactuca* and *Fucus vesiculosus*) which are a good source of nutrients (Table 16) can be eaten fresh. However, due to their perishable nature and handling outside the water, they have to be quickly chilled and transported to the processing factory or final consumer.

Tab. 19. Nutrient and mineral composition of *Ulva lactuca* and *Fucus vesiculosus*

Species	Nutrient Composition (% dry weight)					Mineral Composition (mg 100 g^{-1} dry weight)				
	Protein	Ash	Dietary Fiber	Carbohydrate	Lipid	Na	K	P	Ca	Mg
Ulva lactuca	10-25	12.9	29-55	36-43	0.6-1.6	-	-	140	840	-
Fucus vesiculosus	3-14	14-30	45-59	46.8	1.9	2450-5469	2500-4322	315	725-938	670-994

Source: Elaborated on the basis of Morais et al. (2020).

The storage life wasn't analysed for all seaweed species. For the future applications of seaweeds, the shelf life should be investigated. Also, the quality assessment scheme for the most popular seaweeds for quality assessment during storage should be established. This could be very important for manufacturers. There is limited data of freshness quality and shelf life evaluation of the *Ulva lactuca*, therefore, the date for other seaweeds e.g. *Ulva rigida* as the example of *Ulva* genus will be mostly presented.

Liot et al. (1993) compared the microbiology state and the storage life of fresh edibles seaweeds of *Palmaria palmate* and *Ulva rigida*. The experiment assumed quality and microbiological status tests on 0, 3, 7, 14 days during seaweeds storage at 4°C. Their results showed that *Ulva rigida*, washed in seawater or stored without washing showed no changes in the aroma for 7 days. On day 14 both samples showed reinforced *Ulva* aroma. The reinforced *Ulva* aroma at day 7th and strong *Ulva* aroma at day 14th was investigated in the case of *Ulva rigida* washed in tap water. The samples of *Palmaria palmate* unwashed or seawater-washed showed no change in aroma after 14 days of storage. However, the sample washed in tap water had a soft sticky texture and reinforced *Palmaria* aroma just after 3 days of storage. After 7 days the pink exudative liquid was investigated in the sample. Similar results were obtained in the case of microbial status. The number of mesophilic aerobes in unwashed or washed in seawater *Ulva rigida* and *Palmaria palmate* remained relatively constant during storage, with an initial flora ranging between 10^3 and 10^5 cells g^{-1}. The amount of yeast for above-mentioned samples was also stable and did not exceed 10^4 cells g^{-1}. The results were different in the case of tap water-washed samples of both species. Mesophilic aerobes and yeasts showed strong growth over a 7-days period. Also after that period samples degraded rapidly. Liot et al. (1993) summarised their research that in the case of fresh edible seaweeds during cold storage and the poor conditions for the growth of ordinary food contamination microbes was observed. Moreover, the early degradation of physical quality could alert the user before serious microbial levels develop. Summarising, the use of tap water to wash seaweeds quickly altered their quality, whereas seawater washing resulted in low microbial densities during storage.

The Sánchez-Gracía et al. (2021) applied different analytical methods to test *Ulva rigida* including physical (a_w, pH, colour and texture), chemical (total volatile base nitrogen - TVB-N and trimethylamine - TMA-N) parameters, microbial count and sensory evaluation. The freshness of *Ulva rigida* was evaluated for 12 days period at 4 and 16°C. The results obtained in the survey showed that according to the physicochemical and microbiological parameters a shelf life of *Ulva rigida* at 16°C was established on 6 days and up to 10 days during storage at a temperature of 4°C. The *Ulva rigida* stored at 16°C for 12 days has lower results of pH, higher drip loss (%), lower crispness, hardness and cohesiveness. The TVB-N and TMA-N values had increased significantly in 8 days for *Ulva rigida* stored at 16°C in comparison to seaweed stored at 4°C, which confirm the 6 days of shelf life of *Ulva rigida* stored at 16°C (Sánchez-Gracía et al., 2021).

Various subsequent uses of seaweeds, as food, feed, drugs, nutraceuticals, cosmetics, biofuels may require different postharvest treatments methods. However, due to high water content average for all seaweeds around 80% (Kadam et al., 2015a) and relatively short postharvest life, e.g. for *Gracilaria coronopifolia*, *G. parvispora*, *G. salicornia* and *G. tikvahiae* that time estimates about 4 days (Paull and Chen, 2008) and ease of transportation, the most important and popular postharvest treatment is drying.

