SCOPING A SEAWEED BIOREFINERY CONCEPT FOR IRELAND

Report for Bord Iascaigh Mhara

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CyberColloids is an independent, business driven R&D company, based in Co Cork, Ireland but with a global reach. The company has been working with seaweed and seaweed derived products and ingredients for many years.

The combined expertise within the team spans the seaweed value chain from raw material to end application but with a particular focus on developing novel processing methodologies and in finding new or added value uses for different seaweeds.

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Scope

BIM wishes to scope the potential for a seaweed biorefinery based on European kelp species that are successfully being cultivated in Ireland *(Alaria esculenta, Saccharina latissima & Laminaria digitata)*. The reasons being:

- Irish seaweed industry harvesters and processors are looking to diversify their product offerings and to create value from cultivated seaweed biomass;
- creating value and new commercial enterprise from seaweed biomass is recognised in Ireland (and Europe) as a vital contributor to a healthy Blue Economy;
- the use of seaweed ingredients in food, for health & wellbeing is becoming more mainstream and there is a clear trend for a significant increase in the number of products being launched outside of the traditional Asian markets, Europe is showing steady growth;
- Irish commercial species - *Alaria esculenta, Saccharina latissima & Laminaria digitata* are potentially rich sources of commercially interesting compounds;
- multi-stream processes or biorefineries are favoured to maximise value creation and also adhere to circular economy principles;
- there has been significant research/investment in the use of seaweed biomass as a feedstock for biorefineries elsewhere in Europe, but we are yet to see this translated into real commercial gain;
- the necessary knowledge/technology exists within Ireland to cultivate and commercially exploit the seaweed resource;
- most research has focused on cultivated biomass and the "go-to" species - *Saccharina latissima*, however, bulk markets for *Saccharina latissima* biomass are yet to be identified and there is a fear of future over capacity;
- the focus is shifting towards the cultivation and use of other species including *Alaria esculenta* and *Laminaria digitata*;
- Ireland has a clear advantage in that these two species are already being cultivated successfully at commercial level.

The challenge for Ireland therefore is to:

- identify suitable products and markets for short term value creation from relatively low tonnage of biomass;
- conceptualise a commercially relevant multi-stream/biorefinery approach for Irish kelp cultivators and would be processors of *Alaria esculenta*, *Saccharina latissima* & *Laminaria digitata*;
- propose innovative, longer term strategies for the exploitation of seaweed resources that are currently underutilised or used at the lower end of the value chain.

This report is divided into four sections that cover the following:

- an overview of the resource;
- current uses and potential markets for Irish kelps;
- an overview of existing biorefinery concepts;
- an Irish biorefinery concept, recommendations and next steps.

Information has been obtained via interview with seaweed industry contacts and review of activities as reported by industry and research.

Terms and Abbreviations

This report focusses on three European species of large brown seaweeds (also known as **macroalgae**), all three are commonly referred to as **kelps**. This report utilises the term kelp and the scientific names to refer to each of these seaweeds, however they also have common names that are widely used in the literature:

- *Alaria esculenta* – Atlantic wakame, Winged kelp, Dabberlocks;
- *Saccharina latissima* Sugar kelp, Sweet kelp/kombu, Kombu royale;
- *Laminaria digitata* – Oar weed, Kelp, Kombu.

Other European brown seaweeds with potential biorefinery and/or commercial relevance are also mentioned in this report. These seaweeds are not species of kelps but are **fucoids**, also known as **wracks**. They typically have different compositional makeup and thus different relevance to any biorefinery model. This report utilises the term **fucoid** to refer to such seaweeds and commercially relevant species mentioned include:

- *Ascophyllum nodosum* – Knotted wrack, Egg wrack;
- *Fucus species* – wracks, rockweeds.

European biorefinery research has also focussed on the use of red and green species of seaweeds and **microalgal** feedstocks i.e. microscopic, unicellular species. All have very different compositional makeup and different relevance as potential feedstocks.

Abbreviations used in this report

dw	Dry weight	**LA**	Linoleic acid
CWB	Cell wall bound (polyphenols)	**ARA**	Arachidonic acid
Da	Dalton - unit of mass	**CAGR**	Compound annual growth rate
kDa	kilo Dalton	**NPD**	New product innovation
MW	Molecular weight	**RoW**	Rest of the world
LMW, HMW	Low MW, High MW	**EFSA**	European Food Safety Authority
PET	Polyethylene terephthalate	**FDA**	Food & Drug Administration (US)
PLA	Polylactic acid	**INCI (No.)**	International Nomenclature of Cosmetic Ingredients (No.)
UF	Ultra-filtration	**IUPAC (No.)**	International Union of Pure and Applied Chemistry (No.)
FCSP	Fucose containing sulphated polysaccharide	**CAS (No.)**	Chemical Abstracts Service (No.)
M and G	Mannuronic and Guluronic acids (components of alginate)	**FAO**	Food & Agriculture Organisation (of the United nations)
SCFA(s)	Short chain fatty Acid(s)	**PPP**	Plant protection product
AA(s)	Amino acid(s)	**ABE**	Acetone Butanol Ethanol (fermentation)
EAA(s)	Essential Amino Acid(s)	**AD**	Anaerobic digestion
PUFA(s)	Polyunsaturated fatty acid(s)	**FDCA**	Furan dicarboxylic acid
EPA	Eicosapentaenoic acid	**1G, 2G, 3G**	1st, 2nd & 3rd generation biorefinery
DHA	Docosahexaenoic acid	**CAGR**	Compound annual growth rate
NPD	New product innovation		

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1 AN OVERVIEW OF THE RESOURCE

Laminaria digitata

This section provides a general overview of Irish kelp species (*Alaria esculenta, Saccharina latissima* & *Laminaria digitata*) as a potential feedstock for a biorefinery and also scopes the status of cultivation in the European seaweed industry

1.1. Irish kelps as a potential resource

This section provides an overview of the key components that are found in *Alaria esculenta*, *Saccharina latissima* & *Laminaria digitata* and detail on the current methods used to extract them (commercial where relevant). The key components of Irish kelps that are discussed below are:

polyphenols	mannitol
laminarin	fucoidan
alginate	protein
minerals & vitamins	lipids & pigments

1.1.1. Polyphenols

Description[1]: the polyphenols of brown seaweeds are known as **phlorotannins**. They are unique to species of brown seaweeds and are the only polyphenols found in brown seaweeds (unlike terrestrial plants that typically contain a range of different polyphenols). They are exclusively polymers of phloroglucinol (1,3,5-trihydroxybenzene) and are structurally less complex than other polyphenols. They can comprise quite a high percentage of the dry algal biomass (< 25%) although are found in the European kelp species in much lower amounts (< 4%).

	Phlorotannin content as % dry weight[1]
Saccharina latissima	< 3
Alaria esculenta	< 4
Laminaria digitata	< 0.2

Phlorotannins are located in physodes (storage organelles) in cytoplasm of cells, these are known as free or unbound phlorotannins. However, the physodes can fuse to the cell walls and the phlorotannins become cell wall bound (CWB) phlorotannins. There is little information in general regarding the nature of CWBs or quantitative data for ratio of free to CWB phlorotannins, but it is assumed that binding of physodes to cell walls occurs with maturity of seaweed. Phlorotannins typically have a molecular weight (MW) range of 126 Da to 650 kDa but more commonly fall in the range of 10 to 100 kDa. In ecological terms, high molecular weight (HMW) phlorotannins (≥ 10 kDa) are shown to be most bioactive, they act as natural sunscreen, grazing deterrents and are metabolic waste products. In human systems, it is most likely that low MW phlorotannins (< 10 kDa) are most bioactive. The reader is directed to Ragan & Glombitza (1986)[2] and Koivikko (2008)[3] for comprehensive detail.

1 CyberColloids (2019). Creating Value from Irish Seaweed Biomass. Internal Report 2019.
2 Ragan MA and Glombitza KW. 1986. Phlorotannins, brown algal polyphenols. In Progress in Phycological Research, Round FE and Chapman DJ (ed). Biopress Ltd: Bristol; 129-241.
3 Koivikko, R. 2008. Brown Algal Phlorotannins: Improving and applying chemical methods. SARJA - SER. A I OSA - TOM. 381ASTRONOMICA - CHEMICA - PHYSICA - MATHEMATICA

Commercial extraction: a number of phlorotannin rich extracts are commercially available. Large scale industrial extraction is mostly carried out in South East Asia. Botamedi Inc, Republic of Korea, produce the SEANOL® polyphenol range that is derived from the kelp species *Ecklonia cava*. The SEANOL Science Centre[4] has been dedicated to research in this area for 18 years. SEAPOLYNOL® is a 90% polyphenol rich extract that is used as the active ingredient in many global products including Fibronol® and Fibroboost®.

Most commercial polyphenol products in Europe are derived from fucoid species (e.g. *Ascophyllum, Fucus*) rather than kelps. Extracts of *Saccharina, Alaria* and *Laminaria* are used extensively in the European cosmetics sector however, commercial literature rarely states what actives are being targeted and given the low concentration of polyphenols in European kelp species, it is unlikely that they are the primary active.

Details on commercial processing methods are not readily available although InSea2® is reported to be an aqueous extract whereas the SEANOL® technology was initially based on ethanol extraction. Phlorotannins are readily soluble in water and solvents and are thus easily extracted but there are a number of complicating factors as they complex with alginate and proteins, chelate metal ions and oxidise readily – all of which will affect extraction efficiency and potentially their bioactivity. Typical extraction procedures for phlorotannins tend to be aqueous or use organic solvents or a mix of the both. Enzymes and pH adjustment have been used to free up CWB phlorotannins. Free phlorotannins are not stable and many extraction methods employ a stabilisation step to prevent oxidation and polymerisation.

Uses: the potential health promoting benefits of phlorotannins are well documented and a number of phlorotannin rich extracts are commercially available. These are sold directly or as functional components in a range of health & wellness products. Phlorotannin rich extracts are primarily marketed on the basis of their antioxidant and anti-inflammatory benefits and for weight management. Seaweed extracts that are rich in phlorotannins are also marketed for skin whitening and other cosmetic uses and as functional ingredients/actives in feed and plant protection products (Section 2 below).

1.1.2. Mannitol

Description[1]: mannitol is a sugar alcohol (corresponding to mannose) that has a role as a storage compound and translocant in many species of brown seaweeds. It is also present as a terminal group in some laminarin structures. Typical content in European brown seaweeds ranges from 2-58% as content varies substantially on a seasonal and environmental basis and also between stipe and blade tissues, especially in the kelp species. Thus, at certain times of the year, mannitol can be a major mass component in kelp species.

	Mannitol content as % dry weight[1]
Saccharina latissima	2-58
Alaria esculenta	<14
Laminaria digitata	2-20

Commercial extraction and use: mannitol is produced industrially through the high pressure hydrogenation of D-glucose/D-fructose mixtures, often from starch but it is also extracted from natural plant resources including kelp seaweeds, particularly in China. Mannitol is moderately soluble in water but only slightly soluble in ethanol, thus on a commercial basis it is typically extracted from kelps using water at around 20°C, pH 2 although extraction conditions can vary. The extract is then purified by dialysis and crystallisation. In a biorefinery situation, mannitol and laminarin are often co-extracted and then separated using UF with cut off of 200Da-3 kDa.

The applications of mannitol are extremely diverse: (i) cosmetics – for moisture control/as a humectant in skin hydration formulations or skin care preparation; (ii) pharmaceuticals - as an excipient (it is chemically inert and physically stable) and diuretic; (iii) industrial – used in the paint and varnish industry, leather and paper manufacture, plastics industry and in the production of explosives and (iv) food - specifically for chewy foods like chewing gum and candies (gives a sweet and cooling sensation), in chocolate-flavoured compound coatings for candies, as a sucrose replacer in sugar free and tooth-friendly products and also as a flavour enhancer. From a biorefinery perspective, mannitol is proposed as a potential substrate for conversion into to isomannide and similar intermediates for plasticisers, fuel additives, PET replacements, epoxy resins, for example[5].

4 The SEANOL Science Centre website (http://seanolinstitute.org/ssc/index.html)
5 https://www.researchgate.net/publication/278405499_Process_Development_for_Seaweed_Biorefineries

1.1.3. Laminarin

Description[1]: Laminarin (also known as laminaran) is a water soluble storage polymer in brown seaweeds. It is a (1,3)-β-D-glucan with β (1,6) branching. Two types of laminarin have been described: (i) with chains that are terminated by D-mannitol residues (M-series) which is most abundant and (ii) with chains terminated by D-glucose residues (G-series). Ratios of the two types as well as their structures, can vary according to the seaweed species, age, season and environmental factors [6 7 8].

Laminarin is a small (low molecular weight) glucan, with a molecular weight of ≈ 6 kDa with a DP of 20-25. It does not gel or form a viscous solution. Laminarin is present in either soluble or insoluble forms. Soluble laminarin is completely soluble in cold water whereas insoluble laminarin is only soluble in hot water. Solubility is influenced by the presence of branching, the higher the degree of branching the higher the solubility in cold water. Soluble laminarin has a MW of 5-6 kDa whereas insoluble form has a MW of around 3,500 kDa. The reader is directed Kadam et al (2015) for a study relating to Irish seaweeds[9].

Laminarin is found in species of brown seaweeds but it is more abundant in the kelps. Content varies on a seasonal and environmental basis and also between stipe and blade of kelp species but can comprise < 39% of the seaweed biomass (dry weight).

	Laminarin content as % dry weight[1]
Saccharina latissima	<33
Alaria esculenta	26-39
Laminaria digitata	<18

Commercial extraction and uses: laminarin is typically extracted under hot water (≈ 70°C), acidic conditions (using hydrochloric and sulphuric acids) for several hours and then purified to remove co-extractants. Calcium chloride can be added to prevent the solubilisation of alginate. Laminarin can be obtained as a co-extract of fucoidan and/or alginate extraction (along with mannitol) and vice versa but as it has low molecular weight, can be separated using UF with a small cut off (around 5 kDa). The filtrate is then further purified using diafiltration and dialysis (≈ 1 kDa) to remove the calcium chloride and precipitated with ethanol. Various properties of laminarin are exploited in the health & wellness sector (see Section 2.2.1) and also in horticultural products (see Section 2.3.1).

1.1.4. Fucoidan

Description[1]: Fucoidan (sometimes also referred to as fucoidin) is a term used to describe a class of sulphated fucan polysaccharides that play a structural role in the cell walls of brown algae. Fucoidans are mainly found in European fucoid seaweeds i.e. the wracks, rock weeds, e.g. *Fucus*, *Ascophyllum*, *Himanthalia*) where they can comprise <40% of the dry cell wall matter. They are also found in other brown seaweeds including *Alaria*, *Laminaria* and *Saccharina* but to a lesser extent (see below). The structure and content of fucoidan varies substantially between algal species, within different plant tissues and with season. Numerous methods have been used to extract and characterise fucoidan which has led to much confusion in the literature. The reader is directed to Ale & Myers (2013)[10], Ale et al (2011)[11], Li et al (2008)[12], Jiao et al (2011)[13] for more detail and Fitton et al (2019) for a comprehensive review[14]. In light of the variability in fucoidan structure, Ale et al (2011) proposed that the term "fucoidan" is not appropriate and that the "fucose-containing sulfated polysaccharides" or FCSPs should be adopted. This term is now widely used in the literature. For the purposes of this review, the term fucoidan is used.

6 Rioux et al (2009). Effect of season on the composition of bioactive polysaccharides from the brown seaweed Saccharina longicruris. Phytochemistry 70: 1069–1075.
7 Rioux et al (2007). Characterization of polysaccharides extracted from brown seaweeds. Carbohydrate Polymers 69 (2007) 530–537
8 Rioux et al (2010). Structural characterization of laminaran and galactofucan extracted from the brown seaweed Saccharina longicruris. Phytochemistry 71: 1586–1595
9 https://www.mdpi.com/1660-3397/13/7/4270
10 Ale & Meyer (2013). Fucoidans from brown seaweeds: an update on structures, extraction techniques and use of enzymes as tools for structural elucidation. RSC Advances, 2013, 3,8131
11 Ale et al (2011). Important Determinants for Fucoidan Bioactivity: A Critical Review of Structure-Function Relations and Extraction Methods for Fucose-Containing Sulfated Polysaccharides from Brown Seaweeds. Mar. Drugs 2011, 9, 2106-2130.
12 Li et al (2008). Fucoidan: Structure and Bioactivity. Molecules 13, 1671-1695.
13 J Jiao et al (2011). Chemical Structures and Bioactivities of Sulfated Polysaccharides from Marine Algae. Mar. Drugs 9, 196-223.
14 https://www.mdpi.com/1660-3397/17/10/571

	Fucoidan content as % dry weight[1]
Saccharina latissima	2-12
Alaria esculenta	2-3
Laminaria digitata	<6

Commercial extraction and uses: the primary species used for fucoidan extraction in south east Asia are Wakame *(Undaria pinnatifida)*, Mekabu (only the sporophylls on *Undaria pinnatifida*), Mozuku *(Cladosiphon novae-caledoniae)* and Kagome kombu *(Kjellmaniella crassifolia)*. Various methods are used to extract fucoidan but most centre around the historical use of mild acid extraction at ambient or slightly elevated temperatures in addition to fractionation by molecular weight. Marinova use a patented cold-water process for extracting fucoidans[15] of various molecular weights and structure from different brown seaweeds that are sourced globally. Their extracts are all of high purity (>75% fucoidan) with some very high purity extracts that are marketed for pharmaceutical use15. Fucoidan Force® also use a patented, solvent free process.

The Algues et Mer product Invincity® is a concentrated, high molecular weight fucoidan extract produced from *Ascophyllum nodosum* using an aqueous extraction process followed by ultrafiltration. The DuPont product (ProtaSea®) is produced using a patented process that was developed by FMC[16]. ProtaSea® was presumably produced as a by-product of the FMC alginates business. It is not known if the ProtaSea® technology has been optimised to be species specific. The bioactive potential of fucoidan is well documented and exploited in a range of products (more detail in Section 2 below).

1.1.5. Alginate – alginic acid

Description: alginate[17 18] is a polymer that is extracted from the cell walls of large brown seaweed species and is one of the major components of brown seaweed biomass. In its natural form it exists as insoluble alginic acid but is typically exacted and sold as a soluble salt, usually as sodium (sometimes potassium or ammonium) alginate. Alginate can also be extracted from the extracellular polysaccharide matrix of some bacteria.

Commercial seaweed sources of alginate vary around the world, in Europe, *Laminaria hyperborea*, *L. digitata* and *Ascophyllum nodosum* are used. Alginic acid is a copolymer of two sugar acids - guluronic acid (G) and mannuronic acid (M). The arrangement and ratio of G and M varies with species, locality and growing conditions with repeated units of M (MM blocks) or G (GG blocks or mixed (MG blocks) occurring. The M:G ratio is important as it controls the functionality of the alginate and thus also determines the commercial value. Molecular weight is also important and has bearing on end application. Alginates are typically marketed on the basis of their gelling and viscosifying functionality and by molecular weight.

	Alginate content as % dry weight[1]	Approximate M:G ratio[17 18]
Saccharina latissima	10-33	70:30
Alaria esculenta	10-42	unknown
Laminaria digitata	32-45	55:45–60:40

Commercial extraction: two extraction approaches are used. Both follow the same extraction process but use different precipitation steps. Simply, wet or dried seaweed is acid washed to remove ions that cause the alginate to be insoluble and then dissolved in alkali (typically sodium hydroxide) to produce a viscous solution of alginate and cell wall debris. The solution is filtered and treated to remove colour. The alginate is then precipitated using either calcium or acid to produce calcium alginate or alginic acid, respectively. Calcium alginate can then be further acid washed to produce alginic acid. Typically, alginic acid is neutralised with a carbonate salt to produce a soluble alginate (commonly sodium alginate but potassium, ammonium and calcium alginates are also produced. The end products are dried and milled. The calcium precipitation method is more robust (handles most seaweed species) and thus is more commonly used.

15 https://www.marinova.com.au/
16 https://patentimages.storage.googleapis.com/0e/ca/7d/8aba2653e624e3/US20120302742A1.pdf
17 Draget et al (2005) Alginates from Algae. In: Polysaccharides and Polyamides in the Food Industry. Properties, Production and Patents. Ed. A. Steinbuchel and S.K. Rhee.
18 http://www.fao.org/3/X5822E/x5822e04.htm

Uses: The viscosifying and gelling properties of alginate are widely exploited in the food industry, particularly in ice cream and desserts, fruit preps e.g. bakery fillings, low fat spreads and restructured vegetable, meat and fish products. Similarly, texture functionality is a requirement of many pharmaceutical products. Alginate is used in medical dressings and is being explored for use as a suitable scaffold for regenerative medicine. Alginate also has wide industrial application, traditionally in the textile industry to stabilise dyes and as a sizing agent in the paper industry.

1.1.6. Protein

Description: seaweeds are considered to be a good source of nutritional protein and bioactive components (lectins, phycobiliproteins, bioactive amino acids and peptides) with health promoting properties and also show potential for development as functional food ingredients[19 20]. The protein content and amino acid profile of different species is highly variable. Red and green species typically contain 10–47% protein (dry weight) but brown species typically have a lower protein content on average of 3-20% dry weight but this varies considerably with a number of environmental factors. Of the 20 naturally occurring amino acids (AAs), most are found commonly in macroalgae including all of the essential amino acids (EAAs): histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine.

Bioactive peptides have been isolated from macroalgae at laboratory scale; these tend to be from 2 to 20 amino acid residues in size and are normally inactive until released from the parent protein by hydrolysis[19 20]. Demonstrated bioactive properties include antihypertensive, antioxidative, antithrombotic, hypocholesterolemic, anti-appetising, antimicrobial and immunomodulatory.

	Protein content as % dry weight[1]
Saccharina latissima	5-18
Alaria esculenta	9-20
Laminaria digitata	3-12

Commercial extraction and use: microalgal proteins are commercially available e.g. Algavia® [21]. There is a sizeable (multi-million) Global market for these products. Targeted protein rich extracts are also used in the cosmetics industry but as far as we know, there is no commercial extraction of macroalgal proteins as yet. Bleakley & Hayes[19] outline some of the issues surrounding scaled up extraction of proteins from seaweed and provide a comprehensive review of algal proteins. Conventional extraction in the laboratory involves the use of aqueous solvents (acidic and alkaline) followed by a recovery step (e.g. precipitation, filtration). Cell disruption using physical and/or enzymatic methods can be used to improve extraction, particularly in brown seaweeds where the presence of viscous alginate can impact on extraction yield. The use of ultrasound, microwave and pulsed electric field have all been shown to aid protein extraction in microalgae and seaweeds. Algal derived proteins have potential application in a number of sectors from a nutritional and bioactive perspective. More detail is given in Section 2 below.

1.1.7. Minerals and vitamins

Description: seaweeds are naturally rich in minerals and trace elements due to the marine environment in which they live. They can comprise greater than 50% of their dried biomass as minerals and trace elements but it is generally lower. Irish kelp species can contain between 14-45%. All of the essential minerals and trace elements that are required in the human diet are found in macroalgae. Seaweeds are reported to contain a range of water soluble vitamins such as thiamine (B1), riboflavin (B2), cobalamin (B12) and ascorbic acid (C) and fat soluble (Beta-carotene, A and E) vitamins. Trace amounts of other B vitamins such as niacin, biotin and folates have also been identified. Brown seaweeds are typically higher in vitamin C than other vitamins.

19 https://europepmc.org/articles/PMC5447909
20 https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1529-8817.2011.00969.x
21 http://algavia.com/ingredients/proteins/

	Mineral content as % dry weight[1]
Saccharina latissima	15-45
Alaria esculenta	14-32
Laminaria digitata	14-35

Extraction and use: minerals are not typically extracted from seaweeds unless recovered from various aqueous processing streams. With the exception of iodine. This was a traditional activity for most seaweed economies and still occurs in Asia. Commercially available calcified red seaweed (Maerl) derived products are just milled material from the whole plant. Maerl is naturally high in minerals and Maerl based ingredients have wide application for fortification and enrichment in food (Section 2.1 below) and animal feeds (Section 2.3) and also use in cosmetics (Section 2.2.) and industrial applications.

