Chapter 10
Seaweeds in Ireland: Main Components, Applications, and Industrial Prospects

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10.1 Introduction

Seaweeds have been commercially harvested for thousands of years in more than 50 countries, in waters ranging from cold to tropical. The global market of seaweeds, with a current annual growth rate of 8.9%, it is estimated to reach a value of around USD 22.13 billion by 2024 (Zhu et al. 2021a). In 2016, all the seaweeds harvested in Ireland summed up to 29,500 tons of biomass, accounting for 11% of the overall European seaweed market, making Ireland the third most productive country in Europe, right behind Norway and France (Table 10.1) (FAO 2018). Seaweed species can be classified within 3 phyla namelyRhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green algae). Amongst all the seaweed species available, the Irish industry identified 9 of them (*Ascophyllum nodosum*, *Laminaria digitata*, *Laminaria hyperborea*, *Palmaria palmata*, *Chondrus crispus*, *Himanthalia elongata*, *Fucus serratus*, *Lithothamnion corallioides*, and *Ulva lactuca*) as priorities regarding further exploitation opportunities of the biomass as a source of high-value molecules with added health benefits or bioactive compounds (Troy et al. 2017).

Seaweeds are traditional low caloric foods and their composition includes mainly polysaccharides and dietary fibres, proteins, polyunsaturated fatty acids (PUFA),

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Table 10.1 Top European countries producing wild seaweed biomass as well as main species produced

Country	Main seaweed species	Tonnage of biomass (wet weight)
Norway	Aquatic plants, brown seaweeds, rockweed.	169,407
France	Brown seaweeds, north European kelp, tangle.	55,041
Ireland	North Atlantic rockweed, north European kelp, red seaweeds.	29,500
Iceland	Rockweed, north European kelp, tangle.	17,985
Russian Federation	Aquatic plants, brown seaweeds, north European kelp, red seaweeds.	14,022
Spain	Brown seaweeds, *Gelidium* seaweeds, green seaweeds, ribbonednori, wakame.	3493
Portugal	Red seaweeds.	2328
Italy	Green seaweeds, red seaweeds.	1200
Estonia	Red seaweeds.	348

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and other compounds including pigments, vitamins, minerals and phenolic compounds. The industrial use of this biomass has shifted over the years. At all stages, the 'potential' of the algal industry has been viewed as being larger than its actual scale (Hafting et al. 2015). Moreover, the huge amount of bioactive compounds discovered in seaweeds anticipates promising prospects for the seaweed industry in Ireland and globally in the near future. These algal compounds can be used as functional products, such as value-added ingredients for food and feed (Fleurence 2016; Shama et al. 2019), cosmaceuticals (Wijesinghe and Jeon 2011), nutraceuticals (Shannon and Abu-Ghannam 2019), pharmaceuticals (Moualee and Pradhanang 2019; Rajauria et al. 2016), as well as low value applications, such as bioenergy,ensuring the full utilization of the biomass (Fernand et al. 2017). Currently, seaweed biorefinery has been proposed and multiple exploitation models are currently being developed aiming to minimize waste and environmental impacts of the seaweed industry while utilizing fully these natural resources. To be able to develop these exploitation models, a deep knowledge of seaweed composition, potential health benefits of seaweed compounds, as well as extraction technologies available for the recovery of these molecules, will be relevant in determining the future application of the biomass and derivedcompounds as summarized below.

10.2 Seaweeds as a Source of Major Nutritional Compounds

Seaweeds or macroalgae are a large and diverse group of organisms with over 10,000 species identified worldwide, being only 5% of them currently exploited for food or animal feed applications (Chojnacka et al. 2012). The consumption of seaweeds has a long tradition in many Asian countries, with a documented use of whole or processed algae over millennia (Fleurence et al. 2012). In Western countries, such as coastal areas of Ireland, Brittany, and Iceland, there was a discontinued tradition for eating seaweeds or incorporating them as ingredients or additives to improve the sensory attributes of foods, such as bread (Holdt and Kraan 2011; Mouritsen et al. 2013). The recent change of consumers' perception of seaweeds as healthy, nutritious, and tasty food commodities has increased the demand of food products and dietary supplements containing algae in recent decades (Mouritsen et al. 2013; Roleda et al. 2019; Lafarga et al. 2021).

