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CIRCALGAE

Food • Feed • Cosmetic

CIRCular valorisation of industrial ALGAE waste streams into high-value products to foster future sustainable blue biorefineries in Europe

D1.1 – Report of the current algae industry in Europe

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Version and amendments history

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0.1	03/08/2023	CEVA	First draft shared with partners
0.2	03/23/2023	CEVA	New sections, additional data
0.3	03/28/2023	CEVA	Additional data, summary tables, gaps and opportunities analysis
1.0	03/31/2023	CEVA, A4F, Alginor	Final corrections after internal review and partners' review.
2.0	03/15/2024	CEVA	Minor updates (company changes, taxonomy changes, …), harmonization of data and editorial corrections
3.0	07/05/2024	CEVA	Final update following EC examination

Summary/ Abstract

In November 2022, the European Commission published its communication "Towards a Strong and Sustainable EU Algae Sector", also known as the EU Algae Initiative. This initiative outlines how the EU can increase the sustainable production, safe consumption and innovative use of algae and algae-based products.

Innovation does not only consist in producing additional biomass and developing new uses. Improving existing uses is also a key parameter for sustainable development. Algae biomass is currently often underexploited, and its efficient utilization is one of the main challenges in current and future EU blue/marine sustainable policies.

Indeed, while some sectors can use whole algae, as for example the food sector, many others are extracting ingredients and compounds of interest. The European industry is currently processing hundreds of thousands of tons of either harvested or cultivated algae on a yearly basis. However, the extracted compound often represents only a fraction of the total algal biomass, while the rest is discarded as several effluents and solid residues.

New approaches can be designed to boost the blue bioeconomy and fully valorise the massively produced and vastly underexploited discards and waste streams from these industries. However, they require a good understanding and mapping of the current industry, its raw materials, processes, and streams of co-products and effluents.

This comprehensive report gathers all information as to algae production and uses in Europe, pointing out volumes, species, regions, uses and biomass streams generated. It is divided in several sections according to algae types and production technologies (macroalgae, microalgae cyanobacteria and Labyrinthulomycetes), as well as downstream uses for ingredient production and algae-based products. Recent evolutions will also be evaluated (sourcing constraints, new players, emerging processes) to anticipate future shifts in raw materials availability and quality.

This photography of the European algae landscape will help identify gaps and possible synergies and mark potential opportunities for new biorefineries.

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1. Introduction

1.1. Objectives

The main objective of this Task of CIRCALGAE project is to gather a comprehensive report analysing the use of microalgae and microalgae across Europe. The report covers algae production and uses in Europe, and points out volumes, species, regions, uses and biomass streams generated.

It has been prepared by gathering publicly available information from a broad range of sources (scientific literature, market reports, public reports from various authorities and projects, national and international statistics), and by interviewing major stakeholders of the algae industry.

This report is divided in several sections according to algae types and production technologies (macroalgae, microalgae, cyanobacteria and Labyrinthulomycetes), as well as downstream uses for ingredient production and algae-based products. Recent evolutions were also evaluated (sourcing constraints, new players, emerging processes) to anticipate future shifts in raw materials availability and quality.

This photography of the blue bioeconomy landscape will help identify gaps and possible synergies and mark potential opportunities for a biorefinery.

1.2. Definitions

The so-called "algae" sector is complex, and encompasses a broad variety of biological species, with significant consequences on harvesting/cultivation processes, volumes available/utilized to date, and also downstream processing and typologies of products.

In order to take it into account and clarify the report, we segmented the production data according to the definitions laid out in European Standard (EN 17399:2020).

1.2.1. Macroalgae

Macroalgae are macroscopic eukaryotic organisms composed of single differentiated cells able to obtain energy using chromophores.

Also commonly referred to as seaweed, they are benthic or pelagic photosynthetic organisms mostly found in seawater, but also present to a lower extent in freshwater bodies (lakes, rivers).

1.2.2. Microalgae

Microalgae are microscopic eukaryotic organisms composed of single differentiated cells able to obtain energy using chromophores.

These microscopic algae can be found across all types of fresh or saline waterbodies.

1.2.3. Cyanobacteria

Cyanobacteria are photoautotrophic, mixotrophic or heterotrophic prokaryotic organisms, able to obtain energy by using chromophores.

While Spirulina is the most emblematic example of this very diverse phylum of photosynthetic bacteria, a broad diversity of species can be found in freshwater, saline water and terrestrial environments.

Although this is not true from a biological perspective, they have historically been considered as (micro)algae in most regulations and statistics, and started only recently to be considered as a distinct category in official documents.

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1.2.4. Labyrinthulomycetes

Labyrinthulomycetes are a class of protists that produce a network of filaments or tubes and includes the family *Thraustochytriaceae*.

These microscopic organisms were also historically considered as "microalgae", although not photosynthetic, and are still considered as such by many regulations (e.g. in the context of Novel Food Regulation (EU) 2015/2283). However, their distinct production technologies deserve a separate handling in this report.

1.3. Scope of the study

1.3.1. Geography

This report focuses on continental Europe, with a primary focus on European Union, United Kingdom, Norway and Switzerland. Whenever possible, additional data from neighbouring countries was included, e.g. data from Iceland, or the Baltic countries. Israel was also included due to its key position in microalgae cultivation (as well as links with European companies).

1.3.2. Market perimeter

When assessing market values for the algae value chain, huge discrepancies are sometimes found, depending on the perimeter assessed.

In this report, we focused on:

- Algae production stage (seaweed harvesting and algae cultivation) and 1st transformation (dried algae, frozen algae, …)
- Ingredients: phycocolloids, other purified polysaccharides, carotenoids (β-carotene, astaxanthin, fucoxanthin), phycobiliproteins (phycocyanin, phycoerythrin) and omega-3 oils.
- Extracts for specific markets: cosmetics, agriculture (fertilizers, biostimulants, …) and feed

However, we did not cover downstream markets using these ingredients (food manufacturing, cosmetic formulation, …).

Indeed, it is excessively difficult to assess the "algae" part in the turnover of a company incorporating algae or algae ingredients in its products. To illustrate it with a trivial example, why should a maki roll containing 70% rice, 20% salmon, and 2% Nori seaweed, be considered as an "algae product" rather than a product of the rice or salmon market.

Additionally, most companies formulating with algae or algae ingredients are using "ready-to-use" products or ingredients, and do not generate algae co-products which are the main target of Circalgae project.

1.3.3. Market values

Considering the high variability and uncertainty of the assessment of volumes produced and market data, we did not adjust for dollar/euro conversion change variations over time.

1.3.4. Companies and market sectors

A very extensive review of companies active in the European algae sector was recently published by the European Commission's Knowledge Centre for Bioeconomy in a report "An overview of the algae industry in Europe" (Vazquez Calderon and Sanchez Lopez 2022).

While additional companies might be added, or updates of some data could be considered, this report already provides a relatively robust assessment of the stakeholders. As a result, we decided not to repeat this review and duplicate the work.

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For additional information on algae companies active in Europe, and regular updates, extensive information can also be retrieved in the Phyconomy database (Hermans 2023b).

In their report, Vazquez Calderon and Sanchez Lopez estimate the European algae value chain at 191 million euros, supported by around 500 companies and over 2,000 employees (employment value but also turnover probably underestimated due to missing data).

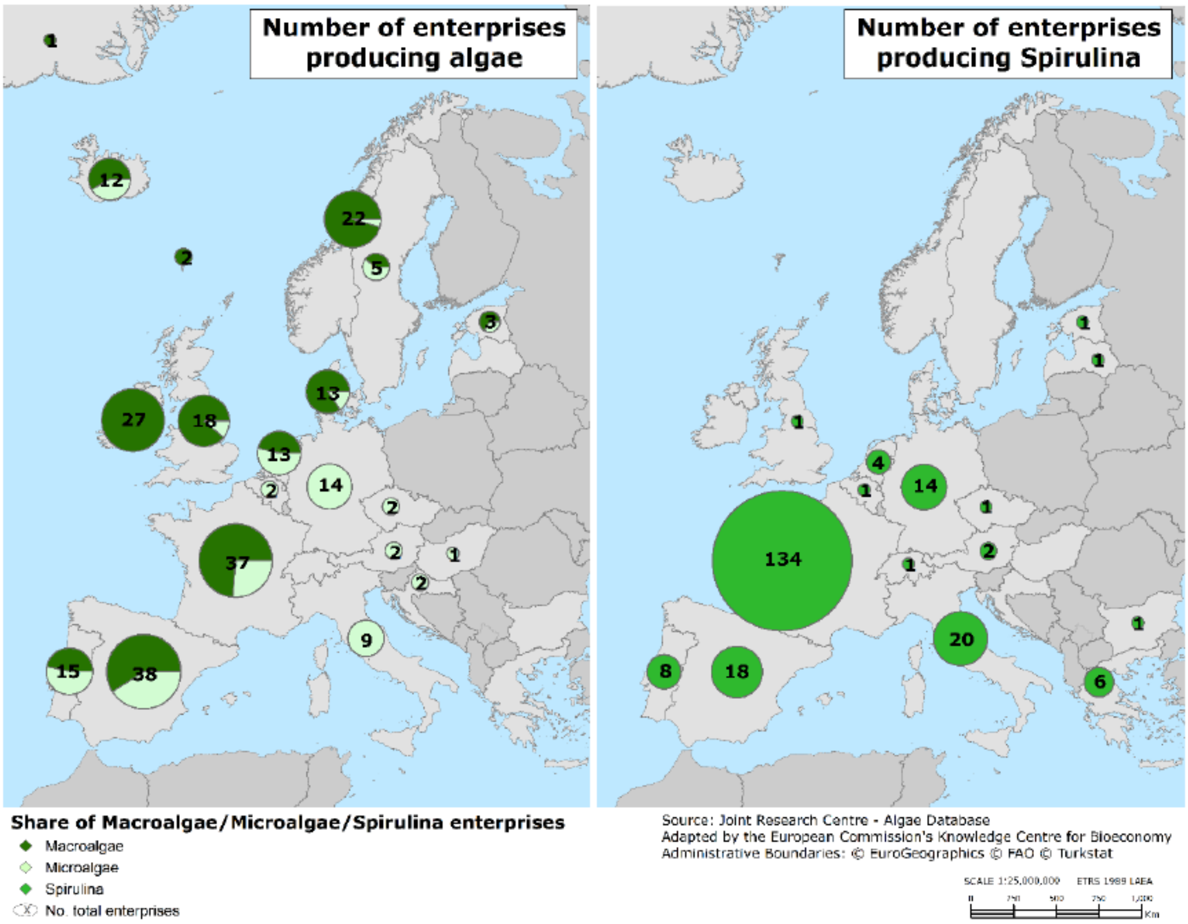

Figure 1 : Number of algae producing companies in Europe (Vazquez Calderon and Sanchez Lopez 2022)

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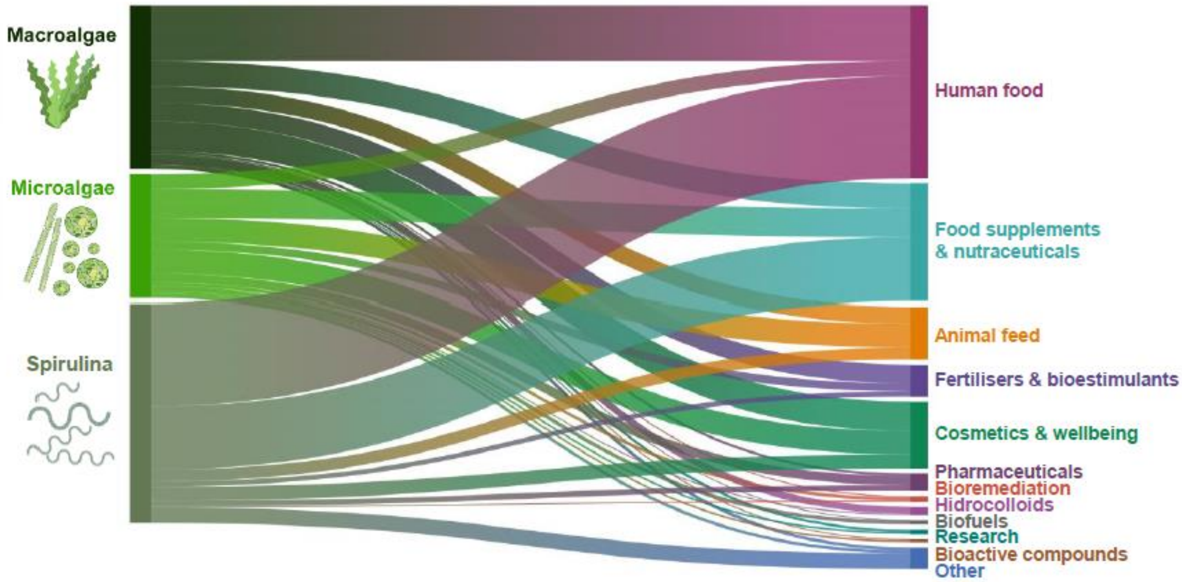

Figure 2 : Algae biomass uses in Europe, based on the number of companies supplying biomass for these uses (Vazquez Calderon and Sanchez Lopez 2022)

However, one of the limitations of the report, is that most data (volumes, species, technologies, applications) is detailed based on number of companies involved, rather than volumes and market values.

This may lead to a biased view (also identified by the authors) over-representing certain sectors with multiple smaller players, while hiding some of the key players and main markets, where the industry is much more concentrated.

1.4. Applying a different approach

In order to complement the work performed in the Overview of the algae industry report (Vazquez Calderon and Sanchez Lopez 2022), we took a different approach and decided to rely less on companies and map the algae value chain by focusing on:

- Algae production
- Algae and algae-based products markets

However, for each of these aspects, the link with companies and major stakeholders was integrated whenever possible.

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2. Algae production in Europe

2.1. Seaweed

With a growth rate 10 times higher than terrestrial plants, seaweed production is a promising contributor, along with conventional agriculture, to meet the future challenges of limited resources. In 2019, the role of seaweed in the future of blue economy was highlighted by the European Commission.

Currently, European algae production represents only 1,4% of the global algae production, with about 99% of the total European seaweed biomass harvested from wild stocks (Araújo *et al.* 2021), The species constituting the bulk of the harvested volumes are *Laminaria hyperborea*, *Laminaria digitata* and *Ascophyllum nodosum*, numerous other species (brown, red and green) are also harvested for various markets.

While *Saccharina latissima* and *Alaria esculenta* are the main commercially cultivated species in Europe, several other species are also produced at a smaller scale.

The seaweed industry in Europe is dominated by Norway, followed by France (Figures 3 and 4). According to *Camia et al*., 98% of the European biomass production is provided by Norway, France, Ireland and Iceland (Camia *et al.* 2018), although UK (mostly Scotland) should also be added to this list. In the Mediterranean area, algae production is limited to few species.