1.1.8. Lipids and pigments

Description: the lipid component of seaweeds essentially comprises fatty acids, phospholipids, glycolipids, pigments, sterols and fat soluble vitamins. The reader is directed to Kumari et al 2013 for an excellent review[22]. Total lipid content is low, generally <5% dry weight but this varies considerably with a number of environmental factors. The fatty acid profile of many species has been determined as this is an important indicator of nutritional potential in feed, for example. Macro algae are particularly rich sources of PUFAs (poly unsaturated fatty acids) including the essential omega (n)-3s LNA, EPA and DHA (respectively α -linoleic, Eicosapentaenoic and Docosahexaenoic acids) and omega-(n)-6 LA (linoleic acid). Fatty acids can comprise <50% of the total lipid content in some species. Cold water species tend to contain higher levels of PUFAs[71].

Macroalgae contain a number of pigments. Those that have most beneficial potential for valorisation are the carotenoids. Carotenoids are C40 tetraterpenes and include carotenes which are hydrocarbons and xanthophylls that contain one or more oxygen molecules. They are found in all macroalgae. Brown seaweeds contain β-carotene and also fucoxanthin. The **fucoxanthin** content of macroalgae is generally low, approximately 3–6% of the total lipid content (TL) of brown species (TL = 1–10% of the dry weight of the macroalga). Shannon & Abu-Ghannam (2016) estimated the fucoxanthin of the Irish kelps to be <1% but stated that this was in range with estimates for northern Europe but lower than some other estimates for similar species[23]. Some carotenoids also function as vitamins (see below).

	Lipid content (% dw)[1]	Fucoxanthin content (% dw)[24]
Saccharina latissima	1-3	<0.09
Alaria esculenta	<2	<0.05
Laminaria digitata	<2	<0.07

Commercial extraction and use of lipids: Lipids are extracted from microalgae on a commercial basis, typically using processes such as enzymatic hydrolysis and osmotic shock to rupture the cell wall before fractionation and recovery of the oil component. Solazyme reportedly use a fermentation process and heterotrophic microalga that secretes oil into the fermentation media which is later recovered and refined[24]. Lipid extraction is more difficult for seaweeds as they have a far more complex matrix from which the lipid component has to be released and recovered. Laboratory extractions typically utilise solvents like chloroform, methanol, dichloromethane, diethyl ether and hexane, in single or multiple phases. As with proteins, various cell disruption techniques can be applied to improve recovery of lipids from the seaweed matrix. Processes such as homogenisation, ultrasound, microwave, pulsed electric field, sonication and supercritical fluid extraction have been applied to algae. Fatty acids can be extracted using similar processes but are also sometimes extracted using direct transesterification methods.

Cost effective and efficient scale up of lipid extraction technology is a key focus, in particular for research/biorefineries that have biofuel (algal oil) as an output. The lipid fraction of macroalgae is important for the formulation of animal, aquatic and pet foods (more detail in Section 2.3) however, most algal derived products come from microalgae.

22 https://www.researchgate.net/publication/258241659_Algal_lipids_fatty_acids_and_sterols
23 https://arrow.dit.ie/cgi/viewcontent.cgi?article=1257&context=schfsehart
24 http://making-biodiesel-books.com/all-about-algae/algae-oil-extraction/

Commercial extraction and use of fucoxanthin: fucoxanthin is extracted from seaweeds and microalgae. Key producer Oryza Fat, Oil & Chemical Co. Ltd., in Japan use an ethanol based extraction procedure with various kelp species to produce a range of liquid and dried products with varying fucoxanthin content (%). Other producers utilise *Undaria pinnatifida* which is reported to have high fucoxanthin content (around 9% of the total lipid content). Fucoxanthin is found in the chloroplasts of algal cells and thus is more abundant in the blades that have more exposure to sunlight. Commercial production therefore preferentially utilises the blade of the kelp and different solvents including hexane, methanol, DMSO, ethanol, petroleum ether, diethyl ether, dimethyl ether, acetone, or ethyl acetate[24]. Laboratory based procedures typically utilise single or multiple solvent extraction phases of the same range of solvents plus a clean-up or fractionation stage. The bioactive properties of fucoxanthin are commercially exploited. Fucoxanthin is used in different cosmetic and health & wellness products, particularly in supplements for weight management (Section 2.2).

1.2. Seaweed cultivation in Europe

Scoping the European seaweed aquaculture is not an easy task as there is generally a lack of consistent and reliable data and producers are not always willing to divulge information on production as competition for markets is high. Most published accounts utilise the FAO (Food & Agriculture Organisation of the United nations) Global Aquaculture Production[25] [26] data and provide various interpretations of this data. Depending on which data set is selected, analysis could also include microalgae and freshwater aquatic plants. The FAO data set includes the Russian Federation and Baltic States as part of the European region unless these are purposefully filtered out, and thus published analyses of the "European" situation may also include these regions. Unless the data set used is clearly stated (not typical), it is difficult to compare reports and/or draw any conclusions.

Estimates and information on aquaculture outputs of key producing countries were included in a series of industry profiles that were generated as part of the Interreg funded NETALGAE (2010-2012) and ENALGAE (2011-2015) projects but the industry has moved on a pace since then and updated analyses are not readily available. The recently published PEGASUS report (PHYCOMORPH European Guidelines for a Sustainable Aquaculture of Seaweeds) provides an **estimation of European aquaculture of seaweeds of 1,450 tonnes and market value of around €237,000** (based on FAO data) but qualifies this with a discussion regarding the uncertainty of the data set[27] (Box 1.1). **Discussion with industry contacts** and collation of various non-FAO data sets suggests that the production of cultivated biomass in Europe could be **closer to 500 wet tonnes in any one year**. Note that despite the general trend for increasing cultivation, biomass produced in any one year can vary depending on growth conditions and whether large collaborative projects are producing biomass for research, but these variations are likely to be in the region of one to 10s of tonnes, not hundreds of tonnes. Norway is the top producer and the only country producing in the hundreds of tonnes range, industries elsewhere in Europe are typically in the 10-60 tonne range.

Irrespective of inconsistency in available data it is clear that European aquaculture of seaweeds still represents a very small percentage of total European algal production (less than 1%) and a mere fraction of the Global production. The reliance of the European industry on local wild harvested seaweed and imports is one of the key drivers for increasing aquaculture in Europe. The situation in Europe is quite different from the global scenario where in any year more than 95% of seaweed production comes from cultivation[28].

There is a definite drive to increase seaweed aquaculture production in Europe with large scale initiatives planned for Norway and the Dutch-Belgian North Sea coast. An initial wave of EU and national funding has enabled a number of individuals, regional clusters and transnational consortia to develop the knowledge and technology platform to a level that allows small scale commercial cultivation. The next phase to scale up is underway and the industry is predicting significant activity and growth in the near future.

25 http://www.fao.org/fishery/statistics/global-aquaculture-production/en
26 http://www.fao.org/fishery/static/Yearbook/YB2017_USBcard/root/aquaculture
27 http://www.phycomorph.org/pegasus-phycomorph-european-guidelines-for-a-sustainable-aquaculture-of-seaweeds
28 https://www.researchgate.net/publication/320306943_Sustainable_harvesting_of_wild_seaweed_resources

Box 1.1. PEGASUS (PHYCOMORPH European Guidelines for a Sustainable Aquaculture of Seaweeds)
http://www.phycomorph.org/pegasus-phycomorph-european-guidelines-for-a-sustainable-aquaculture-of-seaweeds

The reader is directed to this report which *"highlights the current state of European seaweed production and pinpoints challenges for the development of this sector in the current European context. It proposes recommendations for short-term and long-term improvements at different levels of the chain"*.

1.2.1. Species under cultivation/planned cultivation

The main species cultivated in Europe are given in Table 1.1. In any one year the brown seaweeds, predominantly *Saccharina latissima* and *Alaria esculenta*, comprise the major percentage of European production. Cultivation of seaweeds appears to have started in Europe in 1985, at least the first production data were captured by the FAO at this time.

In most Northern European countries that are developing seaweed aquaculture, the "go-to" species is *Saccharina latissima*. The cultivation technology for *Saccharina latissima* was based on potential exploitation for biofuels. This "revolution" has yet to occur, essentially because of insufficient biomass and cost but plans for very large-scale farming in the North Sea (Netherlands & Belgium) could provide the solution.

Table 1.1. Main species under cultivation in key countries

Species	Common name	Countries where cultivated
Alaria esculenta	**Atlantic wakame, Dabberlocks, Winged kelp**	**FR, IE, NO, NL, DK, FO, UK**
Laminaria digitata	**Oar weed, Kombu, Kelp**	**UK, FR, IE, NO, FO**
Saccharina latissima	**Sugar kelp, Sweet kelp/kombu, Kombu royale**	**FR, NO, UK, ES, NL, IE, DK, FO, SE**
Chondrus crispus	Irish Moss, Carrageen	FR, PT
Gracilaria sp.		PT, ES
Palmaria palmata	Dulse, Dillisk	FR, IE, DK, NO, FO, UK, PT
Porphyra spp.	Nori, Laver, Purple laver	FR, IE, NO, PT
Ulva spp.	Sea lettuce	FR, NL, PT, ES, NL, UK, PT
Undaria pinnatifida	Wakame, Asian wakame	FR, ES

Compiled from CyberColloids own data,[27, 29]

There is a real willingness to expand the cultivation of brown seaweeds. Many operators across Europe are licensed and have the capacity to farm small volumes of seaweed but are reticent to invest in the next step – to scale up. The primary reasons appear to be (i) bulk markets for *Saccharina latissima* biomass are yet to be clearly identified and (ii) fear of future over capacity and potential industry crash if markets are not realised. Until bulk or value-added markets are found, the financial risk of setting up/upscaling is too high for many operators.

1.2.2. Top producers

European countries with seaweed aquaculture activity are Norway, France, Ireland, Spain, Portugal, Denmark and the Faroe Islands, United Kingdom, Germany, Sweden, the Netherlands and Belgium. Activity ranges from established, albeit small, production to pilot/research demonstration scale. A summary profile for those engaged in the cultivation of key kelp species is given below.

29 https://www.noordzeeboerderij.nl/public/documents/Valgorize-D4.1.1A_Study-on-the-existing-market-for-seaweed-food-applications.pdf

Norway

Norway is Europe's largest producer of seaweed[30], an industry that is largely based on the supply of material for alginate extraction. This material is essentially wild harvested. Around 150,000 wet tonnes of *Laminaria hyperborea* are harvested each year. The average price is €23/wet tonne and around 5,000 tonnes of alginate are produced. *Ascophyllum nodosum* is also wild harvested, around 10-20,000 wet tonnes per year mostly for use in seaweed meal, agricultural, nutraceutical and cosmetic products. *Ascophyllum nodosum* sells for €50/wet tonne. A small amount of *Ulva lactuca* is also harvested for the restaurant trade (≈ 140 kg @ €50/kg).

Seaweed aquaculture has increased in Norway in recent years. Since 2015 there has been a clear shift in activity with the number of licences, operations and tonnage all gradually increasing. The Norwegian Directorate of Fisheries provides the following information regarding the status of seaweed cultivation in Norway by end 2018. 406 licences have been issued for the following seaweeds - *Saccharina latissima* (78), *Laminaria digitata* (70), *Alaria esculenta* (75), *Palmaria palmata* (60), the remainder (113) are for other seaweeds and/or mixed licences. Only 155 of these are currently operational by 20 companies over 83 different sites. **In 2018, 169 wet tonnes of seaweed were harvested with a value of NOK 1,217000 (≈ €120,000).** In earlier years, more or less equal volumes of *Saccharina* and *Alaria* were grown but now *Saccharina latissima* is the primary crop (165 wet tonnes, vale of NOK 745,000). The price **per tonne for *Saccharina* in 2018 ≈ €450** was the highest value in recent years (average since 2015 = €300/tonne). Only 2 tonnes each of *Alaria esculenta* (NOK 472,000) and "other seaweeds" were cultivated in 2018. In 2016/17 the **price/wet tonne of *Alaria* was €3,100 and €3,800**, respectively. The price/tonne that was reported in 2018 seems erroneous (€23,000).

Box 1.2 SEABEST Project Seaweed Energy Solutions AS, Norway
(http://www.seaweedenergysolutions.com/en/commercial-projects/seabest-sme-instrument)

- An H2020 SME Instrument Phase II project that is focussing on the development of a commercial seaweed supply chain for cultivated organic seaweeds in Norway. Presumably *Saccharina latissima* will be the primary crop.
- The main focus is on developing high quality products for the European food market. Through improved technology and mechanisation, SEABEST also aims to open possibilities for new products and markets in bioenergy, pharmaceuticals and animal nutrition.
- This project started in March 2019 and will run for 2 years. Research updates will be posted on the company website.

There is a clear drive in Norway to establish a sustainable seaweed value chain from cultivated biomass. An industry group, Norwegian Seaweed Farms, has been started. The website gives good information about the associate farmers[31]. The recently funded SEABEST project (Box 1.2) is an example of an industry led, large scale project that aims to drive the industry forward and open up new opportunities to supply bulk markets, particularly in the food sector. The Norwegian Research Council have also recently funded a new project that will establish a seaweed biorefinery for Norway. The SBP-N (Norwegian Seaweed Biorefinery Platform) was launched in May 2019[32].

There are plans in Norway to develop large scale cultivation. The Ocean Forest Project[33] is a partnership between the Bellona Foundation and the Lerøy group. It aims to develop and establish new forms of biomass production tied to aquaculture. The Bellona Foundation is an independent non-profit organisation that has a focus on climate challenges and the implementation of sustainable environmental solutions. The Leroy Group is one of Norway's key seafood companies (salmon and white fish) and also grows seaweed. Leroy Ocean Harvest has one of the largest seaweed farms in Europe including a hatchery and currently produces around 80-130 wet tonnes/yr of *Saccharina*[34].

30 https://www.fiskeridir.no/Akvakultur/Tall-og-analyse/Akvakulturstatistikk-tidsserier/Alger
31 https://www.norwegianseaweedfarms.com/farmers
32 https://www.sintef.no/en/latest-news/kick-off-for-the-norwegian-seaweed-biorefinery-platform/
33 https://www.leroyseafood.com/en/sustainability/oceanharvest/about-us/
34 Sveier (2019). "Sugar kelp production in Norway – from spores to finished product for human consumption". Seagriculture Conference, Ostend 2019.

France

France is Europe's second largest producer of seaweed, employing 1600 people, around 80 companies and a market value of €424 million[35]. An estimated 45,000 to 60,000 wet tonnes are wild harvested each year and this comprises around 99% of the total resource. There are currently 35 licenses in place for harvesting by boat. These 35 boats are allowed to harvest during the summer (from May to October) mostly *Laminaria digitata*, *L. hyperborea* and *Saccharina latissima*. 50 licences have been issued for professional shore harvesters (*Ascophyllum nodosum*, *Fucus vesiculosus*, *F. spiralis, Himanthalia elongata, Pelvetia canaliculata, Chrondrus crispus, Mastocarpus stellatus, Palmaria palmata, Porphyra umbilicalis* and *Codium*), a further 300 occasional harvesters also contribute to this industry. The bulk of the industry is centred in and around the coast of Brittany.

French seaweed resources are classified by regulations as; (i) deep water – harvested by boat or low tide, mainly *Laminaria digitata, L. hyperborea* and *Saccharina latissima*; (ii) shore seaweed – harvested on foot, including *Ascophyllum nodosum, Fucus vesiculosus, F. spiralis, Himanthalia elongata, Pelvetia canaliculata, Chrondrus crispus, Mastocarpus stellatus, Palmaria palmata, Porphyra umbilicalis* and *Codium* and (iii) stranded seaweed – all kinds of seaweed but typically a high crop of Ulva spp. In Spring. Hydrocolloid extraction, mainly alginate from *Laminaria spp.* takes around 60,000 tonnes wet seaweed per year and generates and income of €1.7-2.7 million (i.e. 45 euros/ton). A further 15-20,000 tonnes of dry seaweed are imported each year to satisfy the demand for hydrocolloids extraction (80%) and as extra resource for the fine chemicals sector (20%).

There are around **10 companies with cultivation capability in France**, mostly growing *Undaria pinnatifida* and some *Saccharina latissima*. **Up to 50 tonnes (wet) of seaweed are cultivated** each year which is less than 0.1% of the total harvest. Note: the FAO statistics report 500 tonnes, a sizeable discrepancy.

Like many European states, France is all too aware of the increased burden on natural stocks of seaweed biomass and reliance on imported material to drive the industry forward and thus is investing substantially in research to develop the aquaculture of key species. The IDEALG project is testament to that commitment. It is a 10 year project (2011-2020), Funded by the French National research Agency and draws together a critical mass of seaweed companies and research institutes (Box 1.3).

Box 1.3. IDEALG Project, France https://idealg.u-bretagneloire.fr/en

- A consortium of 18 different industrial and research partners from the French seaweed sector (CNRS, IFREMER, UEB, UBO, UBS, ENSCR, University of Nantes, INRA, AgroCampus, C-WEED, Bezhin Rosko, Aleor, France Haliotis, DuPont, CEVA as well as a technical centre specialised in seaweeds (CEVA) and coordinated by the Marine Station at Roscoff.
- The aim is to improve biomass supply and to foster biotechnology applications within the seaweed field.
- Regular news items posted on the project website.

Ireland

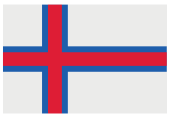
Ireland has one of the most established seaweed industries in Europe. BIM report that in 2018, **77,000 tonnes of seaweed worth €37 million were exported** and 58,000 tonnes (worth €9 million) were imported for reprocessing and export markets. **Farmed seaweed production in Ireland from licensed aquaculture sites was recorded at 40 tonnes in 2018 worth €40,000** at farm gate. This product was destined for further value adding for sale into high end niche markets. There are an estimated 43 seaweed companies in Ireland ranging from farming companies, sea vegetable production to companies producing high end, value added products such as plant biostimulants, soil amendments, animal health and nutrition products and cosmetics. Of the order of 15 Irish companies are processing seaweed for the sea vegetable market.

35 https://idealg.u-bretagneloire.fr/en/key-figures

BIM has led a seaweed development programme in Ireland since 2004. The programme of work has concentrated on developing and perfecting cultivation methods for the brown seaweeds (*Laminaria digitata, Alaria esculenta* and *Saccharina latissima*) and more recently the highly sought after red weeds (*Palmaria palmata* and *Porphyra umbilicalis*). Farming of brown seaweeds, specifically *Alaria esculenta*, takes place at licensed marine sites. It is difficult to pinpoint the actual licensed hectarage as at any one time, licence applications are being handled in the system. A substantial number of new licences for seaweed cultivation were granted in 2018 and 2019. BIM estimates the licensed seaweed hectarage in Ireland to be 150 hectares. The yield of brown weeds is 6 tonnes fresh product/ha (based on best known performance and varies with water depth and long line density). This equates to 900 tonnes fresh harvest if all the sites are fully operational. This is anticipated within the next 5 years.

Denmark

Cultivation of seaweed in Denmark is currently at a level < 10 wet tonnes per year, and it has been at this level since production started in 2008. The cultivated species is *Saccharina latissima*. The major producer is Hjarnø Havbrug[36] (production area of 100 ha). Presently no other commercial producers are in play, but several university sites produce smaller amounts of biomass for R&D. In addition to that around 15 maritime gardens produce seaweed for their own consumption.



Faroe Islands

There are two companies cultivating seaweed in the Faroe Islands, Ocean Rainforest[37] and Tari[38]. Ocean Rainforest are cultivating *Saccharina latissima, Alaria esculenta, Laminaria digitata* and *Palmaria palmata*, Tari is cultivating *Saccharina latissima*. Most of the biomass is sold into the food and cosmetics sectors. Ocean Rainforest is a very proactive small company and has participated in a number of large EU funded research projects (details on their website).

Ocean Rainforest has been working hard to get the cost of production down and has managed to reduce current costs by two thirds in recent years[39]. A key strategy is the ability to have multiple harvests between re-seeding. Ocean Rainforest can carry out a partial harvest in May and a second harvest autumn. This can be done for up to 3 years so **effectively they get 6 harvests from one seeding event[40]**. They currently have capacity for several 10's of tonnes (wet) but are planning to scale to >100 tonne capacity. Ocean Rainforest have a successful ensilation procedure and anticipate a 3-5 year period is necessary to implement the knowledge gained through the MACROCASCADE project which will significantly advance their business (Box 3.3. below).

Sweden – has some cultivation R&D activity only on the west coast but is exploring the potential to develop the industry.

Netherlands

The seaweed industry in the Netherlands is small with some wild harvest and aquaculture activity (on shore and in sheltered environments) with **total production of around 15-20 wet tonnes** ([29] *industry source*) however, the Dutch government's ambition is to develop a thriving seaweed economy. As part of the country's 2050 sustainable energy plan,

36 http://www.havbrug.dk/products/sweet-kelp/
37 https://www.oceanrainforest.com/
38 http://tari.fo/
39 Bak 2021a - Production of macroalgae in the open ocean –a new protein source? Circular Bioeconomy Days, Foulum, Denmarke 2019.
40 Bak 2019b - Commercial kelp processing and storage including ensilage methods for value creation and improved health. Seagriculture conference, Ostende 2019.

the aim is to cultivate seaweed as part of a multi-use farming system around wind turbine infrastructure in the North Sea. One quarter of the North Sea territorial waters are set aside for this initiative. Developing a sustainable supply of high quality food is also a key driver for the Dutch Industry[41].

There are around 5 companies that currently cultivate seaweed in the Netherlands, mostly *Saccharina latissima* and *Ulva spp* although production of other species is coming online. Noordzeeboerderij[42] is non-profit organisation that is the driving force behind the multi-use farming initiative in the North Sea. The organisation is *"committed to accelerate and strengthen the impact-driven seaweed industry in the Netherlands and to creating a healthy and strong value chain"*. Noordzeeboerderij are very active in National and European level research and have excellent facilities for cultivation and associated research, including an offshore lab.

Zeewaar[43] were the first to farm seaweed in the Netherlands. They grow *Saccharina* and *Alaria* and are active participants in collaborative research projects. Seaweed Harvest Holland[44] are well established and have been very active in large funded projects. They are currently producing around 10 tonnes/annum but have the capacity to produce significantly more, potentially 1000's tonnes/year (*industry source*) starting in 2020. Hortimare are seaweed cultivation specialists and very active in promoting the European industry. Hortimare supply high quality starting materials and technical expertise for start-up farmers and existing industry participants. They also have a test farm in Norway.

Belgium

The Belgian seaweed industry is very small and mainly consists of pilot projects for offshore and IMTA cultivation (e.g. SeaConomy, Value@Sea[45], Wier & Wind). *Saccharina latissima* is the main crop. However, like the Netherlands, Belgium has big plans for off-shore multi-use farming in wind turbine developments. The SeaConomy project[46] brings together a multidisciplinary consortium to investigate the feasibility of large scale, sustainable seaweed cultivation in the Belgian North Sea. It involves partners: Colruyt Group, Lambers-Seghers (feed), POM-West Flanders, Pures (food supplements) and Sioen Industries (textiles). The aim is to develop the road map that will be used to fulfil the SeaConomy dream (2025-2035).

Sioen Industries is a Belgian textile company that has been very active in the seaweed cultivation space. As an expert in the production of technical textiles, Sioen has developed, patented and commercialised a range of seaweed cultivation substrates. The technology was developed under the EU funded ST-SEA project but is now being exploited by a spin out company formed by the AT-SEA participants, called AT~SEA Technologies. AT~SEA Technologies sell turnkey seaweed farms.

Players in the North Sea seaweed community share a common vision to develop large scale, multi-use farming activity for the future development of s sustainable seaweed economy. There is a lot of regional collaboration and The Seaweed Platform (Box 1.4) has emerged out of the growing network. Dutch and Belgian companies and research institutes are extremely active in the field. Table 3.2 in Section 3 summarises some of the interesting research projects that are currently addressing the seaweed value chain.

