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Growing Algae Sustainably in the Baltic Sea (GRASS)
WP 3.4 Unlocking the potential of using macroalgae for food purposes

Global production of macroalgae and uses as food, dietary supplements and food additives

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1. Introduction

Macroalgae are a diverse group of aquatic organisms that have been utilized by mankind for multiple purposes for thousands of years. Macroalgae are used as fresh or mildly processed in foods and consumables. Moreover, they are used as raw material for various extracts, the most important ones being agar, alginates and carrageenan. Currently, the use of biologically active macroalga extracts as food and feed supplements is growing. In addition, there is interest towards novel macroalga based food additives such as food flavours, colourants and nutrients.

Macroalgae are divided into three classes: green, red and brown macroalgae (Chlorophyta, Rhodophyta and Phaeophyta, respectively), of which the brown macroalgae species are the commercially most important ones counting for two-thirds of the globally produced macroalga. Brown macroalgae are followed by red macroalgae with a share of approximately one-third and green macroalgae with a share of 5% of the global macroalgae production (Lorenzo et al. 2017). Currently, over 200 macroalga species are used globally and the total production reaches over 30 million tons. Regardless of the diversity of edible and otherwise useful macroalga species, 98% of the seaweed production is accounted for only five macroalga genera (Pereira et al. 2008, Table 1). Utilisation of more diverse species suffers from various bottlenecks including lack of suitable cultivations techniques as well as of the limited distribution and natural abundance of species. Moreover, research on the biochemical composition, nutritional and bioactive properties and sensory characteristics of novel seaweeds is needed to unlock their potential as food or source of natural compounds.

2. Global production of macroalgae

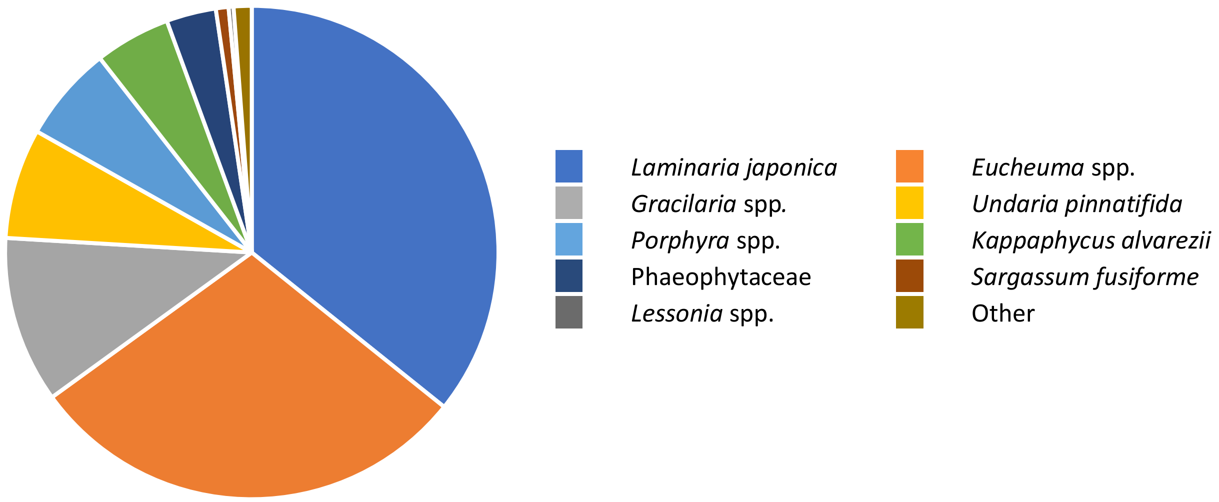
The biggest share of the global macroalga production is used as food and feed. the second biggest share goes to the production of hydrocolloids, namely alginates, agar and carrageenan. These are used in food and feed, cosmetics and pharmaceutical industries. Minor shared of the global production are used for agronomic applications, feed, bioenergy and as a source of natural compounds. In addition, macroalga food supplements are a growing market sector. Historically, seaweeds have also been used for production of potash and iodine, but they have since been replaced by more cost-efficient production methods (Buschmann et al. 2017).

The global macroalga production is dominated by the kelp species *Laminaria japonica* and red macroalgae *Euchema* spp. *Laminaria japonica* is used as food and for production of alginate whereas *Euchema* spp. are mostly used for carrageenan production (Figure 1, Supplemental Tables 1 and 2) Of the other macroalga species with over 100 000 t production volumes, *Gracilaria* spp. and *Kappaphycus alvarezii* are used for production of agar and carrageenan, respectively. *Porphyra* spp. and *Undaria pinnatifida* are popular food ingredients especially in Asia and *Sargassum fusiforme* is used as food especially in Japan and Korea. *Lessonia* spp. are mostly used for alginate production. The global macroalga production by species in 2018 is summarized in the Figure 1 which is based on data presented in Table 1.

Only a limited number of macroalgae species are used in commercial aquaculture and this is heavily reflected to their production volumes (Table 1). Moreover, as macroalgae aquaculture is concentrated in few Asian countries, the species with the highest production volumes are native to the Pacific Ocean and the Indian Ocean. Accordingly, the macroalga species most important for human food use, namely *Saccharina japonica, Undaria pinnatifida*, *Pyropia* spp. and *Sargassum fusiforme* are native to these sea areas. However, these species are popular food ingredients also in Europe and form a notable share of imported macroalgae products. As an exception, *Undaria pinnatifida* is common also in the Atlantic, although its commercial production is centred in Asian countries (Supplemental table 1).