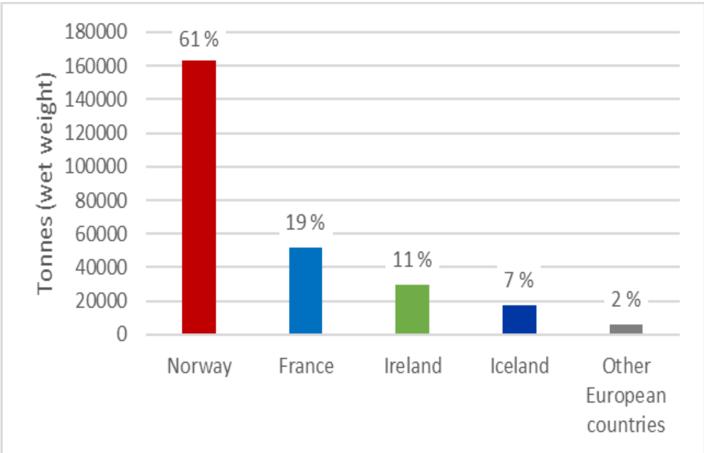

Figure 3 : European seaweed production, farmed or wild, in 2019 (FAO 2021)

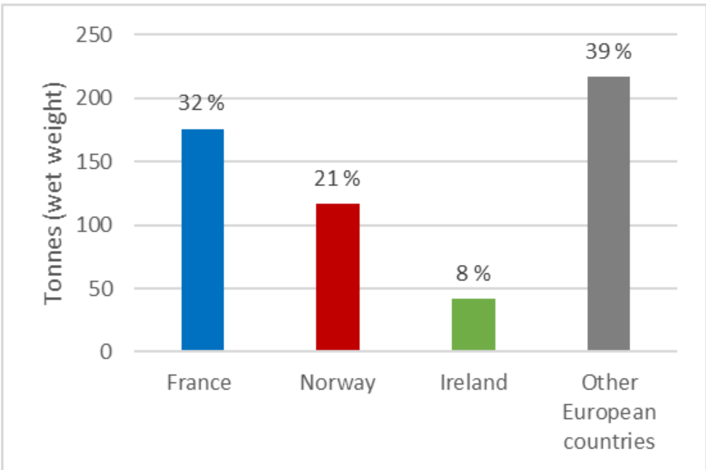

Figure 4 : Total European farmed seaweed production in 2019 (FAO 2021)

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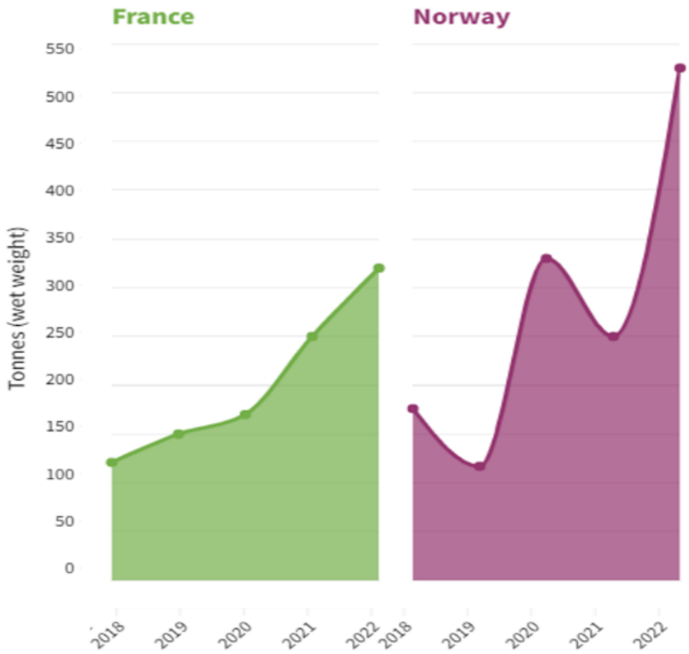

Figure 5 : Cultivated seaweed biomass of the top two European producers between 2018 and 2022 (modified from Hermans, 2023)

2.1.1. Seaweed harvesting

2.1.1.1. Drifting seaweeds

Drifting and stranded seaweeds are seaweeds that have been removed from their substrate due to climatic events, mostly storms, generating strong currents and waves. The seaweeds are unable to resists such forces and are totally or partially torn apart and drifting freely in the water column until being stranded along the shore, and form seaweed edges on the shores.

Some countries harvest these drifting seaweeds, possibly before their landing along the shore, to prevent staining by sand and sediments and keep them as fresh as possible right after being removed from the substrate.

Thus, in South West France, between 1,500-2,000 t (fresh weight) of the floating red seaweed *Gelidium corneum* (also called *Gelidium sesquipedale* in some documents) are yearly harvested by trawling by ten or small fishing ships while still in the water column. *Gelidium* is also collected in the same area as beach-cast seaweed. The biomass is used for the agar industry (AcclimaTerra 2018). Drifting *Gelidium corneum* and another red seaweed *Pterocladiella capillacea* is also harvested on the rest of the Iberian Peninsula, up to 5,000 t in 2018 (Araújo *et al.* 2021).

Similarly, *Furcellaria lumbricalis* can be collected in the Baltic Sea (activity now concentrated in Estonia, around a thousand tons), while *Solieria sp* and *Ulva sp* are also collected in France (several thousand tons for each).

2.1.1.2. Off-shore seaweeds

Off-shore harvested seaweeds are brown seaweeds, forming kelp forests. In Europe, kelp forests are characterized by brown seaweeds belonging to Laminarian family. The two major harvested species are *Laminaria digitata* and *Laminaria hyperborea*, mostly used for the alginates industry.

Harvesting occurs by boats geared with specific tools to harvest seaweeds at the sea bottom. *Laminaria digitata* is harvested by “scoubidou”, while *Laminaria hyperborea* is harvested by trawling using the “Norwegian comb”.

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The "scoubidou" is a rotating articulated arm with a hook at its tip. The articulated arm rotates in the *Laminaria digitata* beds, and the seaweeds are caught by the rotating movement of the hook. Only the tallest individuals (oldest) are collected.

The Norwegian comb tool is designed to harvest only the tallest and oldest seaweeds of *Laminaria hyperborea* beds. Deployed from a vessel, the "comb like" head of the gear is trawled through the kelp bed at approximately 0.5 m above the rock substrate at low speed. Trawls occurs for a few minutes before the head is recovered and the kelp removed. This harvesting method removes the entire kelp plants including holdfasts, although juvenile plants are left *in situ* to promote fast recovery of harvested populations. Removal of whole plants creates bare rock available for colonization by new kelp plants and fosters the kelp bed recovery.

2.1.1.3. Harvested seaweed species in Europe

Norway

With a coastline extending over 100,000 km, Norwegian kelp forests represent a large part of total areas of blue forests in Europe and host more than 400 species of algae (Stévant *et al.* 2017). The Norwegian seaweed harvesting industry is the largest in Europe and industrial kelp harvesting has been conducted for decades (Greenhill *et al.* 2021). In Norway, macroalgae are mainly harvested from the western coast (Rogaland to Trøndelag) into different zones harvested on a 5-year cycle (Camarena-Gómez *et al.* 2022).

However, in northern Norway, sea urchins have been grazing on kelp forests and induced a decline in kelp populations. A recent collapse of urchin populations under ocean acidification might improve recovery of the kelp forests.

In Norway, the main source of harvested species is *Laminaria hyperborea* (about 150,000 tons annually harvested for the last decades), followed by the fucoid *Ascophyllum nodosum,* commonly found along the Norwegian coast (Greenhill *et al.* 2021) .

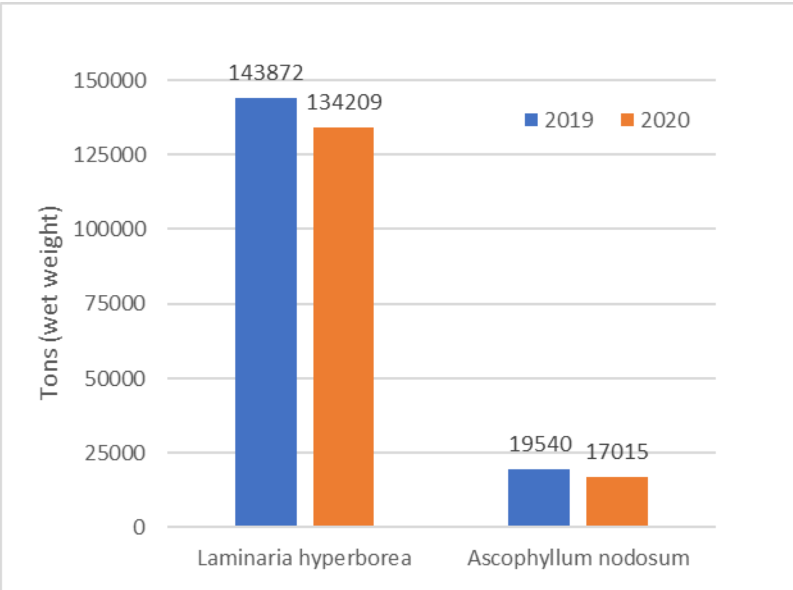

Figure 6 : Production of the most harvested seaweed in Norway in 2019 and 2020 (FAO 2021)

Several other species are also harvested at a smaller scale leading to negligible volumes in comparison: *Laminaria digitata*, *Chondrus crispus*, *Palmaria palmata*, *Fucus vesiculosus*, *Ulva* sp., and *Vertebrata lanosa* (EMODnet Data).

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France

France is the second European seaweed producer after Norway. About 90% of the French seaweed harvest is carried out in Brittany. In France, seaweed is harvested from shore both manually and mechanically (7000 to 8000 t/year), and from boat (80% of the French produced biomass).

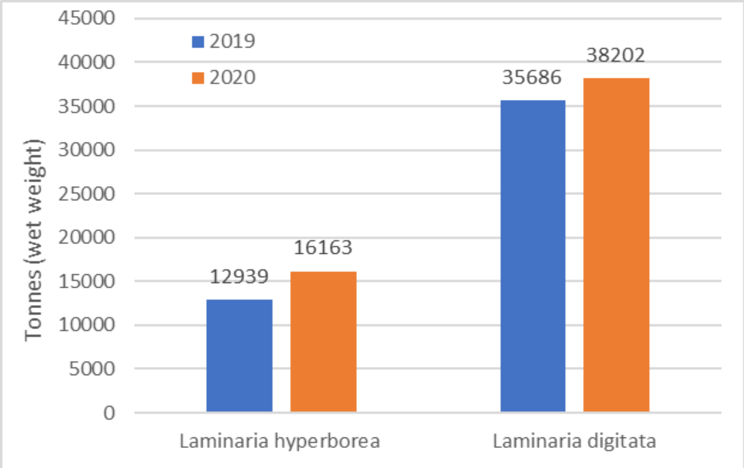

Figure 7 : Main seaweed species harvested from wild in France in 2019 and 2020 (FAO, 2022)

The main harvested species are *Laminaria hyperborea* and *Laminaria digitata* (Figure 7) with a mean value of around 55,000 wet tons of Laminariales harvested at sea every year (Comité Régional des Pêches Maritimes et des Elevages Marins de Bretagne 2022). *L. digitata* is harvested from May to October, while *L. hyperborea* is harvested during winter.

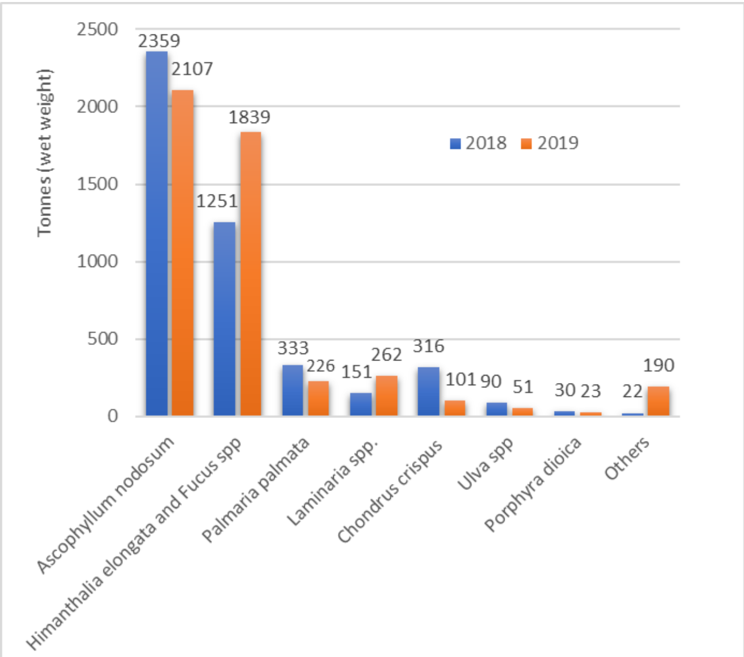

Figure 8 : Harvested shoreline seaweed biomass (wet weight) in Brittany, France, in 2018 and 2019 (CRPMEM, from declarative data)

In Brittany, *Ascophyllum nodosum* represents more than 44% of the total shoreline seaweed harvested, followed by *Himanthalia elongata* and *Fucus* spp. with about 38%. Fallow periods were determined for the collection of *Ascophyllum nodosum* to allow the recovery of the species.

The red alga *Chondrus crispus* is also picked in smaller volumes.

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Green tides is a persistent issue along the coast of Brittany and are related to the green proliferating alga *Ulva*. Estimates of *Ulva* macroalgae coverage is conducted every year by CEVA. While a part of this biomass is already collected in France and used by some companies, the processed volume is insignificant compared to the tens of thousands of tons of seaweed stranding in Brittany every year.

Similar phenomenon has been reported in winter along Southern Brittany coasts with massive strandings of the red alga *Solieria chordalis* (Burlot 2016). About 100,000 tons of of this red alga are stranding every year on the Bay of Biscay (CEVA data). Only a fraction of this biomass is collected for industrial use.

In the South of France (along the Basque coasts), the red algae *Gelidium sesquipedale* is harvested at sea by trawlers from drifting stocks only and along the shore (see 2.1.1.1) from September to February. The whole harvested *Gelidium* biomass is exported to Spain for the agar industry. A recent decline reported during the past 3 years was attributed to the development of the dynoflagellate Ostreopsis (CIDPMEM 64-40, pers. comm.).