The Dutch and Belgians are dreaming big. The Dutch prediction for off-shore, multi-use farming in the North Sea is for a 500 km^2 area that will produce 10 million wet tonnes of seaweed with predicted revenue of €1 million, creating thousands of new jobs and sequestering 1.2 million tonnes of CO_2[47]. The Belgians are predicting that 10% utilisation of the planned off-shore windfarm space for seaweed aquaculture could support 4,000 farms of 20 Ha each. Production could be <16 million wet tonnes/annum of sustainable biomass which equates to 50% of the current global seaweed

41 https://library.wur.nl/WebQuery/wurpubs/fulltext/470706
42 https://www.noordzeeboerderij.nl/en
43 https://www.zeewaar.nl/uk/
44 https://seaweedharvestholland.nl/english.html
45 https://sioen.com/en/news/first-seaweed-on-sioen-mats-harvested-in-flanders
46 http://www.fabriekenvoordetoekomst.be/seaconomy
47 Van Swam (2019). Towards an impact driven seaweed industry: enabling technical and social innovation. Seagriculture conference, Ostend 2019.

harvest. Creating tens of thousands of jobs and sequestering 4.8 million tonnes of CO_2 (yearly production of all cars in Europe)[48].

Germany – there is a small amount of cultivation in Germany, notably Oceanwell[49] that produce active ingredients from kelps for use in health & wellness products. There are also some cultivation R&D activities in operation.

> **Box 1.4. The Seaweed Platform**
> (http://www.noordzeeboerderij.nl/en/community/seaweed-platform)
>
> - Since 2014 Noordzeeboerderij have been building a platform of interested parties with the aims of connecting the seaweed community.
> - Currently the group comprises >90 members, •4 farming initiatives; 5 working groups and a broader community of >300 individuals.

The UK

The UK seaweed industry is relatively small but is undergoing rapid change with a number of new farming initiatives coming online and/or in the planning process. Most activity occurs in Scotland with small amounts scattered around Northern Ireland, England and Wales. In Scotland, wild harvest of seaweed is estimated at 20-30,000 wet tonnes per year[50] (mostly *Ascophyllum nodosum*), the main harvesting company is the Hebridean Seaweed Company, based on Lewis. Others include Uist Asco, Bod Ayre, Shetland and The Orkney Seaweed Company. Aquaculture activity is limited to research and pilot scale demonstration in Scotland, N. Ireland and Wales. Also mostly centred in Scotland where SAMS (Scottish Association of Marine Sciences) has a number of test sites and is involved in collaborative R&D with local industry. The main focus at SAMS is on the cultivation of *Alaria esculenta, Saccharina latissima, Laminaria hyperborea, Palmaria palmata* and *Ulva*. Key commercial farmers in Scotland are New Wave Foods, Caledonian Seaweed, and Seaweed Farming Scotland. Scottish producers are typically producing in the range of **5-10 wet tonnes per annum** (*industry sources*), mostly *Saccharina latissima* and some *Laminaria digitata*. There are a number of community initiatives scattered around Scotland that are at various stages of planning/coming online. A new commercial enterprise is expected to be operational soon and should have the capacity for 100s of wet tonnes. (*industry source*).

In Northern Ireland, Islander Kelp[51] are farming *Laminaria digitata* using bespoke technology that allows year-round cultivation as opposed to the typical seasonal activity. Cultivation R&D is also underway at Queen's University, Belfast. In England there are several farming initiatives in the pipeline/just going online, including Sustainable Seaweed Ltd[52], the Cornish Seaweed Company[53]. SeaGrown[54] in Yorkshire is operational. There is a lot of interest in developing a sustainable seaweed value chain for In Wales, there is some cultivation R&D at Swansea University and Green Seas Resources, Pembrokeshire[55] have a project in the pipeline.

At present, UK production from aquaculture is in the region of several 10s of tonnes per annum with most companies producing in the order of 5 to 10 wet tonnes per annum. Yearly tonnage for the UK also depends on whether any funded research cultivation programmes are running. However, this is predicted to grow quickly as larger farms come online, to 300 tonnes by 2020, 30,000 by 2025 and 250,000 by 2030[56].

48 Vandendaele (2019). At Sea Nova: Large-scale offshore seaweed cultivation. Seagriculture conferenec, Ostende, 2019.
49 https://www.oceanwell.de/en/products/ingredients-effect/
50 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/546679/FC002I__Cefas_Seaweed_industry_report_2016_Capuzzo_and_McKie.pdf
51 https://www.islanderkelp.com/
52 https://www.sustainableseaweed.co.uk/
53 https://www.exeter.ac.uk/news/archive/2019/april/title_714511_en.html
54 https://www.seagrown.co.uk/
55 http://www.greenseas.co.uk/
56 Bavington (2019). Oceanium: accelerating the blue economy. Seagriculture conference, Ostende, 2019.

Spain

The seaweed industry in Spain was/is traditionally built around the wild harvest of red seaweeds including *Gracilaria sesquipedale, Chondrus crispus* and *Mastocarpus stellatus*, for the extraction of agar and carrageenan. Some brown and green species are also wild harvested for use in food and cosmetics. In 2011, an estimated 11,960 wet tonnes were harvested, 10,000 of which went to hydrocolloid extraction.

Aquaculture is underway in Galicia, Asturias and Andalusia, mostly for *Saccharina, Ulva* and various red seaweeds including *Gracilaria, Gracilariopsis* and *Chondracanthus*[27]. In 2011, the Netalgae project reported that 40 tonnes of *Undaria pinnatifida* were cultivated[57]. In 2017, APROMAR (Asociacion Empresarial de Acuicultura de Espana) reported that **8.5 tonnes of cultivated seaweed** (species of *Laminaria* and *Gracilaria*) were harvested[58].

Portugal

Seaweeds have grown in Portugal for some time. There are currently 3 established companies that are cultivating seaweed, primarily *Ulva*, although there have been several trials in recent years and a few more are planned for the autonomous region of the Açores[27]. The recent Portugal Blue Bioeconomy Road map states that 15% of Portuguese stakeholders in the marine space are focused on seaweed activities, including SMEs and research groups[59].

ALGAplus[60] is a successful Portuguese company that sustainably produces a range of different red and green seaweeds including *Palmaria palmata, Chondrus crispus, Porphyra spp., Gracilaria spp., Ulva spp.* and *Codium tomentosum*. The main crop is *Ulva rigida*. They have 700m^2 of saltwater cultivation ponds and utilise an IMTA (integrated multitrophic Aquaculture) set up. ALGAplus have been actively promoting the European aquaculture sector in recent years and have participated in a number of EU funded projects. They have gradually increased production in the range of 10s of tonnes in recent years with the aim to produce in the 100s of tonnes range in the near future[61]. The major market is B2B food as ALGAplus have the ability to customise their biomass for specific end use/requirements.

57 http://www.netalgae.eu/index-en.php
58 http://www.apromar.es/sites/default/files/2019/InformeAcui/APROMAR%20Report%20AQUACULTURE%20IN%20SPAIN%20 2019.pdf
59 http://blueandgreen.ciimar.up.pt/wp-content/uploads/2019/05/Roadmap_DIGITAL.pdf
60 https://www.algaplus.pt/
61 Abrieu 2019. Cultivation of red seaweed in Portugal. Seagriculture conference, Ostende.

Cultivated *Alaria esculenta*, Ireland

2 CURRENT USES AND POTENTIAL MARKETS FOR IRISH KELPS

Wild Alaria esculenta and *Laminaria digitata*

This section provides an overview of current market trends for the use of seaweed biomass and seaweed derived ingredients and also highlights some potentially interesting areas for future exploitation of Irish seaweeds

Current uses and potential markets for Irish kelps

Seaweeds and seaweed derived ingredients and actives are utilised in a wide range of products. Detail on the following key sectors is provided below:

- Food - sea vegetables, processed ingredients and texture ingredients;
- Health & wellbeing – cosmetics and personal care, supplements, functional ingredients and pharma applications;
- Plant and animal health including aquatic feed and pet nutrition;
- Platform chemicals for conversion to biofuels, bulk chemicals, novel materials and bioplastics.

2.1. Food

Key current and potential markets for the application of seaweed in the food sector are:

- sea vegetables;
- processed ingredients;
- texture ingredients;
- supplements and functional ingredients (covered in Section 2.2).

Note that the sale and use of seaweeds and seaweed derived ingredients in Europe is regulated under General Food Law (Regulation (EC) No 178/2002)[62]. "Seaweed" is recognised as a food in Europe under the CODEX classification system as a vegetable or processed vegetable: *"Vegetables" = mushrooms and fungi, roots and tubers, pulses and legumes, and aloe vera, seaweed, and nut and seed purees and spreads and nuts and seeds*. But note that the term "algae" does not come under this definition. At present, EU regulation is not consistent with use of terms algae, microalgae, macroalgae & seaweed. Consumption of seaweed and seaweed derived ingredients is also covered by the Novel Foods Regulation (EU) 2015/2283[63]. In Europe therefore, there are a number of things to consider when bringing new food products to the market: whether the source material is considered a food or whether it falls into Novel Foods territory; whether the processes used to manufacture the product/ingredient are (a) approved, new or novel and (b) give rise to significant changes in the composition or structure of the food ingredient so as to affect nutritional value, metabolism or level of undesirable substances. The three Irish kelp species that are the focus of the current report, are not considered as novel foods as all have a history of consumption in Europe prior to 15. May 1997 when the legislation was introduced. Note however, that under this legislation, *Saccharina latissima* is listed as *Laminaria saccharina*. More detail on the regulatory environment concerning the use of seaweed and seaweed derived products can be found in Holdt & Kraan (2011)[74], Barbier et al (2019)[27] and the online Novel Foods Catalogue[64]. Regular updates are provided by CEVA, France and can be found on their website[132].

62 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32002R0178
63 https://ec.europa.eu/food/safety/novel_food/legislation_en
64 https://ec.europa.eu/food/safety/novel_food/catalogue_en

2.1.1. Sea vegetables

The sea vegetable market (i.e. seaweeds sold for direct consumption) is a significant market Globally and in Europe. In Europe, sea vegetables are mostly sold dried but fresh, salted and preserved products (in brine or vinegar) are also in the market. In 2015, BIM commissioned a comprehensive report - "*The European Market for Sea Vegetables*[65] which scoped the European market and laid out recommendations for the Irish market. The report states the European market for selected sea vegetables was 472 tonnes in 2013, about 25% of which was supplied by European producers. The breakdown was Atlantic wakame (28 tonnes), Kombu (22 tonnes), Nori (3 tonnes) and Dulse (63 tonnes). The major producers were Spain, France and the Netherlands. The reader is directed to that report and key points are detailed in Box 2.1. The sea vegetables market is of relevance to any potential biorefinery enterprise in that increased supply of high quality, food grade seaweeds could alter market dynamics (pros and cons) however this market will not be considered further in this report.

Box 2.1. Key findings "The European Market for Sea Vegetables"[65]

- The European market for sea vegetable in 2013 was estimated ≈ 472 tonnes with value of ≈ €24 million (wholesale).
- Leading markets were France > UK > Germany > Spain (totalling ≈ 80% of the market).
- The market was growing at 7-10% per annum, predicted further future growth.
- Nori/*Porphyra spp*. was the primary product (over 60% of European market), 285 tonnes imported from Asia, only 3 tonnes from Europe, UK largest regional user.
- Dulse/*Palmaria palmata* second largest (70 tonnes), mostly sourced in Europe, only 10% imported, France largest regional user.
- Atlantic wakame/*Alaria esculenta* (64 tonnes), 50% produced in Spain, Netherlands and France, 50% imported, major users Spain, UK, France.
- Kombu/*Laminaria digitata* (50 tonnes), almost 60% supplied by imports, France largest consumer market (40%) followed by UK & Spain.
- Opportunities for Irish producers to supply high quality, organic seaweeds to target markets (retail and food processors) & reduce reliance on imports.
- Perceived barriers – price, distribution and supply of adequate volume to bulk markets.

The reader is also directed to a recent report from the ValgOrize project consortium (Box 2.2) - "*Study on existing market for algal food applications*" that reviews the current use of seaweed in food (Global and European). This report also provides a market analysis for the 2 Seas Region (coastal regions of the Netherlands, France, United Kingdom and Belgium) with the aim of identifying potential markets for cultivated seaweed in the southern North Sea and English Channel region[66].

Box 2.2. The ValgOrize project (https://www.noordzeeboerderij.nl/en/projects/valgorize)

The ValgOrize project is Interreg funded through the 2 Seas Region and runs from 2017-2020. It is a recommended project to follow as it specifically focusses on the application of seaweed (and microalgae) in food and will address key consumer issues surrounding sensory and quality attributes of new seaweed products. The overall aim is to develop the necessary knowledge platform that will enable high quality, tasty and consumer accepted food products containing seaweed to be produced and also to build the roadmap for a viable & sustainable Dutch (and European) seaweed value chain.

65 Organic Monitor (2014). The European Market for Sea Vegetables. Report to BIM.
66 https://www.noordzeeboerderij.nl/public/documents/Valgorize-D4.1.1A_Study-on-the-existing-market-for-seaweed-food-applications.pdf

2.1.2. Processed seaweed ingredients

Seaweed ingredients are typically added for flavour, texture, nutrition and just for novelty or in response to current market trends. Processed seaweed ingredients range from simple dried, powders and flakes to more sophisticated liquid extracts e.g. those used as natural flavourants.

Dried, powdered & flaked ingredients - widely used as savoury ingredients and condiments, often blended with salt or other ingredients. Historically, products were aimed at retail/home use but are now increasingly used as ingredients in processed foods where they are added for flavour, sodium replacement and mineral fortification (e.g. Maerl - *Lithothamnion calcareum*).

Liquid extracts - seaweed extracts are used traditionally in Asia as natural flavour enhancers but there has been an increase in use in Europe. Reference to "kelp/kombu extract" or "kelp/kombu waters" is frequently seen in the ingredients list of savoury products.

Nutritional/functional ingredients – in Europe, unlike other Global markets, the use of functional (bioactive) ingredients is more typical in supplement/nutraceutical type products than in foods due to regulatory constraints. For the purposes of this report, functional ingredients will be covered in the section below that deals with the use of seaweed in health & wellbeing.

CyberColloids has been tracking the use of seaweed derived ingredients in food and drink products since 2004 (using Mintel GNPD), conducting regular searches for new products that have "seaweed" or "algae" on the label. These searches have purposefully avoided picking up products that contain the seaweed derived hydrocolloids alginate, agar and carrageenan and search categories have been refined to exclude these. Also, the terms "red algal extract" or "red seaweed" are excluded as these terms are commonly associated with the use of carrageenan or semi-refined carrageenan. The searches have also excluded the use of microalgae, specifically *Spirulina* & *Chlorella* that are widely used for natural colourants and nutritional supplementation.

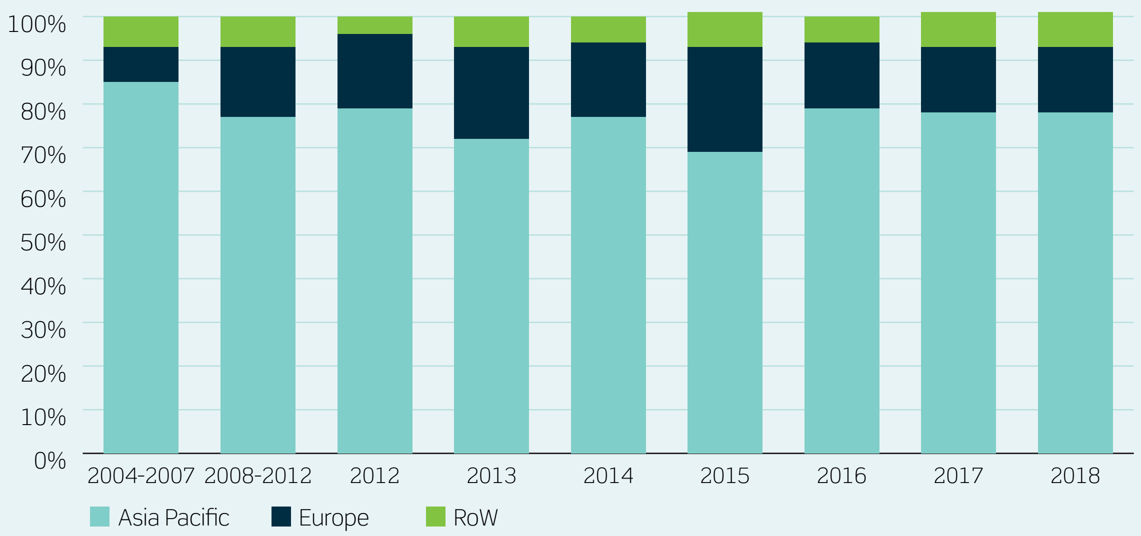
Refining the searches to exclude these ingredients makes it easier to identify the range and types of products that are being targeted for the non-hydrocolloid application of seaweed ingredients. For example, when a search was conducted for the period 2014-2019 using the terms "seaweed" and "algae", over 20,000 products were identified, if the carrageenan associated labels were removed then 10,000 less products were identified, if the *Spirulina* & *Chlorella* labels were removed then the search identified around 2,000 products.

These searches do not define market size or value, but they do show how seaweed ingredients are being used on a global basis and are indicative of market innovation. By studying the ingredients list we can develop an understanding of what types of seaweed are being used and how they are used in different products.

Key observations

The Global situation - in global terms, the number of new products containing seaweed that are launched in any one period is always far higher in the Asia-Pacific region than elsewhere in the world. Figure 2.1 shows the relative distribution of new product development (NPD) in Asia-Pacific, Europe and the rest of the world (RoW) during the period 2004 to 2018. Asia Pacific is seen as the primary innovator with 70-80% of Global NPD for seaweed ingredients in any one year however, Europe is the second most innovative market with NPD ranging from 15-24%.

Figure 2.1. Relative distribution (as %) of new product launches in Asia, Europe and RoW



The European market - over 2,600 new products containing seaweed entered the European market during 2008-2018. This is still small in the global picture, but gradual growth has occurred in the last decade and the number of new products has doubled since 2012 (Fig. 2.2).

Products containing seaweed ingredients have been launched in all EU28 countries during the last decade but during any one period, most new product launches have come from France, UK, Germany and Spain (≈65% of total European NPD). In recent years however, there has been an increase in the number of other countries that have launched products containing seaweed.

Figure 2.2. Number of new products launched in Europe in the last decade

The Irish situation - New product innovation in Ireland is still low, ≈ 2% of the European market in any one year and this has remained stable in last 10 years or so.

Key end users - the number of different companies that utilise seaweed ingredients in Europe is large but the top innovators (i.e. companies that produced more than 10 products in the last 5 years) typically account for <30% of European NPD in any one year which means that that majority of NPD in Europe is by companies that launch only one to few products.

Key products and applications

Seaweed ingredients are used in a wide range of food products although during the last five years, more than 80% of new products fell into the following broad categories (i) prepared meals; (ii) snacks; (iii) dairy based products; (iv) processed products based on meat, fish & egg; (v) sauces & seasonings; (vi) soups and (vii) bakery (Fig. 2.5). A discussion of key market sectors follows.

Prepared meals

More than a quarter of new products launched in Europe in the last five years fell into the prepared meal category. This is in line with the global trend, for a rapidly expanding market for processed and prepared foods. This is being driven in general by an increase in population but also by opposing changes in the world's economies. On one side, recession is forcing consumers to seek value for money, on the other, improved living standards in formerly disadvantaged economies are enabling consumers to look for more diverse and luxurious product offerings.

Seaweed ingredients are being added to prepared meals, primarily for flavour but also for interest and in response to the rapidly growing global food trend for plant-based foods/nutrition. It is clear that a high proportion of new meal products being launched are plant-based (e.g. tofu, seitan, pulse-based) and seaweed often ranks high on the ingredients list suggesting that it is added in a high enough dose to have an impact on the sensory profile of the product i.e. not just for novelty.

A recent market analysis[67] listed "plant based" as the number 2 top trend that is currently driving the global food and beverage industry and that is providing substantial opportunity for NPD in all market segments. The consumer motivation to consume more plant-based foods is broad and not restricted to vegetarian and vegan lifestyles. New Nutrition Business (NNB) reported in 2019[64] that *"creative product development is propelling the plant-based trend, not vegetarianism and veganism"* as *"NPD is making it easier for people to choose more plant-based products"*.

Snacks

Around 18% of European NPD in the last five years was in the snacks category. This is a very traditional market sector for seaweed ingredients, following on from use in the traditional Asian style mixes and crisps. However, the global trend for "healthy snacking" is growing rapidly and is predicted to continue to do so. There is growing demand for "healthy" seaweed derived snacks in both the US and European markets. In 2015 New Nutrition Business reported the US retail sales for seaweed snacks to be worth over $US 250 million and 2017 – Innova Market Insights reported "Seaweed" to be showing continued use in Western markets with >30% growth in the snack sector (2015-2016)[68 69 70]. This is a sector where seaweed can still be expected to play a key role in NPD. Seaweed is recognised as a top "trendy" ingredient to use [71], there is growing awareness of the inherent health and nutritional benefits and the use of seaweed fits very well with key consumer preferences for "natural", "inherently healthy" and "minimally processed" products[72].

Seaweed is undoubtedly added for flavour and novelty but also potentially for nutritional functionality and for natural saltiness. All species offer a rich and balanced source of minerals & trace elements including those that are important from a flavour perspective: sodium, potassium, calcium, magnesium, zinc and iron.

Dairy and dairy alternatives

Most dairy based products that contain seaweed do so for flavour or as a source of natural minerals. Dairy products do not typically lend themselves to the strong flavour profiles of seaweed ingredients, except cheeses but calcified red seaweed ingredients are widely used. Around 11% of European NPD in the last five years was in the dairy category.

67 Mellentin, J. (2018). 10 Key Trends in Food, Nutrition & Health 2019. New Nutrition Business November/December 2018, Volume 24 Number 2/3
68 http://www.foodbev.com/news/seaweed-could-be-next-big-snacking-opportunity-firm-says
69 http://www.new-nutrition.com/article/displayArticle/1308;
70 http://www.new-nutrition.com/article/displayArticle/1331
71 https://www.foodingredientsfirst.com/news/special-report-seaweed-and-microalgae-driving-new-product-development.html
72 http://www.nutritionaloutlook.com/article/algae-and-nutrition-putting-%E2%80%9Csuper%E2%80%9D-superfood

Non-dairy, plant-based drinks and products (yoghurts, puddings, desserts) that contained seaweed ingredients almost exclusively contained calcified red seaweed for mineral enhancement although these products would also typically use carrageenan as a thickening and suspension agent. Brown seaweed ingredients are also found in dairy/dairy style products for natural mineral content.

Sauces & seasonings

This is another traditional sector for the application of seaweed ingredients. For the same reasons as outlined above, kelp species are added for natural flavour but this is a category where the flavour of red (predominantly Dulse and Nori) and green (Sea lettuce) seaweeds are also added for their specific flavour profiles.

This is also a category where seaweed ingredients are also potentially added for sodium (salt) replacement. The use of seaweed ingredients for sodium replacement is a traditional application with many of the early products being seaweed salts, sprinkles and condiments and essentially for home use. However, we are aware of increased commercial use in products that traditionally contain high levels of sodium, such as sauces, seasonings, breads and meats.

Soup

Much like sushi, miso-style soups have become more mainstream products and there are many in the marketplace, but seaweed ingredients are found in more western style soup products, in particular fish-based soups. One fish soup from France that was recently launched, contains *Chondrus crispus*, presumably this is being added for natural texture rather than for any other reason as *Chondrus* is not commonly eaten for its interesting flavour profile. Seaweed is also added for natural flavour in vegetable and meat-based soups.

Processed products based on meat & fish

For essentially the same reasons as those detailed for the prepared meals sector, seaweed is commonly added to processed fish and meat products. The marine flavour profile and consumer acceptance of fish products naturally extends to the addition of seaweed ingredients. In addition, the strong textural and sensory profile of some seaweed products is not so challenging for application in many meat-based dishes that have a more forgiving sensory and textural profile themselves.