In terms of their composition, overall, the scientific literature describes the macroalgal biomass is rich in carbohydrates (up to 60%), with medium or high amounts of proteins (10–47%), low in lipids (1–3%), and variable contents of minerals (7–38%) and pigments (Dominguez and Loret 2019; Kraan 2013). Moreover, seaweeds can adapt to the rapid changes of the marine environmental conditions, i.e. changes in temperature, solar radiation, by producing unique secondary metabolites including polysaccharides, proteins, lipids, and phenolic compounds (Collins et al. 2016; García-Vaquero et al. 2017). Prolonged exposure of macroalgae to environmental stressors, such as fluctuations in water level, solar radiation and temperature, can lead to the formation of reactive oxygen species and other free radicals in the biomass. As a defense mechanism, the stressed macroalgal biomass produces high amounts of antioxidant compounds, such as phenolic compounds and sulphated polysaccharides amongst others, trying to maintain the integrity of the cellular structures (Roleda et al. 2019). Thus, this macroalgal biomass enriched in antioxidant compounds could be incorporated as food ingredients or supplements, providing additional health benefits to those of basic nutrition namely nutraceuticals or functional foods (Garcia-Vaquero and Hayes 2016) that could help in the prevention of chronic diseases, such as cancer, cardiovascular diseases, obesity and diabetes (Déléris et al. 2016; Lordan et al. 2011).

Understanding the composition of the major macronutrients of the macroalgal biomass (carbohydrates, proteins, lipids), as well as other minor compounds and micronutrients produced by macroalgae, will help to understand and elucidate the future utilization of this biomass and their derived compounds and associated health benefit for food and nutraceutical applications.

10.2.1 Carbohydrates

Carbohydrates are one of the major components of macroalgae, with overall contents ranging from 4–76% of the dry weight (DW) of seaweeds (Holdt and Kraan 2011). Significant variations in the overall amount of carbohydrates in seaweeds have been described depending on the species, the season of collection, and even parts of the biomass sampled (Kim 2012; Men'shova et al. 2012; Skriptsova et al. 2012). The main type of carbohydrates described in each seaweed class (red, brown or green macroalgae) together with their biological functions in the biomass and the future uses or applications of these compounds in the food industry are summarized in Table 10.2.

Table 10.2 Main seaweed carbohydrates, biological functions in the biomass and current industrial applications/research gaps

Macroalgae	Carbohydrates	Function in algae[a]	Industrial applications	References
Rhodophyta (red macroalgae)	*Floridean starch*	Storage	Further research is needed to develop applications	Hlima et al. (2019)
	Cellulose	Structural component cell-wall	Emulsifier	Lakshmi et al. (2017)
			Thickener	
			Protective colloid in food industries	
			Film	
	Mannan	Structural component cell-wall and storage	Further research is needed to develop applications	de Jesus Raposo et al. (2015)
	Xylan	Structural component cell-wall	Packaging materials	Sedlmeyer (2011)
			Ingredients for improving water holding capacities	
			Encapsulation of active components or as a slow-release agent	
	Sulphated galactans		κ-Carrageenan (to avoid whey segregation)	Kraan (2012); Kumar et al. (2008)
			λ-Carrageenan (firmness and texture)	
			Gelling carrageenans (gelatin or pectin alternatives in desserts)	
			Agar, as medium for cell culture	
			Galactans are used in the composition of drugs; drug release process and in tissue engineering	

Ochrophyta (brown macroalgae)	*Laminarin*	Energy reserve present in reserve vacuoles	Enhanced quality and shelf life of pork meat when used as feedstock	Øverland et al. (2019)
	Mannitol	Translocation and storage	Food coating	Qin (2018)
	Alginic acid	Structural component cell-wall	Beer foam stabilizers	Goyanes and D'Accorso (2017); Hernandez-Carmona et al. (2013)
			Welding rods	
			Pill disintegrators	
			Protein imprinting	
	Fucoidans		Further research is needed to develop applications	Lorbeer et al. (2015)
Chlorophyta (green macroalgae)	*Starch*	Storage	Animal feed	Wolf (2010)
			Pulp for paper making	
			Film and packaging material	
	Cellulose, mannan and xylan	Structural component cell-wall	Same applications as above	de Jesus Raposo et al. (2015); Lakshmi et al. (2017); Sedlmeyer (2011)
	Sulphated xyloarabinogalactan		Prebiotics for foodstuffs	Delattre et al. (2005)
	Sulphated glucuronoxylorhamnan		Possible application for cholesterol reduction	Husni (2018)
	Sulphated glucuronoxylorhamnogalactan		Further research is needed to develop applications	Kamble et al. (2018)
	Ulvan		Can be used for developing edible films and hydrogels	Chiellini and Morelli (2011); Ganesan et al. (2018)

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[a]Functions if these compounds in macroalgae adapted from García-Vaquero et al. (2017), Kumar et al. (2008), Ojima (2013)

In general, and based on their functions in seaweeds, polysaccharides can be classified as (1) structural carbohydrates, involved in the maintenance of the structural integrity of the macroalgal cell walls; or (2) energy reserve polysaccharides, intracellular polysaccharides present inside reserve vacuoles and functions related to energy storage within the algal cells (García-Vaquero et al. 2017; Kumar et al. 2008; Ojima 2013). Once these compounds are extracted from their original matrices these carbohydrates can (1) exert biological benefits, and thus be used as bioactive compounds; (2) possess relevant physical properties that allow their use as stabilizers, thickeners, and emulsifiers; or (3) both, being valued compounds for both their physical and biological attributes when included in food (Lafarga et al. 2020).In fact, most macroalgal polysaccharides currently used as hydrocolloids, mainly alginate, agar, and carrageenan, have shown also promising biological properties (Gomez et al. 2020) expanding their range of applications to multiple industries including food, pharmaceutical, and cosmaceuticals. Other polysaccharides, such as fucoidans and laminarins, have recently gained momentum in the scientific literature due to their wide range and promising biological activities including anti-inflammatory, anticoagulant, antioxidant, antiviral, antitumor, antiapoptosis, antiproliferative, and immunostimulatory when assayed *in vitro* and/or *in vivo* models (García-Vaquero et al. 2017).