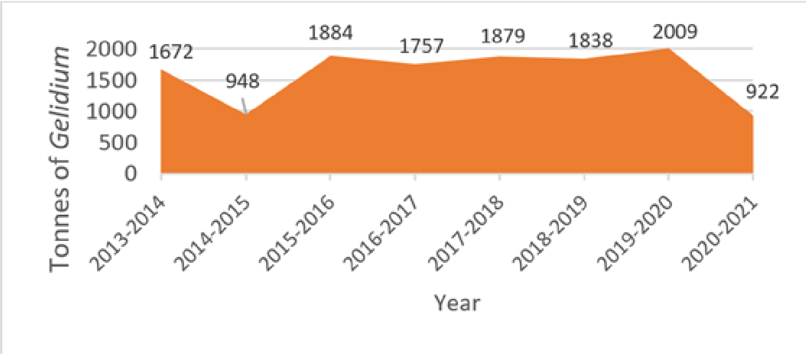

Figure 9 : Biomass of harvested Gelidium sesquipedale along the Basque coast (CIDPMEM 64-40 2021)

Ireland

While most of the seaweed biomass is provided by a small number of species (Laminariales and Fucales), several small companies are exploiting smaller volumes of higher value species (food, cosmetics, …).

About 95% of the Irish seaweed biomass is wild harvested, with an estimate of about 28,000 wet tons per year of *Ascophyllum nodosum*, followed by 1,400 tons *Laminaria hyperborea* (FAO 2021). The main resources of *Ascophyllum* come from Western Ireland where it is harvested by hand all year round using traditional techniques (serrated sickles or scythes). New harvesting methods leading to higher efficiency (depending on the geomorphology of the area) were introduced in 2016 with the use of rakes from boats to collect *A. nodosum* (Mac Monagail and Morrison 2020).

According to FAO (FAO 2021), less than 0.5 % (i.e. <100 tons) of landing seaweeds are red algae, especially the carrageen *Chondrus crispus* and *Mastocarpus stellatus* harvested at low tide from the intertidal zone. In 2011, similar volumes were also reported for *Palmaria palmata* (<100 t) (Walsh and Watson 2011).

Other species include *Fucus serratus* (<200 tons in 2011) and *Laminaria digitata* (< 150 tons in 2011) (Walsh and Watson 2011).

UK/Scotland: Scotland holds a significant part of the UK's kelp forests, but a small volume of it is currently harvested. Harvesting operations are concentrated on the west coast on Orkney, Shetland, and the Western Isles (The Scottish Government 2013). In Scotland, wild harvested seaweed is in the order of 15,000 wet tons per year.

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The main harvested species is the knotted wrack *A. nodosum* with at least 13,000 t per year harvested in the Outer Hebrides (The Scottish Government 2020), harvested both by hand and mechanically. Precise determination is complicated by the fact that a part of the harvesting is performed on private land, with no reporting obligations. *Palmaria palmata* is also harvested in significant volumes (>400 tons), as well as a few dozen tons of a diverse range of intertidal species (The Scottish Government 2020) which can include: *Fucus serratus*, the carrageenan-bearing *Chondrus crispus* and *Mastocarpus stellatus*, *Pelvetia canaliculata*, *Osmundea* spp., and *Porphyra* spp.

Beach-cast seaweeds are also collected from the shore by local communities, but information on collected volumes is lacking (The Scottish Government 2013).

Iceland

Thorverk is the largest Icelandic wild seaweed harvesting company, and lands mostly *Ascophyllum nodosum* (15,000 to 20,000 t per year), and at a smaller scale *Laminaria digitata* (2,000 to 3,000 t per year) (Maack 2019). The harvested biomass of *Ascophyllum nodosum* has increased in the past decades (Figure 10), while the volume of harvested kelp declined from 3,700 tons to 1,700 tons over 14 years (Figure 11). These biomasses are currently harvested by mechanical techniques (Maack 2019).

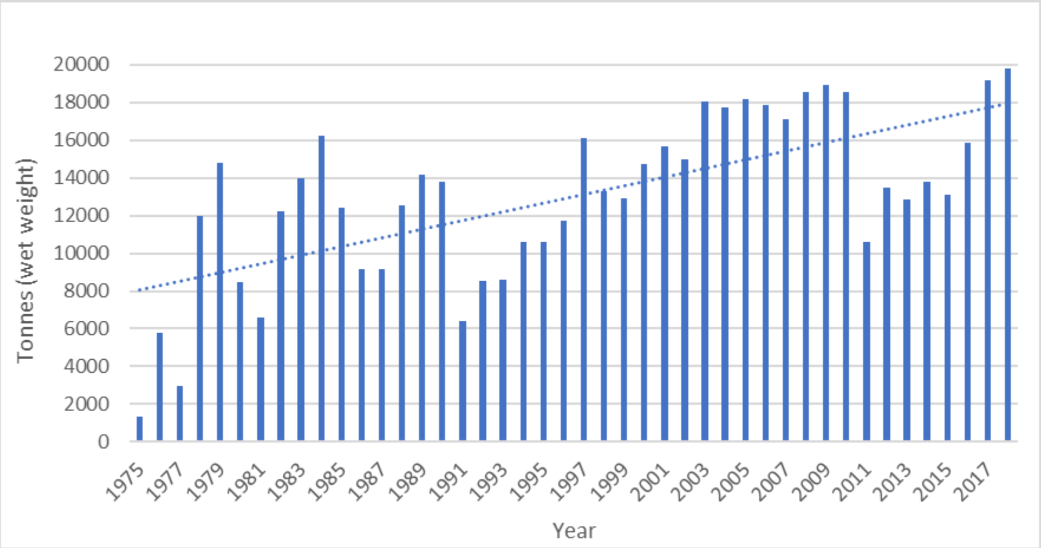

Figure 10 : Thorverk's harvesting volumes of Ascophyllum nodosum from 1975 to 2018 (Modified from (Maack 2019)).

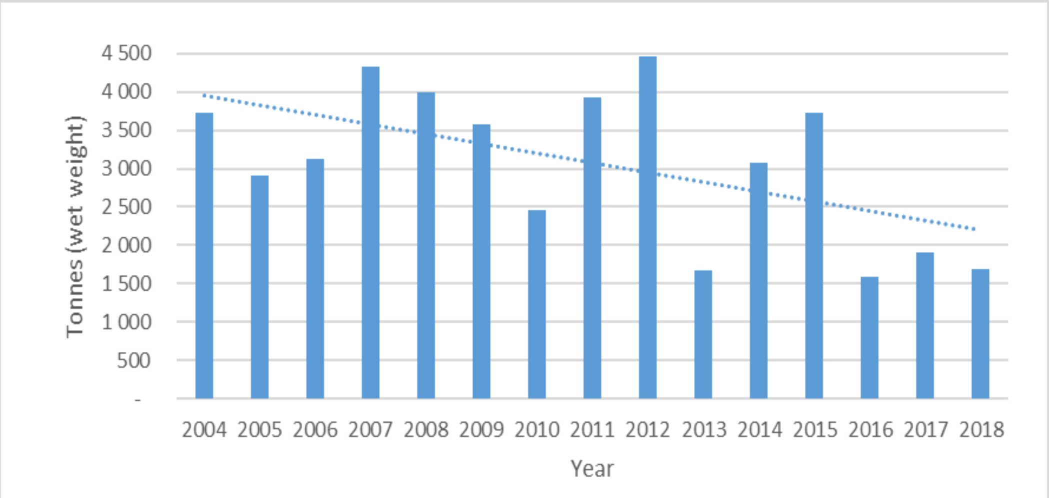

Figure 11 : Thorverk's harvesting volumes of Laminaria digitata from 2004 to 2018 (Modified from (Maack 2019)).

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Other European countries

Spain and Portugal are the main suppliers of *Gelidium* in Europe. Large quantities of *Gelidium* are harvested from the North coast of Spain (220-230 tons per year in 2019 and 2020 according to FAO) and the middle to southern end of the Portuguese coast. Almost half of the total Spanish *Gelidium (*especially *Gelidium corneum*) production is harvested from the Asturias. Harvesting is performed by collection of storm-cast seaweed and hand plucking underwater (Higgins 2022). While being a slow-growing alga with a single annual harvest, *Gelidium* is the only species providing a bacteriological-grade agar.

In Spain*, Undaria pinnatifida* is also harvested in similar volumes with 210 tons harvested in 2019, and 238 tons in 2020.

Furcellaria lumbricalis represents the only seaweed industry in Estonia, where two companies are harvesting the seaweed from wild stocks and from beach-cast seaweed: EstAgar AS and Tinurek OÜ/Vetik OÜ*.* Around 1,000 to 1,500 tons per year of *Furcellaria* are collected from two locations in Kassari Bay (Araújo *et al.* 2021). Several harvesting rules (including harvesting areas, volumes, frequency, and rotation systems) are set by the Fishing Act to avoid overexploitation of the wild stock (Camarena-Gómez *et al.* 2022).

In Sweden, small volumes of macroalgae are picked exclusively from beach cast (Camarena-Gómez *et al.* 2022).

2.1.1.4. Challenges in wild harvesting seaweeds and need for seaweed farming development

The current European seaweed industry relies significantly on harvested biomass, but because of environmental concerns related to wild harvest of macroalgae, lack of knowledge on available biomass and recovery rates of seaweed populations, but also new challenges like impact of global warming, seaweed cultivation needs to be extended to ensure the resource sustainability.

2.1.2. Seaweed cultivation

In Europe, most seaweed cultivation units are located at sea, while less than a quarter of the companies are conducting land-based activities (Araújo *et al.* 2021). The number of cultivated seaweed species is limited compared to the diversity of available seaweed in European waters.

An exhaustive synthesis of seaweeds cultivated in the Interreg Atlantic Area was published, as part of the Integrate project, in two factsheets by the Irish Seaweed Consultancy in 2020, concerning the main cultivated seaweed producers (Soler-Vila *et al.* 2020a, 2020b). The Interreg Atlantic Area programme supports transnational cooperation projects in 36 Atlantic regions of 5 countries: France, Ireland, Portugal, Spain and the United Kingdom.

The fact sheets summarize the current status of cultivated seaweed species, classified by their cultivation system and method, as well as the current status of their production for each country (scientific work and/or commercial culture).

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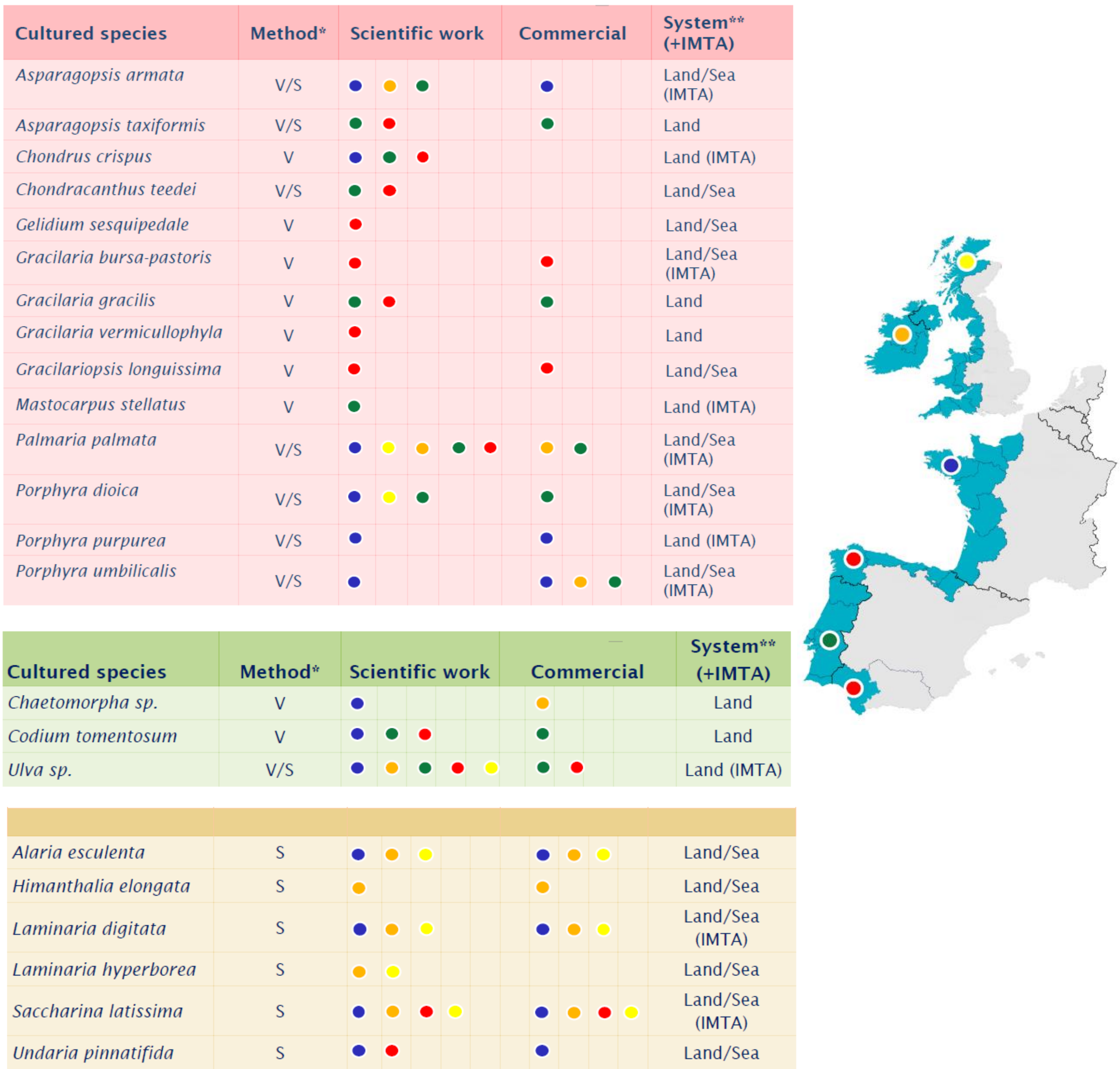

* **Method:** cultivation from Vegetative material and/or from spores. ** **System:** Land (i.e. cultures in flasks, tanks), Sea (i.e. cultures on ropes, nets)

Figure 12 : Mapping of main algae cultivation activities in the Interreg Atlantic Area (Soler-Vila et al. 2020a, 2020b)

2.1.2.1. Seaweed farming methods

Seaweed farming methods are related to species. While some seaweeds can be produced as one-step farming through vegetative propagation, others require more complex farming processes. Indeed, for many species, the life cycle needs to be well known and controlled in order to produce seedlings and perform seeding on culture supports like ropes that can be then brought at sea. Other seaweed species are also not suited for cultivation in open waters with rough winter conditions.

1. **Land-based systems**

Culture using vegetative propagation occurs mostly in land-based systems.

Fragments of seaweed thallus are placed indoor in or outdoor ponds or tanks with enriched and/or renewed seawater to bring nutrients. Ponds/tanks are either built above the ground or dug up directly in the ground and the walls are made up with a liner. Light can be natural or artificial and the temperature can be controlled. The fragments of seaweed are free-floating in the water and moves thanks to agitation systems such as air systems, paddle wheels, etc. Agitation brings gases like O_2 and CO_2 for seaweed growth, homogenizes the nutrients and gives access to light to each fragment. Each fragment grows and provides more biomass.