Around 10% of European NPD in the last five years was seen in this sector. A large number of products were sushi or sushi-style. Consumer demand for sushi has grown significantly in recent years and may be considered mainstream in Europe. Seaweed is still widely used in processed fish products for flavouring and colour (flakes in marinades and dressings) but what is clearly evident is the rise in the number of products that are utilising "kelp". "kombu"; "kelp/kombu waters" and "algae waters" as natural flavourings. Waters typically comprise seaweed, salt and water as a stock. The UK based company Marks and Spencer have been doing this for some time and a range of products (across all sectors) are available in UK and Ireland.

Natural flavour enhancement is a key driver in the global food industry and kelp, or kombu extract is now seen on the ingredients list of a wide range of global products, including soups and sauces, ready meals and snacks. Many species of kelps are renowned for their umami and flavour enhancement potential due to high levels of free amino acids, glutamic acid, alanine & aspartic acid. Some (in particular the Asian kombu species – *Saccharina japonica*) can contain up to 90% of the amino acid content as glutamates in the form of natural MSG (mono sodium glutamate) and this equates to $<$ 2% (dry weight) of the seaweed. This is extremely high when compared with other umami rich substances such as dried shitake mushrooms (0.07%), bonito (0.03%) and tomatoes (1.2%).

Bakery

Seaweed ingredients have been added to bakery products for many years, in particular to artisanal breads, crackers and biscuits. There are many such products on the market, typically in association with coastal and/or regional markets where there is a seaweed connection. This is a sector where calcified red seaweeds are utilised as a mineral source.

Regarding application in sweet products, calcified red seaweed products (e.g. Irelands Aquamin™) are added as a source of minerals and also the Supplex® brand, France, uses "FAL" seaweeds for mineral supplementation in a range of sweet applications. FAL denotes the brown seaweeds that comprise the mix i.e. *Fucus, Ascophyllum & Laminaria*. FAL is typically added at ≈ 0.2%.

2.1.3. Texture ingredients

Extraction of agar, carrageenan and alginate for food texture ingredients is still the primary processing use of seaweed biomass for food. *Alaria esculenta, Saccharina latissima* and *Laminaria digitata* are all alginate bearing seaweeds. Detail on the properties, extraction and use of alginate in food were given in Section 1 of this report and the relevance of alginate as part of a conceptual Irish biorefinery is discussed in Sections 3 and 4.

Alginate (sold as powder) is used widely in the food industry on basis of the following key functionalities: viscosifying & gelling behaviour, cold solubility; cold setting; heat and freeze thaw stability. It is typically used in ice cream & sorbet; bakery creams (e.g. cold whip products); dressings & low fat spreads; fruit fillings, preparations & juices and restructured foods (e.g. heat resistant jellies). Similar texture functionality is also a requirement of many pharmaceutical and cosmetics products (see below).

The alginate market

In 2018, the global market for food and pharma hydrocolloids (excluding China and industrial uses) was estimated at 2.3 million tonnes and with a value of US$ 7,240 million[73]. The seaweed derived hydrocolloids accounted for about 10% of the total Global market value. An estimated 57,000 tonnes of carrageenan (valued at US$ 522 million), **17,000 tonnes of alginate (valued at US$ 314 million)** and 13,000 tonnes of agar (valued at US$ 265 million) were produced[73]. By 2023, volumes and value are expected to rise to 64,000 tonnes (US$587 million), 19,000 tonnes (US$ 357 million) and 15,000 tonnes (US$ 292 million) for carrageenan, alginate and agar, respectively[73].

The global demand for alginate (hydrocolloids in general) is growing substantially but there has been little innovation or diversification in the European processing sector for many years. The European industry has declined. The growing Global markets are increasingly supplied by Southeast Asian processors who are utilising cultivated biomass. Many of the regional European seaweed industries that were supplying biomass for alginates extraction, including Ireland, have suffered in this respect.

Traditional alginate processing is relatively expensive, resource consumptive and generates waste streams that become an environmental and economic burden. Consequently, alginate products can be expensive. In 2018 the average price for alginate was estimated at US$ ≈ 18/kg[70] but ranging from around €10-30/kg in Europe. European producers typically sell powder blends containing alginate for targeted applications whereas Chinese competitors sell powdered base alginates, typically for <€10/kg.

Alginate is classed as a food additive in Europe (thus carries an E number). Even though hydrocolloids are added at very low dosages, they are often seen as "artificial", being purposefully extracted from the seaweed biomass and seen by the consumer as unnatural. Furthermore, additives need to be permitted in the target food application and often dosage is limited and regulated by specific bodies: European Food Safety Authority (EFSA) in Europe, Food and Drug Administration (FDA) in USA. In some sectors, we are seeing a move away from the use of hydrocolloid food additives with end users seeking clean label solutions. The food industry is seeing the emergence of a new category of texture ingredients – functionalised fibres – that can (in many cases) provide label friendly alternatives to hydrocolloids. However, there are many drivers and benefits for the development of new functionalised fibre products. Table 2.1 below gives some of the key incentives.

Various proprietary physical and chemical processes are used to "functionalise" the key texture components in raw materials like citrus, apple, vegetables and cereals. Some of these materials are by products of the food processing industry e.g. fruit pomace and peels. The number of functionalised fibre products is increasing and this includes fibres that are derived from seaweed.

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73 Seisun 2019. IMR International Hydrocolloid Conference – Lisbon, Portugal 2019 www.hydrocolloid.com

Table 2.1. key drivers and opportunities for new functionalised fibre products

Category	Key drivers and opportunities
Consumer trends	growing global demand for healthier, less processed foods with simplified labels increasing trend for plant-based nutrition increased uptake of vegetarian and vegan diets/lifestyle increased awareness of environmental impacts of food processing more demand for "free-from" or "reduced" foods (e.g. potential allergens, fat, salt, sugar and additives (E numbers in Europe)
Industry benefits	potential to add value from processing by-products and side streams reduced waste burden (financial & environmental benefits) diversification of offerings potential for wide application in different market sectors clean label alternatives opportunity to service lucrative, emerging market sector
Global drivers	contribution to circular (bio) economy smart/sustainable use of underutilised resources minimising food loss & waste – addressing food security targets opportunities for meeting reduction targets in food (e.g. fat & sugar)

Seaweed fibre ingredients

As far as we know, there are only two seaweed derived fibres in the market. Until recently phytaFIBER® from Java Biocolloid, Indonesia was the only seaweed fibre but now, Fibersea® from Olmix, France is available.

phytaFIBER® (Java Biocolloid) is marketed as a 2-in-1 texturiser and dietary fibre made from 100% pure, pulverised *Gracilaria verrucosa* (red seaweed). The fibre is produced using an innovative aqueous process with no chemical input. It contains around 52% dietary fibre (insoluble component) and 25% other carbohydrates (soluble). *Gracilaria* is an agar containing seaweed, so the fibre offers gelation as a unique functionality and claims to be the only non-animal gelling agent that is E-number free and able to solubilise at 45°C.

It is used for thickening and to give richness and mouthfeel. It is also used for dietary fibre enhancement. It has recommended application in non-dairy milks (soy, almond, oat), coffee drinks and desserts (puddings, yogurt) and dietetic foods drinks and foods for the elderly. It is gluten-free, GMO-free and organic. In Europe it is labelled as seaweed powder or *Gracilaria verrucosa* powder.

Fibersea® R84 (Olmix) is marketed as a clean label, algal based solution for texture and structure. It claims to be a blend of vegetable and marine algae (brown seaweeds). It specifically targets syneresis reduction and texture formation for soups, sauces, bakery dairy, meats and vegan products. It has recommended application for fat reduction, fibre enrichment and is allergen free. The manufacturers recommend usage at 0.5-4.0%. The product is certified organic.

Faux seafood - potential for new seaweed texture ingredients

2.2. Health & wellbeing

There is a considerable platform of evidence for the potential health promoting benefits of seaweed derived components/extracts. Holdt & Kraan (2011)[74] provide a comprehensive general overview and more detail is given on key components in Section 2 of this report. Potential benefits for health and wellbeing essentially fall into the following sectors:

Personal care (cosmetics, skin & hare care);

Supplements and functional Ingredients;

Pharma and medical.

2.2.1. Personal care

Seaweed extracts are used in a wide range of personal care products including skin and hair care, make up, beauty and spa treatments. This is a global trend but Europe in particular has an active market. At one end of the available product range are simple "home remedy" type products that are often available as value-added or spin-off offerings from seaweed harvesters, processors and related local artisans. Such products typically contain dried seaweed ingredients (powders and flakes) or crude/extracts that are "rich in" certain target bioactives and are marketed on the basis of testimonials. At the other end of the scale are sophisticated extracts and formulations that are produced/utilised by large established cosmetic companies. These products are backed with science however details are closely guarded. The science behind any functional claims is often implied but not divulged.

The manufacture and sale of cosmetic products in Europe is regulated (Regulation (EC) No 1223/2009)[75] to ensure consumer safety and to secure an internal market for cosmetics. The manufacturer is responsible for the safety of their products and must ensure that they undergo an expert scientific safety assessment before they are put into the market. However, providers of extracts/ingredients used in any cosmetic formulation will also have to provide assurance and necessary product and process information to anyone buying and using their extracts for cosmetic application.

There is a dedicated online portal/database for cosmetic substances and ingredients, called CosIng[76] that provides relevant information (names, INCI names, INN names, chemical/IUPAC names, CAS or EC numbers, scope and/or status) and any legal requirements and restrictions. All products to be marketed in the EU must also be registered in the Cosmetics Products Notification Portal (CPNP)before being placed on the market. This process requires the completion of an information file including a product safety evaluation.

Key components of interest

The key components from seaweed that are targeted in extracts for this market are listed below:

- carbohydrates and oligomers
- pigments e.g. fucoxanthin (carotenoid pigment) in browns
- lipids (ceramides), high omega content and fatty acids
- proteins
- minerals

Table 2.2 below summarises some of the main benefits of using seaweed ingredients in personal care products (cosmetics, skin care and hare care) – as reported by the manufacturers. The reader is directed to Bedoux et al for a detailed review (2014)[77].

74 Holdt, S.L. and S. Kraan. 2011. Bioactive compounds in seaweed; functional food applications and legislation. Appl. Phycol. 23: 543-597
75 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02009R1223-20150416&from=EN
76 https://ec.europa.eu/growth/sectors/cosmetics/cosing_en
77 Bedoux et al 2014. Bioactives from seaweeds in cosmetics. Advances in Botanical research 71

Table 2.2. Main benefits of using seaweed extracts/ingredients in personal care products

Brown seaweeds	Red and green seaweeds
■ control the build-up of skin oils and to keep pores unclogged – detoxification & acne control ■ antioxidant and protective properties – natural sunblock ■ cell renewal, nourishment & circulation boost - for antiaging, firming ■ modulation of enzymes responsible for ageing – anti wrinkle ■ antibacterial protection ■ for skin lightening (reduction of melanin synthesis) & whitening in some Asian ■ countries ■ in hair products for protection and conditioning	■ antioxidant and protective properties ■ re-mineralisation ■ improved circulation ■ modulation of enzymes responsible for ageing ■ antimicrobial protection for skin and hair ■ anti-ageing ■ fresh-ness, eye contour control ■ in hair products for protection and conditioning

The global market

L'Oreal are the leaders (29% of sales) in a global cosmetic market that was estimated to be worth €200 billion in 2018[78]. Other key players are Unilever (21.5%), Estée Lauder (12.8%) and Proctor and Gamble (12.5%) – all of whom utilise algal and marine ingredients in their products. Since 2010 the global market has been growing steadily at 3.6-5.5% annually. The largest regional market is Asia Pacific (39%), followed by Europe and North America (25% each).

In 2018 the skin care sector was the largest (39%), followed by haircare (21%) and make up (19%). The skin care sector in particular is growing rapidly (up 9% from 2017). Product ranges include facial and body applications, cleansers and sun care products. Extracts of *Saccharina, Alaria* and *Laminaria* are used in skin and hair care and make up products.

Saccharina latissima in cosmetics products

Saccharina latissima is still listed in CosIng and the INCI directory (International Nomenclature of Cosmetics Ingredients) and seen in cosmetics ingredients lists as *Laminaria saccharina*.

> **Laminaria saccharina Extract**
>
> INCI name: LAMINARIA SACCHARINA EXTRACT
> Alternative names:
> Definition: an extract of the thallus of the alga Laminaria saccharina (Laminariaceae).
> INCI function: skin conditioning, emollient.

Extracts of *Saccharina* are widely used in face creams and cleansers, anti-blemish products, foundation (with SPF) and makeup to control the build up of skin oils and to keep pores unclogged. It has particular application in acne control products. Examples include:

- The Body Shop® (UK) - Ionic Clay Mask and Pore Perfector contain *L. saccharina* as a "natural additive";
- Origins (UK) - Zero Oil™ range with *Laminaria saccharina* to Inhibit excess oil production;
- Oceanwell™ face and body skincare products (Germany) use a proprietary extract produced by yeast fermentation of *Saccharina*, products are marketed on basis of antioxidant and protective properties; cell renewal and nourishment, circulation boost and antibacterial protection for clear skin;
- Estée Lauder™ – Idealist pore minimiser and skin refinishing product and the premium products La Mer for skin brightening formulation;

78 https://www.loreal-finance.com/en/annual-report-2018/cosmetics-market-2-1/

- Clinique™ – anti-blemish, foundation and cleansing products;
- Symrise produce Actipone® extract of *Laminaria saccharina* that is marketed on the basis of antioxidant, anti-aging, anti-cellulite, anti-wrinkle, anti-stress and anti-inflammatory activity.

Alaria esculenta in cosmetics products

Extracts of *Alaria esculenta* are used in skin creams for antiaging, firming and detoxification properties, also for skin lightening (reduction of melanin synthesis) and in hair products for protection and conditioning, lipids (ceramides), high omega content and fatty acids appear to be the key actives. Extracts also have wide use in makeup where mineral content is possibly important.

Alaria esculenta Extract

INCI name: ALARIA ESCULENTA EXTRACT
Alternative names:
Definition: an extract of the thallus of the algae Alaria esculenta (Alariaceaea).
INCI function: skin protecting.

Selected products containing *Alaria*:

- Exsymol (Monaco) produce EXSYMTAL® which is marketed on the basis of anti-aging, anti-pollution, antioxidant, anti-stress, anti-wrinkle and regenerating properties.
- Biotech Marine (France), a subsidiary of the Seppic/Air Liquide group produces a range of skin care products that contain an extract of *Alaria* e.g. JUVENESSNCE™, and KELPARIANE™ which have anti-aging, ant-wrinkle, firming activity and SEASHINE™ which is used as skin sublimer and lightening agent. Seppic also utilise extracts of *Alaria* in hair care products, ALARIANE™ is an anti-frizz, hair control product.

Laminaria digitata in cosmetics products

Laminaria digitata is used in a greater number of products than the aforementioned kelps. Both an extract and a powder of *Laminaria digitata* are listed in the CosIng database. Extracts and powders are used in skin care products as emollients, rejuvenation and anti-aging agents. High trace element and iodine content are listed as key actives. Extracts of *L. ochroleuca* (Golden kelp found more commonly on Continental European shores) are not distinguished from *L. digitata*.

Laminaria digitata Extract

INCI name: LAMINARIA DIGITATA EXTRACT
Alternative names: braunalge, *Laminaria ochroleuca*, Finger tang.
Definition: an extract of the alga *Laminaria digitata* (Laminariaceae).
INCI function: skin protecting, moisturising, regeneration.

Selected products containing *Laminaria digitata*:

- Codif (France) produce cosmetic, skin and haircare products containing extracts of various kelp species. Phycojuvenine contains "kombu"for antiageing and antiwrinkle;

Seaweed ingredients commonly used in face masks

- Provital (Spain) also utilise extracts of several seaweeds, the Polyplant Marine Seaweeds GNFN products is water soluble extract that delivers energising, tonifying, revitalising, moisturising, and soothing benefits;
- Lessonia (France) produce a range of aqueous and glycerine extracts of various seaweeds including Aqualgae laminaria. They also produce fine powdered products for use in mask masks and body wraps etc.

> **Laminaria digitata Powder**
>
> INCI name: LAMINARIA DIGITATA POWDER
> Alternative names: LAMINARIA DIGITATA (ALGA) EXTRACT
> Definition: a powder obtained from the dried, ground thallus of the alga, Laminaria digitata (Laminariaceae).
> INCI function: skin conditioning.

2.2.2. Supplements and functional ingredients

The use of seaweed tablets and tonics to promote health is not a new concept and basic dietary supplements including capsules, tablets and liquid products are available. The use of kelp species in such products is common. Most are marketed on the basis of their high mineral content; in particular iodine, with some aimed at specific issue e.g. thyroid health. Powder and extract suppliers of kelp products (including *Alaria, Saccharina* and *Laminaria*) commonly refer to commercial use in nutraceuticals and supplements although details are generally not provided.

Of more interest to a biorefinery concept, is the development of specific extracts and ingredients with targeted activity. Major target markets for such extracts are:

- anti-inflammatory – general health, skin, joints and bones;
- antioxidant – general health, skin, anticancer;
- weight management – implications for anti-obesity, anti-diabetes;
- gut health – gut health & colonic function and to increase satiety;
- cardiovascular health;
- immunity.

Unlike medicinal products, the marketing of food supplement product does not need individual marketing authorisation in Europe i.e. preparation of a dossier for assessment by an expert body. However national and EU regulatory provisions are in place for the **ingredients** and there is **a list of authorised ingredients**. These include vitamins, minerals and plant extracts. The provision also gives information on maximum daily intake. The manufacturer is responsible for ensuring that food supplements placed on the market comply with the regulatory provisions in force for the intended end market, both in terms of safety and consumer information[79]. Holdt & Kraan give a comprehensive overview that includes other global markets[74].

Europe is flagged as a growing market for functional seaweed ingredients as consumers become more aware of the potential health benefits of seaweeds and industry more aware of the potential to innovate[80]. Key drivers in this sector are reported as being a growing demand for weight loss supplements and food supplements that support the immune system. These markets are estimated to reach US$37 billion and US$25 billion, respectively, in the next five to six years[80].

In 2017, The French Agency for Food, Environmental and Occupational Health & Safety (ANSES) reported that around 30% of French adults were taking food supplements in 2016[79]. Target markets were vitality (17%), sleep (14%), digestive transit (14%) and weight management (10%). Seaweed based food supplements were positioned in the digestive transit and weight management segments which together accounted for about one quarter of the French market in 2016.

Functional ingredients can be delivered as pure extracts, as “active-rich” extracts and sometimes as co-extracts, particularly if there is known synergy between certain components. Detail on commercially relevant components and their extraction was given in Section 1.1 above, information on key uses and markets follows.

79 https://www.anses.fr/en/content/food-supplements-0
80 https://www.cbi.eu/market-information/natural-ingredients-health-products/seaweed/

Fucoidan

There is a substantial scientific platform for the potential health promoting benefits of fucoidan including anticoagulant and antithrombotic, antivirus, antitumor and immunomodulatory, anti-inflammatory, reduction of blood lipids, antioxidant and anticomplementary properties. Fucoidan is also shown to provide protection from viral infection and can interfere with mechanisms involved in fertilisation. It is understood that the bioactivity and bioavailability of fucoidans is related to the type of bonding present, molecular weight and degree of sulphation,

The global hub for fucoidan extraction is south east Asia, key companies include Kanehide Bio (Japan), Haerim Fucoidan (South Korea), Qingdao Rongde Seaweed (China). Outside of this region, the primary producers of fucoidan are Marinova, Australia[81] and Fucoidan Force®, US[82]. In Europe, Marinova fucoidan products are distributed by UK based company Glycomix[83]. In Europe, Algues et Mer, France produce Invincity®[84] concentrated fucoidan extract which has application in cosmetics. DuPont also have a fucoidan product in their portfolio (ProtaSea®) but it is not actively marketed.

Marinova fucoidans are marketed on the basis of being *"the only fucoidan ingredients with global regulatory acceptance"*. Fucoidans from *Undaria pinnatifida* and *Fucus vesiculosus* were awarded novel food status in Europe in 2018. The same fucoidan extracts also have FDA approved GRAS in US, are TGA listed in Australia[85] and NHP listed in Canada[86]. ProtaSea® is approved in the US by the FDA as a dietary polysaccharide".

Fucoidan products are primarily utilised as functional ingredients in functional foods and dietary/health supplements (≈85%) also in cosmetics, pharma and plant nutrition. The major markets are in Southeast Asia where the bulk of production occurs and where dietary intake of fucoidan is more or less a daily staple. There is also significant consumption in USA[87].

Recent market estimates for the Global fucoidan industry are in the region of 10-15 tonnes. It is difficult to get any consensus on market value as estimates vary significantly. The price/kg will vary depending on purity of extract and intended end use application. Prices of €8-200/kg are reported which makes it difficult to estimate the global markets. Bjerre et al[88] reported the market to be in the region of €3 million in 2017 whereas Big Market Research[87] reported US$30 million in 2019.

Phlorotannins (polyphenols)

Phlorotannins are shown to have significant potential for human health, they: modulate inflammation; reduce oxidative stress; modulate the metabolism of fats and sugars with beneficial implications for diabetes and weight management; improve cardiovascular function; improve brain and cognitive function; induce immunomodulatory and chemo preventative effects. In Europe polyphenol rich extracts are used directly or as functional components in a range of health & wellness products.

Phlorotannin rich extracts are primarily marketed on the basis of their antioxidant and anti-inflammatory benefits and for weight management. Because of higher natural content, commercial products in Europe are typically produced from fucoid species e.g. *Ascophyllum* & *Fucus*. They are not pure extracts and also contain fucoidan, laminarin and alginate with the polyphenol content typically ranging from 10-40%. Examples include the ID-alg™ extract from Nexira, France[89] and InSea2® that was developed by Algues et Mer, France and Innovactiv, Canada[90]. Some kelp derived phlorotannin products are available outside of Europe.

InSea2® has GRAS status in the USA and has been approved by the Natural Health Product Directorate (Canada) with the following health claims, helps support healthy blood glucose levels and; helps reduce the glycaemic index of ingested foods. In 2019, the German Federal Institute for Drugs and Medical Devices (BfArM) granted approval to Diapharm pharmaceutical company for a weight loss product produced from *Fucus vesiculosus*. Details on the active ingredients are not known but it is reasonable to assume that phlorotannins have some efficacy here.

For reasons outlined above it is difficult to get a perspective on the size and value of the seaweed-derived polyphenol market.

81 The Marinova website - https://www.marinova.com.au/
82 https://fucoidanforce.com/
83 http://www.glycomix.co.uk/
84 http://www.algues-et-mer.com/cosmetique
85 https://www.tga.gov.au/
86 https://www.canada.ca/en/health-canada/services/drugs-health-products/natural-non-prescription.html
87 https://www.theinnovativereport.com/2019/09/30/global-fucoidan-market-industry-set-for-rapid-growth-and-trend-by-2024/
88 http://www.marinebiotech.eu/sites/marinebiotech.eu/files/public/2-16%20SeaRefinery.pdf
89 The Nexira website https://www.nexira.com/IDalG%E2%84%A2-calorie-reducer-and-weight-management_11.html
90 https://insea2.com/insea2/

Fucoxanthin

Fucoxanthin is commercially extracted from macro and microalgae. Fucoxanthin is a potent antioxidant and has demonstrated anti-inflammatory, anti-cancer, anti-diabetic and anti-obesity effects. It is globally marketed as a weight management supplement with a focus on anti-obesity and anti-diabetes. The metabolic pathway of fucoxanthin is well understood. Metabolites are concentrated in adipose tissues where they exert a number of key effects: (i) antioxidant effects; (ii) increased synthesis of DHA (docosahexaenoic acid) in the liver; (iii) upregulation of UCP-1 (uncoupling protein involved in heat generation through fat burn) in white adipose tissue and (iv) glucose-regulating effects in muscles. These effects all have implications for the management of diabetes and weight management. Peng et al (2011) provide a comprehensive overview of the properties and potential health promoting benefits of fucoxanthin[91].