The industrial application of these carbohydrates in the food industry relies on the extraction of these high-value compounds from the seaweed biomass.These extraction processes should ideally be selective, achieve high yields of compounds, minimize the generation of waste and reduce the use of solvents and energy during the extraction process. Thus, increased research activity and industry interest has focused in recent years on using innovative technologies, including enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, ultra-high pressure extraction, and pressurized fluid extraction (Gomez et al. 2020). Moreover, recent technological trends in the sector include the use of a combination of technologies, applying multiple extraction forces in the biomass either sequentially or simultaneously aiming to increase the yields of polysaccharides extracted from the biomass. Garcia-Vaquero et al. (2020) explored ultrasounds, microwaves, and the simultaneous application of both extraction forces to extract fucoidan from *A. nodosum*. The authors demonstrated that both innovative technologies alone had a significant influence on the extraction of fucoidan, however, the yields of fucoidan extracted from this brown macroalgae using a simultaneous application of both ultrasounds and microwaves achieved yields of fucoidan of approximately 10 and three fold compared to the use of ultrasounds and microwaves alone, respectively (Garcia-Vaquero et al. 2020).

10.2.2 Proteins

Seaweeds have been increasingly studied as a source of proteins. Proteins are essential nutrients in both animal and human nutrition, as well as one of the most expensive ingredients in the diet. Thus, increased research interest has focused on proteins

Table 10.3 Total protein concentrations (% dry weight) and proposed extraction methods in selected brown, red, and green seaweed species

Macroalgae (sp.)	Protein content (% DW)	Protein extraction methods (main results)	References
Phaeophyta (brown macroalgae)			
Ascophyllum nodosum	3–15%	Ultrasound and a combination of acid and alkali solvents (59% of protein recovery)	Fleurence (1999); Kadam et al. (2017)
Laminaria digitata	3.8%	Enzyme hydrolysis and fermentation (97% of protein recovery)	Hou et al. (2015)
Saccharina latissima	4–16.1%	pH shift (protein yield of 25.1 ± 0.9%)	Mols-Mortensen et al. (2017); Harrysson et al. (2018)
Rhodophyta (red macroalgae)			
Palmaria palmata	11.9–21.9%	Combination of enzyme and alkaline (>90% of recovery)	Naseri et al. (2020), Galland-Irmouli et al. (1999)
Porphyra umbilicalis	13.5–20.6%	pH shift (protein yield of 22.6 ± 7.3%)	Biancarosa et al. (2017), Harrysson et al. (2018)
Gracilaria sp.	9.2–12.6%	Ultrasound combined with an alkali solvent (protein yield of 86%)	Chan and Matanjun (2017); Kazir et al. (2019)
Chlorophyta (green macroalgae)			
Ulva sp	11.2–15%	Pulsed electric fields (seven-fold increase in total protein extracted compared to osmotic shock samples)	Biancarosa et al. (2017); Robin et al. (2018)
Ulva lactuca	11.2–15%	Ultrasound using water as a solvent (protein yield of 19.6 ± 0.8%)	Biancarosa et al. (2017); Harrysson et al. (2018)

from seaweeds as novel and cheap alternative sources of protein (Nunes et al. 2014; Fleurence et al. 2018). However, the exploitation of seaweeds as a source of protein still offers challenges, mainly related to the wide ranges of protein content described in different seaweed species, ranging between 3 and 47% (Harnedy and Fitzgerald 2013); as well as the influences of external factors, such as season of harvest and place of collection (Zhu et al. 2021a), on the protein contents of the biomass.

Moreover, the methodology used to determine the levels of protein in seaweeds also represents a huge variation in the protein levels reported in the scientific literature. Commonly, the protein contents of bseaweeds have been assessed by measuring the nitrogen content of the biomass and then multiplying it by specific conversion factors. In terms of seaweeds, these conversion factors range from 3.75 to 5.72 (Lourenço et al. 2002). However, as some of the seaweeds are regarded as edible green food, many studies are using 6.25, the general nitrogen-to-protein factor, in their studies. Macroalgae may have non-protein nitrogen, including free amino acids, chlorophyll, nitrates, ammonium ions, and nucleic acids, and thus, the protein content calculation with 6.25 often results in an over estimation of algal protein (Makkar et al. 2016). Table 10.3 summarizes total protein concentrations (% DW) in selected brown, red, and green seaweed species. Generally, the protein content decreases in the order of seaweed group: red>green>brown (Černá 2011).