Once the biomass is sufficient, it can be totally or partially harvested. Land-based systems for cultivation by vegetative propagation are usually tanks or circular ponds with air systems, or raceway ponds with paddle wheels. The main cultivated species for commercial use with this kind of system is *Ulva spp*. Other green seaweeds like *Codium tomentosum* and red seaweed species such as *Palmaria palmata* or *Gracilaria* sp. have been successfully cultivated in tank systems.

The advantages of in-land systems are the total or partial control of growth parameters: light irradiance, nutrient supply, temperature, pH and salinity. It also prevents contaminations (total or partial) by other seaweeds or microalgae/cyanobacteria, which are competitive with the targeted species for light and nutrients, but also predation by grazers that would decrease the yields. Land based systems also allow a rapid action when maintenance is required, and avoid important losses of biomass.

For these reasons, land-based systems are also used for research purposes and for nursery systems for species that have fragile early stages, or when sexual reproduction is needed to perform cultivation. Controlled sexual reproduction allows to produce spores to make seedings of seaweed, especially when they need to be cultivated at sea. Nursery systems are dedicated to the control of sexual reproduction, seeding of supports with spores (especially ropes), germination of spores and culture of plantlets before transportation at sea. This process is well known and widely used for cultivated brown seaweeds *Saccharina latissima*, *Alaria esculenta* and *Undaria pinnatifida*. Mature individuals are usually collected from wild stocks. Maturation can also be induced on non-fertile individuals in the nursery. This technique is well known for *Saccharina latissima*. Spore release from fertile seaweeds is then performed to seed ropes, but also sometimes to keep strains in order to dispose of available genitors. Seeded supports can then be either immediately deployed at sea or kept in ponds in nursery to raise plantlets in controlled conditions before their transfer at sea.

Nevertheless, it is important to point that land-based systems are costly in terms of infrastructure (and its maintenance), energy and, of course, land. Ponds for vegetative culture have to cover a big surface to produce enough biomass. The bigger they are, the more it becomes difficult to control all culture parameters. Fragmentation, harvesting and cleaning efforts increase as well as the size of the system, involving more labour force and adapted equipment. Besides, as seaweeds culture requires seawater, the culture units or nursery systems still need to be located close to the sea, so that seawater can be pumped regularly to supply the whole system. According to the desired water quality, some purification might be required such as filtration systems, sterilisation systems (UV, autoclave) to prevent from contaminations from the pumped seawater.

2. Sea-based systems

Sea-based culture systems are usually located in shallow and sheltered marine environments, a few kilometers from the coastline. These open systems are made of permanent elements at sea : anchoring systems (concrete, anchor and chains) to maintain the structure against currents and wave, moorings (structural ropes) and buoys to mark and support the culture ropes or other culture substrates. The main sea-based system used in Europe for seaweed cultivation (brown seaweeds *Saccharina latissima*, *Alaria esculenta* and *Undaria pinnatifida*) are floating lines. (Peteiro *et al.* 2016) schematized the three main floating line systems used in Europe (Figure 13). Artificially or naturally seeded ropes are deployed vertically or horizontally along fixed lines at sea. The lines are usually separated by 10 meters intervals to prevent tangling and allow navigation with a boat to allow seeded lines setup, harvesting and maintenance. The seaweeds are harvested after a few months of growth. Each line can be maintained close to the surface by floating buoys , in addition to the marker buoys holding each ends of each line. Horizontal culture lines are called “long-line” systems. The horizontal line is located between 0 to 5 meters depths thanks to weights, so that all plantlets have the same exposition to light irradiance (Figure 14). Vertical culture lines are called “hanging rope” system. In that case, the plantlets located closer to

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the surface are more exposed to light irradiance. The rope is held vertically thanks to weights at its bottom and a buoy at the top. A third method is also used, called “Garland type”, consisting in putting the line diagonnaly; it is a mash up between the horizontal and vertical culture systems.

The existing systems are often adapted to each location by the seaweed cultivation companies, in order to optimize the yields and implement trials for new species cultivation. For instance, this is the case in the Faroe Island with the Macroalgal Culture Rig (MACR), developped by the company Ocean Rainforest, which has been used both for commercial and scientific work cultivation trials on novel species like *Palmaria palmata* (Grandorf Bak 2019). The MACR uses the vertically type of culture, but the structural rope is below the surface instead of floating (Figure 16). Successful trials on *Palmaria palmata* in long-line systems have also been carried out in France (CEVA, Figure 14). *Palmaria palmata* domestication has been the subject of many scientific studies over recent years, in order to get commercial and viable culture of this valuable species (Stévant *et al.* 2023).

Sea-based system implies high cost of construction, especially to be strong enough to resist currents and wave. The used materials and architecture of the structure must be carefully made up to avoid breakage and too frequent maintenance. It is indeed directly exposed to climatic events like storms, in which currents and waves can be too strong for the structure but also for the growing seaweeds. Heatwave can be harmful as well. Seasonnality of the cultivated species has to be taken in account too. Some seaweeds cannot grow optimally below or upon thresholds of temperature. These dependency towards climate conditions will be one of the biggest challenge for seaweed cultivation in the current context of climate change. Sea-based cultivation is a completely open system where no nutrient supply is required, but it makes them vulnerable to competition by other seaweeds but also to predation by grazers too, which can affect the yieds. For artificially seeded lines, inland nursery systems are required. But natural seeding at sea can be possible for some species, like *Asparagopsis armata*, cultivated at sea only by natural recruitment on ropes by one company in Brittany, without the inland nursery step.

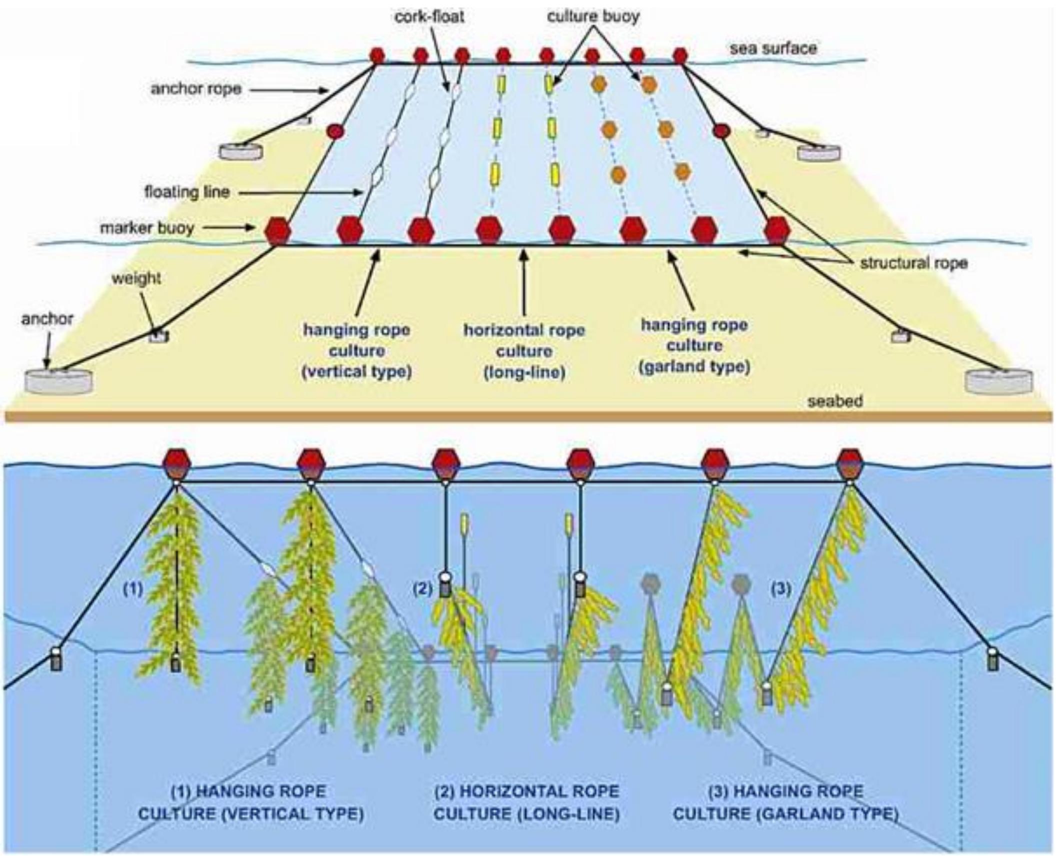

Figure 13 : Illustration of the three floating lines systems on a raft designed by (Peteiro et al. 2016), showing the main components of sea-based culture structures

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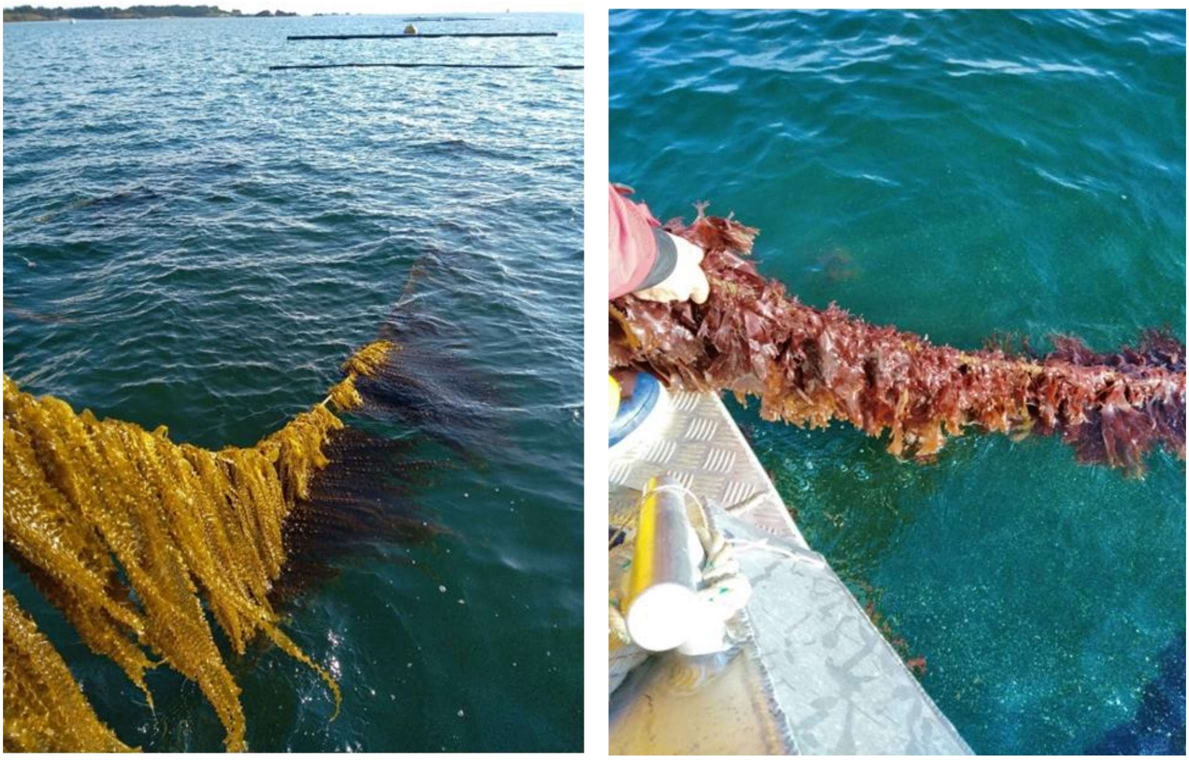

Figure 14 : Seeded lines of Saccharina latissima (left) and Palmaria palmata (right) after 3 months of growth at sea (long-line system) ©CEVA 2022

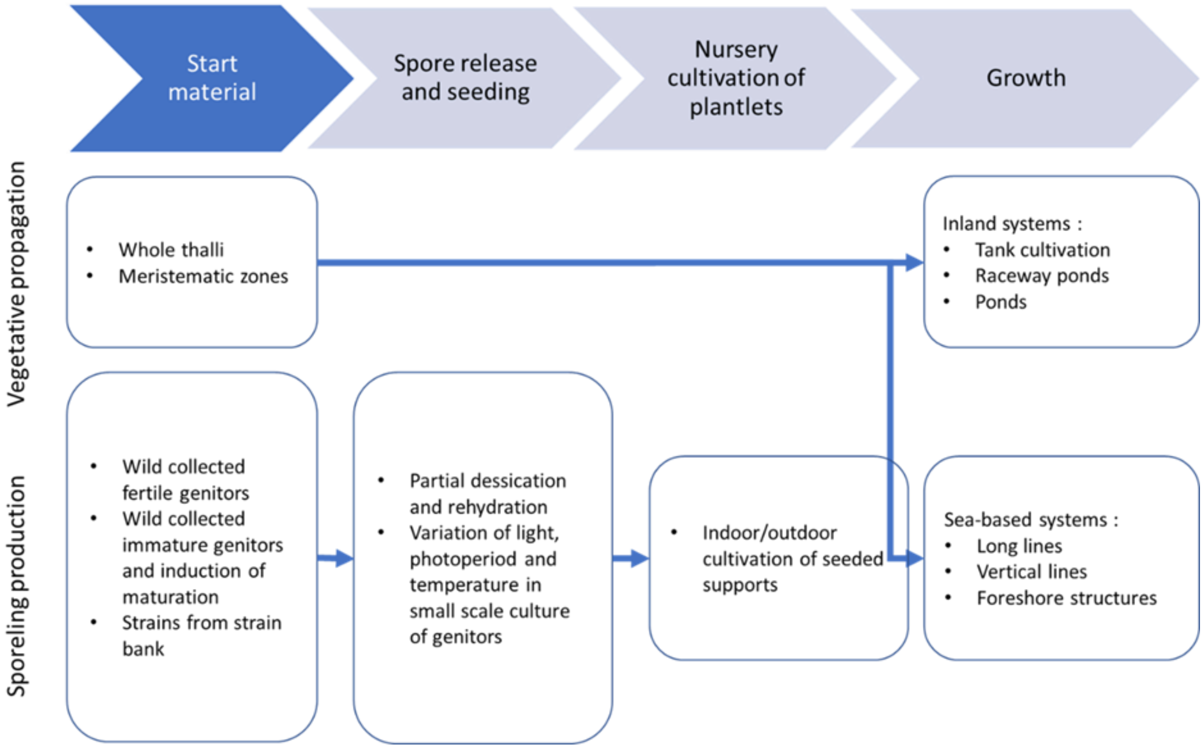

Figure 15 : Summary of seaweed cultivation main steps adapted from (Stévant et al. 2023)