Fucoxanthin and fucoxanthin rich seaweed extracts are shown to have a number of beneficial effects on skin health including antioxidative, anti-inflammatory and inhibition of key enzymes such as elastase, hyaluronidase and collagenase. Fucoxanthin also inhibits tyrosinase and melanogenesis and thus has skin whitening properties.

Key players in the global market are Oryza Oil & Fat Chemical, PoliNat, Amicogen, Nutraceuticals, Yigeda Bio Technology, Ciyuan Biotech, Tianhong Biotech. The Oryza Oil & Fat Chemical company have made a significant investment into research on the benefits of fucoxanthin[92]. Outside of Asia, Polinat (Polifenoles Naturales) is the leading producer with the Xanthigen® product. Xanthigen® contains fucoxanthin derived from *Undaria pinnatifida* plus other ingredients. It is the active component in a range of weight loss/fat burning products like FucoThin™, Fucoxanthin-Slim™ and XanthiTrim™. Shannon & Abu-Ghannam (2016) reported the Global market for fucoxanthin in 2015 to be around 500 tonnes with and estimated market value of US$ 1.5 billion[23].

Polysaccharides and oligosaccharides

Macroalgae are renowned for the diversity of their polysaccharides. Many polysaccharides and their oligosaccharide derivatives exhibit beneficial health properties and also act as a source of bioactives. Polysaccharides represent a source of soluble and insoluble fibre, in the range 20-60% and 5-25%, of dry weight, respectively. Various algal derived poly- and oligosaccharides have been shown to have prebiotic effect i.e. promote the growth of healthy gut bacteria and production of short chain fatty acids (SCFAs).

Laminarin is utilised in the pharmaceutical, cosmetic and health & wellness sectors. It is reported to have wide bioactivity including anti-inflammatory; anticoagulant; hypocholesterolemic and hypolipidemic responses; Immunostimulating properties; antioxidant properties and also implications for digestive health. Cosmetic use specifically focusses on stimulating, regenerating, conditioning and energising effects on human dermis fibroblasts and epidermal keratinocytes in skin preparations. In Europe it is mostly used in the cosmetics and agri sectors. Modifilan® extract of *Saccharina japonica* is marketed in the US. It is rich in laminarin although it also contains fucoidan and fucoxanthin. The marketing information refers to the benefits of laminarin for cardiovascular health[93].

Online market estimates report the Global laminarin market to be around US$ 1-2 million but forecast to grow to US$ 2-3 million by 2024. Use in dietary supplements, food and beverages, feed and pharma applications is reported to be fuelling the growth. Holdt & Kraan[74] reported a market price of €350/tonne for use in food and pharma. The market is segmented by purity (20-30%, 36-60% and 60-95%) in addition to end use. Major production sites are located in China, top producers include Shaanxi Huike Botanical, Hangzhou Skyherb Technologies, Shaanxi Senfu, Xi'an SR Bio, Xi'an Tianrui Biotechnology, Guilin Fengrunlai Biotech, Nutra Green, Xi'an Yunuo and Xi'an Haijia.

Alginate is shown to improve general gut health and colonic function and also to increase satiety. Commercially available products containing a patented fibre complex extracted from *Laminaria digitata* are available. The extract, Bioginate Complex™ is manufactured by UK company Goldshield and is used in the APPEsat™ product.

In south east Asia, marine oligosaccharides are commercially exploited e.g. Agaroligo Takara Bio, Japan and Marineoligo, Qingdao BZ Oligo Biotech Ltd, China. They are marketed ion the basis of a range of potential health benefits including antioxidant, anti-cancer and hepatoprotective activity.

91 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3210606/
92 https://www.oryza.co.jp/html/english/pdf/Fucoxanthin2.0M.pdf
93 https://www.modifilan.com/

2.2.3. Pharma

Seaweed (and marine organisms in general) have been the focus of intense bioprospecting activity in recent years but as with most biomass resources that have been investigated for new natural products, a limited number of commercial products have launched. Seaweeds have proven particularly challenging in that identification and characterisation of new actives cannot always be based on terrestrial plant standards and techniques. Some commercial products containing Carragelose® which is an iota carrageenan are marketed for their antimicrobial/antiviral activity. Boots, UK, sell a "Cold and Flu Defence" nasal spray that contains Carragelose®. Similar products are available in other European countries. We are not aware of any similar products that utilise brown seaweed extracts/actives.

Seaweed derived ingredients and extracts are widely used in pharma applications for textural functionality. High purity and specific grade **alginates and alginic acid** are used for controlled delivery/release and disintegration in tablets. Alginate is also used for its film forming properties. In liquid and semi-solid preparations, alginate is used as a thickener and stabiliser. Particular properties of the alginates that are important include molecular weight, effects of shear, pH, Ca ions and concentration. Preparations that are used to combat gastric reflux/heart burn commonly contain alginate in the texture system. The Gaviscon brand is a well-known example. Alginate has been used in wound care for many years, alginate dressings are used for moisture control, absorbance of exudates and haemostatic control.

The scientific platform of evidence for **Laminarin** shows bioactive potential in the area of digestive health, immunomodulatory, control of blood lipids and anticancer in humans. Research grade laminarins are sold for <€500 for a few grams, depending on purity and supplier. A few years ago, Phycarine®, a beta-glucan extract of *Laminaria* was promoted for immune response benefits but is now only sold as a bio-fungicide for plant health.

Until more recently, research projects with a biorefinery focus have tended to develop the extraction technology but not necessarily evaluate product streams for pharma application. The FUCOSAN project (Box 2.3) is specifically focused on developing cosmetic and pharma applications for fucoidan. Extracts will be evaluated in medical fields including ophthalmology (age-related macular degeneration) and regenerative medicine (tissue engineering). Regenerative medicine appears to be a key area for innovation re. seaweeds, various textural and bioactive functionalities can play a role in the development of scaffolds for cell based research.

Fucoidan, laminarin and **fucoxanthin** have demonstrated anti-inflammatory properties. As part of the SEAREFINERY project (Box 4.1), the anti-inflammatory potential of different extracts of *Saccharina latissima, Ascophyllum nodosum Alaria esculenta* and *Fucus vesiculosus* was evaluated using in vitro models of gastrointestinal inflammation. The potential inhibitory effect of different extracts on IL-8 production was investigated. The results indicated that extracts from brown seaweed species, particularly from *S. latissima, A. esculenta*, and *A. nodosum*, had potent anti-inflammatory properties which could be utilised in the treatment of gastrointestinal inflammatory disorders.

Box 2.3. The FUCOSAN project (www.fucosan.eu)

FUCOSAN is an Interreg funded project that is dedicated to the development of a platform for economic & ecologically sustainable harvesting practices and fucoidan extraction technology for Baltic Sea seaweeds. The project aims to establish a Danish-German value chain. Fucoidan extracts will be evaluated for application in a range of medical and cosmetic fields including ophthalmology (age-related macular degeneration) and regenerative medicine (tissue engineering).

As an example of a fucoidan-focussed research project with interesting target end markets, this is one to track. The project began in March 2017 and will run until February 2020.

Europe is a growing market for functional seaweed ingredients

2.3. Plant and animal health

Traditional sectors where seaweed/extracts are used:
plant health
animal feed
Growing markets
aquatic feed
pet nutrition

The agricultural and horticultural market is considered a back bone sector for most traditional seaweed industries, including Ireland. Historically and even now, this sector is seen an opportunity to find short-term solutions for the valorisation of seaweed biomass i.e. relatively simple products and "low hanging fruit". However, this is not necessarily the case. This is a highly competitive sector (both local and export markets) and is considered by many to be sated. The sector is evolving and has become very sophisticated, it has had too. Current strategies to deal with the competition are: (i) to produce differentiated products backed by science and (ii) having a significant cost advantage for raw materials and processing.

2.3.1. Plant health

The benefits of applying seaweeds and seaweed derived products to plants and crops are well recognised. In their natural state, seaweeds contain a wide range of bioactive components that can act on both the plants and the soil to promote stronger, healthier growth and to provide protection against physical and biotic stresses. However, these components are often bound into the structural matrix of the seaweed and are not readily available to plants until they are unbound by the physical and biological processes that occur in the soil. Seaweed concentrates (liquid & dry) not only provide a source of bioactive components that are more readily available to plants and the soil microbiota, but also can be applied in a number of convenient ways e.g. foliar sprays, drenches, root dips, seed soak. Three broad categories of products are marketed:

- fertilisers – products that enrich the growth environment of the plant;
- biostimulants – products or bioactive components that promote the growth of the plant by acting on the metabolic processes of the plant itself e.g. by affecting hormonal control or stress tolerance mechanisms;
- natural plant protection products (PPPs) – including pesticides, fungicides, weed killers, herbicides, plant growth and root growth hormones. These products are regulated under European law and use must be authorised[94].

The relative concentrations of components/bioactives in seaweed concentrates vary significantly between species, locality, season and concentration method used. Commercial concentration processes generally employ physical (freezing, cell burst) or chemical (alkaline hydrolysis, fermentation) methods, sometimes a combination, to formulate seaweed concentrates. Thus, depending on the raw material and stability of the bioactives concerned, different concentration processes will produce different products with quite different plant health potential.

The key components of interest to this sector are:[95] [96]

Minerals and trace elements

The total mineral content of seaweeds generally falls within the range of 8–40% dry weight. Those that are essential for healthy growth and function include the macronutrients N, P, K, Na, Cl, Mg, S, Ca and micronutrients I, Cu, Fe, Zn, Mn, B, Mo. Seaweeds also contain vitamins, A, B1, B2, B3, B9, B12, C, E.

94 https://ec.europa.eu/food/plant/pesticides/authorisation_of_ppp_en
95 CyberColloids. Seaweed Concentrates (Extracts) For Horticulture. Internal Report.
96 Khan et al (2009). Seaweed Extracts as Biostimulants of Plant Growth and Development. Journal of Plant Growth Regulation 28(4):386-399

Polysaccharides and oligosaccharides

Seaweed polysaccharides are known to play an important role in soil conditioning whereas various oligosaccharides and the sulphated forms (fucoidans) can act as biostimulants. Extracts that are rich in laminarin and alginate derived oligosaccharides are commonly used in horticultural products. There is some conflict over the use of laminarin oligosaccharides and extracts being "natural" because hydrolysis is achieved using acid and then neutralised using "chemicals" but in the EU, laminarin is recognised as a natural biocide[97].

Polyphenols/phlorotannins

Seaweeds deploy a range of metabolites, including phlorotannins, as natural defence agents against environmental stresses, UV, grazer deterrents and as antimicrobial agents. Seaweed derived polyphenols have been shown to reduce the risk of microbial disease in the roots and leaves and also act as a source of antioxidants that are important in stress relief mechanisms.

Plant Growth Regulators – auxins & cytokinins

Seaweed concentrates exert auxin-like and cytokinin-like activities in plants. Auxins like indole acetic acid (IAA), indole -3-butyric acid (IBA) and cytokinins - kinetin, zeatin, isopentyl adenosine (IA) have been identified in seaweed concentrates. Auxins and cytokinins exert very different roles on plant growth mechanisms. Their presence and relative concentrations in seaweeds and derived liquid concentrates has become a key aspect in processing, formulation and marketing of products. Cytokinins are more stable molecules than auxins and thus are likely to be less affected by concentration method.

Amino acids and betaines

Amino acids are used as the building blocks not only for protein tissues but for enzymes, nucleotides, vitamins and other components essential for cell survival. Plants will readily utilise external sources of amino acids and peptides in preference to building their own.

Betaines are plant growth regulator type bioactives that play a role in maintaining the osmotic balance in cells. Thus, they have been identified in seaweeds as playing an important role in alleviating the effects of frost and drought. They also elicit a similar response in plants to that of cytokinins. The key betaines found in brown seaweeds are glycinebetaine, gammaaminobutyric acid betaine, delta-aminovaleric acid betaine, laminine and occasionally lysinebetaine and ascophylline.

Markets and drivers

Recent market analyses estimate the global biostimulant market to be in the region US$2 billion and project continued growth at a CAGR of 10-12% until 2025. Europe is the largest market with key drivers being the stringent regulatory framework, expansion of the organic farming sector and shift towards more sustainable farming practices. The seaweed extracts market is anticipated to register the fasted growth over the next period according to one report[98].

This sector has been a backbone for the Irish seaweed industry for decades and the markets are well understood by Irish companies that operate in this space. From a potential biorefinery perspective, there are opportunities to utilise side streams (including proteins and minerals) and to develop innovative products such as natural PPPs, seaweed concentrates high in bioactive polysaccharides and oligomers, bespoke products with targeted efficacy in particular crops.

2.3.2. Animal health

There is a growing Global demand for protein and thus a growing Global demand for feed. Animal feed and feed additives is a traditional market for European seaweed and it is a highly competitive sector. Until relatively recently, NPD was limited and marketing was based on anecdotal and historical evidence but the focus has shifted to one of "nutrition" rather than "feed" and the industry is demanding more sophisticated products that are underpinned with science based evidence.

97 https://news.algaeworld.org/2014/08/eu-authorises-use-laminarin-biocide/
98 https://www.grandviewresearch.com/industry-analysis/biostimulants-market

The animal feed additives market is mainly segmented into: (i) nutritional components - vitamins, amino acids, omega fatty acids, proteins and minerals; (ii) active components – antioxidants, antibiotics, prebiotics, mycotoxin binders and pH modifiers and (iii) texture and palatability additives e.g. emulsifiers, flavours, sweeteners.

Amino acids take about a quarter of the overall market share in terms of volume. Some of the most widely used amino acids include lysine, methionine, threonine, and tryptophan. Important vitamins include fat-soluble vitamins (A, K, E, and D) and water-soluble vitamins (B12, riboflavin, choline, and niacin).

Markets and drivers

An annual industry analysis of the animal feed market by Alltech® estimated Global feed production in 2018 to be in excess of 1 billion metric tonnes[99]. Growth over the 2017-18 period was about 4% in Europe making it the second fastest growing market. There was growth in all sectors except beef. European (EU) countries contributed to more than 50% of all major species feeds including poultry (layers & broilers), pigs, dairy and beef cattle.

Available online market analyses estimated the Global feed additive market for the same period 2017-2018 to be in the region of US$ 20 billion and expected to exceed US$ 25 billion by 2025, an estimated CAGR of around 4%.

Key drivers are: (i) rising awareness of nutrition and health, (ii) regulatory constraints forcing innovative alternatives to antibiotics and growth promoters; (iii) technological advancements in the equipment industry; (iv) requirements for bespoke nutrition and (v) increased Global demand for protein i.e. feed. In addition, the cost of animal feed and feed additives is rising in Europe and farmers are looking for alternative/cheaper solutions. Europe in particular is trying to reduce the reliance on imported soya.

Of direct relevance to the seaweed industry is the recent push to reduce methanogenesis in ruminants and this is a key focus area for research at present. The high profile research that has had significant media coverage is focussed on the use of red seaweed *Asparagopsis taxiformis* that contains an active compound bromoform ($CHBr_3$). Bromoform blocks methane production by disrupting the enzymes used by gut microbes that produce methane gas. Other species of seaweeds from Europe (mostly reds & browns) & elsewhere (red, green & brown) have shown some efficacy. Anti-methanogenesis is achieved via number of metabolic pathways and different compounds, in brown seaweeds, phlorotannins appear to be key.

An interesting approach is to develop new feed additives through co-fermentation of seaweed with other agri-waste streams, for example press cake from rapeseed. A recent study has shown that lactic acid fermentation of these two biomass streams can be used to produce feed additives with demonstrated (*in vivo*) positive effects on gut microbiome modulation, improved immune system, reduction of inflammation and strengthening of the gut lining in pigs. Further trials are under way and the principle is also being transferred to the development of new supplements for human health[100].

2.3.3. Aquatic feed

The use of algal ingredients (macro and micro) in aquatic feed is well established and many different species are used, typically in blends and in targeted formulations depending on fish species, cultivation environment and performance[101] [102]. Key performance indicators include, better yields, improved fish health (general nutrition and resistance to disease and parasites), improved texture and taste of end products. Like many other industries, there is a drive to reduce the use of chemical and synthetic additives in aquatic feeds and to produce inherently healthy formulations.

The protein and lipid content of aquatic feeds has traditionally come from fish meal which is rich in amino acids and PUFAs (polyunsaturated fatty acids) including omega-3 and omega-6 fatty acids. The price for fish oils is rising, due to over fished wild stocks and the global demand for natural ingredients thus, alternatives to fish meal are being sought[103]. Plant based protein alternatives (e.g. soy) are used but typically lack some of the amino acids that are essential for fish nutrition, notably, lysine, methionine, threonine, and tryptophan.

99 https://www.alltech.com/sites/default/files/2019-02/GFS_Brochure_2019_English.pdf
100 Kjaeulff 2019. Novel feed additives based on ensiled seaweeds and rapeseed. Seagriculture conference, Ostende 2019.
101 https://www.alltech.com/blog/hooked-nutrition-why-quality-fish-feed-matters
102 http://marineagronomy.org/sites/default/files/Kraan%20and%20Mair%20-%20Seaweed%20as%20Ingredient%20in%20Aquatic%20Feeds.pdf
103 https://www.globalmeatnews.com/Article/2017/03/20/Three-fish-feed-producers-start-partnership

These are however found in algae as are the fatty acids eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and arachidonic acid (ARA) that are also important to fish nutrition[99,100].

Feed costs can count for >50% of farm production costs[99] thus aquatic feed is a lucrative sector. However, large investment in product development and providing the scientific platform is required and there is typically a lengthy time to market. The development of aquatic feeds has been a key focus in several biorefinery models where protein and/or lipid rich residues have been generated e.g. the BIOSEA project (Box 2.4) and others (Table 3.2).

Box 2.4. The BIOSEA project (http://biosea-project.eu/)

The BIOSEA project is focussing on the development and validation of innovative, competitive and cost-effective upstream and downstream processes for microalgae and macroalgae (including *Saccharina latissima*) to produce high value actives at low cost for use in food, feed & cosmetic/personal care products. Actives include proteins, carbohydrates, fatty acids, lipids and pigments – a slightly different & more diverse range than other current biorefinery projects. BIOSEA is due to finish in May 2020 thus is worth tracking for project outputs.

Markets and drivers

Aquaculture has been the fastest growing food sector over the last three decades[98]. A recent industry estimate for the Global aquafeed market was for 40 million tonnes in 2017[96]. The largest producer was Asia-Pacific 28.5 million tonnes. Europe and Latin America both produced around 4 million tonnes each. Norway was Europe's largest producer (45% of European production). Growth In Europe was strong, Norway and Turkey grew by 7% each but Spain recorded a substantial growth of 31%.

2.3.4. Pet nutrition

Nutrition for pets is growing market and evidence shows that even during recession, pet owners do not stint on providing for their animals. It is a high value premium market that is being driven by many of the same global issues as those facing the human food market. For example: more natural, less processed ingredients, sustainability and cleaner label declarations.

The three key areas in which seaweed extract/ingredients can be utilised in pet food are:

- texture – to provide gelling, thickening and stabilising functionality;
- fortification – natural sources of minerals, trace elements, vitamins and antioxidants;
- innovation/differentiation – building an interesting sales story.

There are many products in the market that contain seaweed derived ingredients, in particular for cats and dogs. These range from simple powders and flakes that are added to food or used as sprinkles & coatings to more sophisticated extracts and additives.

Texture

Seaweed derived hydrocolloids (carrageenan and alginate) are used in gelled and gravy products, traditionally as cheap ingredients but as with human food, there is a move away from using additives towards more natural texture solutions. Mannasol, a UK based company, has just launched Spindrift[104], a premiere range of seaweed based products for use as texture and palatability ingredients in pet food. Spindrift is derived from seaweed and is marketed as all-natural, flexible texture base for pet food gels, gravies, meat chunks and loaf. It is 100% natural, is sustainable and traceable.

Fortification & nutrition

Seaweeds are a potentially interesting source of minerals, trace elements and vitamins that could bring added nutrition to pet foods. These days, pet food is also marketed on the basis of prebiotic, omega fatty acid and antioxidant content. Note that the recommended intake of these nutrients and minerals and vitamins varies between animals and is different to humans.

104 https://www.mannasolproducts.com/our-seaweed-story

Opportunities for new texture solutions in petfood

Sales story & product differentiation

This is a very competitive market but also one that is cost driven as traditional pet foods and bulk market products are made with cheap ingredients. Hence, products such as Spindrift target the premium markets. Having a particular functional or health promoting benefit is key to differentiation.

Markets and drivers

The market value of wet and dry pet food is about $125 billion worldwide (2017) with the US market being the biggest at $26 Billion. Wet pet food is around 20% of the market on average (*industry source*). There are possibilities to develop new functional ingredients from seaweed and biorefinery residues and side streams for use in pet foods. Texture and nutrition are the obvious drivers.

As with human food, taste and palatability are key. In formulation, seaweeds can bring colour, odour and taste to a product. A recent study showed that dog kibble supplemented with *Ascophyllum nodosum* seaweed was acceptable to dogs to a point but that there was dose dependent inhibition. At higher concentrations, dogs preferentially ate the un-supplemented kibble[105].

Mineral and nutritional component content of a product is not only important from a nutritional perspective but also from a regulatory and technical perspective. The processing conditions used for some pet foods e.g. retort conditions, are harsh and this could impact on the bioavailability and/or bioactivity and stability of various components.

Heavy metal content, in particular arsenic (in Asian seaweeds) and iodine, is reported to have limited the application of seaweed in petfood[106]. Some companies can overcome this by blending to reduce overall levels of particular components.

2.4. Platform chemicals

The polysaccharide component of seaweeds can be broken down into sugars which are then converted into other molecules that can be used to produce a range of industrially interesting compounds and building blocks. Similarly, the proteinaceous and lipid components can also be utilised, although the lipid content of brown seaweeds is typically low. The biorefinery approach particularly lends itself to the generation and conversion of sugars in this way. Biorefinery models based on terrestrial biomass initially focussed on the conversion of sugars (sucrose) and latterly lignocellulose (glucose) into molecules for use as energy carriers (biofuels), chemicals and bioplastics, for example.

These biorefinery models were termed 1G (sugars) & 2G (lignocellulose), respectively and utilised feedstocks such as sugar cane, cereal derived starches, straw and other agri wastes. The use of seaweed biomass as a feedstock for the conversion of sugars into similar end products is considered to be 3G. Much of the research platform that now supports the development of seaweed biorefineries and value chains based on cultivated biomass has come from the exploration of seaweed as a potential source of biofuel. *Saccharina latissima* in particular, being naturally high in laminarin (glucose rich polymer).

Section 3 (following) gives more detail on existing biorefinery concepts but at this stage, it is useful to note that two general approaches are taken although they are not necessarily exclusive and may be integrated:

(i) **cascading extractive biorefinery** approach to remove valuable components such as polyphenols, fucoidan etc. (detailed in section 1.1). Sometimes referred to as a primary biorefinery. Processing is often "gentler" to retain the bioactive properties of extracted components i.e. high temperatures and pH extremes are typically avoided. Suited to small or large scale operations;

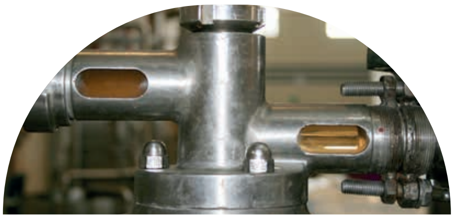
105 https://link.springer.com/article/10.1007/s10811-019-01799-5
106 https://www.feednavigator.com/Article/2018/05/14/Seaweed-to-animal-feed-producer-in-European-push

(ii) energy and/or material driven biorefinery approach which involves the hydrolysis of key components – primarily carbohydrates - to sugars, followed by conversion into platform chemicals and fuels. Hydrolysis of proteins and lipids into component molecules is also possible but is more typical of microalgal biorefineries[120]. Often referred to as a secondary biorefinery approach and can be applied to the whole seaweed biomass or to the processing residues of a cascading extractive biorefinery. The energy and material driven biorefinery approach relies on the breakdown of the seaweed biomass or saccharification (breakdown of carbohydrates into sugar components) and can use harsh processing conditions. Such biorefineries are typically restricted to large scale conversion of biomass to relatively cheap products (Fig. 4.1) as processing on a smaller scale would not be cost effective or commercially viable.