Before drying, the seaweeds have to be well washed to remove salt and other impurities. The popular method of that operation uses soaking in a mixture of water and glycerine at a 1:1 ratio (Kadam et al., 2015a). Due to the perishable nature of seaweeds, the ways of prolonging the shelf life are in great demand among the producers and researchers. Paull and Chen (2008) show that treating *Gracilaria parvispora* and *Gracilaria tikvahiae* with hot seawater at 42°C for 5 min was beneficial for seaweeds and allowed maintaining the appearance and extended postharvest life by 40–60%. The other methods of increasing the postharvest life of red seaweed are, depending upon species, stored at 15°C and submerged in seawater or treated at 42°C for 5 min. Also, the darkness can extend the postharvest life of seaweed submerged in seawater for about 30 days (Paull and Chen, 2008).

Nowadays, two drying technologies are used commercially: a direct sunlight dryer and a conventional convective dryer (Kadam et al., 2015a). The drying techniques affect the functional, nutritional and biological properties of seaweeds. The sun drying system is relatively low cost and simple, however, the product (e.g. *Sargassum hemiphyllum*) has a lower content of total amino acids, total polyunsaturated fatty acids, and total vitamin C than freeze-dried products (Chan et al., 1997). In contrast to sun drying, the conventional hot air oven drying is spatially limited and energy-consuming. Similarly to sun drying, it causes the higher degradation of nutritional components. Therefore, the solar energy has recently become increasingly attractive. It is also clean and low cost (Kadam et al., 2015a). Fudholi et al. (2014) have developed a solar dryer for seaweed with energy consumption at the level of 2,62 kWh/kg, average solar radiation 500 W/m^2 and airflow rate of 0.05 kg/s.

The drying conditions vary according to the method used and the species of seaweed. The effect of oven drying at 25, 40 and 60°C was evaluated on three macroalgae of relevance in Europe, namely *Ulva rigida*, *Gracilaria* sp. and *Fucus vesiculosus* by Silva et al. (2019). The results of the studies showed that the moisture content of *Fucus vesiculosus* is decreasing rapidly after 2 hours (from 80% to around 16%) in the temperatures of drying –45°C and 60°C. The temperature 25°C applied for 7 hours in the oven allows reducing the moisture content only to 60%. Dryness of seaweed is established at the 10% of moisture content (Silva et al., 2019). Therefore, the drying process has to last longer than 7 hours. Moreira et al. (2016) show that approximately three kilograms of *F. vesiculosus* (with moisture content 84.4±2.9%) required 25 h to dry at 35°C and at least 20 h at 60 and 75°C.

Poeloengasih et al. (2019) analysed the rinsing methods (tap water and seawater) of *Ulva lactuca* after harvesting and also drying methods (sun drying and oven drying at 50°C for 18 h) for mineral content, morphology and appearance of that green seaweed. Their results showed that *Ulva lactuca* rinsed in seawater has higher mineral content than rinsed in tap water. The comparison between the two methods of drying by Poeloengasih et al. (2019) confirm that sun drying caused discolouration of the thallus. The authors of the publication recommend for chip production from *Ulva lactuca* the rinsing seaweeds in seawater and then drying them in the oven at 50°C for 18 h.

Also, the different types of drying pre-treatment were analysed by the researchers. Research done by Kadam et al. (2015b) shows that even 12% less time-consuming drying (compared to hot control drying) was obtained when the samples of brown seaweed *A. nodosum* were ultrasound pre-treated at 75.78 W/cm^2.

The other type of postharvest treatment of seaweeds is freezing. Obluchinskaya (2020) compared the influence of postharvest treatment (fresh, freezing and air-drying) on the free amino acids content in *Fucus vesiculosus*. The one part of samples was frozen in a freeze at –25±2°C and the other was dried in the greenhouse for 5 days (15°C in the night and up to 25°C in the middle of the day with average humidity 50±5%) and then stored in a controlled temperature of about 20°C and humidity 45±5%. The fresh seaweeds were already analysed and the other two parts were analysed every 3 months for a year. The obtained results showed that the content of free amino acids increased during storage for both groups (frozen and air-dried) in comparison to fresh algae. However, the results were the highest for dried seaweed.