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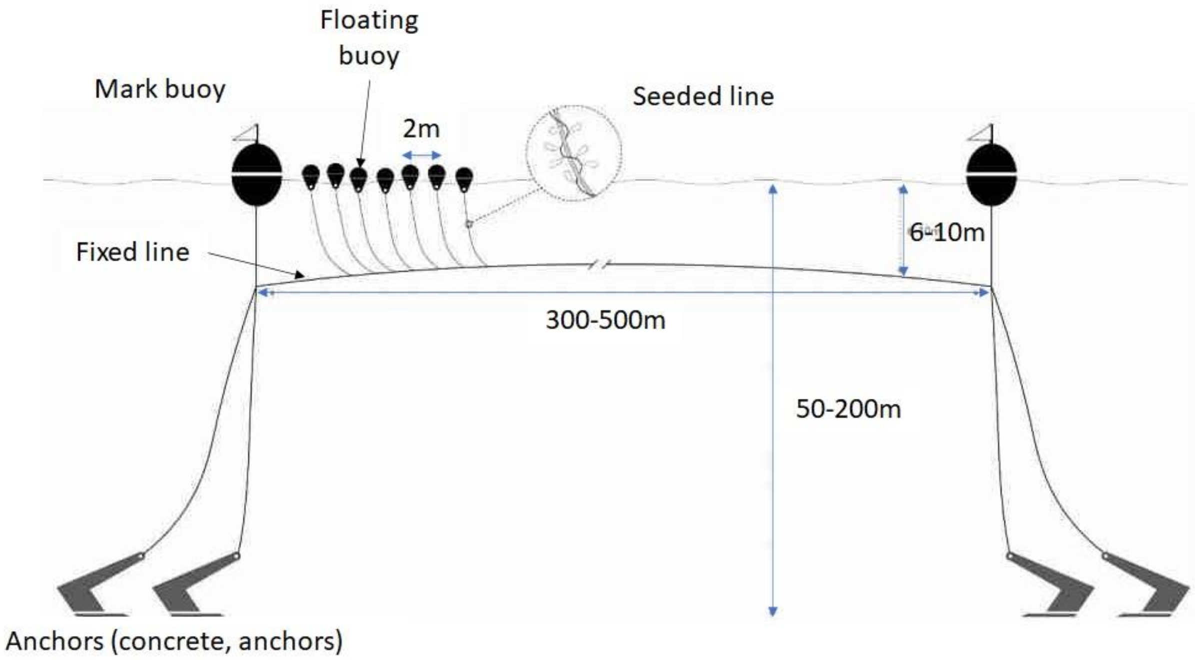

Figure 16 : Macroalgal Cultivation Rig (MACR) used in the Faroe Islands for commercial cultivation of Saccharina latissima and Alaria esculenta. illustration modified from (Grandorf Bak 2019)

2.1.2.2 Seaweed species cultivated in Europe

Seaweed farming is associated with a potential for larger production of renewable biomass, and may contribute positively to the environment. Within the different European countries, we could highlight a strong interest for the sugar kelp considered as a high potential alga with interesting biomass yields and valuable nutrients content.

Norway

While still low at a global scale (about 350 tons of cultivated macroalgae in 2020 (Nøkling-Eide et al. 2023), the seaweed market is rapidly growing in Norway. Norway is the largest European cultivated seaweed producer, with a seaweed industry historically mainly dedicated to alginate extraction, but now extending into other applications. Considering its extensive rocky coastline and nutrient rich cold waters, Norway presents favourable growth conditions for brown algae.

Table 1: Synthesis of cultivated seaweed species in Norway

Type	Scientific name	Norwegian name
Phaeophyceae	*Saccharina latissima*	Sukkertare
	Alaria esculenta	Butare
	Laminaria digitata	Fingertare
	Laminaria hyperborea	Stortare
Rhodophyceae	*Palmaria palmata*	Søl
Chlorophyceae	*Ulva lactuca*	Havsalat

The kelp industry represents the major part of the total Norwegian macroalgae farming industry with the predominant cultivated species *Saccharina latissima* and in smaller volumes the winged kelp *Alaria esculenta* (Figure 17). Sugar kelp is cultivated by four main companies in Norway: the company Lerøy

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Ocean Harvest (producing itself about half of the sugar kelp biomass, and an expected a production of 300 tons in 2022), Seaweed solutions, Tango Seaweed AS, and Folla AlgerAS.

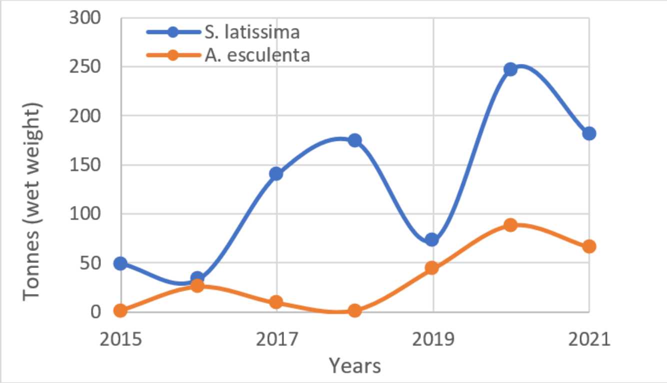

Figure 17 : Evolution of kelp farming in Norway between 2015 and 2021 (Fiskeridirektoratet)

Several sites allocated to seaweed cultivation have been recorded along the Norwegian coast. Part of these sites is located near intensive salmon aquaculture facilities. In 2019, Norway produced 1,36 million tons of salmon (Statistik Sentralbyrå, 2020), and this production is likely to rise over the coming decades. Seaweed provides several key ecosystem services and could solve sustainability challenges such as excess nutrients discharged by aquaculture. Therefore, benefits of IMTA (Integrated multitrophic Aquaculture) with seaweed as extractive component to recover nutrients discharged from fish farms high dissolved inorganic nutrients presents a high potential in Norway.

France

Seaweed cultivation represents less than 1% of the French seaweed production in volume (121 tons in 2018 according to (Grebot 2021))

Most of the French seaweed production is located at sea. Until recently, the predominant cultivated species is the non-native species *Undaria pinnatifida* with around 68 tons of cultivated wakame in 2018 (AGRESTE 2020a), and 105 tons in 2019 (AGRESTE 2021). However, a ban on new farming licences or extension of existing farms is in place since 2013 (non-native species) and a stagnation of this production is expected. It is followed by *Saccharina latissima*, with 45 tons produced in 2018, and a similar quantity in 2019. A few tons of the brown seaweed *Alaria esculenta* are also cultivated at sea by two companies in Brittany (Algolesko and C-Weed). Some companies have been involved in developing culture techniques for this species (Luthringer 2020) from existing methods used for *Saccharina latissima* and *Undaria pinnatifida*.

2020 was marked by COVID and a reduction of cultivated seaweed volumes (AGRESTE 2020b). Official statistics for 2021 are not available yet, but should confirm the progression of *Saccharina latissima* cultivation.

While France is the European leader in oysters' production, the natural *Porphyra* sp. exploitation could be very attractive and of high added value for oyster farmers. Indeed, very large and pure proliferations of colonies of *Porphyra* species, especially *Porphyra purpurea*, are noticed each year in Atlantic French seafarms located on the foreshore. Oyster farms systems are also yearly colonized by tubular species of *Ulva* sp. (formally called *Enteromorpha* sp.). Oyster farms then offer a great potential for these two species cultivations. Studies have been carried out on these natural seedings in Brittany and in the South Atlantic French coast, were most of the oyster production is located (CEVA 2012; Eustache and Pien 2018; Grassien 2018; Hennache 2019; Integrate 2020; Luthringer 2021). Natural and artificial seedings trials of *Porphyra purpurea* have been recently successfully conducted on oyster bags in Brittany and Normandy. Cultivation of *Porphyra purpurea* within oyster farms has become one of the main challenges of developing IMTA.

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UK

In the UK, the seaweed industry is slowly growing, especially in Scotland, with a small activity in Northern Ireland, England and Whales. The current sector depends mostly on harvested wild stocks and seaweed farming is still at an early stage (research and pilot scale). Kelp is the predominant cultivated seaweed: especially *Saccharina latissima*, associated with a small production of *Laminaria digitata (Wilding 2021)*. The Scottish Association of Marine Sciences (SAMS) is a key stakeholder involved in several R&D projects for the cultivation of *Saccharina latissima*, *Laminaria hyperborea*, *Palmaria palmata* and *Ulva*.

Ireland

Ireland shows high potential for seaweed farming regarding its favourable climatic conditions. In 2018, Ireland produced a total of 40 tons of farmed seaweed (FAO 2021). In 2019, 42 tons of cultivated *Alaria esculenta* were recorded (FAO 2021; Irish Sea Fisheries Board 2020).

The red algae *Palmaria palmata*, *Mastocarpus stellatus* and *Chondrus crispus* are also grown in small volumes on longlines in Ireland (Wilding 2021).

Sweden

The Swedish Maritime Strategy Program approved in 2022 mentioned the strong potential of macroalgae cultivation in the aquaculture industry (Camarena-Gómez *et al.* 2022). To date, in Sweden, seaweed farming is still a marginal activity.

Nordic Seafarm is the largest company cultivating seaweed at commercial scale (around 30 tons in 2022 (Metingil 2022)), and is mainly selling raw biomass (frozen or dried) for the food industry. Cultivated species include *S. latissima* (representing the main part of their production), *L. digitata* and *Ulva sp*. The company is currently increasing cultivation capacity for *S. latissima* and *Ulva sp.* (Camarena-Gómez *et al.* 2022; Industry interviews 2023)

Several other companies are conducting pilot scale cultures of *Saccharina latissima*, *Ulva* sp., *Chondrus crispus* and *Asparagopsis (Hermans 2023b)*.

Finland

To date, there is no commercially produced seaweed in Finland. The start-up company Origin by Ocean is developing *Fucus vesiculosus* farming around the Archipelago Sea, and is expected to be fully operational in 2026.

Denmark/Faroe Island

Denmark: Seaweed farming in Denmark started in 2008. Nevertheless, the current production is still marginal with less than 10 tons of *Saccharina latissima* produced per year by one major producer: Hjarnø Havbrug. Small volumes of *Ulva* sp. in land-based cultivation systems are also grown by the company Pure Algae.

Faroe Islands: The Faroe Islands present promising geo-biophysical conditions for seaweed cultivation with a high production yield (Christensen 2020). Two companies are currently cultivating seaweed at commercial scale in the Faroe islands: Ocean Rainforest (cultivating *Saccharina latissima*, *Alaria esculenta*, *Laminaria digitata* and *Palmaria palmata*) and Tari (cultivating *Saccharina latissima*). (Irish Sea Fisheries Board 2020). The annual production capacity of Ocean Rainforest in the Faroe Islands is around 500 tons per year.

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Spain

In Spain, the seaweed production is concentrated around the North-Western coast: Galicia (83%) and Andalucia (17%), produced a total of 5,2 tons in 2019. According to FAO, the main cultivated species in Spain in 2020 were *Ulva lactuca* (6 t) and *Saccharina latissima* (1,3 t). *Codium* and *Gracilaria* are also produced in negligible volumes.

Portugal

In Portugal, three companies are currently cultivating macroalgae (especially *Ulva* sp.). ALGA+ is an important stakeholder of the Portuguese seaweed economy. The company mostly produces *Ulva rigida*, and is conducting experimentations on the production of *Codium tomentosum*, *Gracilaria* and *Porphyra.*

The Netherlands

The Netherlands presents a small seaweed farming activity with a total production of 15 to 20 tons per year of the fast-growing species *Saccharina latissima*, and at a smaller scale *Ulva* sp. (in tanks), but the government has a strong ambition to develop seaweed farming systems around off-shore wind turbines.

The project North Sea farm led by North Sea Farmers will set up the world's first seaweed farm between offshore wind turbines. The first harvest of this 10-hectares seaweed farm is expecting a production of at least 6 tons of kelp in 2024.

2.2. Microalgae and cyanobacteria

2.2.1. Production technologies for microalgae and cyanobacteria

Microalgae and spirulina can be cultivated in various systems from non-regulated open-ponds to very sophisticated closed technologies. The choice of the technology mostly depends on the biology of the cultivated species, the availability of the land, the climate and the target market. A compromise must be found between the performance and the cost of the culture system to have an economically sustainable global process (Borowitzka 1999).

Some examples of productivities by species and culture systems are presented in Table 2. An average value of 30 ton/ha/year for fast growing species can be attained, with solar light, in Mediterranean areas (Industry interviews 2023).

To limit costs of microalgae production, some culture systems can be integrated in other systems like factories releasing CO_2 and heat, wastewater treatment units or building facades (Barros *et al.* 2022; Grivalský *et al.* 2022; Lu *et al.* 2020; Mayers *et al.* 2016; Pruvost *et al.* 2016). A number of large-scale facilities (hectare-size) have also been built and operated to bring these technologies to scale, often in Southern Europe as for instance Cecil/Allmicroalgae Algafarm or Algatec Eco Business Park developed by A4F in Portugal, but also in Northern Europe with Algenfarm Klötze facility in Germany, or AlgaePARC research facility in the Netherlands.

In Europe, 72 % of companies use photobioreactors (PBR) to produce microalgae. About 20 % of companies also use fermenters or open ponds (Figure 18).

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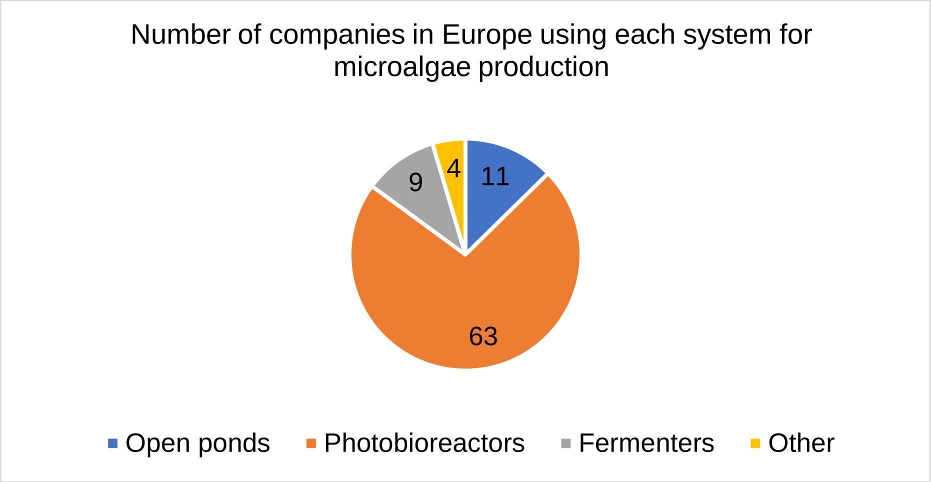

Figure 18 : Number of companies in Europe using each system for microalgae production. note: Companies using several production systems have been counted several times.

On the contrary, for Spirulina production, 80 % of companies use open ponds. The other companies use photobioreactors (Figure 19).