From a technical/processing perspective, the two approaches can be integrated and in fact, polysaccharides such as mannitol, laminarin and alginates can be directly broken down and converted into platform chemicals, depending on objectives and requirements. However, the key consideration is cost and many economic appraisals of conceptual biorefineries have shown that prior extraction and valorisation of valuable components is critical for economic viability (see Section 3 below). This is of particular relevance to cultivated biomass, which at present is still relatively expensive.

Key sectors of relevance here are:

- bulk chemicals and minerals;
- energy carriers/biofuels;
- biomaterials & bioplastics.



2.4.1. Bulk chemicals and minerals

Numerous sugar derived platform chemicals can in theory be generated from seaweeds, depending on the source carbohydrates (red, green or brown) and availability of technology for the extraction and conversion, and of course market demand. Platform chemicals are typically derived via biochemical (e.g. fermentation and anaerobic digestion), chemical (extraction, catalysis, depolymerisation) and thermochemical (liquefaction) pathways.

With the current focus on Irish kelps, potentially interesting components will likely be derived from alginate, laminarin and mannitol which comprise the bulk of the carbohydrate fraction. Fucoidan is a recognised high value product stream although not found in very high levels in the kelps[1]. The mineral content of the seaweed biomass will invariably be separated out at one of more stages in a biorefinery. There are several valorisation pathways for the mineral stream, including feed, agri/horticultural products and industry.

A few examples of platform chemicals that have been derived from European brown seaweed biorefinery research are given below as an indication of what is possible[107 108 109].

- Isomanide - from mannitol, used as an intermediate for conversion into plasticisers, fuel additives, PET (Polyethylene terephthalate) and PUR (polyurethane) replacements, epoxy resins;
- Lactic acid - precursor of polylactic Acid (PLA);
- Succinic acids - precursor for new biopolymers e.g. polyesters, polyamides, and polyesters;
- Levulinic acid - from laminarin, commonly derived from cellulosic material, can be converted into diphenolic acid, a component in lubricants, adhesives, and paints;
- Acetone, butanol, ethanol from fermentation of mannitol and glucose (from laminarin) for use as chemicals or energy carriers;
- 2,5-Furandicarboxylic acid (FDCA) – from alginate, precursor for new biopolymers;
- Pyruvic acid – derived from glucose, used in cosmetics and health & wellness products;
- Carboxylic fatty acids (palmitic and palmitoleic acid) – potential use in health & wellness products.

Reports on the value of seaweed derived platform chemicals are highly variable and range from €100s to €1000s per tonne, presumably this is dependant on purity/grade and end application but there is little consensus in the literature.

107 https://publications.tno.nl/publication/34630537/E4Sl57/l13064.pdf
108 http://www.ieatask33.org/download.php?file=files/file/2015/Ponferrada/WS/Biorefinery_Sandquist.pdf
109 http://marineagronomy.org/sites/default/files/ECN%20Seaweed%20Biorefinery.pdf

2.4.2. Energy carriers/biofuels

There are several routes to producing biofuels from seaweed biomass depending on the nature of the feedstock. For dry biomass, direct combustion, pyrolysis and gasification can be used. (Fig. 3.3 in following section). For the lipid-rich microalgae, trans-esterification to biodiesel is common. For wet biomass, hydrothermal, fermentation and anaerobic digestion can be used. The various end products are solid, liquid and gaseous fuels (Fig. 3.3). There are technical pros and cons to each (comprehensively detailed in Milledge et al (2014)[110] and Khoo et al (2019)[123] but use of wet biomass as the feedstock is the most likely way forward, being more economical. There are also potential economic, social and environmental factors (detailed in Gegg & Wells (2017)[111]).

Liquid bioethanol and biodiesels derived from seaweeds are the most likely way forward as replacements/additives for petrol and diesel. The liquid biofuel sector is the fastest growing due to global incentives to find new fuels and to demand, these fuels represent ≈ 3% of the global bioenergy sector and ≈ 0.3% of global energy demands. A number of EU and regionally funded projects have investigated the potential of different feedstocks, predominantly *Saccharina latissima*, and demonstrated small scale (few-10's of tonnes) production of biomass. These include the SeaGas project[112], the MacroBioCrude consortium[113] and the MACROFUELS project (Box 2.5).

Box 2.5. MACROFUELS PROJECT - https://www.macrofuels.eu/

The MacroFuels project aims to produce advanced biofuels from seaweed including ethanol, butanol, furanics and biogas for use in the heavy transport sector as well as potentially for the aviation sector. MacroFuels will develop the necessary technology for the production of fuels and improve cultivation and storage techniques for the sustainable, year-round supply of biomass. Biomass will be hydrolysed to fermentable sugars using existing and novel enzymes. The project is due to finish in December 2019, thus final project outputs and conclusions are due.

2.4.3. Novel materials/bioplastics

The polysaccharides in seaweed (reds, greens and browns) are of interest for the development of bioplastics. The inherent hydrocolloid properties of some are important (e.g. film forming properties of alginates and agars). Seaweed polysaccharides can also be hydrolysed and converted for the production of chemical building blocks as outlined in 2.4.1 above (Fig. 3.3 next section). Bioplastics derived from seaweed have received a lot of media attention in last few years with several new products from red and brown seaweeds entering the market. Evoware[114] from Indonesia is edible and biodegradable. It is a carrageenan-based product but made from cultivated whole seaweeds and not extracted carrageenan. Ooho[115] developed by Skipping Rocks is an edible, clear product that can be used to form bubbles and pockets of liquid. Ooho is cheaper to produce than conventional plastics and is biodegradable in 4-6 weeks. Bioplastic bottles made from sodium alginate and calcium chloride are reported to be being manufactured for €0.01[116]. Algopack in Brittany[117] have been producing a range of algal plastics for several years and these plastics have wide use. Oceanium, Scotland[118] have also developed a clear, alginate based bio-packaging, but it is not in the market as yet.

The SEABIOPLAS project, which had Irish participation (Bantry Marine Research Station)[119], investigated the use of cultivated *Gracilaria vermiculophylla*, *Ulva spp* and *Alaria esculenta* as sources of agar, ulvan and alginate, respectively and fermented seaweed as a feedstock for lactic acid production (Box 2.6).

110 https://www.researchgate.net/publication/267922412_Macroalgae-Derived_Biofuel_A_Review_of_Methods_of_Energy_Extraction_from_Seaweed_Biomass
111 https://eprints.whiterose.ac.uk/119669/1/JMSE%20FINAL%202017.pdf
112 www.seagas.co.uk
113 http://community.dur.ac.uk/p.w.dyer/page2/styled-2/index.html
114 https://www.newplasticseconomy.org/innovation-prize/winners/evoware
115 https://www.notpla.com/
116 https://jonaa.org/content/2018/01/19/algaibioplastics
117 http://algopack.com/algopackgb.php
118 https://www.oceanium.co.uk/
119 https://www.bmrs.ie/bmrs-projects/past/seabioplas

Box 2.6. SEABIOPLAS PROJECT - https://www.bmrs.ie/bmrs-projects/past/seabioplas

The aim of the SEABIOPLAS project was to introduce sustainably cultivated seaweeds as a feedstock for biodegradable bioplastics and to investigate the suitability of seaweed as a basis for fish and cattle feed. The project was successful in developing customised cultivation of seaweed biomass for plastics production and a process to use seaweed as a novel base for bioplastics. Processing residues were positively evaluated as additives for use in fish and cattle feeds.

The global market for bioplastics is currently in the region of 7.8 billion tonnes, with an estimated value of US$34.23 Billion[56]. The limiting factors for algal plastics in the short term are: (i) manufacturing capacity; (ii) algal biomass supply and (iii) optimisation. With some current technologies there is still a trade-off between biodegradability and durability which has obvious implications for transport, storage and shelf life and sensory properties.

Seaweed derived sugars can be converted into a range of chemicals

3 OVERVIEW OF EXISTING BIOREFINERY CONCEPTS

Wild Saccharina latissima

This section provides an overview of relevant European projects (current/recent past) that have focussed on the development of seaweed value chains and valorisation of seaweed biomass through a biorefinery approach.

Overview of existing biorefinery concepts

Creating value and new commercial enterprise from marine algal resources has been a been a key thematic focus for Irish national and European funded research in recent years. This reflects the wider ambition to valorise aquatic biomass (still considered to be underutilised) for sustainable development within the National and EU bio economy and indeed, **building a healthy Blue Economy is recognised as a vital contributor to economic growth in Ireland** and a vehicle for rebuilding and revitalising regional marine economies.

In recent years, there has been significant EU and regional funding allocated to projects that have investigated the use of seaweed as a feedstock for multi-stream processing/biorefinery models for biofuel, food, feed and pharma applications. Table 3.2 below summarises a number of the most recent & relevant projects that take a real value chain approach and/or address viable commercial scale, however, it must be noted that there are many more examples. Note: several key projects have focussed on the utilisation of seaweed biomass for conversion into various biofuels. Whilst some detail is provided in this report, biofuels are an unlikely focus for Ireland unless cultivation moves off-shore and/or increases substantially. Boxes 3.1-3.3 below (and in other sections of this report) provide more detail on selected new projects that are expected to generate significant advances and outcomes for the European seaweed sector.

3.1. Seaweeds used as feedstock

A relatively small number of seaweed species have been investigated but the list includes *Alaria*, *Laminaria* and *Saccharina* (Tab. 3.1). In keeping with the focus on sustainability, most studies are framed around the future use of cultivated biomass (*Alaria, Saccharina, Ulva*) although wild harvested equivalents may have been used for certain aspects of the research. Some studies focus on the use of wild harvested biomass i.e. *Laminaria digitata* (e.g. AORTA), *L. hyperborea & Ascophyllum nodosum* (e.g. SBP-N) and *Fucus spp.* (e.g. FUCOSAN) where commercial harvesting of wild stocks is in existence and/or species are yet to be cultivated successfully (Tab. 3.2). Most studies focus on the utilisation of brown seaweed biomass although the need to diversify feedstocks is recognised and red and green species are considered. However, only a few species of green and red seaweeds have been investigated to date including *Palmaria palmata, Gracilaria vermiculophylla* and *species of* Ulva.

A number of studies have focussed on seaweeds plus other potential feedstocks including microalgae, fish and marine invertebrates (e.g. AQUAVITAE, VALGORIZE). The SEABEST project is the only one that directly mentions the use of organically grown seaweed biomass to target organic markets although the general emphasis of all projects is on the use of "natural", "sustainable" and "high quality" algal biomass. More detail on key projects is provided in Table 3.2.

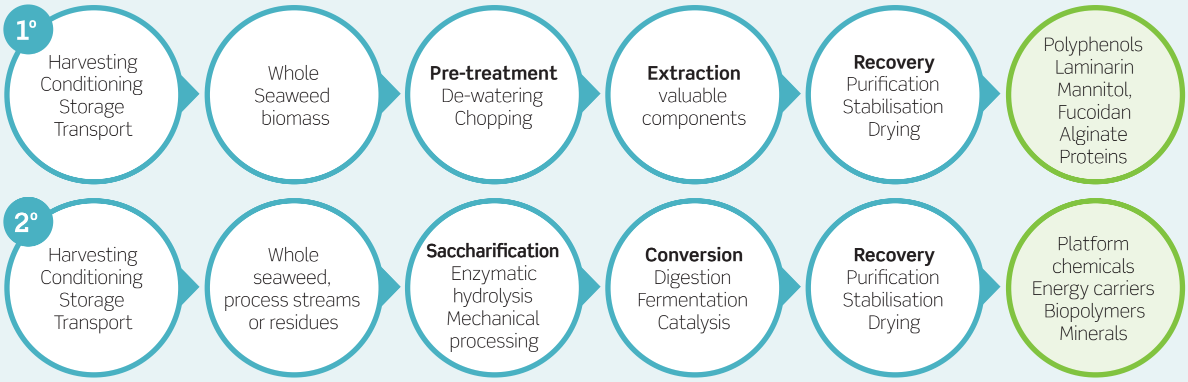
Table 3.1. Main seaweed species investigated as potential biorefinery feedstock

Species	Cultivated	Wild Harvest
Alaria esculenta	✔	
Fucus spp.		✔
Gracilaria vermiculophylla	✔	
Laminaria digitata		✔
Laminaria hyperborea		✔
Palmaria palmata	✔	
Saccharina latissima	✔	
Ulva spp.	✔	

3.2. Biorefinery concepts

As briefly mentioned in Section 2.4 above, two general approaches to the biorefinery of seaweeds are taken: (i) **cascading extractive biorefinery** to valorise valuable components such as polyphenols, fucoidan etc. (detailed in section 1.1.) and (ii) **energy and/or materials driven biorefinery** to essentially extract and convert sugars (or proteins and lipids) to typically lower value chemical intermediates for biofuels, bioplastics and new biopolymers. The two approaches may be operated in isolation or in combination depending on feedstock, processing capability and end product requirements. Note however that the energy and/or materials driven biorefinery approach typically targets high volume, low value bulk chemicals and biofuels and has to operate at large scale to be viable, although valorisation of high-value components is a feature. Figure 3.1 shows a schematic of the two concepts and details key steps in the process flow. Each step will be further discussed in the following text.

Figure 3.1. Schematic process flow for a seaweed biorefinery showing key steps



Note: top row depicts a cascading extractive biorefinery model for the recovery of valuable components, bottom row depicts an energy/materials driven biorefinery approach for lower value platform chemicals.

The primary emphasis of all current concepts is to utilise a cascading approach and technology that will result in clean, green, cost effective and resource efficient processing, based on total utilisation of the seaweed biomass and with towards zero waste streams. The AORTA technology from Alginor, Norway (Box 3.1) goes as far as to aim for zero emissions to air and sea[120].

Harvesting, conditioning, storage & transport

This report does not focus on the technical aspects of seaweed cultivation, nevertheless, any cost efficient biorefinery will be dependent on upstream factors that influence the feedstock supply chain. Considerable R&D effort has been invested in building the knowledge and technology platform for more robust and efficient cultivation of European species. The GENIALG project (Box 3.2.) is an example of an EU funded project with a particular emphasis on this.

Although seaweed biorefineries have been designed for use with dried biomass, the use of fresh material is preferable. From a cost perspective i.e. less energy consumptive drying steps and from a quality perspective as processing from fresh limits the degradation of unstable bioactive components e.g. polyphenols. However, transport of fresh biomass is logistically difficult, expensive and can have quality implications. Unless the biorefinery is located close to the seaweed production areas (ideal scenario) biomass typically has to be processed to stabilise it for subsequent transport and/or storage. Drying and freezing may be viable options if infrastructure is already in place e.g. existing seafood processing facilities or access to excess waste energy streams but the general preference (currently) is to ensile the biomass.

120 The Alginor website - (https://alginor.no/company/#aorta-technology)

Box 3.1. Alginor ASA, Norway AORTA technology (https://alginor.no/company/#aorta-technology)

Alginor are developing a portfolio of **ultra-pure, formulation specific life science ingredients** from wild harvested ***Laminaria hyperborea***, for application in key markets - Pharma & API, Health & Nutrition, Food, Biomaterials, Feed, Agro and Chemical industries. The initial focus will be on food-, health- and nutrition industries. The proposed product portfolio is: alginate, fucoidan, cellulose, mannitol, laminarin, polyphenols, bioactives, amino acids, savoury (flavour), minerals, bark and Borea powder.

The AORTA concept is branded as **green and innovative** and aims to: facilitate new value chains, meet customer demands, evolve into a zero-waste system that **uses 100% of the seaweed biomass** with environmentally harmful emissions. Alginor is an SME and this research is being funded under H2020 SME Instrument Phase II funding. The current project follows on from similar Phase I funding. The project is due to end in February 2020. This research will deliver the technology platform for a commercially focussed biorefinery for *Laminaria hyperborea* and thus, future developments are worth tracking.

Ensiling typically involves preserving the biomass under low pH conditions, around 4, using biological or chemical methods[121]. The approach has been successful but note that development of ensiling practices is generally on a case-by-case basis with different feedstocks requiring different conditions. Also ensiling may alter the composition of the feedstock, particularly with biological ensiling as the microorganisms used require a food source e.g. mannitol and laminarin.

The seasonal nature of the seaweed supply is critical to the success of any biorefinery and thus storage options need to be thought through if processing is to occur outside of the window of supply. The supply of cultivated biomass, in particular, is generally limited by seasonal growth although some farmers have the capacity to grow year-round. The seasonal variability in biomass composition is well documented and is a key focus in most R&D projects. **An understanding of the variability in biomass composition and supply must form the basis of any biorefinery concept** as both factors will have a direct influence on the type and nature of processing that is carried out, potential volumes and importantly cost.

Box 3.2. The GENIALG project (https://genialgproject.eu/)

GENIALG has a strong emphasis on cultivation and biomass supply for seaweed biorefinery but also aims to develop and demonstrate a technical pathway for the total valorisation of ***Saccharina latissima*** and ***Ulva sp.*** biomass. Using **new environmentally benign processes for extraction and processing (enzymes and environmentally sustainable chemicals and solvents).** Scaled up demonstration of the integrated process is planned and market & LCA studies will be conducted.

The project claims to be the first industry driven, European consortium that brings together pioneering companies and research partners to address the issue of large-scale integrated European biorefineries. The project started in January 2017 and will finish in December 2020. Regular progress updates are published on the project website.

Pre-treatment

It is likely that the feedstock biomass will require some pre-treatment prior to refining (primary and secondary refining). For cultivated biomass, removal of extraneous matter is not such an issue but for wild harvested biomass sand, rocks, shells and marine organisms may need to be removed. A washing step may or may not be sufficient. The presence of extraneous matter will affect various quality parameters and can also damage equipment. Chopping or grinding to a given particle size is typical. Particle size is important parameter that will affect extraction efficiency but also has implications for physical processing in that long fronds, for example, can get tangled in stirrers or clog outlet valves etc. The various extraction steps in a biorefinery should have been optimised for all reaction conditions including particle size however, in any cascading approach a compromise is likely as the conditions set for each process will also have to be suitable for any subsequent steps.

121 http://www.algecenterdanmark.dk/media/16447/s_ren_ugilt.pdf

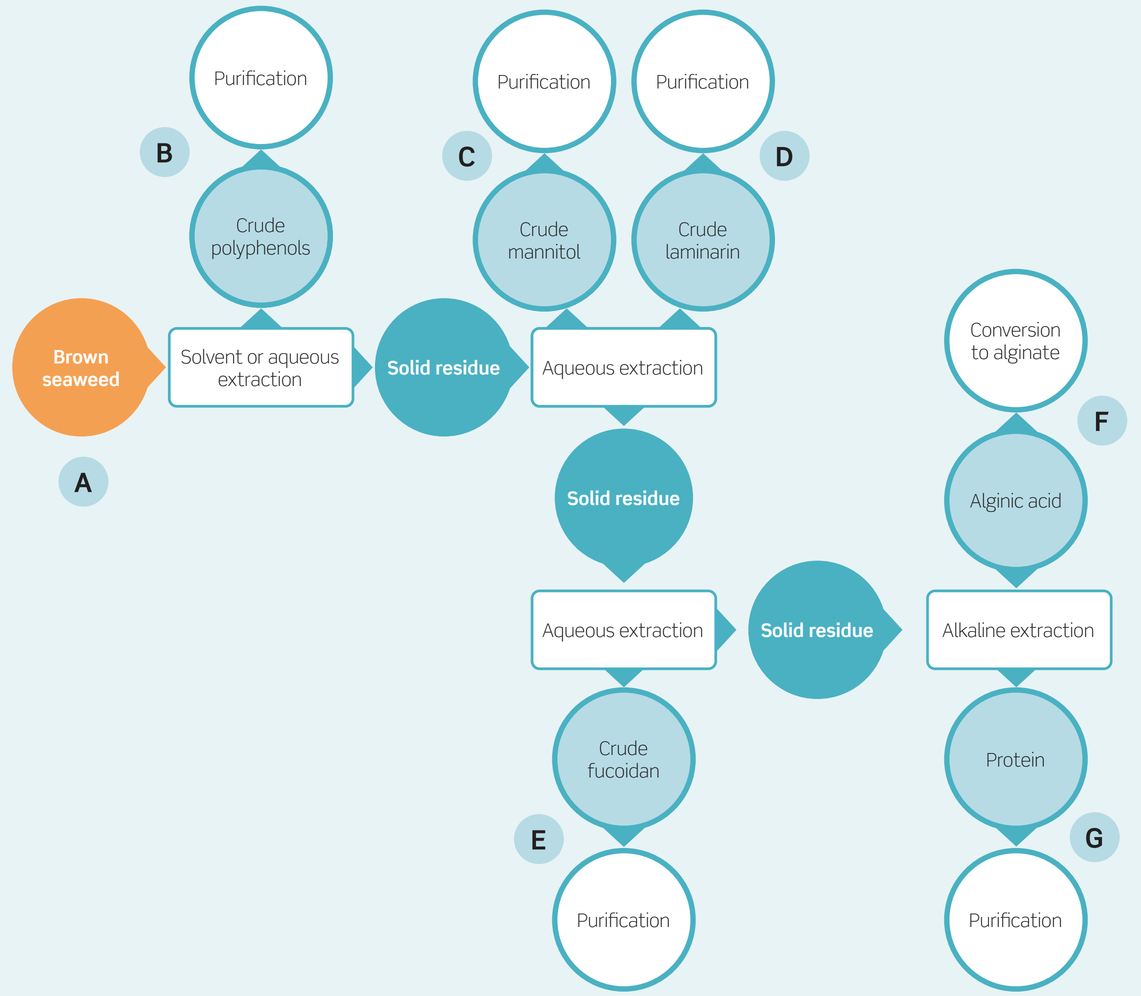
Some biorefineries utilise a de-watering step or a primary fractionation step that separates a crude liquid and a crude solid fraction. Fresh biomass can comprise upwards of 80% water which can be mechanically removed. Commonly equipment such a spiral filter press is used. This step can also be carried out prior to ensiling.

Cascading extractive technologies tend towards the use of less harsh physical and aqueous extraction methods but sometimes pre-treatment is needed to open up the seaweed matrix. This allows for better extraction of bound components such as proteins and polyphenols. Enzyme assisted extraction is commonly used but also technologies such as microwave and pulsed electric field. Note use of approved enzymes is typical where short term exploitation is required whereas use of novel, often marine derived equivalents is explored for longer term potential (pending approval of any new enzymes).

Extraction

Figure 3.2. below gives a very **general schematic of a cascading extractive biorefinery for brown seaweed biomass** that is based on the sequential extraction of key components using aqueous extraction techniques. Note that the processes used, and general process flow will vary, depending on feedstock and target product streams. At any step, further processing can be applied or be substituted in, to break down the seaweed matrix and/or improve target product yield (e.g. use of enzymes and or green extraction technologies such as microwave, super critical extraction). Note: a number of other potential product streams are not depicted in Figure 3.2, these include minerals, vitamins, pigments and the break-down products of key components such as oligosaccharides, peptides and amino acids. Detail on these has been provided in various sections above.