Fucus versiculosus as a source of the high content of fucoidan is also intended for the solvent extraction process. However, studies done by Fletcher et al. (2017) shows seasonal variation of Fucoidan in three brown macroalgae species (*Fucus serratus*, *Fucus vesiculosus* and *Ascophyllum nodosum*). The highest quantities of fucoidan were extracted in autumn and lowest in spring. Fucoidan content, varied in between 8,1 (Feb) and 12,2 (Dec), 6,5-8,9 (Feb, Oct) and 4,2-7,5 (Apr, Nov) wt% for *Fucus vesiculosus*, *Ascophyllum nodosum* and *Fucus serratus*, respectively. The results are not extremely different however show that the best time for harvesting *Fucus vesiculosus* is late autumn - December.

Summarising the postharvest treatments of seaweed, the used methods need to be suitable for the particular purposes and customised to particular species. Modern methods of drying allow us to obtain better quality products from seaweed, but they are much more energy-consuming and cost-intensive in comparison to sun drying. The important part of the economic analysis of postharvest methods is space availability, size of the batch and cost of each batch treatment. However, as shown by the results of seaweed research, they should be rinsed in seawater after harvesting.

9. Operational cost production for macroalgae cultivation in the Baltic Proper

(Joanna Krupska)

Investment and operational cost calculation

Based on scientific literature, reports and interviews, insight was gathered into the current and potential status of offshore seaweed production. Data collection first, a review literature was conducted to collect information on the estimated production costs and revenues. The lack of reliable information on the costs of offshore production required us to also utilize the judgements of sector experts. The collected data was used as input to the model.

The following assumptions were made

The calculations required making several assumptions. It was assumed that the potential farm is located in the South East Baltic Sea. Mainly due to the low labour cost in this area and favorable conditions for cultivation. The calculations were prepared for a 1 ha farm. Additionally, the assumption was made that the exchange rate between the euro and the Polish zloty is 1 €/ 4.2693 zł. In addition, the calculation was based on the assumption that the average hourly wage in the agriculture, forestry, hunting and fishing sector is 7.6 € per hour.

Two species of seaweed were used in the calculations, i.e.:

- *Ulva intestinalis*,
- *Fucus vesiculosus*.

However, when it comes to growing *Saccharina latissima*, the costs have not been calculated. The data presented in the article (Hasselström et al. 2020) were used here. In this article, the authors assessed the economic potential of large-scale cultivation of *Sacharina latissima* along the west coast of Sweden.

Tab. 20 General assumptions for the calculation

GENERAL ASSUMPTIONS	
SEAWEED SPECIES	*Ulva intestinalis*, *Fucus vesiculosus*
CULTIVATION AREAS	south-east of the Baltic Sea: Poland, Latvia, Estonia
BREEDING SIZE	1 ha
EXCHANGE RATE	1 € / 4.2693 zł
REMUNERATION	7.6 € / h

9.1. I model - The estimation of cost of *Ulva intestinalis* cultivation - calculation based on literature data

The cost estimation was prepared for two variants: optimistic and pessimistic.

Investment costs

It was assumed that the *Ulva* should be chained on ropes (long lines). For 1ha of *Ulva intestinalis* cultivation is needed 10,000 m of based lines. Investment costs also included buoys, mooring and cost of labor (Linden et.al., 2014), inflatable boat with engine (engine in KM 5PS short, load capacity max 450 kg), design costs, permits, licenses (including water and environmental permit). The total investment amount would be 33,432 € in the optimistic variant and 83,432 € in the pessimistic variant.

The investment has an expected lifespan of 10 years, so depreciation cost is 10%.

Estimated seaweed production costs

Production operational costs have been divided into two phases:

- seeding and cultivation,
- harvesting.

Seeding usually takes place in the period of April-May, once a year. Estimating the production costs of the *Ulva* seeding and cultivation phase requires making several assumptions. Spores are obtained in the laboratory/ hatchery from mature individuals collected from the natural environment. As the lines are 1 m apart, the hectare requires a total of 10,000 m of secondary lines with seed. In the optimistic version it costs 1€/m (Linden et.al, 2014), in the pessimistic variant 1,14 €/m (van den Burg et.al, 2016). The system is labour-intensive, as the seedings need to be attached to the rope manually, and capital-intensive.