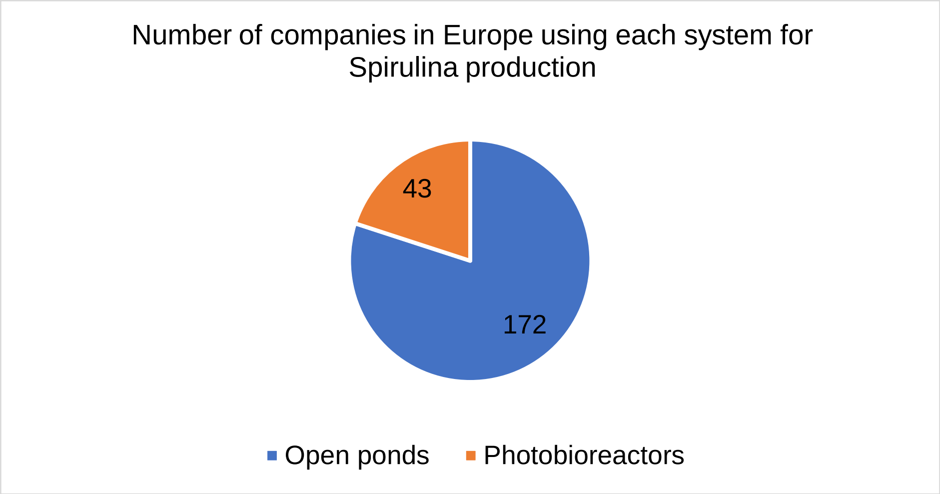

Figure 19 : Number of companies in Europe using each system for Spirulina production. Note: Companies using several production systems have been counted several times.

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Table 2: Non-exhaustive examples of productivities by species and system of production.

Species	Culture system	Country	Volume (L)	Areal productivity (g m^{-2} day^{-1})	Volumetric productivity g L^{-1} day^{-1}	Reference
Dunaliella salina	Raceway pond	Spain	2000	1.7		(García-González *et al.* 2005)
Haematococcus pluvialis	Raceway pond	Hawaii	50000	15.1	0.13	(Huntley and Redalje 2007)
Haematococcus pluvialis	Tubular	Hawaii	25000	10.2		(Huntley and Redalje 2007)
Chlorella sp.	Thin layer raceway pond	Czech Republic	2200	14.3	1.46	(Masojídek *et al.* 2011)
Chlorella sp.	Thin layer cascade	Czech Republic	170-225	18.7	1.87 - 2.52*	(Masojídek *et al.* 2011)
Phaeodactylum tricornutum	Open pond	Italy	2500	10.9	0.04	(Buono *et al.* 2016)
Tetradesmus obliquus	Open pond	Italy	2500	7.5	0.03	(Buono *et al.* 2016)
Phaeodactylum tricornutum	Tubular bag	Italy	100	4.9		(Buono *et al.* 2016)
Tetradesmus obliquus	Tubular bag	Italy	100	6.2		(Buono *et al.* 2016)
Chlorella sorokiniana	Plastic bag		5		0.24	(Chen *et al.* 2013)
Nannochloropsis oceanica	Plastic bag		5		0.25	(Chen *et al.* 2018)
Scenedesmus obliquus	Plastic bag		320 (20x16)		0.14	(Abomohra *et al.* 2014)
Tetraselmis suecica	Airlift column	Italy	120	38.2	0.42	(Chini Zittelli *et al.* 2006)
Chlorella sp.	Airlift column + porous centric tube				0.61	(Chiu *et al.* 2009)
Chlorella vulgaris	Vertical tubular	Taiwan	50		0.27	(Chen *et al.* 2016)
Chlorella vulgaris	Fermenter	Portugal	200		27.5	(Barros *et al.* 2019)
Chlorella vulgaris	Fermenter	Portugal	5000		31.9	(Barros *et al.* 2019)
Chlorella vulgaris	Flat panel	Portugal	1000		0.11	(Barros *et al.* 2019)
Nannochloropsis sp.	Horizontal tubular	Netherland	560	12.1	0.65	(Vree *et al.* 2015)
Nannochloropsis sp.	Vertical tubular	Netherland	1060	19.4	0.57	(Vree *et al.* 2015)

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Nannochloropsis sp.	Flat panel	Netherland	60	20.5	0.90	(Vree *et al.* 2015)
Nannochloropsis sp.	Raceway pond	Netherland	4730	9.7	0.03	(Vree *et al.* 2015)
Nannochloropsis sp.	Flat panel	Australia	140	19	0.14	(Nwoba *et al.* 2020)
Nannochloropsis sp.	Horizontal tubular	Italy	600		0,8	(Zittelli *et al.* 2003)
Dunaliella salina	Flat panel	India (Indoor)	34		0.013	(Rhadim, S., R. *et al.* 2018)
Dunaliella salina	Horizontal tubular	Spain	55	2.2	0.08	(García-González *et al.* 2005)
Phaeodactylum tricornutum	Flexible flat panel	Portugal	125	10.0	0.08	(Quelhas *et al.* 2019)
Phaeodactylum tricornutum	Horizontal tubular	Portugal	35000	19.1	0.07	(Quelhas *et al.* 2019)
Haematococcus pluvialis	Tubular	Hawaii	25000	13	0.05	(Olaizola 2000)
Dunaliella salina	Fibonacci-type tubular	Chili	1250		0.12	(Díaz *et al.* 2021)
Arthrospira platensis	Open pond	Italy	2500	17	0.14	(Vonshak *et al.* 2014)
Arthrospira platensis	Horizontal tubular	Italy	145	27.8	1.5	(Torzillo *et al.* 1993)

** depending on the surface/volume ratio considered*

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2.2.1.1. Open ponds

The cheapest and oldest technology to produce microalgae is the artificial pond or lagoon. It consists of a water basin with a 20 to 40 cm depth.

To avoid sedimentation and improve the light diffusion in the culture depth, agitated basins have been designed. These basins can either be circular or raceway-shaped. Circular basins are agitated with a rotating arm but the mixing is still poor in these systems. Raceway ponds consist of ponds with a central divider and are agitated with a paddle-wheel. Compared to circular ponds, raceway ponds have a better mixing and the scale-up is easier (Borowitzka 1999; Legrand *et al.* 2021).

By reducing the thickness of the culture, it is possible to increase the biomass productivity in open ponds. The thin layer cascade system (Figure 20) has been developed for this purpose in the 1960's and is still used in Trebon, Czech Republic (Grivalský *et al.* 2022). It is characterized by a low depth (inferior to 10 mm) which confers a high surface/volume ratio leading to high biomass concentration (25-35 g L^{-1}) (Borowitzka 2013; Masojídek *et al.* 2011).

More recently, a 3,000 m^2 / 180 m^3 cascade raceway was developed and optimized by A4F in Portugal within European project BIOFAT (Figure 21).

Figure 20 : Algatech Thin layer cascade in Trebon, Czech Republic (Malapascua et al. 2014)

Figure 21 : A4F Cascade raceways in Pataias, Portugal

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Historically, open ponds have been largely used because they are cheaper than closed PBR. In 2010, the cost for a 100 ha open pond system was estimated to be 0.37 M€/ha (Norsker *et al.* 2011).

Moreover, these systems are easy to clean, they need low energy input, their maintenance is not complicated and they can easily be scaled up. However, they require significant available land and they allow limited control on various parameters (temperature, CO_2, mixing, contaminations) resulting in a low productivity (Brennan and Owende 2010). Only species which are not, or weakly, subject to contamination can be cultivated in open ponds. For example, the large utilization of open ponds for Spirulina is explained by the fact that optimal pH for Spirulina is comprised between 9.5 and 9.8 reducing the contamination by bacteria (Richmond and Hu 2013).

2.2.1.2. Closed photobioreactors

To improve the productivity and the quality of the product, it is possible to cultivate microalgae in closed photobioreactors (PBR). Indeed, these systems provide a better control of culture conditions and limited contaminations. Moreover, in these systems the water evaporation is lower compared to open systems. But depending on the technology, closed PBR can be expensive, difficult to scale-up and some problem can occur like high temperatures, high dissolved oxygen concentration, biofouling and limited light diffusion (Brennan and Owende 2010).

To overcome these problems, different PBR technologies have been developed.

<u>Plastic bags</u>

One of the least optimised PBR that can be used for the commercial production of microalgae is the plastic bag. These reactors are aerated from the bottom. They have the advantage to be low cost in the short term and easily scaled-up by multiplication of the plastic bags. However, they confer a low mixing and a low light surface to volume ratio leading to a weak productivity (Huang *et al.* 2017).

In 5 L plastic bags, maximal productivity of *Chlorella sorokiniana* was equal to 0.24 g L^{-1} day^{-1} (Chen *et al.* 2013) and maximal productivity of *Nannochloropsis oceanica* was equal to 0.25 g L^{-1} day^{-1} (Chen *et al.* 2018). In 20 plastic bags of 16 L each, the maximal productivity of *Scenedesmus obliquus* reached 0.14 g L^{-1} day^{-1} (Abomohra *et al.* 2014).

<u>Airlift columns</u>

Another closed system is the airlift column. It is the oldest closed PBR described in literature (Chaumont 1993). As plastic bags, rigid airlift columns are aerated from the bottom and illuminated through transparent plastic glass walls. They induce low-operation cost and present an acceptable gas-liquid mass transfer performance. However, in these systems, microalgae are often light limited leading to a low productivity. To limit this problem, the diameter of an airlift column should not exceed 0.2 m (Huang *et al.* 2017). In these systems, it was reported an area productivity of 38.2 g m^{-2} day^{-1} and a volume productivity of 0.42 g L^{-1} day^{-1} for *Tetraselmis suecica* (Chini Zittelli *et al.* 2006).

To improve the mixing, it is possible to add a centric or a porous centric tube in the airlift column (Figure 22). In batch mode, a maximal *Chlorella* sp. concentration of 3.5 g L^{-1} was obtained after 4 days of cultivation in the column equipped with a porous centric tube whereas the concentration was equal to 2.4 g L^{-1} in the simple column. In the column equipped with a porous centric tube, the productivity of *Chlorella* sp. reached 0.61 g L^{-1} day^{-1} in a semi-continuous mode (Chiu *et al.* 2009).

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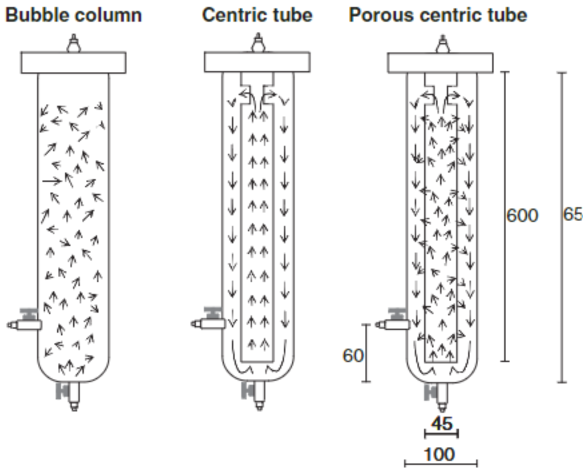

Figure 22 : Scheme of the different types of airlift column.
Arrows indicate the liquid flow pattern of each system. Distances are given in mm (Chiu et al. 2009).

Tubular reactors

Among industrial closed systems, tubular reactors are the most used. These reactors are considered as expensive. In 2010, investment was estimated to be € 0.5 M/ha for 100 ha horizontal tubular plant production (Norsker *et al.* 2011), but investments costs are usually higher (and current production site do not reach this scale).

The oldest tubular reactor is the serpentine photobioreactor composed of straight tubes connected by U-bends. It can be horizontal or vertical. In this system, nutrients supply and gas exchanges are done in a separate vessel and the culture is mixed through a pump or an airlift system.

To decrease heat losses and oxygen concentration of tubular PBR, manifold PBR have been set up. In these reactors, parallel tubes are connected by two manifolds at each extremity: one for culture distribution and the other for culture collection.

Growing *Arthrospira platensis* in tubular PBR also allowed to reach 33 t ha^{-1} $year^{-1}$ while the same species reached 18 t ha^{-1} year $^{-1}$ in open ponds (Vonshak 1997).

Various examples of industrial tubular reactors can be found in Europe.

Algenfarm Klötze (formerly Roquette), in Germany, operates a covered (greenhouse) PBR composed of 500 km of glass tubes (Figure 23) to produce *Chlorella* and other microalgae species.

Secil/Allmicroalgae's Algafarm operates a 1,300 cubic meter PBR facility (Figure 24), complemented by additional fermentation capacity, with an annual potential output of around 100 tons of dried biomass. They produce mainly *Chlorella sp*, as well as other species (*Nannochloropsis* sp., *Phaeodactylum* sp. and *Tetraselmis* sp).

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Figure 23 : 500 km long, 600 m^3 tubular manifold PBR in a greenhouse operated by Algenfarm Klötze, Germany

Figure 24 : 1.300 m^3 tubular PBR designed by A4F for Secil/Allmicroalgae Algafarrm in Pataias, Portugal

To improve the productivity of tubular PBR, other shapes and arrangements exist.

For example, helical PBRs have been developed to provide the deployment of long tubes on a small area. Another recent example of tubular PBR is the Fibonacci-type tubular photobioreactor (Figure 25) which allows to maintain temperature, pH and dissolved oxygen within optimal range leading to an increase in the high light utilization (Díaz *et al.* 2019). In this system, the biomass concentration of *Dunaliella salina* reached 0.96 g L^{-1} and the productivity reached 0.12 g L^{-1} day $^{-1}$ (Díaz *et al.* 2021) whereas the productivity of the same species reached 0.08 g L^{-1} day^{-1} in horizontal tubular PBRs (García-González *et al.* 2005).

The tubes arrangement versatility is also an asset for optimal cost-effective production. For instance, it can be designed to act as a solar collector (Unilayer Horizontal Tubular PBR) or provide the highest amount of photosynthetic area using the minimum implantation surface (Multilayer Horizontal Tubular PBR) (A4F 2023).