Figure 3.2. Schematic of a generic cascading extractive biorefinery for brown seaweed biomass showing major processing steps and product streams



Step	Detail
A	Brown seaweed biomass as feedstock: dry, fresh and ensiled material used. Physical (dewatering, grinding, maceration) and enzymatic pre-processing might be applied.
B	Polyphenols can be extracted using aqueous solvents but better yields achieved if organic solvents used. Aqueous solvents can also remove other components (minerals, mannitol, fucoidan, laminarin) and thus crude extracts would need fractionation and/or purification. Additional physical and enzymatic processing to break up the seaweed matrix can improve yields.
C	Mannitol is typically extracted using water at defined temperature and pH, other water soluble compounds can also be co-extracted and crude extracts would need fractionation and/or purification.
D	Laminarin is present in soluble and insoluble forms and is extracted using water at defined temperature and pH, other water soluble compounds can also be co-extracted and crude extracts would need fractionation and/or purification.
E	Fucoidan is also water soluble and is typically extracted under mild acid pH and at ambient or slightly elevated temperatures. Extracts are usually fractionation by molecular weight.
F	The alginate component in the form of alginic acid will remain mostly insoluble, especially if acidic conditions are maintained. It can be extracted using an alkaline process, precipitated and converted to a range of alginate salts depending on end use requirements
G	Proteins are typically extracted under acidic or alkaline aqueous conditions. Some protein may be co-extracted with other components but is typically bound up in the carbohydrate matrix and requires use of physical and/or enzymatic treatments to disrupt cells and free up the protein. Use of ultrasound, microwave and pulsed electric field can be used to improve yields.

Hydrolysis & saccharification

The primary step in any energy and/or materials driven biorefinery process is generally to break up the seaweed matrix, essentially the structural and storage carbohydrates, so that the target sugar components can be released and isolated for subsequent conversion. The feedstock for this step can be whole seaweed or the process streams and residues from preceding steps in the cascade of extractions (Fig. 3.3). Chemical (normally acidic), thermal (super critical solvents, high temperature liquefaction) and enzymatic methods are typically used to hydrolyse the carbohydrates. These methods might be used in combination to achieve optimum release of sugars. Viscosity can be an issue with some of the marine polysaccharides, alginate in particular can be difficult to work with. This is an area where the use of novel enzymes, from marine resources, has been investigated. Commercially available enzymes are used but tend to lack specificity for the seaweed derived carbohydrates. Novel alginases, in particular, have been a key focus area. Note that use of novel/non-approved enzymes is regulated and could limit end use of any resultant new products e.g. use of novel enzymes for the production of new food ingredients would not be allowed. Note: direct bio-conversion (no separate saccharification step) is possible. Microorganisms that directly utilise the mannitol, laminarin/glucose and alginate from the un-hydrolysed biomass can be used to produce ethanol[122].

122 https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-016-0494-1

Box 3.3. The MACROCASCADE project – (https://www.macrocascade.eu/)

MACROCASCADE has a heavy emphasis on the use of microbial refining and enzyme assisted extraction technology for high value product streams. Physical and chemical extraction approaches are also being explored. The project covers the entire biorefinery platform from cultivation to end products but specifically aims to develop economically feasible processes for producing food and feed ingredients via microbial refining from cultivated and conditioned seaweed biomass (***Saccharina latissima*** and ***Palmaria palmata***).

The MACROCASCADE consortium comprises 13 partners, a mix of SMEs, large industry and research centres. The consortium includes seaweed cultivators, fermentation and enzyme specialists in addition to research centres with a track record of research in this area. The project is funded by Horizon 2020 Bio-Based Industries Joint Undertaking. It started in October 2016 and is due to finish in September 2020.

Conversion

Once released, the sugars can be converted to energy carriers and chemical building blocks/intermediates. Different conversion processes are used[123]. Biological conversion processes include fermentation and anaerobic digestion (AD) pathways that utilise microorganisms to convert the sugars. For biofuel production, fermentation and AD typically result in bioethanol and biogas production, respectively. Chemical conversion pathways are also used. Significant efforts have been focused on finding appropriate microbial strains (often of marine origin) for use with fermentation systems as strains typically used with terrestrial biomass are not always efficient.

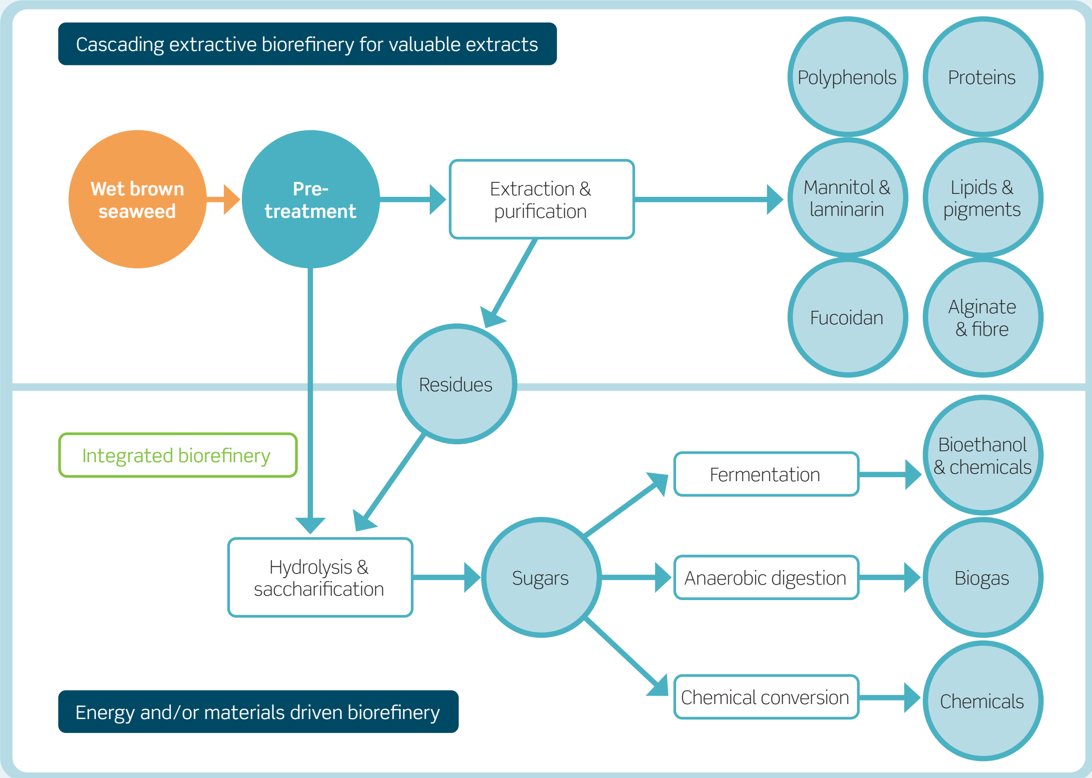
Microbial fermentation – various microorganisms (yeasts and bacteria) have been shown to utilise seaweed derived sugars to produce ethanol. Some sugars are utilised more efficiently than others and hence different feedstocks will be variably suited to fermentation as a process to produce biofuels[110]. Microbial fermentation can be used to convert sugars into various building blocks or intermediates for the production of chemicals e.g. lactic acid for production of PLA (more examples given in 2.4.1 above). These compounds can be recovered from the fermentation broth and purified or are further converted.

Fermentation is generally carried out under oxygen limiting conditions as this triggers the microorganisms to switch to a different metabolic pathway and thus generate the target components for the biorefinery. However, an anaerobic fermentation pathway, known as **ABE fermentation** (Acetone, Butanol and Ethanol) can be used to ferment seaweeds. A wide range of sugars can be utilised although mannitol and laminarin (glucose) are more readily utilised[110] Fermentation of alginate has proven more difficult, but research has focused on finding appropriate strains of microorganisms and on optimising the fermentation process. For several reasons, fermentation of seaweed to produce butanol, rather than ethanol, is considered a more efficient scenario[110].

Fermentation using microalgae as a feedstock occurs at commercial level, Khoo et al (2019) give a comprehensive overview[123] but there is still a sizeable knowledge gap for the optimisation and upscale of macroalgal systems. A case-by-case approach needs to be taken for different feedstocks as variations in target components e.g. mannitol/glucose can have a significant impact on fermentation efficiency. The SEABIOPLAS project (Box 2.6) showed that the cultivation of feedstock biomass could be manipulated to produce biomass that was rich-in certain sugars to improve fermentation and to overcome seasonal variability in feedstock composition. Research has also shown that a trade-off can exist between various pre-treatment and conversion methods, with pros and cons associated with each[110,123]. Despite the knowledge gaps, the real commercial potential of utilising fermentation in a biorefinery approach is recognised.

123 Khoo et al (2019). Algae biorefinery: Review on a broad spectrum of downstream processes and products. Bioresource Technology 292 (2019) 121964

Figure 3.3. Schematic of a generic biorefinery showing potential for integrated approach



Note: this figure depicts a simplified biorefinery concept and shows how various processing approaches can be integrated. In taking an integrated approach, biomass valorisation can be maximised.

Anaerobic digestion is also used for biofuel production[110]. The main differences between fermentation and AD are (i) AD is carried out under strictly anaerobic conditions and (ii) multiple microorganisms are typically used in the process. The main products from AD are biomethane and biohydrogen and a solid-liquid digestate.

Chemical conversion processes such as transesterification, polymerisation, dehydration, oxidation and solvent extraction (organic and supercritical fluids) have been used to convert the sugar and lipid fraction of seaweeds into valuable end products. Transesterification of fatty acids and triacylglycerols is typically used to produce biodiesel (bio-oil) from algae. Catalysts may or may not be required for chemical conversion. Acids (e.g. HCl and H_2SO_4), alkalis (e.g. NaOH and KOH) and other inorganic catalysts can be used[120].

Post extraction considerations

After any extraction or conversion step there will be a requirement to clean up, purify or recover key components. The target requirement may be for a "pure", "co-extract" or "active-rich" product. Salts and processing aids may need to be removed as a minimum requirement. Fractionation by molecular weight may also be required to concentrate certain active components.

Note: that all processes used to manufacture the product/ingredient will fall under the appropriate regulation for the intended end market. In the case of food, all processes including the use of enzymes need to be approved and if processing gives rise to significant changes in the composition or structure of the food ingredient (so as to affect nutritional value, metabolism or level of undesirable substances) then the end product will most likely fall into Novel Foods territory.

Note also that processing may act to concentrate certain components such as minerals, heavy metals, pollutants and allergens. Iodine levels are of particular relevance to kelp species. Although the current European regulation for allowable thresholds for these components is not comprehensive, legislation is in place for certain components in food, supplements, feed and cosmetics. Holdt & Kraan (2011)[72] and Barbier et al (2019)[27] provide comprehensive detail on this and the reader is directed to both.

The Technical Commission CEN/TC 454 Algae and Algae Products[124] has been set up to address the issue of standardisation for algal based products and will issue recommendations to the European Commission (EFSA) for drafting new standards in the next 3 to 4 years[27]. Information from the CEN/TC 454 working group will allow for the provision of harmonised methodology, standards and legislation for the use of seaweed ingredients in food and feed.

Stabilisation of any end product will need to be addressed. It is likely that most end products will take a dry form although liquid extracts are common in certain sectors e.g. horticultural products. The use of preservatives and/or sterilisation/pasteurisation steps will need to be considered. Choice of drying method can be critical from a technical and cost perspective. There will probably be a requirement to remove a high percentage of water from any extract/product stream which has cost implications. Where active components are present, low temperature drying may be needed. Viscosity and hygroscopicity of extracts can be an issue and both will impact on ability the to dry and store certain products. Microbial stability during and post processing will need to be monitored and shelf life determined for any new products.

Standardisation of product specification is a key factor and one that has substantial implications for end use and potential markets. Natural products are notoriously difficult to standardise (especially for year-round production) given the significant levels of natural and seasonal variability in biomass and target components. A thorough understanding of feedstock variability is required.

3.3. Example of a commercial seaweed biorefinery

The Arkhangelsk Experimental Seaweed Factory in Arctic Russia[125] was established in 1918 to extract iodine from locally harvested kelps. Iodine was in demand during World War I as a disinfectant in hospitals. Today the factory produces a wide range of products and is probably the only example of a commercial seaweed biorefinery outside of Southeast Asia.

The factory utilises locally harvested brown seaweeds from the White Sea (*Laminaria digitata, Saccharina latissima* and *Ascophyllum nodosum*). The bulk of processing utilises hand harvested biomass which is air/sun dried when necessary. Mannitol is extracted for use in the pharma sector. This presumably leaves a significant residue which is further processed to obtain a range of extracts for use in health supplements and cosmetics. Some alginate production also occurs, the alginate is sold into the food industry and alginate wound dressings are manufactured on site and sold locally. A fertiliser product is made from the filter press cake. The full cosmetic range and the fertiliser product are sold in a small chain of shops in Russia.

It is easy to envisage a simple cascading, extractive approach scenario in which all of the biomass is utilised. The factory is a great example of how a biorefinery approach can be utilised to create value from local resources.

124 https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:2278882&cs=1F20FCBCD6123B309AAB0F52C8CDEF169
125 https://russianseaweed.com/en/seaweed/

Table 3.2. Relevant European projects that have addressed the seaweed biorefinery concept

AORTA (09/2018-02/2020) - https://alginor.no/company/#aorta-technology		
Aim: to take a combined harvesting and processing approach AORTA (Alginor's Ocean Refining Total utilising Application) for clean, green, cost effective and resource efficient bio-marine processing and to transform the existing seaweed value chain.	**Species focus:** *Laminaria digitata* (wild harvest)	**Planned outputs:** 100% biomass utilisation; a product portfolio of 12 products including bioactives; green processing with no emissions.
AQUAVITAE (06/2019-05/2023) - https://cordis.europa.eu/project/rcn/223644/factsheet/en		
Aim: to increase aquaculture production (incl. macroalgae) in and around the Atlantic Ocean in a sustainable way; developing new and emerging low trophic species and optimising production in existing aquaculture value chains.	**Species focus:** Unstated as yet, new project (cultivated)	**Planned outputs:** new processes and products based on a cascading product stream/circular economy/zero waste approach with improved sustainability.
BIOSEA (06/2017-05/2020) - http://biosea-project.eu/		
Aim: development and validation of innovative, competitive and cost-effective upstream and downstream processes for microalgae and macroalgae to produce high value actives at low (up to 55% less than with current processes) for use in food, feed & cosmetic/personal care products.	**Species focus:** *Ulva ohnoi, Saccharina latissima* (cultivated)	**Outputs:** cascading biorefinery approach for seaweeds defined; extracts being characterised; initial formulations developed for food and feed applications.
BLUE & GREEN (01/2016-03/2019) - https://cordis.europa.eu/project/rcn/199596/reporting/en		
Aim: to strengthen the performance of CIIMAR (Interdisciplinary Centre of Marine and Environmental Research), Portugal in the emergent area of marine biotechnology i.e. boosting scientific excellence and innovation capacity in biorefineries based on marine resources for Portugal.	**Species focus:** not stated	**Outputs:** roadmap for blue economy in Portugal, strengthened capacity to build value chains.
BLUE IODINE II (08/2016-12/2018) - https://cordis.europa.eu/project/rcn/205022/factsheet/en		
Aim: to develop protein and mineral rich seaweed extracts for tackling iodine deficiency in target groups (children, pregnant and breastfeeding women and older people) using land-based seawater cultivation and a biorefinery approach.	**Species focus:** not stated	**Outputs:** (i) biorefinery process using cold press extraction and filtration to obtain purified extracts; (ii) new cost-effective seaweed iodine products (iii) clinical trials of IODOBEM product underway.
FUCOSAN (03/2017-02/2020) – www.fucosan.eu		
Aims: to develop a platform for economic & ecologically sustainable harvesting practices and fucoidan extraction technology for Baltic Sea seaweeds and to establish a Danish-German value chain.	**Species focus:** Baltic brown seaweeds, presumably species of *Fucus* (wild harvest)	**Outputs:** (i) database of fucoidan characteristics; (ii) pilot applications of fucoidan extracts in the fields of ophthalmology (age-related macular degeneration), regenerative medicine (tissue engineering) and cosmetics; (iii) business models for use in a sustainable value-added chain.

Table 3.2. Relevant European projects that have addressed the seaweed biorefinery concept

GENIALG (01/2017-12/2020) - https://genialgproject.eu/		
Aim: to boost the European Blue Economy through high-yielding seaweed cultivation systems.	**Species focus:** *Saccharina latissima, Ulva rigida* (cultivated)	**Outputs:** two pilot pre-industrial seaweed biorefinery plants to provide seaweed compounds for cosmetics, pharmaceuticals, food and feed ingredients, fine and specialty chemicals, additives and blends such as gels, as well as precursors for biodegradable plastics.
MAB3 (03/2012-02/2016) - https://energiforskning.dk/en/projects/detail?program=All&teknologi=All&field_bevillingsaar_value=&start=&slut=&field_status_value=All&keyword=MAB3&page=0		
Aims: to develop an integrated biorefinery concept for conversion of brown macroalgae into energy carriers (ethanol, butanol and methane), and a protein and lipid enriched fish feed derived from residual biomass.	**Species focus:** *Saccharina latissima, Laminaria digitata*	**Outputs:** developed and demonstrated an integrated biorefinery process for biofuel and feed production.
MAB4 (05/2016-04/2020) - https://mab4.org/		
Aim: improved cultivation of brown seaweeds as feedstocks for biorefinery production of valuable components for use in feed, food and cosmetics.	**Species focus:** *Saccharina latissima* (cultivated) and others	**Outputs:** (i) extracted antioxidants, alginate, fucoidan, laminarin. Protein & minerals, (ii) refined ingredients for cosmetics, food and feed, (iii) formulated products; (iv) feed trials.
MACROCASCADE (10/2016-09/2020) - https://www.macrocascade.eu/		
Aim: to prove the concept of the cascading marine macroalgal biorefinery as a production platform that covers the whole technological chain for processing sustainable cultivated macroalgae biomass to highly processed value-added products.	**Species focus:** *Saccharina latissima, Palmaria. palmata* (cultivated)	**Outputs:** cascading product streams of (i) biomass; (ii) protein components for pre & probiotic feeds and human health; (iii) alginate, fucoidan, mannitol and protein for biomedical and feed; (iv) laminarin and alginate oligosaccharides for feed and food application; (v) residues to be evaluated for potential fuel and feed application.
MACROFUELS (01/2016-12/2019) - https://www.macrofuels.eu/		
Aim: to produce advanced biofuels from seaweed using a biorefinery approach. Research is focussing on the cultivation, storage and conversion seaweed biomass into fuel (ethanol, butanol, furanics and biogas) and on the techno-economic, sustainability and risk assessment of the entire seaweed to biofuel chain.	**Species focus:** cultivated red, green and brown species	**Outputs:** yet to be reported but side streams are being evaluated as sources of high value components. Specifically, proteins for use in animal feed and minerals for use in fertilisers.
NEPTUNA (02/2016-01/2018)- http://www.marinebiotech.eu/sites/marinebiotech.eu/files/public/2-15%20NEPTUNA.pdf		
Aims: to develop novel enzymatic extraction methods for multiple high value compound extraction from algal resources with a particular focus on antimicrobial and antioxidant activity.	**Species focus:** not defined	**Outputs:** knowledge platform for identification and characterisation of compounds with antioxidant and antimicrobial activity, novel extraction methodology and applied biorefinery concept; extracts with potential use in food, cosmetics, animal health (aquaculture) and personal/home care.

Table 3.2. Relevant European projects that have addressed the seaweed biorefinery concept

PROMAC (2015-2018) - http://promac.no/about-the-project/, https://prosjektbanken.forskningsradet.no/#/project/NFR/244244/Sprak=en		
Aims: to evaluate different approaches to the production of proteins and health promoting ingredients for human food and animal feed through the sustainable production and processing of macroalgae.	**Species focus:** *Alaria esculenta, Saccharina latissima, Palmaria palmata* (cultivated & wild harvest)	**Outputs:** information platform; feed trials; commercial strategies for the expansion of the Norwegian seaweed industry through integrated primary and secondary processing for multiple product streams.
SBP-N (Norwegian Seaweed Biorefinery Platform) (05/2019-04/2024) - SBP-N - http://seaweedplatform.no/		
Aims: to build a platform for research, knowledge, methods and stakeholders within the development of an economically and environmentally sustainable biorefinery of seaweeds (macroalgae).	**Species focus:** *Saccharina latissima, Alaria esculenta, Palmaria palmata* (cultivated), *Laminaria hyperborea, Ascophyllum nodosum* (wild harvest)	**Planned outputs:** knowledge platform and products – not yet reported, very new project.
SEABEST (03/2019-02/2021) - https://cordis.europa.eu/project/rcn/221036/factsheet/en		
Aim: to be the first to close the circle from seaweed spore to a high-quality organic food product using a large-scale and cost-competitive approach in Europe.	**Species focus:** *Saccharina latissima, Alaria esculenta, Laminaria digitata* (cultivated)	**Planned outputs:** (i) <14,000t of seaweed to be produced <56% less cost compared to current practises; (ii) new markets in bioenergy, biopharmaceuticals and animal nutrition.
SEABIOPLAS (10/2013-09/2015) - https://cordis.europa.eu/project/rcn/110672/brief/en		
Aim: to introduce sustainably cultivated seaweeds as a feedstock for biodegradable bioplastics, contributing to innovation in the bioplastics sector and to investigate the suitability of seaweed as a basis for fish and cattle feed.	**Species focus:** Gracilaria vermiculophylla, Alaria esculenta, Ulva spp. (cultivated)	**Outputs:** (i) customised cultivation of seaweed biomass for plastics production; (ii) a process to use seaweed as a novel base for bioplastics; (iii) demonstrated positive benefits when extracts used in fish and cattle feeds.
SEAREFINERY (11/2015-10/2018) - https://searefinery.eu/		
Aims: to develop and test an innovative, industry led, biorefinery approach for seaweed exploitation in Northern Europe, to produce bioactive molecules for nutraceuticals, functional foods, cosmetics, pharmaceuticals and biobased materials.	**Species focus:** *Saccharina latissima, Alaria esculenta* (cultivated)	**Outputs:** conceptual biorefinery demonstrated at pilot scale (600kg reaction scale); evaluation of bioactive and alginate streams in commercially relevant formulations; economic feasibility assessment produced.
SEAWEED AD (09/2011-08/2013) - https://cordis.europa.eu/project/rcn/99329/factsheet/en		
Aim: to develop and optimise anaerobic digestion (AD) fermentation technologies for the production of methane biofuel from seaweeds and to address the fractionation and characterisation of any value-added components released by the hydrolysis process.	**Species focus:** *Laminaria hyperborea, Ascophyllum nodosum, Fucus serratus* (wild harvest)	**Outputs:** optimised lab-scale process for AD of seaweed.
VALGORIZE (06/2017-05/2020) - https://www.noordzeeboerderij.nl/en/projects/valgorize		
Aims: (i) to stimulate sustainable, controlled cultivation of high quality, safe algal biomass that meets the requirements of the European market; (ii) Optimise the organoleptic qualities of algae to match the European taste pallet and (iii) produce a road map for sustainable, zero waste future use.	**Species focus:** undefined micro and macroalgae (cultivated)	**Outputs:** (i) a demo plant for seaweed (also one for microalgae) based on a feasibility study and market exploration, (ii) an investment roadmap for each algal source describing the investment needed to scale up production from pre-commercial to the commercial stage.

4 AN IRISH BIOREFINERY CONCEPT

Wild Irish Laminaria digitata

In this section, a biorefinery concept for *Alaria esculenta*, *Saccharina latissima* & *Laminaria digitata* is proposed and recommendations for next steps given.