The most promising seaweed protein families,from a biotechnological point of view,are lectins and phycobilli-proteins. Lectins are carbohydrate binding proteins contributing in cell communication, including recognition of foreign or cancerous cells (Ziółkowska and Wlodawer 2006). Some red algal lectins have painkilling effects, anti-inflammatory, anti-cancer properties, and the potential to develop antiviral agents with activity against HIV and coronavirus (Singh and Walia 2018).

Other compounds derived from algal proteins, such as amino acids (AA) and bioactive peptides, are being studied in recent years due to their promising biological benefits when included in foods, but also as cosmetic, pharmaceutical, and other applications in the biotechnologicalindustry (Harnedy and Fitzgerald 2011). Macroalgae contain all AA (Matanjun et al. 2009) and are regarded as an excellent source of essential amino acids (EAA),especially red and green species (Organization 1991; Wong and Cheung 2000). Contradictory results have been reported on the levels of particular AA between seaweed species. Methionine and cysteine were described to be at higher levels in red seaweeds compared to green and brown seaweeds (Qasim 1991), but an opposite behavior was reported by Gressler et al. (2011). Gaillard et al. (2018) studied the amino acid content in 9 seaweed species and determined that glutamine was the most abundant AA followed by Asp and Ala. In general, the seaweeds were rich in threonine, serine, glycine, valine, leucine, lysine, and arginine (on average 4.58 g/16 g N, ranging from 4.06 to 4.99 g/16 g N), and low in cysteine, histidine, and methionine (on average 1.70 g/16 g N, rangingfrom 1.24 to 2.28 g/16 g N).The AA concentrations of crude protein varied with the seasons, species, and methods of AA analysis used.

Moreover, seaweeds as well as other protein-rich products can be ideal candidates for the generation of bioactive peptides or cryptides (Garcia-Vaquero et al. 2019). Bioactive peptides are sequences of 2 to 30 amino acids in length that have hormone-like beneficial properties once these compounds are released from their original or parent proteins through several hydrolytic processes (Garcia-Vaquero et al. 2019). In Japan, a number of functional foods have been already commercialized as permitted by the Japanese Ministry of Health and Welfare (Arai 2000). Although there is a growing trend in isolating proteinand bioactive peptides from marine algae, the number of biologically active compounds generated from seaweed is still limited. Most seaweed bioactive compounds, including protein, are contained inside the algal cells by a highly rigid and structurally complex cell wall and thus, this has been described as one of the major obstaclesfor an efficient utilizationand digestibility of algal proteins (Fleurence et al. 2012; Harnedy and Fitzgerald 2011). There is a need to extract these compounds from seaweed, optimizing these processes in terms of resources (i.e. chemicals, solvents, energy…) consumed during the extraction, while maintaining or increasing the yields of protein achieved. Some protein extraction processes extracted from the recent scientific literature are summarized in Table 10.3. Some of the potential technologies with promising applications improving the extraction of protein from seaweeds include the use of ultrasound (Kadam et al. 2017), microwaves (Chemat 2012), supercritical fluid extraction (Liang and Fan 2013) and ultrahigh-pressure extraction (Xi et al. 2013) amongst others.

10.2.3 Lipids

Lipids are essential macronutrients in the diet as a source of energy and other antioxidants, such as tocopherols and carotenoids (Bialek et al. 2017). Lipids in seaweeds are present at relatively low levels (1–5% of DW), and thus, fresh seaweeds can be considered as low-energy foods. The health benefits of any source of dietary fat are linked to the fatty acid composition of the lipids, especially the content of PUFA. PUFA, such as eicosapentaenoic acid and arachidonic acid, are proved to be beneficial in controlling blood pressure and blood clotting and reducing the risk of cardiovascular diseases, osteoporosis, and diabetes (Maeda et al. 2008). The optimum dietary ratio of PUFAs (omega-6 to omega-3) of 5:1 is recommended by the European Nutritional Society, however, most of the European diets failed to meet these recommendations (Holdt and Kraan 2011). Fish oils have been utilized as the source of omega-3 or n-3 PUFAs (Rubio-Rodríguez et al. 2010). However, due to the environmental, economic, sustainable and food safety concerns, novel sources of PUFAs are currently required (Vannuccini et al. 2019).

As shown in Table 10.4, total PUFAs in selected seaweeds range from 16.64 to 23.8% of the total amount of fatty acids.*Undaria pinnatifida* has eicosapentaenoic acid at concentrations of up to 0.14 g per 100 g DW of seaweeds' thallus (Khan et al. 2007). Gosch et al. (2012) reported that the green seaweed *Derbesia tenuissima* had high levels of fatty acids (39.58 mg/g DW) with a high proportion of PUFA (n-3) (31% of total fatty acid), which are suitable as nutraceuticals or fish oil replacers.Regarding biofuel production, *Spatoglossum macrodontum* had the highest fatty acid contents (57.40 mg/g DW) with a high content of C18:1, which is suitable as a biofuel feedstock (Gosch et al. 2012).