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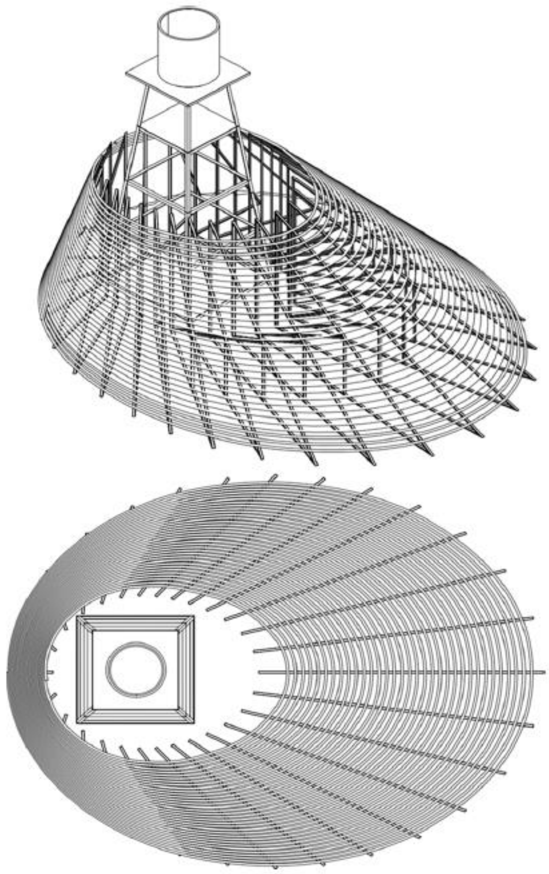

Figure 25 : Scheme of the Fibonacci-type tubular photobioreactor (Díaz et al. 2019)

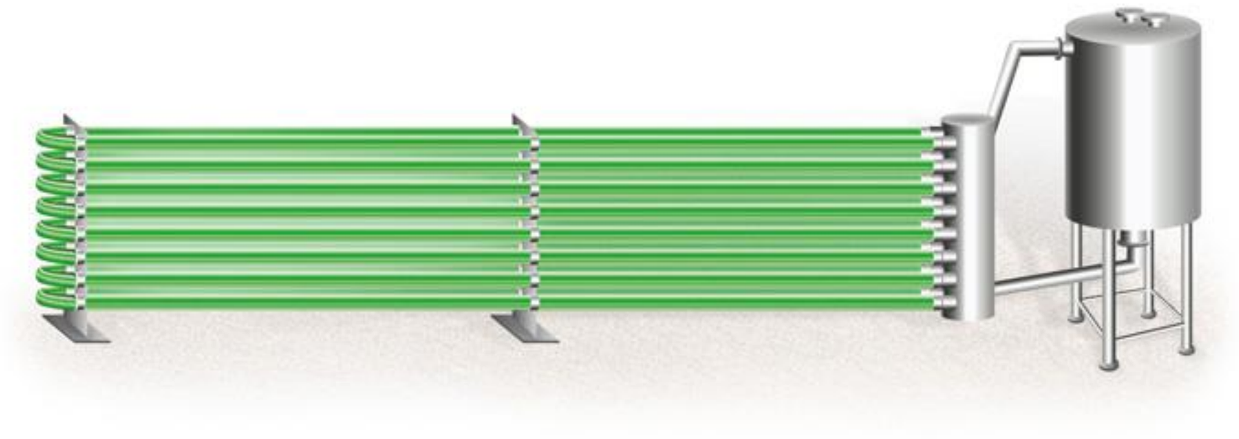

Figure 26 : Unilayer Horizontal Tubular PBR (A4F 2023)

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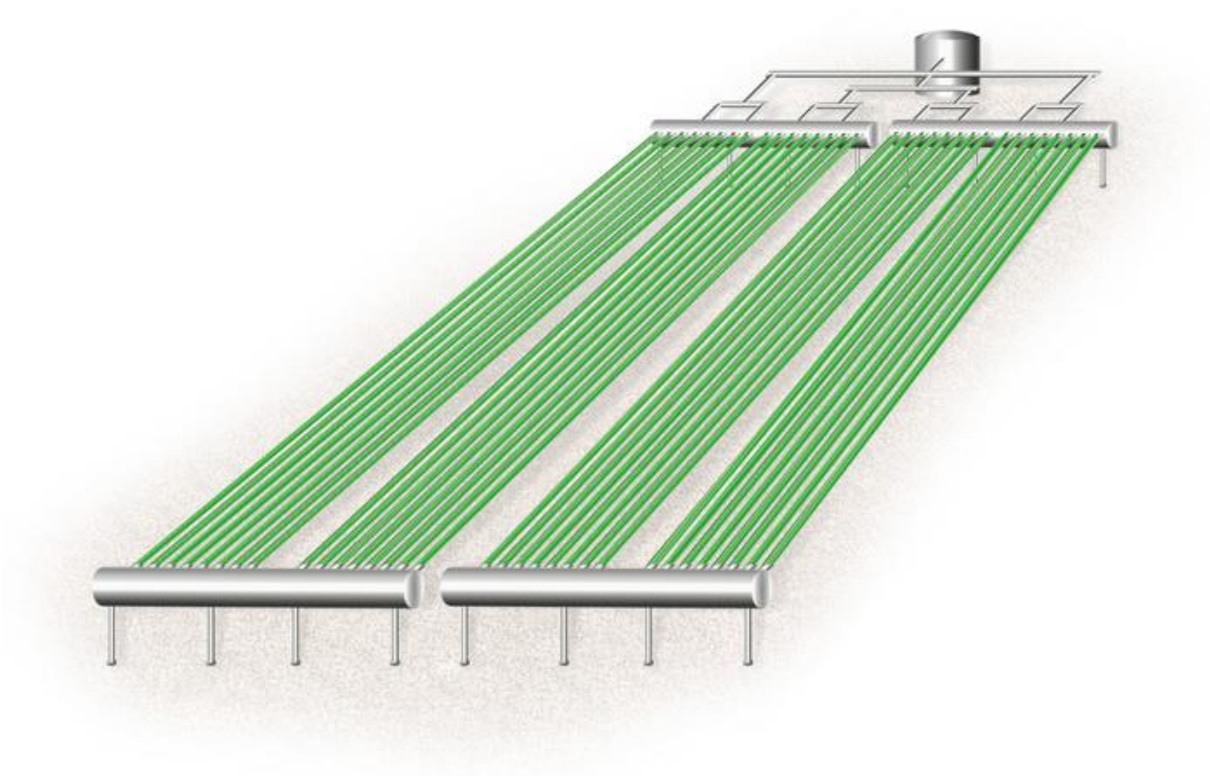

Figure 27 : Multilayer Horizontal Tubular PBR
(A4F 2023)

Flat panels

The last PBRs used for mass cultivation of microalgae are the flat panels. Due to their good biomass illumination, they are considered as more efficient compared to tubular photobioreactors. For example, growing *Nannochloropsis* sp. in flat panels allowed to increase the volume productivity from 0.6 to 0.9 g L^{-1} day^{-1} compared to growing it in tubular PBR (Vree *et al.* 2015).

Flat panels consist of transparent flat vessels where culture is mixed by air-lift aeration. Compared to other systems, they are more difficult to scale up because of mechanical constraints (Legrand *et al.* 2021). However, they claim optimized energy consumption like the "Flat Panel Air-Lift" system designed by Subitec GmbH (Patel *et al.* 2012). Investment is estimated to be around € 0.8 M/ha for a 100 ha production plant using flat panels (Norsker *et al.* 2011; Vree *et al.* 2015).

Some improvements can be done on these systems. For example, light capture can be improved by the use of lenses (Zijffers *et al.* 2008). Temperature can also be controlled by spraying fresh water on the surface or even by adding a film on the surface that reflected Ultra-violet and Infra-Red wavelengths (Nwoba *et al.* 2020). The panels can also be immerged in a large volume of water that can be cooled or heated through a heat exchanger (Vree *et al.* 2015).

Another example of a patented flat panel is the "Green Wall Panel" (Figure 28) which consists of plastic culture chambers contained by vertical uprights connected themselves to an horizontal bar (Tredici *et al.* 2011; Tredici *et al.* 2015).

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Figure 28 : Green Wall Panel-II photobioreactors at the F&M facility in Siesto Fiorentino (Italy)

In order to increase the productivity and limit the costs, new technologies of PBR are being developed. For example, Algofilm photobioreactor is an intensified PBR which allows higher biomass concentrations compared to traditional systems due to a culture thickness of 1.5 mm (Goetz *et al.* 2011). Another example of newly developed technology is the DiCoFluV (Solar Flux Volume Controlled Dilution). It is a 21 L PBR in which light is diffused through optical fibres (Rochatte *et al.* 2016).

However, even if these technologies are promising, they are only available on a laboratory scale.

2.2.1.3. Fermenters

Some microalgae are able to grow in heterotrophy. This cultivation mode is interesting to counter some problems linked to PBR like light or CO_2 distribution in the culture (Richmond and Hu 2013). As a consequence, for some species, biomass concentrations and productivities can be higher in fermenter than in PBR. For example, productivity of *Chlorella vulgaris* can reach more than 30 g L^{-1} day^{-1} in fermenter, whereas it rarely exceeds 1 g L^{-1} day^{-1} in photoautotrophic systems (Barros *et al.* 2019). Another advantage of fermenters is their simple geometry allowing an easier scale-up compared to PBR technologies (Liang *et al.* 2009).

However, the fermenters can be used only on a few species of microalgae and a carbon source is necessary leading to a higher cost.

Cultures in fermenters are mainly done to produce high value compounds in very controlled conditions. In heterotrophy, the composition of microalgae is modified. They can lose up to 94 % of their chlorophyll and present an increase in lipids and some carotenoids compared to culture in autotrophy (Perez-Garcia *et al.* 2011; Xu *et al.* 2006).

To optimise the culture in fermenters, it is also possible to change the carbon source. Generally, better productivities are obtained with glucose but acetic acid and glycerol can also be used (Griffith *et al.* 1960).

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2.2.2. Production of microalgae in Europe: species, volumes and producing countries

Due to the small amount of microalgae volume produced compared to other biomasses, there is no obligation to report the productions in most of European countries. As a consequence, there is almost no official statistic on microalgae production volumes and existing statistics are uncomplete.

In 2021, (Araújo *et al.* 2021) collected data from 225 producers of macroalgae, microalgae or Spirulina in the 27 EU member states, United Kingdom, EEA countries and Switzerland *via* a questionnaire. Today and to our knowledge, it is the most complete study on algal production in Europe. However, data regarding microalgae and spirulina need to be taken with caution as they are estimations for most of them. Some countries and companies producing microalgae and Spirulina are not included in this study.

Other statistics like FAO reports exist. However, they seem to underestimate the production of microalgae as they count only 4 countries in Europe cultivating Spirulina and 2 countries cultivating green microalgae (FAO 2021). Inversely, some numbers are overestimated following confusions between fresh and dry weight (e.g. reporting of French data in the same report).

For some countries, local reports or national statistics can be found on spirulina and/or microalgae productions.

Some existing data regarding production volumes of microalgae are gathered in Table 3 to

Table *5*.

The global production of microalgae was estimated to be 130,000 tons (dry weight) in 2022 for a market value equal to €2.6 billion according to EABA (EUMOFA 2023) but this value most likely encompasses all microalgae, as well as cyanobacteria and possibly Labyrinthulomycetes.

In Europe, it was estimated inferior to 650 tons in the same report (EUMOFA 2023), but this likely encompasses cyanobacteria and Labyrinthulomycetes again. There are between 82 and 87 companies producing microalgae in Europe (Vazquez Calderon and Sanchez Lopez 2022).

Table 3: Global Production volumes for microalgae.

Country	Species	Tons per year	Year	Economic value (€)	Reference
World	All	130,000 *(incl. Spirulina and Labyrinthulomycetes?)*		2.6 billion	EABA reported in (EUMOFA 2023)
World	*Chlorella* spp.	> 3,500	2020		CEVA, *unpublished*
World	*Haematococcus pluvialis*	750	2020		CEVA, *unpublished*
World	*Dunaliella* spp	700	2020		CEVA, *unpublished*
World	*Euglena* spp.	370	2020		CEVA, *unpublished*

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Table 4: Production volumes of microalgae in Europe.

Country	Species	Tons per year	Year	Economic value (€)	Reference
Europe	All	182			(Araújo *et al.* 2021)
Europe	*Chlorella* spp.	82			(Araújo *et al.* 2021)
Europe	*Nannochloropsis spp.*	21			(Araújo *et al.* 2021)
Europe	*Haematococcus pluvialis*	66			(Araújo *et al.* 2021)
Europe	*Tysochrysis lutea*	< 1			(Araújo *et al.* 2021)
Europe	*Dunaliella salina*	2			(Araújo *et al.* 2021)
Europe	*Phaeodactylum tricornutum*	4			(Araújo *et al.* 2021)
Europe	*Tetraselmis* spp.	5			(Araújo *et al.* 2021)
Europe	*Porphyridium* spp.	< 1			(Araújo *et al.* 2021)

Table 5: Production volumes in individual European countries.

Country	Species	Tons per year	Year	Economic value (€)	Reference
Austria	*Haematococcus pluvialis*	15	2021		(Bundesministerium Klimaschulz, Umwelt, Energie, Mobilität, Innovation und Technologie 2021)
France	*Tetraselmis*	0.3	2019	33,000	(AGRESTE 2021)
France	*Chlorella*	1	2019	27,000	(AGRESTE 2021)
France	other microalgae	3.6	2019	943,000	(AGRESTE 2021)
France	Microalgae	4.6	2020	371,000	(AGRESTE 2020b)
Iceland	*Haematococcus pluvialis* for astaxanthin	~50	2020	10.6 M	(Government of Iceland - Ministry of Food, Agriculture and Fisheries 2023); CEVA, *unpublished*
Italy	All	25			https://agronotizie.imagelinenetwork.com
Italy	All	< 50			*Personal communications*
Italy	Microalgae	< 6.5	2021		AISAM reported in https://www.aquafeed.co.uk/microalgae-cultivation-updates-presented-at-the-algaefarm-24498/
Spain	Microalgae	0.8	2020		(APROMAR 2022)
Spain	*Tetraselmis* sp.	0.78	2021	41,181	(Ministerio de agricultura, pesca y alimentacion 2022a)
Sweden	*Haematococcus pluvialis* for astaxanthin	~40	2022		CEVA, *unpublished*
UK	*Spirulina and microalgae*	1 to 5	2013		(Ministère de l'agriculture et de la souveraineté alimentaire 2022)

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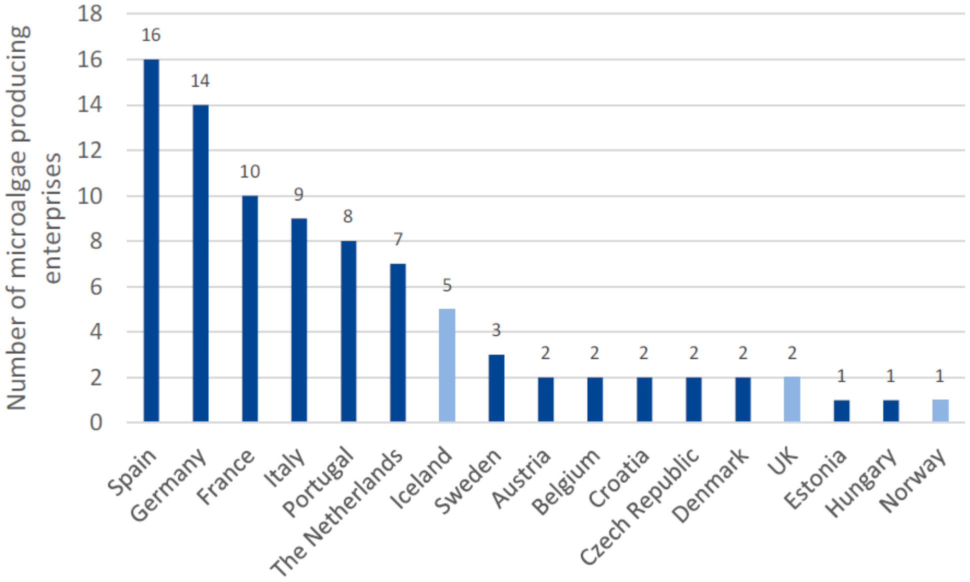

Figure 29 : Number of microalgae producing companies per country in the EU (dark blue) and other European countries (light blue) (Vazquez Calderon and Sanchez Lopez 2022).