The production phase therefore requires the involvement of employees. During seeding, workers are required for logistics, installation at sea, seeded line deployment and during the cultivation phase for operation, monitoring and maintenance. It is estimated that the time needed to perform these activities is 158 hours per year, which on average costs 1,200 €/year.

During cultivation, it is also necessary to use a pontoon to monitor the cultivation and to make any minor repairs. About 120 liters of fuel are needed for this. It was assumed that the average annual cost of operating a pontoon is 139 €. Total amount of seeding and cultivation cost is 11,340 € in the optimistic version and 12,740 € in the pessimistic scenario.

Harvest is the next calculated phase of production. It takes place in the months September–October. The main harvest costs include boat rental, employment and the cost of packaging.

In addition, the employees are involved to the greatest extent during the harvest.

Boat rental for 4 days costs 2,811 €. It has been estimated that for the harvest it is necessary to involve workers in the amount of 78 working hours, and the collected seaweed should be placed in jute bags (jute bag 60x110cm for up to 50 kg), the cost of which is 2,038 €. Total cost of harvesting is 5,442 €.

Estimating the costs according to van den Burg et al. 2016, who assumes that they are 104€/t, the total harvest costs in the pessimistic version are 9,048 €/ha.

Total cost of *Ulva* farming

Assuming performance 87 t/ha [3], the unit cost of producing 1 kg of fresh *Ulva intestinalis* is 0.23 € in the optimistic variant and 0.34 € in the pessimistic variant.

Tab. 21 The estimation of cost of *Ulva intestinalis* cultivation (own calculation based on literature data)

Costs of Ulva intestinalis cultivation (model I)	optimistic variant	pessimistic variant
Depreciation cost 10% (€/year)	3,343.24 €	8,343.24 €
Total cost of seeding and cultivation per year	11,339.79 €	12,739.79 €
Total cost of harvesting	5,441.58 €	9,048.00 €
Total cost of *Ulva* production	20,124.60 €	30,131.02 €
Yield	87 t/ha	
Unit cost of producing 1 kg of fresh *Ulva*	**0.23 €**	**€ 0.35**

When analyzing the structure of cultivation costs, it can be noticed that the largest share in the costs is constituted by the costs of the cultivation phase with a 56% share in the overall cost structure. 27% of the harvest phase costs and 17% of the depreciation.

9.2 II model - The estimation of cost of *Ulva intestinalis* cultivation - calculation based on literature data and 2.1 Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks

Investment costs

The third model based on data from literature and output 2.1 Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks assumes a farm of 1 ha contains 13 horizontal parallel ropes, each 200 m long placed within 1 m of surface water. The average distance between the ropes is 4 m. Additionally, the cost of mooring, buoys and inflatable boat with engine, were included. The investment has an expected lifespan of 10 years, so depreciation cost is 10%. In this assumption the total investment amount is 14,932.4 € in the optimistic variant, and 27,932.4 € in the pessimistic variant.

Estimated seaweed production costs

Production operational costs have been divided into two phases:

- seeding and cultivation,
- harvesting.

A typical deployment period for *Ulva intestinalis* in the Baltic Sea region would be from May to September. The initial biomass of *U. intestinalis* in the farm is 20 g ww per 1 m long-line.

The optimistic option assumed that the species can be harvested 2 times in a growing season and in the pessimist option 5 times.

Renting a boat for 2 days of harvesting with remuneration for workers costs about 1,648 euro (optimistic variant) while assuming that one harvest cycle is 1 month and the species can be harvested 5 times in a growing season (once in a month), it increases the cost to 4,121 € (pessimistic variant).

Total cost of *Ulva* farming

Assuming performance 9,8 t/ha, the unit cost of producing 1 kg of fresh *Ulva intestinalis* is 0.6 € in the optimistic variant and 1 € in the pessimistic variant. The table shows the detailed costs of the individual stages of *Ulva* cultivation.