In Africa, *Euchema* spp., *Gracilaria* spp. and *Kappaphycus alvarezii* are among the macroalgae with highest production volumes and mostly used for production of carrageenan and agar (Supplemental tables 1 and 2). However, the production volumes are small compared to Asian production. In Canada and the USA, harvesting of wild *Acophyllum nodosum* forms a notable share of the macroalga production (Supplemental table 1). In South America, Chile is the biggest macroalga producer followed by Peru (Supplemental table 1). The macroalga species produced in South America include *Lessonia* spp., *Macrocystis* spp. and *Gracilaria* spp. as well as the red algae *Sarcothalia crispate* and *Gigartina skottsbergii* and brown algae *Durvillaea antarctica* (Supplemental Table 1). In Europe, the macroalga production is small in volume and concentrates on brown algae *Ascophyllim nodosum, Laminaria digitate* and *Laminaria hyperborean* and is complemented with small scale production of other species (Supplemental Table 1).

A



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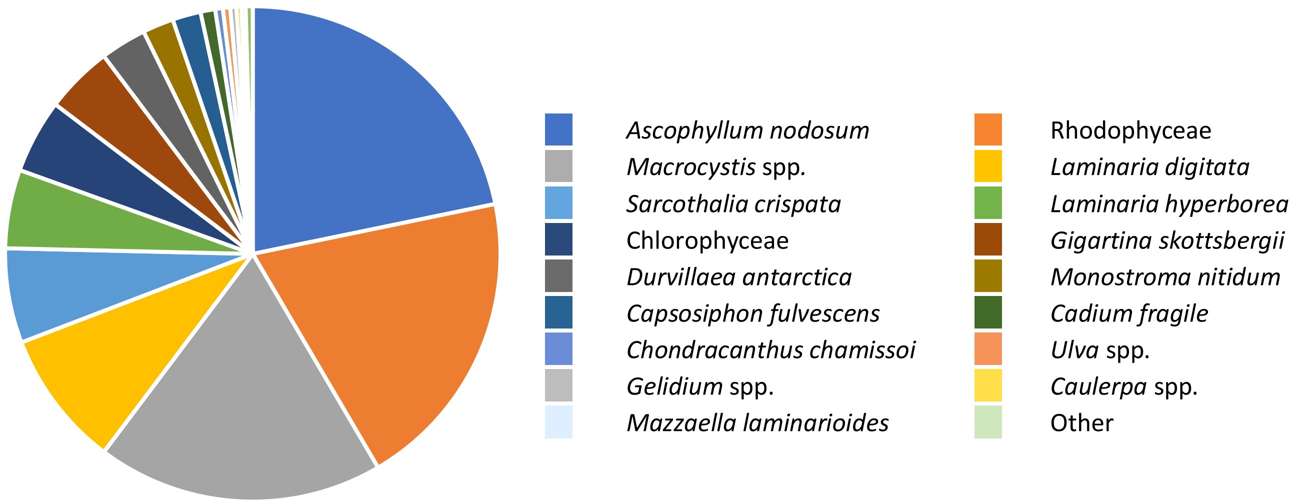

Figure 1. Global macroalga production by species in 2018. (A) Macroalga species with the production volume of more than 100 000 t. (B) Macroalgae species with production volumes of less than 100 000 t but over 1000 t. Figures A and B are based on FAO data listed in Table 1. In charts A and B, some closely related species on same family have been combined (E.g. *Ulva* spp. or *Porphyra* spp.). In Figure 1A, Pheophytaceae indicates the production volume of brown algae whose species has not been defined in the statistical data collected by the FAO and may contain multiple species used as food and for production of alginates.

Table 1. Global macroalgae production by species in 2018 according to FAO. F = production volumes are estimates by FAO.

Species	Production 2018 (t)	FAO estimate
Laminaria japonica	11 504 164,00	
***Eucheuma* spp.**	9 237 529,50	
***Gracilaria* spp.**	3 512 945,30	
Undaria pinnatifida	2 323 517,00	
***Porphyra* spp.**	2 018 085,00	
Kappaphycus alvarezii	1 597 332,82	
Phaeophyceae	1 047 211,00	
Porphyra tenera	855 054,00	F
Sargassum fusiforme	268 660,00	
Eucheuma denticulatum	174 930,69	
Ascophyllum nodosum	82 363,00	F
Rhodophyceae	74 905,00	
Lessonia nigrescens	66 436,00	
Lessonia trabeculata	36 562,00	
Macrocystis pyrifera	35 657,51	
***Macrocystis* spp.**	35 120,00	
Laminaria digitata	33 768,00	
Sarcothalia crispata	23 389,00	
Laminaria hyperborea	19 435,00	
Chlorophyceae	18 238,00	F
Gigartina skottsbergii	16 688,00	
Durvillaea antarctica	11 378,00	
Monostroma nitidum	7 672,00	F
Capsosiphon fulvescens	7 000,00	F
Codium fragile	3 620,00	F
Chondracanthus chamissoi	1 885,00	
***Ulva* spp.**	1 687,07	
***Gelidium* spp.**	1 514,00	
***Caulerpa* spp.**	1 218,14	
Mazzaella laminarioides	1 027,00	
Gymnogongrus furcellatus	728,00	
Gracilaria verrucosa	686,93	
Meristotheca senegalense	300,00	
***Sargassum* spp.**	250,00	F
Haematococcus pluvialis	222,53	F
Saccharina latissima	175,24	
Gracilaria gracilis	130,00	
Ulva pertusa	113,00	
Alaria esculenta	41,76	
Nemacystus decipiens	20,00	F
Pterocladia lucida	12,00	
Porphyra linearis	3,00	
Chlorella vulgaris	1,42	

3. Food use and processing of edible macroalgae

Most of the macroalgae used as food are only mildly processed. Because of the poor preservation of fresh macroalga, it is often dried and may be later rehydrated and cooked (McHugh 2003). Wakame and kombu are examples of popular seaweed foods that are first dried and then cooked to prepare a dish. Wakame is dried brown alga *Undaria pinnatifida* that is often used in soups (McHugh 2003). Similarly, kombu is mostly made of dried *Laminaria japonica*, although other *Laminaria* spp. are used as well (McHugh 2003). Kombu may be cooked, marinated or seasoned and then dried for storing. For use, dried seaweed is rehydrated by cooking (McHugh 2003). Kombu is also used as dry powder to prepare tea.