Generally, macro- and micronutrients, the lipid content and fatty acid composition in seaweeds are influenced by their intrinsic traits andalso climatological conditions (light intensity, seawater salinity, and temperature). Generally, red and brown seaweeds are rich in eicosapentaenoic and arachidonic acids, and green seaweeds like *Ulva pertusa* predominantly contain hexadecatetraenoic, oleic, and palmitic acids (Ortiz et al. 2006). Regarding the environmental conditions affecting the biomass, high light intensity and low salinity results in a decreased level of total fatty acids within the same species (Floreto and Teshima 1998). Furthermore, Ortiz et al. (2006) reported a strong influence of the temperature of the water (particularly low temperatures) on the fatty acid levels produced in different seaweed species.

There is an increased interest in the extraction of lipids from seaweed biomass. Traditionally the recovery of lipophilic compounds has been achieved by using a Soxhlet apparatus or soaking the biomass in organic solvents (Dickson et al. 2020). Recent developments in lipid extraction include the use of supercritical fluid extraction,as well as the application of ultrasounds and microwaves (Cravotto et al. 2008).

Table 10.4 Summary of fatty acid composition (expressed as % of total fatty acids) and method of extraction from selected seaweed species

	Saccharina japonica	*Palisada flagellifera*	*Ulva fasciata*
Extraction methods	Supercritical carbon dioxide	Chloroform/methanol	Chloroform/methanol
Fatty acids (% total fatty acid)			
(C14:0) Myristic acid	11.36 ± 0.29	6.4 ± 0.0	0.7 ± 0.0
(C16:0) palmitic acid	20.60 ± 0.86	37.6 ± 0.4	45.0 ± 3.4
(C17:0) Heptadecanoic acid	4.13 ± 0.12	0.3 ± 0.0	0.4 ± 0.0
(C18:0) stearic acid	2.68 ± 0.15	1.1 ± 0.1	0.7 ± 0.1
(C20:0) Arachidic acid	1.02 ± 0.11	0.2 ± 0.1	0.2 ± 0.1
(C22:0) Behenic acid	n.d.	n.d.	2.0 ± 0.3
(C23:0) Tricosanoic acid	10.31 ± 0.22	n.d.	n.d.
(C24:0) Lignoceric acid	n.d.	n.d.	0.3 ± 0.0
Total SFA	50.66 ± 1.08	45.6 ± 0.6	49 ± 3.9
(C14:1) Mystoleic acid	n.d.	0.7 ± 0.1	0.6 ± 0.1
(C16:1) Palmitoleic acid	2.82 ± 0.18	1.4 ± 0.1	2.4 ± 0.1
(C17:1) cis-10-Heptadecenoic acid	0.16 ± 0.01	0.4 ± 0.0	0.8 ± 0.2
(C20:1) Gondoic acid	n.d.	n.d.	0.2 ± 0.1
(C18:1n9c) Elaidic acid	29.65 ± 0.35	7.7 ± 0.2	2.4 ± 0.1
Total MUFA	32.71 ± 0.70	11.5 ± 0.4	17.2 ± 0.4
(C18:2n6c) linoleic acid	7.30 ± 0.21	1.7 ± 0.1	5.9 ± 0.7
(C18:3n6) r-Linolenic acid	2.04 ± 0.13	1.5 ± 0.2	5.4 ± 1.4
(C18:3n3) Linolenic acid	2.71 ± 0.15	2.6 ± 0.1	7.8 ± 1.5
(C20:3n6) cis-8,11,14-Eicosatrienoic acid	0.44 ± 0.07	0.6 ± 0.0	0.2 ± 0.0
(C20:4n6) arachidonic acid methyl ester	n.d.	16.2 ± 0.3	0.5 ± 0.2
(C20:5n3) EPA	4.14 ± 0.18	0.6 ± 0.7	2.1 ± 0.2
C22:6n3 DHA	n.d.	0.6 ± 0.2	0.4 ± 0.4
Total PUFA	16.64 ± 0.71	23.8 ± 1.6	22.3 ± 4.4
Nutritional index			
Σ n-3	6.85 ± 0.33	21.4 ± 6.7	16.6 ± 3.1
Σ n-6	9.78 ± 0.41	18.9 ± 0.1	7.5 ± 0.3

Table 10.4 (continued)

	Saccharina japonica	*Palisada flagellifera*	*Ulva fasciata*
Ratio n-6/n-3	1.4	0.9	0.5
References	Getachew et al. (2018)	Santos et al. (2019)	Santos et al. (2019)