Tab. 22 The estimation of cost of *Ulva intestinalis* cultivation (own calculation based on literature data and GRASS Report 2.1 Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks)

Costs of Ulva cultivation (model II)	optimistic variant	pessimistic variant
Depreciation cost 10% (€/year)	1,493.2 €	2,793.2 €
Total cost of seeding and cultivation per year	2,677.1 €	2,964.0 €
Total cost of harvesting	1,879.1 €	4,352.1 €
Total cost of *Ulva* production	6,049.5 €	10,109.4 €
Yield	9,84 t/ha	
Unit cost of producing 1 kg of fresh *Ulva*	**0.6 €**	**1.0 €**

Read also: Assessing the PanBaltic potential of macroalgae cultivation and of harvesting wild stocks

https://www.submariner-network.eu/grass

9.3 III model - Estimating the cost of *Fucus* breeding

Investment costs - *Fucus* vesiculosus farming

In order to estimate the costs of growing *Fucus vesiculosus*, it was assumed that *Fucus* should be grown inflexible and durable HDPE baskets with dimensions 1 m x 1 m x 0.18 m. 1,700 baskets are needed for the cultivation of one hectare. The baskets are very durable, therefore it is assumed that the lifetime of the project will be 15 years.The baskets are kept floating by the attachment to polyethylene foam pipe insulations. (Meichssner et al., 2020, FucoSan, 2020, Meichssner personal communication) Baskets require additional equipment such as clip hook, pipe line, anchoring system, assembly. In addition, the farm should be equipped with buoys (4 pieces of buoy with signalling lights support 15 l) and inflatable boat with engine (engine in KM 5PS short, load capacity max 450kg). Investment cost also include design costs, permits, licenses (including water and environmental permit). The total amount of the investment expenses that must be incurred when building a *Fucus* farm is 23,405.43 €.

Estimated production operational costs

Production operational costs have been divided into three phases:

- spore preparation,
- seeding and cultivation,
- harvesting.

Spore preparation, seeding and cultivation

The collection of vegetative thalli from the environment (beach) requires the equipment of a quad bike with a trailer for about 4 days, petrol and the involvement of employees in the amount of 64 working hours. This phase costs 1,125 €.

The seeding and cultivation stage is associated with the need to place the material (free floating vegetative apices (3-10 cm) cut from collected individuals) in baskets, then monitoring and possible minor repairs. These activities require the use of a pontoon and the employment of 138 working hours. The total cost of this phase is 2,643 €.

Harvesting

The harvest phase of *Fucus vesiculosus* grown in cages is technically complicated, labor-intensive and therefore cost-intensive. There are 1,700 cages per 1 ha. It was assumed that from 1 cage it is possible to obtain 6 kg of raw material, but 1 kg of material should be left. So the material is collected only once and then a part, i.e. 1 kg out of 6 kg, is left for the next year. As a consequence, an efficiency of 10 t/ha was assumed. In order to harvest *Fucus*, you should rent a boat equipped with a basket winch for about 21 days. The number of working hours necessary for this phase was estimated at 384 h. Additionally, the harvested raw material must be packed in jute bags (jute bag 60x110 cm for up to 50 kg). The total cost of the harvest is estimated at 18,085 €.

Tab. 23 *Fucus vesiculosus* cultivation - assumptions for the calculation

***FUCUS VESICULOSUS* CULTIVATION - ASSUMPTIONS**		
TECHNOLOGY		Baskets
LIFESPAN		15 years
INVESTMENT COSTS		Baskets (1700 pieces)
		Buoys, clip hook, pipe line, anchoring system, assembly
		Labour
		Inflatable boat with engine
		Design costs, permits, licenses
PRODUCTION OPERATIONAL COSTS	SPORE PREPARATION	Labour
		Quad bike (rent)
	SEEDING and CULTIVATION	Labour
		Transport - petrol for inflatable boat
	HARVESTING	Transport vessel (rent)
		Labour
		Packaging (jute bag)

Total cost of *Fucus vesiculosus* farming

The total cost of growing *Fucus* is 23,413 € per year. Assuming that the crop yield per hectare is 10t/h [4], the unit cost of growing *Fucus* is 2.34 €.

Tab. 24 The estimation of cost of *Fucus vesiculosus* cultivation (own calculation based on literature data)

Costs of Fucus cultivation	
Depreciation cost 10% (€/year)	1,558.80 €
Spore preparation	1,125.57 €
Total cost of seeding and cultivation per year	2,642.73 €
Total cost of harvesting	18,085.83 €
Total cost of *Ulva* production	23,412.93 €
Yield	10 t/ha
Unit cost of producing 1 kg of fresh *Fucus*	2.34 €

When analyzing the cost structure of *Fucus* cultivation, it can be noticed that the decisive share in the total costs is the harvest, i.e. as much as 77%. Phase spore preparation and cultivation 17% share in the cost, and depreciation only 7%.