Nori sheets are popular seaweed food products prepared of *Porphyra* spp. belonging to red algae. Fresh *Porphyra* blades are washed, chopped and pressed to fine sheets that are then dried (McHugh 2003). Another widely used group of red algae are *Gracilaria* spp., that are used mostly as fresh or pickled and popular for example in the Caribbean and Hawaii, where it is called sea moss, whereas in Japan, *Gracilaria* is called ogonori (McHugh 2003). Green algae of *Ulva* and *Monostroma* genera are commonly used for food and called aonori or green laver. These green macroalgae may be dried after harvesting, crushed to small flakes and springled on top of dishes (McHugh 2003). Alternatively, algae may be boiled and preserved and used in salads and soups.

Some seaweed foods take advantage of the morphological features of specific macroalga species. *Caulerpa lentillifera* forms clusters of small green bubbles that resemble wine grapes and are thus called “sea grapes”. *Caulerpa lentillifera* is eaten fresh and used especially in Japan. Similarly, brown algae *Himanthalia elognata* grows as long thin strings that resemble tagliatelle pasta and is often called “sea spaghetti”. Sea spaghetti is cooked and used as a side dish or in soups and salads. Red alga *Palmaria palmata* on the other hand is known for its smoky aroma and sold as “sea bacon”.

Whereas most macroalgae for human consumption goes through only mild processing, more complex processing procedures are established for specific seaweed dishes. The goals of the processing are to alter the structure or taste of the seaweed and make it more palatable. *Hiziki fusiforme* offers an example of this. Hiziki has a high content of phlorotannins and pigments that give it a bitter and astringent taste. To make hiziki more palatable, it is boiled for several hours with other macroalgae, *Eisenia bicyclis* or *Ecklonia cava*, that have a milder taste (McHugh 2003). During boiling, pigments in hiziki are replaced by those of *Eisenia* and *Eclonia* making hiziki taste milder. After boiling, hiziki is steamed for further 4-5 hours to reduce the amount of phlorotannins (McHugh 2003). After this, hiziki is dried and stored.

Besides the use of macroalgae as sea vegetable as described above, a large variety of species have been used to add nutrients and minerals as well as flavour to another foodstuff. For these purposes, macroalgae are usually dried and ground to fine powder that can be used in baking and cooking. Recent innovations are expanding the use of seaweeds in the food sector to uses 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/).

4. Macroalgal polysaccharides as food additives

Hydrocolloids produced from macroalgae, namely agar, alginates and carrageenan, are important additives in food industry. Agar is a hydrocolloid extracted from red macroalgae, mostly from *Gracilaria* spp. and *Gelidium* spp. (McHugh 2003). It is composed of D-galactose and 3,6-anhydroL-galactose that may contain substitutions for examples with sulphates or methyl ethers (Hernández-Carmona et al. 2013). Agar is practically tasteless in food since the formation of agar gel does not require addition of calcium or potassium salts. Moreover, agar is not readily digested and thus has low caloric value. Agar is dissolved in hot water and forms a strong gel after it is cooled down to 32-43 ^{o}C. After formation, agar gels are stabile also in higher temperatures up to 85 ^{o}C. In the food industry, agar is used especially in desserts, pastries and dairy products. The physical properties of the agar gels vary slightly according to the macroalgae species from which it has been extracted. Some agar types can be used in products with high sugar content and thus agar is popular also in sweets and candies. Approximately 90 % of the produced agar is used by the food industry and the remaining 10 % goes mostly for bacteriological and biotechnology applications (McHugh 2003).

Alginates are extracted from brown seaweeds of the order Laminariales including *Macrocystis* spp., *Laminaria* spp. *Saccharina* spp., *Lessonia* spp. and *Ecklonia* spp. as well as from Fucales such as *Durvillaea* spp. and *Ascophyllum* spp. (Peteiro 2018). Alginates are composed of β-D-mannuronate and α-L-guluronate connected by 1–4 glycosidic bonds (Hay et al. 2013). The ratio of the monosaccharide residues varies between macroalgae species and affects the gelling properties of the alginates (Hay et al. 2013). Alginate is isolated from macroalgae as sodium alginate and it forms gels when it is dissolved in water and sodium ions are replaced by calcium. Alginate gels are thermostable and the dissolving or gel formation do not require heating, which makes alginate gels preferable for thermo-sensitive applications. Alginates are used in candies, jellies and dairy products. They can be used to stabilize foams and to bind minced meat products. Global demand for alginates is expected to increase in the future due to their use in biomedical and bioengineering applications (Hay et al. 2013, Peteiro 2018).

Carrageenan is extracted from various red macroalgae, especially from *Kappaphycus* spp., *Eucheuma* spp. and *Chondrus* spp. (Hernández-Carmona et al. 2013). Three types of carrageenan may be extracted from macroalgae, namely kappa, iota and lambda, which all have their typical gel strengths and properties (McHugh 2003). Moreover, the properties of the carrageenan gels can be modified depending on the cations that react with the polysaccharides to form a gel (McHugh 2003). Kappa carrageenan reacts strongly with potassium salts and iota carrageenan with calcium salts (McHugh 2003). Carrageenan forms elastic gels in a reaction with potassium ions and brittle gels with calcium ions (McHugh 2003). Carrageenan is often used to win dairy products, since its negative charge binds the positively charged milk casein forming a gel. It stabilizes milk products even in very low concentrations. Moreover, the gel properties may be modified by mixing carrageenan with other thickening agents like locust bean gum, konjec flour and starch. In addition to dairy products, carrageenan is used in meat to retain tenderness and texture while cooking.