“n.d.” stands for not detected

10.3 Macroalgae as a Source of Other Minor Compounds

Apart from the aforementioned dominant macronutrients, minerals, vitamins, and other pigments are also highly valued compounds present in seaweeds. Seaweeds contain significant amounts of minerals (I, Ca, Fe, Zn, Mn, and Cu), which perform many important biological functions, including assisting in cell transportation and other metabolic processes (Mišurcová et al. 2011). Seaweeds can absorb inorganic substances from the environment due to the interactions of these compounds with cell surface polysaccharides (Yoshioka et al. 2007). Similar to the levels of macronutrients, the mineral profiles of seaweeds are also really variable depending on the type of seaweeds, season and place of collection (Teas et al. 2004). High contents of minerals have been reported in the literature in certain seaweed species. I.e. in *Ulva clathrata* biomass collected from Mexico the mineral contents of this seaweed represented approximately 49.6% of the dry matter of the biomass (Peña-Rodríguez et al. 2011). Mišurcová et al. (2011) summarized the mineral contents in selected marine algae and claimed that many of the seaweed species can be excellent contributors of these compounds based on the reference daily intakes (RDIs) in EU countries, United States, Australia, and Asia, especially when seaweeds are used as sources of I and Fe (Mišurcová et al. 2011).

Other micronutrients of nutritional relevance produced by seaweeds are vitamins. Vitamins are essential catalysts in human body that must be obtained from the diet, as they can only be synthesized to a limited extent. Certain vitamins from seaweeds have antioxidant activity, while other vitamins may contribute to maintaining and promoting health by providing additional health benefits, such as decreasing blood pressure, prevention of cardiovascular diseases, or reducing the risk of cancer (Škrovánková 2011). Ortiz et al. (2006) claimed that 100 g of seaweed provides more than the recommended daily requirements of vitamin A, B_2, B_{12}, and two-thirds of the recommended vitamin C levels (Ortiz et al. 2006). Many vitamins have been detected and measured in seaweeds, including L-ascorbic acid (vitamin C), thiamine (vitamin B_1), riboflavin (vitamin B_2), cobalamin (vitamin B_{12}), folic acid and its derivatives, tocopherols (vitamin E), and carotenoids (Mišurcová 2012). Generally, red and green seaweeds are rich in vitamin C ranging from 500 mg/kg to 3000 mg/kg DW. Levels of up to 2000 mg/kg DW have been reported from the red seaweed *Eucheuma denticulatum* and 3000 mg/kg DW in the green seaweed *Enteromorpha flexuosa* (Mcdermid and Stuercke 2003). Other red seaweeds, such as *Palmaria* and *Porphyra* spp. contain a large amount of vitamins of the B group

(Mabeau and Fleurence 1993). Although lipid content in seaweed is low, seaweed fats contain high levels of vitamin E. Generally, brown seaweeds contain more α-tocopherol (also β- and γ-tocopherols) than red and green algae which contain only α-tocopherol. Ortiz et al. (2009) reported a high amount of vitamin E detected in kelp *Macrocystis pyrifera* with 132.77 mg/100 g fat of α-tocopherol from total tocol content of 145.72 mg/100 g fat. Regarding the vitamin content in seaweeds, it also varies depending on the seaweed species and the aforementioned environmental factors. I.e., the highest levels of vitamin E in *Eisenia arborea*collected in Mexico were appreciated during the month of September (Hernández-Carmona et al. 2009). Furthermore, other factors affecting the biomass including the concentration of certain compounds in the sea, the depth of growth of the biomass or the sunlight intensity at particular sea depths in which the biomass is growing will affect the vitamin content of the biomass even within the same species (Smith et al. 2007).

Other minor compounds from seaweeds include pigments such as chlorophylls, carotenoids and xanthophylls with promising potential applications in the food, cosmetics and pharmaceutical industries. Algal pigments can be applied in foods to impart the desired sensorial properties in food products, as well as for their health benefits including antioxidant, antidiabetic, immune-modulatory, and anti-angiogenic (Manivasagan et al. 2018). In order to meet the industry demands of algal pigments, many novel extraction techniques have been developed in recent years. Supercritical fluids were employed to obtain carotenoids, fucoxanthin, and phlorotannins from *Saccharina japonica* (Saravana et al. 2017). Microwave, ultrasound, and pulsed electric fields were reported to increase the extraction yields and reduce processing time to get carotenoids from *Undaria pinnatifida* (Zhu et al. 2017).

Other minor constituents from seaweeds with health benefits, such as anti-diabetic, anti-inflammatory and anti-microbial, are phenolic compounds (Generalić Mekinić et al. 2019; Nwosu et al. 2011; Lopes et al. 2012). Phenolic compounds encompass a widely diverse chemical group of compounds including phlorotannins, bromophenols, flavonoids, and terpenoids produced by seaweeds. Phlorotannins are the main phenolic compounds present in brown seaweeds. The highest total phenolic content of 47.16 mg galic acid equivalent/g dry *Ascophyllum nodosum* after post-harvest treatments was reported by Zhu et al. (2021b). Other large proportions of phenolic compounds detected in green and red seaweeds are bromophenols, flavonoids, phenolics acids, and terpenoids (Wells et al. 2017). As an example of the chemical diversity of these compounds, the chemical structures of the main phlorotannins produced by brown macroalgae are represented in Fig. 10.1.