10. SWOT analysis and recommendations

(Tomasz Kulikowski)

Below we present an original summary of the strengths and weaknesses of the development of seaweed farming in the Baltic Sea Region, as well as the analysis of opportunities and threats for such a business in the near future.

We want to relate the internal factors analysis to the results of all GRASS Work Packages as a project laying the foundations for the future development of seaweed farming in the Baltic Sea Region.

Strengths

Potential strengths of the future seaweed industry in the Baltic Sea Region are:

- a favorable pro-ecological image and the ability to prove that this type of activity has a low negative impact on the environment, is low-emission and complies with the recommendations for the development of blue bioeconomy in Europe,
- identifying the places where these species achieve optimal growth rates,
- identification of where seaweed aquaculture is allowed in the context of spatial plans (and even places where this aquaculture benefits from synergies with other users of the water bodies).

Weaknesses

The weaknesses of the future industry are primarily:

- lack of proven (confirmed in practice) breeding techniques dedicated to species that can be grown in the Baltic Proper and Adjacent Basins,
- lack of know-how in relation to seaweed farming,
- lack of know-how in relation to post-harvest treatment,
- no know-how for the processing of the specific species of seaweed identified for the region, but also no know-how to assess their quality and technological suitability for specific applications.

The weaknesses also include high estimated production costs - both *Ulva* and *Fucus*, especially in a small-scale production.

Opportunities

There are a number of opportunities in the Baltic Sea Region for the future seaweed industry. They are mainly:

- consumer trends that cause the growing demand for alternative aquatic food products,
- quite good market penetration by the currently offered seaweed food products, with a high declared openness to try these products by consumers who have already reached for them,
- good consumer opinion on seaweed (both in the form of food and cosmetics) and its health-promoting properties,
- searching by consumers for unique food, produced locally/regionally,
- a developed fish processing sector that may be interested in processing seaweed and that may benefit from the EU aid for investments (including investments in seaweed processing),
- the existing scientific and research potential, which is ready to support the emerging seaweed business in relation to: algae biology, breeding techniques, chemical analyzes of the product, implementation of innovative processing techniques and obtaining active substances,
- the existing potential of sea workers - including fishers who have the appropriate skills and qualifications needed to work on the sea farms.

A potential - perhaps the most important - opportunity for the development of seaweed farming would be the creation of a water and environmental compensation system in which countries (e.g. under the EU funds) would pay seaweed farms for specific ecosystem services - primarily for nutrient reduction, limiting the eutrophication of the Baltic Sea. Unfortunately, this remains in the sphere of potential opportunities, as no such compensations are currently applied.

Threats

The most important threat is competition in the global market for seaweed raw materials. The countries of Southeast Asia supply the world market with both raw materials and finished products, and the estimates carried out leave no illusions - at such prices the seaweed business in the Baltic Sea Region will not be able to offer them. This means that on the mass market, where the basic decision-making parameter is the price (with adequately guaranteed quality), the seaweed from the Baltic farms cannot be competitive.

Another threat is that while local products are sought on the food market, a significant segment of the seaweed food products market may not be sensitive to the origin of the product - for example, shops and restaurants with the Far Eastern cuisine are a large distributor of seaweed - it is doubtful that they would be especially interested in a product from the Baltic Sea, especially if it is more expensive than Asian.

The fact of the lack of knowledge about the (sensory) acceptance for potential food products produced in the Baltic Sea Region on the basis of *U. intestinalis* and *F. vesiculosus* should also be taken into account as a threat.

Recommendations

Taking into account the strengths, weaknesses, opportunities and threats, it is proposed to adopt the following mini-roadmap:

(1) establishment of experimental, semi-industrial farms to confirm in practice the technical solutions of cultivation, but also to confirm the impact on the environment - including determining the parameters of reducing nutrients in water - the ability to reduce the eutrophication of the Baltic Sea waters,

(2) performing a qualitative and technological evaluation of the produced seaweed, creating food model products and carrying out their consumer (sensory) tests on target groups for the consumption of Baltic seaweed,

(3) continuing lobbying showing the administrations of the Baltic Sea Region countries the advisability of using public funds to support the cultivation of seaweed, also in the form of compensation for environmental services provided.

(4) creating a cluster of cooperation between scientific and implementation institutions and businesses interested in the cultivation and processing of seaweed.

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