5. Macroalga based food supplements and bioactive extracts

Use of brown macroalgae in food supplements

Brown macroalgae are important raw material for commercial food supplements. Depending on the species, various extracts such as polysaccharides, phenolic compounds, pigments and minerals are extracted and used in food supplements. Fucoidan extract and *Ecklonia cava* phenolic extract are authorised for use as food supplement in the EU (Lähteenmäki-Uutela et al. 2021). However, outside the EU also other extracts are on the market, including laminarin and fucoxanthin. In addition, many seaweeds are used as dried and ground whole extracts in food supplements. Macroalga food supplements are marketed with statements about their biological activities such as antioxidative activity or improvement of metabolism. Although the biological functions of the macroalga phytochemicals are under active research, in many cases the *in vivo* studies and evidence of bioavailability of the compounds are limited (Alfonso et al 2019).

Fucoidans are found in brown algae and composed mainly of fucose and sulphate. In addition, they may contain glucose, galactose, mannose, xylose and uronic acid. Fucoidans may also be acylated and their content and composition varies between and within species (Ale et al. 2011, Bruhn et al. 2017). Fucoidans have shown antioxidative, antitumor, immunoregulatory, anti-inflammatory and antiviral activities (Wang et al. 2019). Moreover, they are putative anticoagulants and pose antithrombotic effects (Wang et al. 2019). However, most effects are demonstrated in preclinical studies (Alfonso et al 2019). *In vivo* experiments have demonstrated fucoidans to reduce oxidative stress and modulate levels of cholesterol and triglycerides in serum of hyperlipidaemic rats (Alfonso et al. 2019). Fucoidans have also been shown to alter gut microbiota and be putative prebiotics (Chen et al. 2018).

Laminarin is a β-glucan storage polysaccharide found in brown algae, especially in the *Laminaria* spp. and *Saccharina* spp. where they can account for up to 35% of the macroalgae dry weight (Kadam et al. 2015). Laminarins are low molecular weight polysaccharides composed mainly of glucose but containing also small amounts of uronic acid. The composition and structure of laminarins vary according to the season and environmental conditions (Rioux et al. 2007, Schiener et al. 2014). Laminarins are classified into two types, M chains and G chains depending on the type of sugar in the reducing end of the polysaccharide chain. Laminarins accumulate to macroalgae fronds during summer and autumn whereas their levels are low in winter (Schiener et al. 2014). The physicochemical properties of laminarin can be altered by side group modifications such as sulfation to improve its bioactivities (Zargarzadeh et al. 2020). Laminarins are intensively studied for their therapeutic properties, including potential in cancer therapies and anti-inflammatory and antioxidative activities, and for use in tissue engineering (Zargarzadeh et al. 2020). However, at the moment, commercial use is limited to the use of laminarin extracts as food supplements and biofertilizers.

Phlorotannins are the most abundant phenolic compounds in brown seaweeds. Phenolic extracts from brown seaweeds have been demonstrated to exhibit various biological activities, including antioxidant, antidiabetic, anti-inflammatory activities (Alfonso et al. 2019). Whereas the faith of seaweed polysaccharides like fucoidans in the human digestive system and the mode of bioactivity remain poorly characterised, phlorotannins from *Ascphyllum nodosum* have been shown to be metabolised and absorbed into the systemic circulation (Baldrick et al. 2018). Phlorotannin extracts are currently commercially available as food supplements and phlorotannin extracts from *Ecklonia cava* have been authorised as a novel food for use as food supplements also in the EU (Lähteenmäki-Uutela et al. 2021).

Fucoxanthin is a xanthophyll pigment that belongs to carotenoids and is found in brown algae giving them the typical brownish greenish colour (Mikami and Hosokawa, 2013). Its levels vary greatly between and among species and values between 170-660 mg/kg have been reported (Alfonso et al. 2019). Moreover, fucoxanthin levels are affected by environmental factors (Fung et al. 2013). Xanthophyll has been studied for its antidiabetic, anti-obesity and antioxidant activities and the studies are supported by *in vivo* experiments (Peng et al. 2011, Mikami and Hosokawa, 2013). Research has mainly focused on xanthophylls extracted from *Undaria pinnatifida* (Alfonso et al. 2019). Like phlorotannins, also fucoxanthins are currently commercially available as dietary supplements that are claimed to increase metabolic rate and help in weight loss.

Iodine and mineral extracts

Macroalgae are rich in minerals such as calcium, potassium, magnesium, zinc, iron. manganese, copper and iodine (Circuncisão et al. 2018). The physiological features of macroalgae and their cell wall composition contributed the binding of minerals and nutrients from the surrounding water resulting in superior concentrations of minerals compared to land plants. Brown macroalgae are especially rich in minerals and may have ash content up to 40% of the dry weight, but also red and green macroalgae have notable amounts of essential mineral nutrients (Circuncisão et al. 2018). Dried and powdered macroalga may be used to fortify food and feed with minerals and add flavour to foods. Brown macroalgae are especially rich in iodine and have reported iodine content of up to 9000 µg/g of dry weight (Circuncisão et al. 2018). Thus, even small amounts of seaweed in the diet help to achieve the recommended iodine intake of 150 µg/day for adults set by EFSA (EFSA, 2014). Moreover, the high iodine content together with low Na/K ratios make powdered macroalga a healthy alternative to iodized salt.

Use of green macroalgae for food supplements and additives

Food supplements based on green algae are usually composed of microalgae such as *Chlorella* spp. and blue-green algae (cyanobacteria) such as *Spirulina* spp. However, some *Ulva* dietary supplements are also on the market. Green macroalgae of the genus *Ulva* have a characteristic cell wall polysaccharide called ulvan, that is composed of sulfated rhamnose, uronic acids and xylose (Kidgell et al. 2019). Research on ulvan has demonstrated that it has various bioactivities including antiviral, anticancer and immunostimulatory activities making it a potential raw material for nutraceuticals and functional foods (Kidgell et al. 2019). However, commercial applications of ulvan are still scarce.