10.4 Prospects of the Seaweed Industry

Public awareness towards sustainability hasrecently increased in response to current global challenges, such as climate change, intensive production, poor waste management, and overpopulation, among others. To reduce the negative impact of these challenges in the environment, population, and economy, new alternatives and

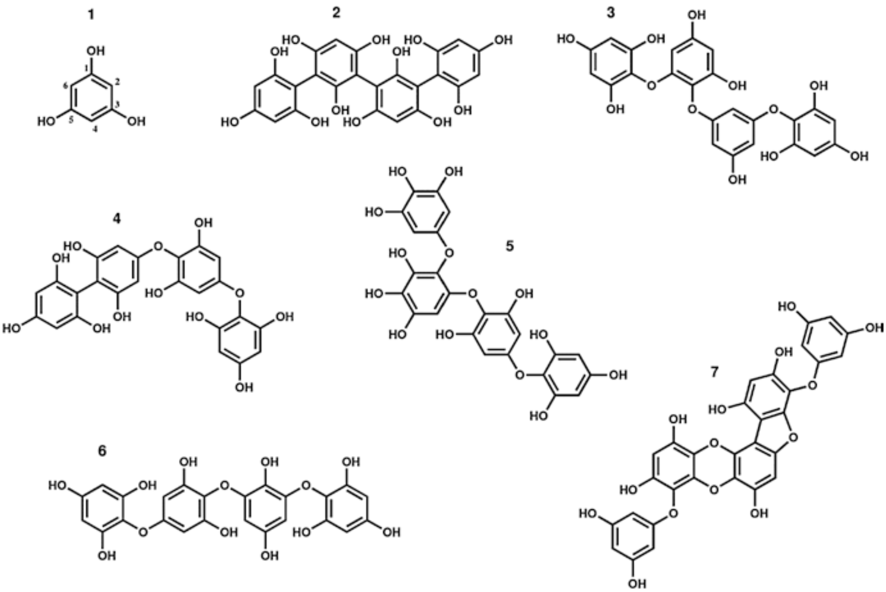

Fig. 10.1 Chemical structures of phlorotannins as described by Lopes et al. (2012) originally published by PLOS ONE. Numbers inside the image represent: phloroglucinol (1), tetrafucol A (2), tetraphlorethol B (3), fucodiphlorethol A (4), tetrafuhalol A (5), tetraisofuhalol (6), and phlorofucofuroeckol (7)

production systems are currently being considered in replacement of conventional processes and products. In the past decades, seaweed production and cultivation have increased the interest of the scientific and industrial communities as a more sustainable system compared to traditional agricultural practices. Moreover, seaweedshave been demonstrated as excellent source of nutrients and have a multipurpose nature (e.g. animal feed, biofuel, biomass) (Tiwari and Troy 2015; Mohammad et al. 2019; Hessami et al. 2019). Additionally, the global market of seaweed aquaculture and wild capture has been increasing with an annual production of 31.1 million tonnes at the global level. This rising trend is explained by the increased consumer acceptance of seaweeds as food and the broad applicability of these raw materials and theirby-products in biotechnological, pharmaceutical, and chemical industries (Kraan 2020).

The cultivation of seaweeds is now facing the challenge of variability and availability of biomass. In general, aquaculture of seaweeds usually enhances the content of protein and also decreases the pressure of harvesting large quantities of biomass from wild populations. However, in Europe, more than 97% of seaweed production is harvested from the wild in Norway, France, and Ireland (Grote 2019). This current scenario represents a challenge in utilizing seaweed protein, but can also be an opportunity to develop the seaweed industry further. Eco-intensification and sustainability of seaweed cultivation can be improved through seaweed permaculture by recreating seaweed forest habitat and other ecosystems water environments. For example, *Rhodymenia pseudopalmata* showed an increase of total protein content after 3 days of cultivation (18.7% DW) in fishpond effluents rich in ammonium (NH_4+) than it harvested from the wild (9.4% DW) (Pliego-Cortés et al. 2019). Seaweed permaculture allows seaweeds to absorb the NH_4+ that is produced by seafood production system, and meanwhile, reduces the negative impact on the ecosystems due to the capacity of seaweeds to absorb inorganic nutrients (Grote 2019). The high protein content of seaweed biomass can be recycled as feed. *U. lactuca* (37.4% DW) and *Gracilaria conferta* (29.4% DW) produced by seaweed permaculture were used to feed sea urchins as a sole feed. Compared with traditional fish diet, *U. lactuca* enhanced somatic and gonad growth, and improved the protein assimilation efficiency at levels of 81% compared to urchins receiving formulated diets (59%) (Shpigel et al. 2018).