4.1. A potential Irish biorefinery

The primary factors that have been considered when conceptualising a seaweed biorefinery for Ireland are centred around:

- Biomass supply chain
- Identifying the right processing approach
- Identifying marketable product streams

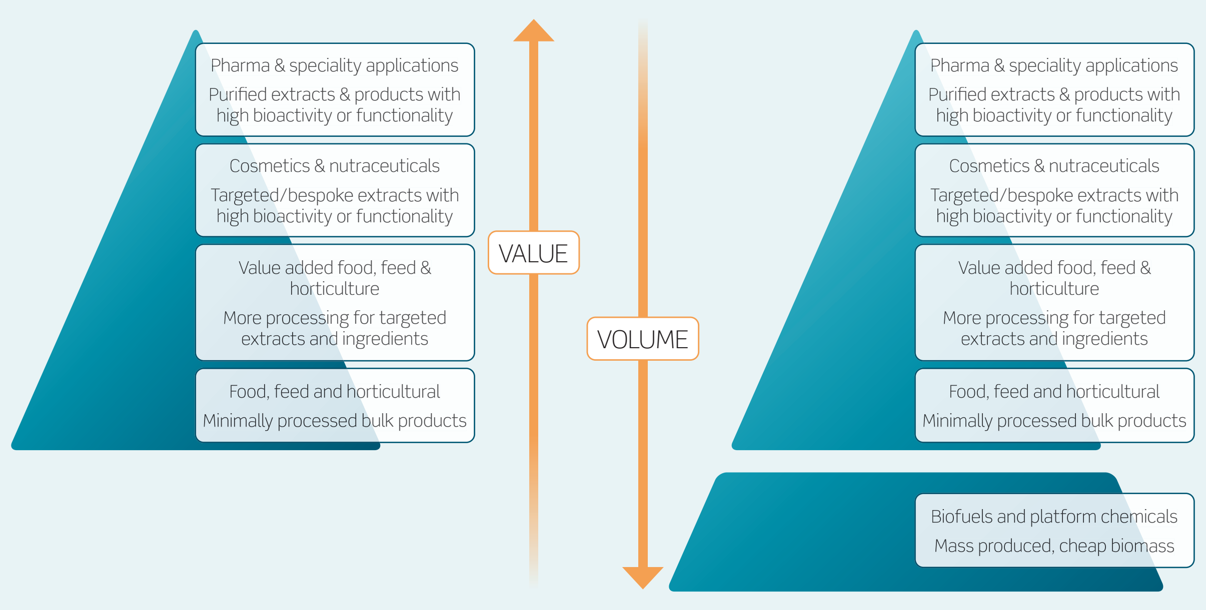
4.1.1. Biomass supply chain

There are many factors relating to the cultivation of seaweed biomass that are outside the scope of this report. The following discussion relates more to the actual supply of biomass as a feedstock for any processing activity. The Irish seaweed industry is currently producing around 40 wet tonnes of cultivated seaweeds (primarily *Laminaria digitata*, *Alaria esculenta* and *Saccharina latissima*). Cultivation of these species is predicted to rise in the next 5 years as recently licensed operations (2018/19) come online. If all licenses that are granted become fully operational then Ireland will have the capacity to produce < 900 tonnes of cultivated biomass (BIM data and estimates). In dry weight equivalents the current and future tonnage is roughly ≈ 8 tonnes and ≈ 180 tonnes, respectively. **Both of which may be considered small scale**.

The supply chain for a potential Irish biorefinery is likely to (initially) comprise many smaller operators feeding tens of tonnes of mixed cultivated biomass into one or two (?) small central processing units. With the potential to supply hundreds of tonnes (< 900) within the next 5 years and presumably with the potential to supplement with wild harvested biomass. Biomass supply will be on a seasonal basis unless year-round or extended cropping is possible (as is currently happening in Northern Ireland and the Faroe Islands).

Seasonal production at this scale imposes a number of limitations on the type and level of biorefining that can be sensibly (i.e. cost effectively) operated and, **in the short term, Ireland will be restricted to focussing on a cascading, extractive biorefinery model for niche markets and with maximised biomass valorisation**. This is evident when put into context with the wider European situation, where cultivation is moving off-shore. The multi-use farms that are being proposed for the Dutch and Belgian North Sea zone will occupy 100s of km^2 in area and are estimated to produce 10s of millions of wet tonnes of seaweed per annum (Section 1.2.2). The aim of these farms is to bulk supply cheap biomass for energy and materials driven biorefining but also to supply food markets and high-value sectors with targeted products. Figure 4.1. illustrates a typical value pyramid for the seaweed industry at present, with bulk, lower value products at the base of the pyramid – moving towards higher value, lower volume products at the top. Figure 4.1 also illustrates how the value pyramid will change when future, mass cultivation will allow for the production of biofuels and platform chemicals. This may open opportunities for Irish farmers as different European seaweed markets grow and develop however, such large scale production will substantially drive down the price of cultivated seaweeds (as is the aim). This will undoubtedly close certain markets for Irish grown seaweed if the Irish cultivation sector remains relatively small and expensive.

Figure 4.1. The seaweed value pyramid. Left: current European situation. Right: future situation when large-scale multi-use farms are operational (5-10 years?).



The following issues regarding the Irish biomass supply chain will need to be addressed before any biorefinery concept is implemented:

- what will be the tonnage of each key species and when will this biomass be available?
- is year-round cultivation an option for some species/growers?
- how variable are the key components in each species on a seasonal and locational basis?
- is there a preferential window for harvest to obtain maximum content of key components e.g. laminarin?
- Is wild harvest of some species an option to extend cropping season and/or increase volumes?
- growers will have to collaborate to maximise opportunities and benefits, what form will this collaboration take?
- what will be the strategy for storage and logistics i.e. transport of biomass to any potential biorefinery/processing facility?
- processing from fresh is preferable if not always practical, ensiling or other pre-treatments could be considered;
- are existing facilities available in Ireland that could be used initially for a small/pilot scale biorefinery process? Or are new facilities to be established?

4.1.2. Identifying the right processing approach and product streams

Table 4.1 below gives the composition of key components in the target species. Note that this data is compiled from a range of academic and industry sources that have reported on European wild harvest and cultivated biomass[1]. The data ranges given in Table 4.1 are indicative for Irish seaweeds but need to be confirmed for specific feedstocks (as mentioned above).

Table 4.1. Composition of Irish seaweeds, key components as % dry weight

Species	Alaria esculenta	Saccharina latissima	Laminaria digitata
Mannitol	<14	2-58	2-20
Laminarin	26-39	<33	<18
Fucoidan	2-3	2-12	<6
Alginate	10-42	10-33	32-45
Cellulose	11-12	<10	3-9
Phlorotannins	<4	<3	<0.2
Protein	9-20	5-18	3-12
Lipids	<2	1-3	<2
Fucoxanthin	<0.05	<0.09	<0.07
Minerals	14-32	15-45	14-35

The basic principle for any biorefinery is to **extract valuable first** followed by **maximal utilisation of the remaining biomass**. It does not necessarily follow that all components should be separated out as this is dependent on the cost/effort of extraction versus return (volume and price) and also on end product requirements.

Thinking through the information presented in Table 4.1 above and how this relates to a potential small scale biorefinery set up for Ireland, key components and potential processes are discussed. **The likely scenario for an Irish seaweed biorefinery in the short term will be focused on a simple model that involves an initial separation step into a soluble and an insoluble fraction** (Fig. 4.3). The soluble stream can be further fractionated using cascading aqueous extractions and/or fractionation by molecular weight (membrane filtration methods) to produce extracts that are "rich-in" key components for targeted markets. The insoluble fraction will be rich in alginate and has possibilities for valorisation as a seaweed fibre for use in food or as a feed additive.

Potential soluble streams

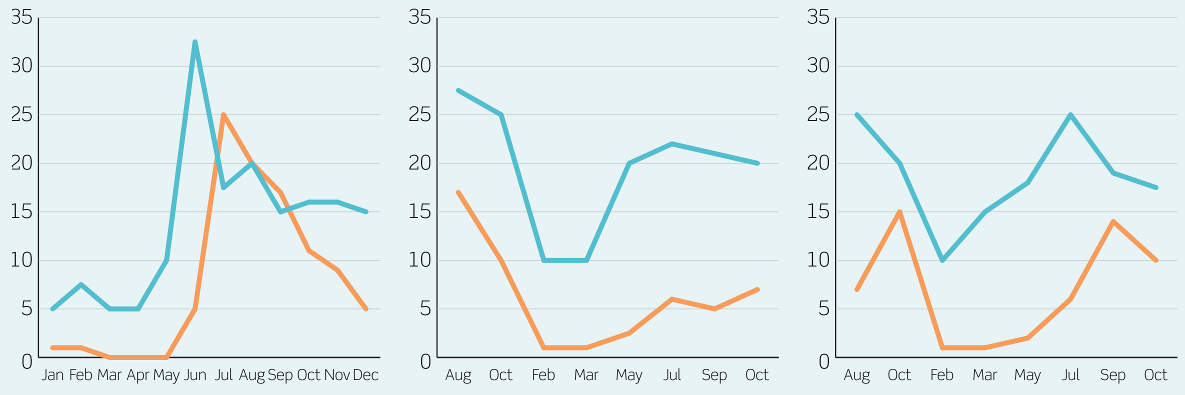
Laminarin and mannitol are the bulk components of *Alaria esculenta, Laminaria digitata* and *Saccharina latissima*, in addition to alginate, and both have market value (Sections 1.1.1 and 1.1.2 and Section 2). However, the content of laminarin and mannitol varies significantly on a seasonal basis. Fig. 4.2 provides an example of the seasonal variability in laminarin and mannitol content of *Laminaria digitata* and *Saccharina latissima*, based on European research that has been recently reported[126, 127]. It clearly shows that time of harvest will have a significant influence on the yield of laminarin and mannitol that can be recovered as content varies on a seasonal and yearly basis. Consideration of this variability must be factored into any biorefinery concept.

In a simple biorefinery (Figure 4.3), mannitol and laminarin can be co-extracted under acidic aqueous conditions. Laminarin is typically extracted at ≈ 70°C whereas mannitol can be extracted at lower temperatures. Note: extraction parameters would have to be optimised to suit the specific feedstock. Calcium chloride can be added to prevent the solubilisation of any alginate and other water soluble components that may also be co-extracted, can be recovered. The various components in the liquid extract can be separated by molecular weight using sequential ultrafiltration and dialysis. Mannitol and laminarin are relatively low molecular weight and can be separated from the higher molecular weight components using UF with a small cut off (around 5-6 kDa), a further UF step with cut off of 200Da-3 kDa will separate the laminarin and mannitol. A diafiltration step with a cut off of ≈ 1 kDa can be used to remove any mineral salts and calcium chloride (if added). Both laminarin and mannitol can be precipitated using various alcohols if a purified rather than "rich-in" extract is the required end product[128].

126 van Hal & Huijgen 2013. Chemical and biofuels from the third generation biomass seaweed ECN Report ECN-L-13-064.
127 Schiener et al 2015. The seasonal variation in the chemical composition of the kelp species Laminaria digitata, Laminaria hyperborea, Saccharina latissima and Alaria esculenta. J Appl Phycol (2015) 27:363–373
128 Rioux & Turgeon (2015) In Tiwari & Troy (eds) Seaweed Sustainability Food and Non-Food Applications

Depending on species and compositional variability in feedstock, **fucoidan** may or may not be of interest in an Irish biorefinery. Fucoidan can be extracted under mild, acidic aqueous conditions at ambient or elevated temperatures and fractionated/separated by molecular weight. The molecular weight of fucoidan varies substantially depending on species, environmental factors and methods used to extract and characterise the fucoidan[12] (Section 1.1.4). Feedstock specific optimisation will need to be carried out to establish the molecular cut off for fucoidan separation but in general the molecular weight will be higher than that for laminarin. Ale et al (2011) report molecular weights in the range of <10 kDa to >100 kDa 11. It would be possible to build in a cascading extraction step to fit with the extraction of mannitol and laminarin.

Figure 4.2. Examples of seasonal variability in laminarin (orange) and mannitol (blue) content (% dry weight) of *Laminaria digitata* (left & middle) and *Saccharina latissima* (right).



Note: difference in seasonal sampling (x axis). Data modified from van Hal & Huijgen 2013[126] and Schiener et al 2015[127]

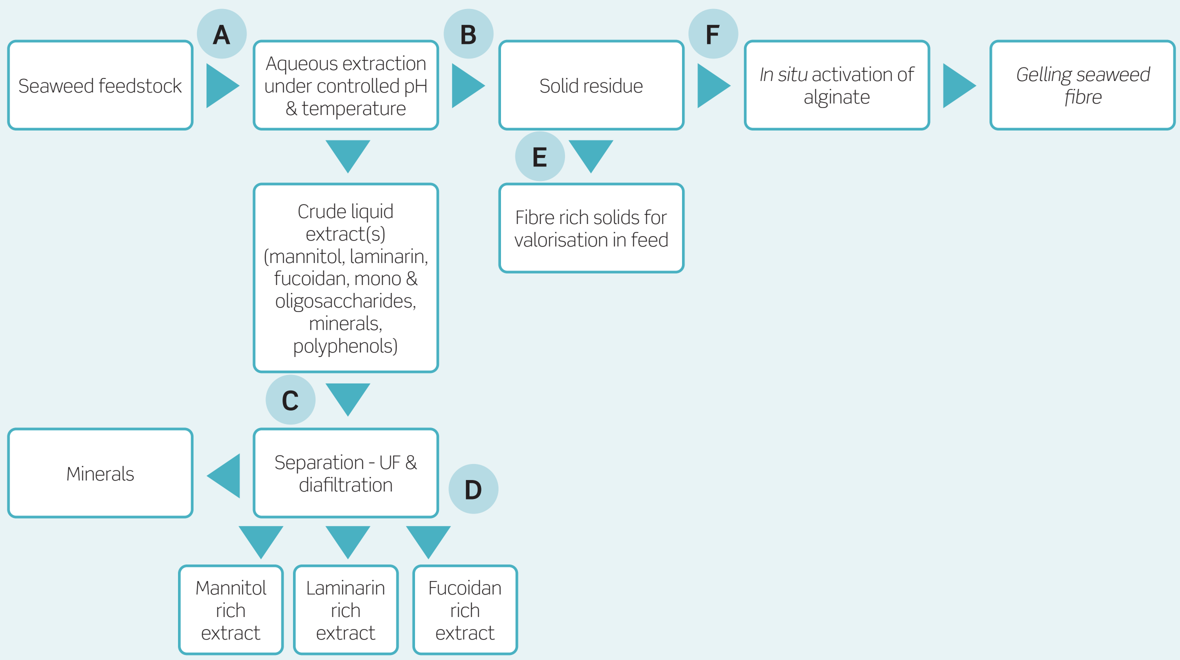
The **polyphenol (phlorotannin)** content of the Irish kelps is relatively low (<4%) and recovery using aqueous extraction techniques is not as efficient as using alcohol or alcohol:water mixes[129]. For a small scale biorefinery, the cost and effort of extracting the polyphenols will most likely outweigh any benefit unless there is a clear market opportunity within Ireland to warrant the effort once biomass supply has increased. The same is true for the **lipid fraction** and **fucoxanthin**, both of which require extraction using alcohol for good recovery.

Extraction using alcohol or alcohol:water mixes can increase yields but is expensive, even at laboratory scale, and there are particular safety measures that need to be put in place. The solvents need to be evaporated off and recovered. For a potentially small step in any potential biorefinery, the use of alcohol extraction would not be cost efficient and is not recommended unless a key market is identified.

Proteins can be extracted using aqueous techniques (acidic and alkaline) followed by a recovery step (e.g. precipitation, filtration) however, yields are significantly improved after cell disruption using physical and/or enzymatic methods. Introducing enzyme technology to the overall process adds another level of complexity which is best avoided in the short term. Unless, there is a specific market opportunity within Ireland that warrants the additional R&D. If cell disruption methods are not employed, then the protein is likely to remain bound into the insoluble fraction and may be beneficial in improving the nutritional profile of the insoluble stream for certain applications.

129 CyberColloids 2012. SWAFAX project technology transfer report. Internal Report.

Figure 4.3. Simplistic biorefinery concept for Irish kelps



Step	Detail
A	Aqueous extraction techniques can be used as a first step to separate the soluble and insoluble components of the seaweed biomass. Typically, a cascading approach would be taken to recover individual components based on optimal process conditions, pH and temperature (as per Fig 3.2 above). Multiple (re-extraction) steps may also be incorporated to maximise extraction of certain components. Where aqueous extraction methods are employed, prior dewatering of the biomass is not necessary as the solid fraction can be recovered using filtration and/or centrifugation after the extraction step(s).
B	The solid & liquid fractions can be separated using a centrifuge or decanter. This is usually sufficient to remove any insoluble matter that could affect future filtration/fractionation.
C	Crude extracts are further fractionated as required by molecular weight, using filtration techniques. Crude extracts will typically contain mannitol, laminarin, fucoidan, polyphenols and minerals, depending on selectivity of the prior extraction steps.
D	Components are recovered and/or purified to requirement (detail in sections below).
E	The solid fraction will mostly comprise alginate but there will be cellulose, protein and other bound components present. Brown seaweed residues have been evaluated for use in animal and aquatic feeds. The solid material will most likely just require drying and grinding to required particle size.
F	CyberColloids have developed a process to activate the gelling potential of the alginate fraction *in situ* and without the need to extract. The process involves a series of aqueous reaction steps followed by separation and drying.

Insoluble fraction

Alginate is frequently proposed as a key component of brown seaweed biorefineries however, for low biomass volume this is generally not a viable commercial option. Opportunities exist to develop "alginate rich" seaweed ingredients (i.e. seaweed fibres) with added textural functionality. Processing involves the activation of the alginate *in situ*, thus removing the necessity for further extraction. The end product is a functionalised fibre that will also contain protein, lipid and any bound components such as polyphenols. The seaweed fibre technology was developed by CyberColloids for *Saccharina latissima* as part of the SEAREFINERY project (Box 4.1)[130] but in principal can be applied to any alginate bearing biomass.

130 https://searefinery.eu/

Box 4.1. The SEAREFINERY project - (https://www.searefinery.eu/)

The SEAREFINERY project focussed on the valorisation of cultivated ***Saccharina latissima*** biomass as part of a cascading biorefinery. Bioactive extracts containing fucoidan, laminarin and phlorotannin polyphenols were evaluated in a range of model cosmetics and food products/concepts. Extracts were also assessed for potential anti-inflammatory activity with a particular focus on gastrointestinal benefit and some extracts derived from ***Alaria esculenta*** were evaluated. A biorefinery based on *Saccharina latissima* was demonstrated at pilot scale (600 kg reaction volume). The final product stream was an alginate based seaweed fibre that was successfully used in different model foods as a replacement for sodium alginate.

Utilising the texture functionality of the insoluble fraction does not have to be restricted to food use, seaweed gels also have potential application in other sectors. For example, in face masks (cosmetics sector), in delivery systems for seeds and plantlets (horticulture/agri) and in the production of films and bio-packaging although the latter would be limited by the small scale of an Irish biorefinery in the short term.

An alternative to developing seaweed fibre from the solid residue would be to evaluate its potential for feed (livestock, aquatic and pet nutrition). This has been a typical approach in biorefinery research to date (Tab. 3.2) and would fit well with the Irish market. Residues from a biorefinery aimed at producing biofuel from *Saccharina latissima* and *Alaria esculenta* feedstocks have been evaluated as potential aquatic feeds[131]. This research showed that biorefining enhanced the nutritional value of the residue by removing polyphenols and by concentrating the protein and lipid content. When evaluated against a commercial comparator, the residue showed good potential. There has been much research conducted in this area for livestock and aquatic animals however, this approach would require further R&D to optimise for seaweed and target livestock/aquatic species.

4.1.3. Potential future focus

Ireland has existing positive markets (internal and export) for seaweed derived ingredients and extracts, namely food, feed, personal care and horticultural applications. Given that the outputs of any biorefinery will be limited by scale in the short term (and longer term unless significantly more biomass becomes available) it makes **sense to focus on the development of high value new products for existing and niche markets**.

It is recommended that a **needs analysis is conducted for each key sector** to identify any specific requirements, improvements or new seaweed derived products that could be produced as part of a biorefinery. There is **potential to produce bespoke ingredients or extracts from *Saccharina latissima, Laminaria digitata* and *Alaria esculenta* to satisfy the different Irish market sectors**. Based on the findings in Sections 1-3 above a number of recommendations for further consideration and follow up are given below:

Food

Ingredients – the European market for food containing seaweed ingredients is growing albeit still small. Ireland is not a key innovator at the moment. We are seeing markets and NPD being driven by consumer demand. Food manufacturers and ingredient distributors are interested to source new and different ingredients. There is an opportunity to produce good quality ingredients that are sustainable, traceable, low in iodine and with good organoleptic and technical qualities e.g. particle size s important from a technical perspective (ease of inclusion) but also can impact on sensory. Although such ingredients would not necessary be produced as part of a biorefinery, they could be complementary and utilise some of the pre- and post- biorefinery processing steps.

Natural flavour – the use of "kelp/kombu water" and "kelp/kombu extracts" for natural flavour was identified in Section 2.1 as a growing trend. *Saccharina latissima, Laminaria digitata* and *Alaria esculenta* are all relatively high in minerals and proteinaceous components that contribute to natural flavour and have potential for the development of new flavour products. This is an interesting area and could fit into a potential Irish biorefinery concept but requires more R&D.

Texture – replacement of hydrocolloids food texture agents (i.e. food additives with E Numbers in Europe) is an important driver in the food industry and there is a growing global market. Process technology for the production of seaweed fibres that have water binding and gelling functionality has been demonstrated and resides in Ireland (CyberColloids Ltd). This technology can be applied to any alginate bearing biomass (whole and residue from a biorefinery process).

131 Schiener et al (2015). The by-products from marine biofuels as a feed source for the aquaculture industry: a novel example of the biorefinery approach. Biomass Conversion and Biorefinery. 10.1007/s13399-015-0190-6

Human health & wellbeing

Cosmetics and personal care - there are possibilities to develop bespoke extracts and ingredients for this sector. All three Irish species are commonly used in cosmetics and personal care products and a biorefinery approach could be utilised to target key components. Provenance can be a key differentiator in the cosmetic industry and having a sustainable, clean, Irish sales story could be beneficial.

Functional ingredients – seaweed derived actives/ingredients are finding application in the growing European market for supplements and functional foods. These markets are expected to continue to grow and seaweed based products are positioned in key, lucrative segments including digestive health and weight management - segments that can also be expected to continue to grow given current lifestyle and dietary trends. Development of new functional ingredients is not a short-term opportunity and will require significant R&D investment not only for development but also for testing.

Plant health

The agri/horticultural sector has become very sophisticated. High end products typically have a unique sales story and a solid platform of science to back this up. A biorefinery approach could be utilised to produce bespoke products for plant protection and plant nutrition. Similarly, to the development of functional ingredients for human and animal health, this approach is not short term and will require R&D investment for product development and testing.

Animal health

Whether the focus is livestock, aquatic species or pet nutrition, there are a number of global drivers for R&D in new feed and feed additive products (i) rising demand for cost effective nutrition; (ii) naturalising animal nutrition, (iii) finding alternatives to antibiotics and growth promoters and (iv) bespoke nutrition/differentiated products for different animal needs. It is possible that a biorefinery approach could be utilised to produce bespoke extracts/ingredients for use in this industry. Development in all areas will require significant R&D investment and close collaboration with target sectors.

Biofuels, chemicals and biomaterials

In the short term (next 5 – 10 years) it is unlikely that volume of feedstock to an Irish biorefinery will be sufficient to supply many of the innovative/trending markets such as biofuels, bioplastics and packaging as these are all based on very large volume feedstocks to be cost efficient. Elsewhere in Europe, the large scale, multi-use farming initiatives that are due to come online in next 5-10 years with the aim of driving down the cost of bulk seaweed biomass for refining will service these markets.

The aim of this report was to scope the potential for Ireland to develop a seaweed based biorefinery and to propose some short and longer term opportunities to valorise cultivated Irish seaweed. **There is certainly potential however, scale and cost of feedstock are limiting factors**. In 2018, BIM reported that Ireland produced 40 wet tonnes of cultivated seaweed with a farm gate price of €40,000, thus the average price of cultivated seaweed was €1,000 per wet tonne. **Utilising such an expensive feedstock for a biorefinery would not be viable**, even if the focus was on high value product streams. Key to taking the Irish biorefinery thinking forward will be:

(i) an analysis of feedstock supply chain, including cost, type and variability of different biomass resources (current and future);

(ii) key sector market analysis to identify specific Irish & niche markets for potential extracts/ingredients;

(iii) based on (i) and (ii) identify priority focus and any knowledge/technology gaps that will need to be addressed in order to take the thinking further;

(iv) a plan for a coordinated approach, how to bring growers and processors together so as to maximise opportunities and bring cost down.

Alaria esculenta

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