Use of red macroalgae for food and feed supplements

Red macroalgae are mostly used directly as food ingredients like nori or for the extraction of agar and carrageenan but not for production of dietary supplements. Development of extraction methods would allow the simultaneous extraction of other phytochemicals together with the hydrocolloid production including proteins, pigments, lipids and phenolic compounds (Francavilla et al. 2013, Torres et al. 2019). These high-value phytochemicals could be used as food additives and nutraceuticals as well as in applications in the cosmetics industry (Francavilla et al. 2013). Moreover, recent studies have demonstrated that red macroalga supplementation 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 macroalga feed supplements could significantly decrease the carbon footprint of ruminant livestock and increasing interest towards the red macroalga feed supplements can be expected in the future.

6. Sustainable use of macroalgae in the future

Currently, macroalgae are seen as versatile biomass with a multitude of possible end uses. In the future, they may provide various higher value biochemicals and raw materials. Direct use as consumables or as feed may not be economically profitable, considering the seaweed cultivation and harvesting expenses. Extraction of various higher value fractions and phytochemicals can make macroalgae aquaculture economically possible also on new production areas. The higher value products include polysaccharides, proteins, lipids, pigments and antioxidants. Moreover, global agriculture is in the middle of transformation to more sustainable and environmentally friendly cultivation practices that include increasing use of biofertilizers, biostimulants and biopesticides. Although macroalgae beach cast has been used as fertilizer for centuries, utilisation of macroalgae as biostimulants and pesticides is under active research.

Figure 2 presents different categories of macroalgae products in a value pyramid according to the value of the end product and the size of the market for each product category. Pharmaceuticals, cosmetics, functional food and feed products and other high-value extracts have the highest revenue while the demand for these products and compounds is relatively low. Below the high-value compounds come agricultural biostimulants and other agricultural applications excluding bulk fertilizers. Next are macroalgae derived polysaccharides used as emulsifiers and thickening agents. These are followed by food products which, however, may in some cases have higher revenues than bulk macroalgae hydrocolloids. At the bottom of the pyramid with low value but big market sectors are biomaterials, bulk fertilizers and bioenergy. Nonetheless, the value of the product largely depends on the characteristics of the final product and how it is valued by the customers. For example, in Asia, the demand for certain edible macroalgae is higher than in western countries and thus some macroalgae food products may have higher revenues there.

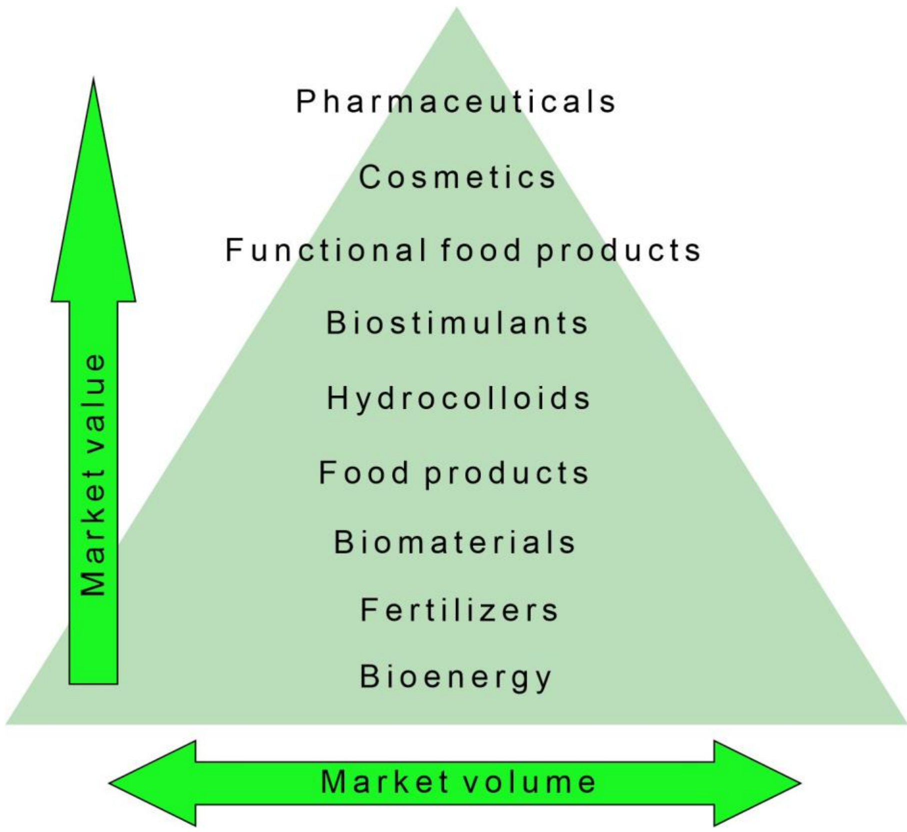

Figure 2. Value pyramid of macroalgae products and uses. Adapted from Barbier et al. (2019) and Hellesträm et al. (2020).

Higher revenue for the macroalgae biomass will be obtained if multiple products are extracted simultaneously or after one other from the same biomass (Rajak et al. 2020). Moreover, processing macroalga biomass in a sequential biorefinery concept allows the extraction of various higher value fractions while the remaining biomass may still be used for example for feed, fertilizers or bioenergy. Pipelines and extraction procedures for macroalgae biorefinery are under active research and have gathered interest also from business operators (Rajak et al. 2020). When macroalgae are used for extraction of higher value biochemicals, their yield and quality may be optimised by considering the environmental, genetic and seasonal variation in the composition of the algal biomass. This requires further research on macroalgae ecology, physiology and biochemistry.

7. Conclusions

While macroalga hydrocolloid production and traditional macroalga based foods remain big sectors of macroalgae industry, interest towards new products such as macroalgae food supplements and novel macroalgae consumables is evident. Although the diversity of the currently used macroalgae species is wide, lack of efficient cultivation technologies has a big impact on the production volumes of different macroalgae species. Harvesting of wild macroalga populations is often unsustainable and utilisation of many macroalgae species is dependent on development of new aquaculture techniques. Diverse selection of sustainably produced macroalgae species would allow the development of novel macroalgae food and feed products and novel high-value phytochemicals. In addition, subsequent extraction of various fractions and raw materials from macroalgae biomass and utilisation of side streams of the hydrocolloid production could bring higher revenue for the macroalgae production. However, more research is still needed to unlock the potential of macroalgae phytochemicals for different applications.