Seaweed cultivation is commonly carried out in open water and requires a prior optimisation to assure the productivity of the process and the continuous monitoring of different cultivation factors (e.g. seawater temperature, available nutrients, water movement and quality) to maintain its commercial quality. The physiological processes of the seaweed can affect the biomass production in the seaweed aquaculture and therefore, a deeper understanding of the physiological and metabolic mechanisms of seaweed could improve its productivity (Hayashi et al. 2020). Additionally, controlling environmental and process parameters of the seaweed cultivation in open water can be difficult due to climate conditions and negative actions of wild animals and marine microbiota. In this way, cultivation in open water could be replaced by an intensive system in tanks or ponds which facilitates the monitoring of the biomass and prevents unnecessary depreciation of the production as a result of natural causes. Nevertheless, the maintenance of seaweed on tanks is expensive and can lead to the stress of cultivated seaweeds and thereby, a previous selection of the seaweed species is required (Hayashi et al. 2020; Kim et al. 2017). Another strategy that could be applied in seaweed cultivation is the implementation of an integrated multi-trophic aquaculture (IMTA) in a closed environment like ponds, tanks, bays, and coastal lagoons. IMTA consist of farming fish or seafoodin a shared environment with other living individuals (e.g. macroalgae, mussels, sea-cucumber) to increase the productivity of the cultivation system, enhancing the sustainability of the process and product, and generate enriched products and/or species with high commercial value. In open-water systems, IMTA cultivation has been also contemplated; however, the impact of this type of cultivation in the environment and the final product has been difficult to measure due to the unpredictability of nutrients and high dilution (Ramli et al. 2020).

The harvesting of wild seaweeds is also being currently carried out.Small countries with a long harvesting tradition like Ireland are the focus of international and large-scale companies. Ireland's shores meet suitable conditions for the proliferation of a large range of seaweed species. In addition, the cultivation of seaweeds is limited as a result of the important tradition of harvesting wild species and the pristine state of the Irish's shores. A growth rate in seaweed cultivation together with an increase in automation and scaling up processes are expected in many of these countries which would lead to an increase in intensive production (Monagail and Morrison 2020).

In general, the cultivation of seaweeds has been demonstrated to be a sustainable system beneficial for the ecosystems.Some of these positive effects of seaweed proliferation in the environment relate to water purification,production of nutrients and oxygen, and the reduction of greenhouse gas emissions and the eutrophication phenomenon (Buschmann et al. 2017). Although seaweed cultivation has been considered as a potential strategy to reduce anthropogenic CO_2, a portion of this materialized gas into the organic matter has been observed to be easily decomposed back to CO_2 gas and therefore, further research is necessary to understand the underlying mechanisms of CO_2 assimilation by seaweeds. Other concerns have been raised in the last few years with regard to seaweed aquaculture. Global environmental changes,such as increased atmospheric CO_2 and temperature, and intensification of ultraviolet light levels and ocean acidification are likely to affect the productivity of seaweed cultivation worldwide (Chung et al. 2017). Furthermore, the intensive cultivation of seaweed could also entailsevere repercussions like the hybridism between wild and domesticated seaweed strains and the proliferation of parasites or pathogens that could lead to disease outbreaks within the seaweed industry (Buschmann et al. 2017; Hayashi et al. 2020). The implementation of IMTA could reduce some effects of global climate change and the selection of seaweed species could prevent the spread of infectious diseases (Buschmann and Camus 2019). Thus, there is a need for strategies or alternatives to be applied in the seaweed cultivation that could mitigate the already mentioned negative impacts.

10.5 Conclusions and Future Perspectives

Seaweeds, either from wild or aquaculture, are valuable resources. During their cultivation, seaweeds can efficiently absorb CO_2 from the seawater and thus, have the potential to neutralize greenhouse gas emissions. Moreover, seaweeds produce a wide range of bioactives mainly carbohydrates, proteins and lipids, as well as other minor compounds that have expanded the interest of this biomass for multiple applications as pharmaceuticals, cosmetics, functional foods, fertilizers, animal feeds and biofuels. Currently Ireland has a long coastline, a wide variety of seaweed species and over 97% of Irish seaweeds are wildly harvested, thus, the development of seaweed farms or permaculture systems are promising businesses in the near future. However, there are still many challenges remaining with respect to the use of seaweeds for the production of high value compounds. These challenges refer to (1) the raw biomass, including aspects of biomass production, availability and chemical or compositional stability of the raw biomass for future industrial use; (2) industrial utilization of these natural resources by developing biorefinery exploitation models, including the use of pre-treatments and novel or disruptive technologies aiming to utilise the full biomass. Moreover, these new seaweed exploitation models should be evaluated from economic, social, and environmental perspectives to contribute to the circular economy of Ireland, addressing current challenges, such as the recycling of nutrients,while alleviating current and upcoming environmental challenges related to greenhouse emissions.

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