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Supplemental table 1. Macroalgae production by region in 2018 according to FAO. F=production volumes are estimates by FAO.

Land Area	Ocean Area	Species	Production in 2018 (t)	FAO estimation
Africa				
Kenya	Indian Ocean	*Eucheuma denticulatum*	**400,00**	F
Madagascar	Indian Ocean	*Eucheuma* spp	5 337,00	
	Indian Ocean	Rhodophyceae	800,00	F
		Total	**6 137,00**	
Morocco	Atlantic Ocean and adjacent seas	Rhodophyceae	14 828,00	
	Atlantic Ocean and adjacent seas	*Gracilaria gracilis*	130,00	
		Total	**14 958,00**	
Namibia	Atlantic Ocean and adjacent seas	*Gracilaria spp*	**130,00**	F
Senegal	Atlantic Ocean and adjacent seas	*Meristotheca senegalense*	**300,00**	
South Africa	Atlantic Ocean and adjacent seas	Phaeophyceae	10 095,00	
	Atlantic Ocean and adjacent seas	*Ulva* spp	1 687,07	
	Atlantic Ocean and adjacent seas	*Gelidium* spp	714,00	
		Total	**12 496,07**	
Tanzania	Indian Ocean	*Eucheuma* spp	1 329,50	
	Indian Ocean	Rhodophyceae	600,00	
		Total	**1 929,50**	
Zanzibar	Indian Ocean	*Kappaphycus alvarezii*	260,00	
	Indian Ocean	*Eucheuma denticulatum*	102 960,00	
		Total	**103 220,00**	
Belize	Atlantic Ocean and adjacent seas	*Eucheuma* spp	3,00	F
	Atlantic Ocean and adjacent seas	*Kappaphycus alvarezii*	700,00	F
	Atlantic Ocean and adjacent seas	*Gracilaria* spp	30,00	F
		Total	**733,00**	
America				
Canada	Atlantic Ocean and adjacent seas	*Ascophyllum nodosum*	**11 497,00**	
Chile	America, South - Inland waters	Chlorophyceae	22,53	
	Pacific Ocean	*Durvillaea antarctica*	11 378,00	
	Pacific Ocean	*Lessonia nigrescens*	65 530,00	
	Pacific Ocean	*Macrocystis pyrifera*	0,51	
	Pacific Ocean	*Macrocystis* spp	32 819,00	
	Pacific Ocean	*Lessonia trabeculata*	36 153,00	
	Pacific Ocean	*Gelidium* spp	148,00	

	Pacific Ocean	*Gracilaria* spp	78 832,69	
	Pacific Ocean	*Sarcothalia crispata*	23 389,00	
	Pacific Ocean	*Porphyra* spp	295,00	
	Pacific Ocean	*Gigartina skottsbergii*	16 688,00	
	Pacific Ocean	*Chondracanthus chamissoi*	646,00	
	Pacific Ocean	*Gymnogongrus furcellatus*	728,00	
	Pacific Ocean	*Mazzaella laminarioides*	1 027,00	
		Total	**267 656,73**	
Ecuador	Pacific Ocean	*Kappaphycus alvarezii*	**5,00**	F
Grenada	Atlantic Ocean and adjacent seas	*Eucheuma* spp	**20,00**	F
Mexico	Pacific Ocean	Phaeophyceae	5 606,00	
	Pacific Ocean	Rhodophyceae	1 174,00	
		Total	**6 780,00**	
Peru	Pacific Ocean	*Lessonia nigrescens*	906,00	
	Pacific Ocean	*Macrocystis pyrifera*	35 657,00	
	Pacific Ocean	*Lessonia trabeculata*	409,00	
	Pacific Ocean	*Chondracanthus chamissoi*	1 239,00	
		Total	**38 211,00**	
Saint Kitts and Nevis	Atlantic Ocean and adjacent seas	*Kappaphycus alvarezii*	**1,00**	
Saint Lucia	Atlantic Ocean and adjacent seas	*Eucheuma* spp	**14,00**	F
Saint Vincent/Grenadines	Atlantic Ocean and adjacent seas	*Eucheuma* spp	**2,00**	F
United States of America	Atlantic Ocean and adjacent seas	*Macrocystis* spp	9,00	
	Atlantic Ocean and adjacent seas	*Ascophyllum nodosum*	6 333,00	
	Atlantic Ocean and adjacent seas	Chlorophyceae	3 851,00	
	Pacific Ocean	*Macrocystis* spp	2 234,00	
	Pacific Ocean	Chlorophyceae	1,00	
		Total	**12 428,00**	
Asia				
Cambodia	Pacific Ocean	*Eucheuma* spp	**2 200,00**	F
China	Asia - Inland waters	Chlorophyceae	200,00	F
	Pacific Ocean	*Phaeophyceae*	886 420,00	
	Pacific Ocean	*Sargassum fusiforme*	232 460,00	
	Pacific Ocean	*Laminaria japonica*	10 292 350,00	
	Pacific Ocean	*Undaria pinnatifida*	1 755 030,00	
	Pacific Ocean	*Eucheuma* spp	18 200,00	
	Pacific Ocean	*Gracilaria* spp	3 303 440,00	
	Pacific Ocean	*Porphyra* spp	2 017 790,00	
		Total	**18 505 890,00**	
India	Indian Ocean	Phaeophyceae	3 960,00	F

	Indian Ocean	Chlorophyceae	13 585,00	F
	Indian Ocean	Rhodophyceae	10 392,00	
		Total	**27 937,00**	
Indonesia	Indian Ocean	Rhodophyceae	22 854,00	
	Pacific Ocean	*Eucheuma* spp	9 204 724,00	
	Pacific Ocean	*Gracilaria* spp	115 574,00	
	Pacific Ocean	Rhodophyceae	21 529,00	
		Total	**9 364 681,00**	
Japan	Pacific Ocean	*Laminaria japonica*	89 200,00	
	Pacific Ocean	*Undaria pinnatifida*	49 800,00	
	Pacific Ocean	*Porphyra tenera*	284 200,00	
		Total	**423 200,00**	
Dem. People's Rep of Korea	Pacific Ocean	*Laminaria japonica*	550 000,00	F
	Pacific Ocean	*Porphyra tenera*	3 000,00	F
		Total	**553 000,00**	
Republic of Korea	Pacific Ocean	Phaeophyceae	1 575,00	F
	Pacific Ocean	*Sargassum fusiforme*	36 200,00	F
	Pacific Ocean	*Laminaria japonica*	572 614,00	F
	Pacific Ocean	*Undaria pinnatifida*	518 485,00	F
	Pacific Ocean	*Sargassum* spp	250,00	F
	Pacific Ocean	*Codium fragile*	3 620,00	F
	Pacific Ocean	*Monostroma nitidum*	7 672,00	F
	Pacific Ocean	Chlorophyceae	1,00	F
	Pacific Ocean	*Capsosiphon fulvescens*	7 000,00	F
	Pacific Ocean	*Gracilaria* spp	889,00	F
	Pacific Ocean	*Porphyra tenera*	567 848,00	F
		Total	**1 716 154,00**	
Malaysia	Pacific Ocean	*Kappaphycus alvarezii*	**174 083,20**	
Myanmar	Indian Ocean	*Kappaphycus alvarezii*	**1 356,10**	
Philippines	Pacific Ocean	*Caulerpa* spp	1 218,14	
	Pacific Ocean	*Kappaphycus alvarezii*	1 405 412,92	
	Pacific Ocean	*Gracilaria* spp	99,09	
	Pacific Ocean	*Rhodophyceae*	346,00	
	Pacific Ocean	*Eucheuma denticulatum*	71 570,69	
		Total	**1 478 646,85**	
Sri Lanka	Indian Ocean	*Kappaphycus alvarezii*	**322,00**	
Taiwan Province of China	Pacific Ocean	*Ulva pertusa*	113,00	
	Pacific Ocean	*Gelidium* spp	11,00	
	Pacific Ocean	*Porphyra tenera*	6,00	
	Pacific Ocean	*Gracilaria verrucosa*	686,93	
		Total	**816,93**	
Timor-Leste	Indian Ocean	*Eucheuma* spp	**1 500,00**	F
Vietam	Pacific Ocean	*Kappaphycus alvarezii*	5 372,60	
	Pacific Ocean	*Gracilaria* spp	13 949,90	
		Total	**19 322,50**	
Europe				

Bulgaria	Europe - Inland waters	*Green seaweeds*	**1,42**	
Denmark	Atlantic Ocean and adjacent seas	Phaeophyceae	**12,00**	
France	Atlantic Ocean and adjacent seas	Phaeophyceae	500,00	F
	Atlantic Ocean and adjacent seas	*Laminaria hyperborea*	8 978,00	
	Atlantic Ocean and adjacent seas	*Laminaria digitata*	31 768,00	
	Atlantic Ocean and adjacent seas	Rhodophyceae	12,00	
		Total	**41 258,00**	
Iceland	Atlantic Ocean and adjacent seas	*Ascophyllum nodosum*	17 000,00	F
	Atlantic Ocean and adjacent seas	*Laminaria digitata*	2 000,00	F
		Total	**19 000,00**	
Ireland	Atlantic Ocean and adjacent seas	*Alaria esculenta*	40,00	
	Atlantic Ocean and adjacent seas	*Ascophyllum nodosum*	28 000,00	F
	Atlantic Ocean and adjacent seas	*Laminaria hyperborea*	1 400,00	F
	Atlantic Ocean and adjacent seas	Rhodophyceae	100,00	F
		Total	**29 540,00**	
Italy	Atlantic Ocean and adjacent seas	Chlorophyceae	800,00	F
	Atlantic Ocean and adjacent seas	Rhodophyceae	400,00	F
		Total	**1 200,00**	
Norway	Atlantic Ocean and adjacent seas	*Alaria esculenta*	1,76	
	Atlantic Ocean and adjacent seas	Phaeophyceae	125 468,00	
	Atlantic Ocean and adjacent seas	*Ascophyllum nodosum*	19 533,00	
	Atlantic Ocean and adjacent seas	*Laminaria hyperborea*	8 016,00	
	Atlantic Ocean and adjacent seas	*Saccharina latissima*	173,59	
		Total	**153 192,35**	
Portugal	Atlantic Ocean and adjacent seas	Rhodophyceae	**1 848,00**	
Russian Federation	Atlantic Ocean and adjacent seas	Phaeophyceae	399,00	
	Atlantic Ocean and adjacent seas	*Laminaria hyperborea*	1 041,00	
	Pacific Ocean	Phaeophyceae	11 120,00	
	Pacific Ocean	Rhodophyceae	8,00	

		Total	**12 568,00**	
Spain	Atlantic Ocean and adjacent seas	Phaeophyceae	133,00	
	Atlantic Ocean and adjacent seas	*Saccharina latissima*	1,65	
	Atlantic Ocean and adjacent seas	*Undaria pinnatifida*	202,00	
	Atlantic Ocean and adjacent seas	*Gelidium* spp	641,00	
	Atlantic Ocean and adjacent seas	*Gracilaria* spp	0,62	
	Atlantic Ocean and adjacent seas	Rhodophyceae	14,00	
	Atlantic Ocean and adjacent seas	*Porphyra linearis*	3,00	
		Total	**995,27**	
Oceania				
Australia	Indian Ocean	Phaeophyceae	**1 923,00**	F
Fiji	Pacific Ocean	*Eucheuma* spp	**550,00**	F
Kiribati	Pacific Ocean	*Eucheuma* spp	**3 650,00**	F
New Zealand	Pacific Ocean	*Macrocystis* spp	58,00	
	Pacific Ocean	*Pterocladia lucida*	12,00	
		Total	**70,00**	
Papua New Guinea	Pacific Ocean	*Kappaphycus alvarezii*	**4 300,00**	F
Solomon Islands	Pacific Ocean	*Kappaphycus alvarezii*	**5 520,00**	
Tonga	Pacific Ocean	*Nemacystus decipiens*	**20,00**	F

Supplemental table 2. Global trade of seaweed in 2017 according to FAO. nei=not elsewhere included.

Land Area	Trade flow	Commodity	Volume (t)		Value (1000 USD)
Africa	**Export**	Agar agar nei	1 072		32 310
		Other seaweeds and aquatic plants and products thereof	11 565	F	6 100
		Seaweeds and other algae, fit for human consumption, nei	1 357		1 700
		Seaweeds and other algae, unfit for human consumption, nei	3 666		10 730
		Total	**17 660**		**50 840**
	Import	Agar agar nei	288		3 624
		Laver, dry	n/a		5
		Other brown algae (laminaria, eisenia/ecklonia)	1	F	5
		Other seaweeds and aquatic plants and products thereof	8		47
		Seaweeds and other algae, fit for human consumption, nei	116		837
		Seaweeds and other algae, unfit for human consumption, nei	4 723		2 440
		Total	**5 136**		**6 958**
Americas	**Export**	Agar agar nei	1 845		45 302
		Other seaweeds and aquatic plants and products thereof	n/a		3
		Seaweeds and other algae, fit for human consumption, nei	2 512		25 230
		Seaweeds and other algae, unfit for human consumption, nei	115 234		172 635
		Total	**119 591**		**243 170**
	Import	Agar agar nei	2 432		47 473
		Laver, nei	n/a		4
		Other brown algae (laminaria, eisenia/ecklonia)	n/a		2
		Other seaweeds and aquatic plants and products thereof	11		66
		Seaweeds and other algae, fit for human consumption, nei	12 743		97 486
		Seaweeds and other algae, unfit for human consumption, nei	30 320		53 251
		Undaria pinnafitida (brown algae)	n/a		1
		Total	**45 506**		**198 283**
	Processed production	Agar agar nei	1 018		
	Re-exports	Agar agar nei	11		33
		Seaweeds and other algae, fit for human consumption, nei	7	F	83
		Seaweeds and other algae, unfit for human consumption, nei	20	F	457
		Total	**38**		**573**
Asia	**Export**	Agar agar in powder	370		8 478

		Agar agar in strips	83	3 341
		Agar agar nei	8 107	106 118
		Green laver	62	1 110
		Hizikia fusiforme (brown algae)	1 701	24 013
		Laver, dry	9 618	226 260
		Laver, nei	40	1 094
		Other brown algae (laminaria, eisenia/ecklonia)	5 882	21 145
		Other red algae	9 578	13 610
		Other seaweeds and aquatic plants and products thereof	9 434	14 814
		Seaweeds and other algae, fit for human consumption, nei	157 815	169 985
		Seaweeds and other algae, unfit for human consumption, nei	41 307	36 042
		Undaria pinnafitida (brown algae)	20 590	38 143
		Total	**264 587**	**664 153**
	Import	Agar agar in powder	282	4 364
		Agar agar in strips	23	346
		Agar agar nei	6 341	96 814
		Green laver	11	49
		Hizikia fusiforme (brown algae)	4 652	41 913
		Laver, dry	1 476	28 682
		Laver, nei	1 511	31 352
		Other brown algae (laminaria, eisenia/ecklonia)	8 624	10 498
		Other red algae	136 365	152 260
		Other seaweeds and aquatic plants and products thereof	6 386	7 514
		Seaweeds and other algae, fit for human consumption, nei	21 986	218 270
		Seaweeds and other algae, unfit for human consumption, nei	140 896	175 550
		Undaria pinnafitida (brown algae)	27 517	100 872
		Total	**356 070**	**868 484**
	Processed production	Other seaweeds and aquatic plants and products thereof	**310**	
	Re-exports	Agar agar nei	10	22
		Seaweeds and other algae, fit for human consumption, nei	17	112
		Seaweeds and other algae, unfit for human consumption, nei	n/a	1
		Total	**27**	**135**
Europe	**Export**	Agar agar nei	3 676	90 892
		Other seaweeds and aquatic plants and products thereof	38	39
		Seaweeds and other algae, fit for human consumption, nei	5 281	37 303
		Seaweeds and other algae, unfit for human consumption, nei	82 174	75 862
		Total	**91 169**	**204 096**

	Import	Agar agar nei	6 027		119 313
		Other seaweeds and aquatic plants and products thereof	446		1 217
		Seaweeds and other algae, fit for human consumption, nei	26 321		98 601
		Seaweeds and other algae, unfit for human consumption, nei	92 138		83 536
		Total	**124 932**		**302 667**
	Processed production	Other seaweeds and aquatic plants and products thereof	**7 463**		
Oceania	**Export**	Agar agar nei	18		1 100
		Hizikia fusiforme (brown algae)	n/a		1
		Other red algae	25	F	15
		Seaweeds and other algae, fit for human consumption, nei	451	F	2 303
		Seaweeds and other algae, unfit for human consumption, nei	1 072		1 438
		Total	**1 566**		**4 857**
	Import	Agar agar nei	47		1 216
		Hizikia fusiforme (brown algae)	n/a		6
		Seaweeds and other algae, fit for human consumption, nei	2 433		30 797
		Seaweeds and other algae, unfit for human consumption, nei	9 613		5 908
		Total	**12 093**		**37 927**
	Re-exports	Agar agar nei	n/a		7
		Seaweeds and other algae, fit for human consumption, nei	35	F	196
		Total	**35**		**203**