In Europe, Spain has the largest number of companies producing microalgae with 16 companies (Figure 29). The biggest Spanish company for microalgae production is AlgaEnergy with 2 production sites in Madrid and Cadiz. In Spain, the production of microalgae was estimated to reach 0.8 tons in 2022 with a majority of *Tetraselmis* produced (APROMAR 2022; Ministerio de agricultura, pesca y alimentacion 2022b).

After Spain, Germany, France, Italy, Portugal and the Netherlands have the largest numbers of companies producing microalgae.

In Germany, most of the companies (Algenfarm Klötze GmbH & Co., Algenland, Algova, Astaxa, BlueBioTech, Alga Pangea) produce *Chlorella* spp.. Most of them cultivate also other diverse species.

In France, the production of microalgae was estimated to reach 4.6 tons in 2022 (AGRESTE 2020b). In 2018, the percentage of loss was about 2 % (AGRESTE 2020a). The species the most produced is *Chlorella* spp.. (Microphyt, Algosource AS, Greensea, LLDC Algae). Some companies (Fermentalg and Biorea) are specialised in the fermentation of microalgae in particular for the production of *Galdieria sulphuriara* and *Chlorella* sp..

In Italy, the total production of Spirulina and microalgae is estimated to be 25 tons/year. However, the microalgae production represents only a small part of this volume.

In Portugal, the major microalgae producers are Necton S.A., Allmicroalgae and Greenaqua, which recently opened the largest microalgae facility in Europe (on the 14 hectares Algatec Eco Business Parc). They produce several microalgae species like *Nannochloropsis* spp., *Chlorella* spp., *Phaeodactylum tricornutum* or *Tetraselmis* spp.

In Netherlands, the major microalgae producer is AlgaSpring with *Nannochloropsis*, *Chlorella* and *Tetraselmis* cultivation in raceways. Others producers like Corbion or Veramaris, are experts in fermentation (*Schyzochitrium*). We can also cite Phycom company with the *Chlorella* production, and GNT company, for spirulina production.

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- *Chlorella* spp.

World production of Chlorella is estimated to be 3,500 T/year (CEVA, *unpublished*). In Europe, *Chlorella* spp. is the microalgae the most produced. Araùjo *et al.* (2021) estimates the Europe production of *Chlorella* spp. To reach 82 tons with 30 companies producing this microalga. In Europe, the major producers of *Chlorella* are located in Germany (Algenfarm Klötze) and Austria (Jongerius ecoduna). The production of *Chlorella* by Roquette Klötze (now Algenfarm Klötze) was estimated to be 150 T/year in 2019 (Barkia *et al.* 2019), which is not consistent with the estimation of Europe production by Araújo *et al.* (2021). More than 50 % of companies produce *Chlorella* in photobioreactors, 10 % in open ponds and 10 % in fermenters. Some companies also use different systems depending on the production stage.

Chlorella is mainly used in food and feed sectors. It is sold as fresh, dry or freeze-dry biomass (powder, tablets, flakes). Some companies also extract pigments or proteins from this microalga.

- *Haematococcus pluvialis*

Production of *Haematoccocos pluvialis* is estimated to be 750 tons/year in the world (CEVA, *unpublished*). In Europe, this production can be estimated to be 66 tons (Araújo *et al.* 2021), although it might be slightly underestimated, with 19 companies producing this species.

In Europe, the *H. pluvialis* production of Algalif in Iceland, was estimated to be 50 tons in 2020 with a potential increase to 150 tons in the next future based on company information on astaxanthin production capacity and turnover (Algalif 2020; Government of Iceland - Ministry of Food, Agriculture and Fisheries 2023). In Austria, *H. pluvialis* production was estimated to be 15 tons in 2021. BDI-BioLife Science GmbH is the major company producing this species in this country. Sweden and Portugal are also big producers of *H. pluvialis.* Astareal AB (Sweden) was one of the pioneers of the astaxanthin market. The company does not communicate on volumes produced, but their current turnover (8.6 M€ in 2022) might indicate a production in the range of 40 tons, although (Li *et al.* 2020) indicate a production that might be less than 25 tons.

It is important to note that Israel is also a big producer of *H. pluvialis*. Algaetechnologies (purchased by French company Solabia in 2019) would produce about 50 tons (dry weight) of this species per year.

H. pluvialis is mainly grown to produce astaxanthin, a pigment with antioxidant properties used as nutraceutialc or in the cosmetic sector. To obtain the best yield and productivity of astaxanthin, the culture conditions must be controlled. Indeed, to produce astaxanthin, two culture stages are necessary: a green phase where biomass is grown in the optimal conditions for the algae and a red phase where the pigment is produced in unfavourable conditions for the algae (high light, starvation). This is why, the culture of *H. pluvialis* is mainly done in closed photobioreactors, which provide the best control of conditions.

- *Nannochloropsis* spp.

In Europe, the production of *Nannochloropsis* spp. is estimated to be 21 T/year (Araújo *et al.* 2021) with 25 companies producing this microalga. This figure could be underestimated regarding EABA evaluation of 70T/y in Europe. The major producers of *Nannochloropsis* spp. are Portugal (Necton S.A., All microalgae, Green Aqua), Spain, Netherlands and Germany. Nannochloropsis, is mainly produced in PBR (Necton, Allmicroalgae, ...) but also in open ponds system (GreenAqua, Algaspring, ...).

Nannochloropsis spp. is mainly produced for its high content in eicosapentaenoic acid (EPA; C20:5), an omega-3 unsaturated acid known to play a role in the regulation of inflammations and immunity (Winwood 2013). The biomass is often sold fresh or freeze-dried (powder, tablets) but some extracts can also be obtained.

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- *Tetraselmis* spp.

The production of *Tetraselmis* spp. is estimated to 5 tons/year in Europe (Araújo *et al.* 2021) including 1 ton in France (FAO 2021) and 0.73 tons in Spain (Ministerio de agricultura, pesca y alimentacion 2022b). 16 companies produce this microalga in Europe. It is mainly grown in photobioreactors.

Tetraselmis biomass is mainly sold fresh or freeze-dried (powder, tablets) and it is largely used in aquaculture (Chini Zittelli *et al.* 2006).

- *Phaeodactylum triconutum*

Phaeodactylum tricornutum production is estimated to be 4 tons/year in Europe with 8 companies producing this microalga in Portugal, Italy, Spain, France, Germany and Sweden. Its production is carried out in photobioreactors. As *Nannochloropsis* spp., this microalga is interesting for its content in EPA (Hamilton *et al.* 2015) but also for its content in fucoxanthin, a carotenoid with antioxidant properties (Algatech 2018).

P. tricornutum can be sold as fresh or freeze-dried biomass to be used in aquaculture. Pigment and lipid extracts can also be used in cosmetic or nutraceutical sector.

- *Dunaliella salina*

The world production of *Dunaliella* spp. can be estimated to be 700 tons/year (CEVA, *unpublished*). In Europe, the production of *Dunaliella* spp. is estimated to be 2 tons/year (Araújo *et al.* 2021) with 8 companies producing it. In Spain (Algalimento and Monzon Biotech SL), production of *Dunaliella* is done in open ponds and PBR but this production is carried out in photobioreactors in Portugal, Sweden, Italy, Estonia and Germany.

Dunaliella bardawil is also produced in open ponds in Israel by the company NBT, with a production capacity of 35 tons/year (Harvey 2017; Harvey and Ben-Amotz 2020).

Dunaliella is interesting for its high content in β-carotene. Large scale production of β -carotene under intensive cultivation would produce around 200 mg β-carotene m^{-2} d^{-1} (yearly average). Therefore, 50,000 m^2 facilities could produce 3,650 kg β-carotene per year (Richmond and Hu 2013).

In Europe, *Dunaliella* is mainly sold as fresh or freeze-dried biomass or as pigment extracts.

- *Scenedesmus* spp.

In Europe, 10 companies produce *Scenedesmus spp.*. All companies grow this microalga in photobioreactors except one (Albitech Botechnology Ltd., Hungary) which produces it in fermenter. This microalga is mainly sold in B2B.

- *Tisochrysis*

In Europe, the production of *Tisochrysis lutea* is inferior to 1 T/year with 10 companies producing it (Araújo *et al.* 2021). The production is carried out in photobioreactors. This microalga is interesting for its content in omega-3 unsaturated acid and fucoxanthin.

- *Porphyridium* spp.

In Europe, the production of *Porphyridium* spp. is inferior to 1 T/year (Araújo *et al.* 2021) with 6 companies producing it. Its production is mainly done in photobioreactors. This microalga, produced in

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photobioreactors, is interesting because it can produce phycoerythrin and exopolysaccharides (Borowitzka 2013). Biomass and extracts are mainly produced for B2B.

2.2.3. Production of cyanobacteria in Europe: species, volumes and producing countries

As for microalgae, there is almost no official statistic on cyanobacteria production volumes and existing statistics are uncomplete. Some existing data regarding production volumes of cyanobacteria are reported in Table 6.

It shoud be noted that recent molecular and ultrastructure analyses split the genus *Arthrospira* into two different lineages distinguishing *Arthrospira* and the genus *Limnospira* (Roussel et al. 2023), For clarity, we maintained the taxonomy used in the prior publications and commercial designations.

Table 6: Production volumes of cyanobacteria in the world and in Europe.

Country	Species	Tons per year	Year	Economic value (€)	Reference
World	Spirulina	55,204	2019		(FAO 2021)
World	Spirulina	> 15,400	2020		CEVA, *unpublished*
Europe	Spirulina/*Arthrospira* sp	347	2019		(FAO 2021)
Europe	*Spirulina*	142			Araújo et al. (2021a)
France	Spirulina/*Arthrospira* sp	201	2019		(FAO 2021)
France	Spirulina	222	2020	7,3 M€	(Ministère de l'agriculture et de la souveraineté alimentaire 2022)
UK	Spirulina and microalgae	1 to 5	2013		(Schlarb-Ridley and Parker 2013)
Spain	*Arthrospira platensis*	2.59	2021	256850	(Ministerio de agricultura, pesca y alimentacion 2022a)
Italy	Microalgae	< 12.5	2021		AISAM reported in https://www.aquafeed.co.uk/microalgae-cultivation-updates-presented-at-the-algaefarm-24498/
Italy	Microalgae + Spirulina	25			https://agronotizie.imageline network.com

- Spirulina / *Arthrospira* sp / *Limnospira* sp

In 2021, CEVA estimated the production of Spirulina to be at least 15 400 tons/year (CEVA, *unpublished*). In Europe, the annual production was estimated to be 142 tons (Araújo *et al.* 2021) with 223 companies producing Spirulina.

France is the leading producer of spirulina in Europe. In 2020, there were 177 companies producing about 56 tons/year of dry Spirulina (AGRESTE 2022). A previous study reported that operators had an average loss of biomass of 13 % in 2018 (AGRESTE 2020a).These companies employed 390 full-time equivalent in 2020. Most of the companies (about 100) are farms which are members of the Federation of Spirulina producers from France (FSF). Italy, Spain, Portugal and Germany are also big producers of Spirulina. In Italy, production of Spirulina is estimated to be inferior to 12.5 tons/year. In Spain, production of *Arthrospira platensis* was estimated to be 2.59 tons in 2021 (Ministerio de agricultura, pesca y alimentacion 2022b).

The production of spirulina is mainly used for food purpose. For most of the farms, Spirulina is sold as dry biomass (powder, flakes, tablets). In France, the average price for Spirulina is 130 €/kg (AGRESTE 2022), which is representative of a high proportion of the production being sold directly to consumers.

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However, larger industrial actors are also (or mostly) present in BtoB markets, or grow Spirulina to produce extracts, in particularly phycocyanin, a blue pigment used in food.

- Other Species

Apart from Spirulina production, the production of other cyanobacteria is marginal in Europe. 3 companies (Cyano Biotech GmbH, Kyanos Biotechnologies and Photanol) are specialised in the production of cyanobacteria other than Spirulina.

Cyano Biotech GmbH cultivates *Microcystis*, *Planktothrix*, *Nodularia* and *Cylindrospermopsis* to produce toxins for the pharmaceutical sector.

Kyanos Biotechnologies produces the cyanobacterium *Aphanizomenon flos aquae* in controlled conditions to use it in nutraceuticals. This species is generally harvested in Klamath Lake (USA) and its world production was estimated to reach more than 1,000 T/year in 1998 for a total market value about 100 M$ (Carmichael *et al.* 2000).

Photanol also develops the production of cyanobacteria for green chemistry.

2.3. Labyrinthulomycetes

2.3.1. Introduction

Labyrinthulomycetes are the most ubiquitous unicellular stramenopilan protists (heterotrophic eukaryotes) found in the global ocean. As microalgae, Labyrinthulomyces (Thraustochytrid) have the capacity to produce very high level of EPA and DHA in their lipids, with some species reaching over 60% of total fatty acids as omega-3. Thus, the production of such oils not only has an interest from the point of sustainability, they also allow new nutritional approaches to incorporating n-3 LC-PUFA into the diet.

2.3.2. Production

As describe in section 2.2.1 "Production technologies for microalgae and cyanobacteria", the cultivation of heterotrophic microorganism is interesting to counter some problems linked to PBR like light or CO_2 distribution in the culture (Richmond and Hu 2013), and because biomass concentrations and productivities can be higher in fermenter compared to in PBR. Cultures in fermenters are mainly performed to produce high value compounds in very controlled conditions, and in the present case, for naturally only heterotrophic microorganisms like Labyrinthulomycetes.

Biomass is produced using fermentation process with several industrial strains. The strains have been selected or improved using classical screening program. The fermentation process used media containing carbon (organic) and nitrogen sources, bulk nutrients, trace minerals and vitamins, The fed-batch process can be used, where a portion of the carbon and nitrogen is added during the initial fill, and a portion of them is added throughout the fermentation.

The biotechnological production of omega-3 polyunsaturated fatty acids (PUFAs) from microorganisms has become a commercial alternative to fish oil over the past twenty years. It has increased due to its promising durability and high product safety and growing awareness of the expanding vegan market. Although autotrophic production by microalgae appears to be more sustainable in the long term, to date most microbial omega-3 production is achieved under heterotrophic conditions using conventional fermentation technologies (Russo *et al.* 2021). However, the fermenters can be used only on a few species of microalgae and a carbon source is necessary leading to a higher cost.

It was recently estimated that with the production of DHA from *Schyzochytrium* cultivated with glucose as Carbon source, the cost of substrate per kg of DHA would be 12.56 US$ therefore 15% higher than

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price of DHA fish oil, considering glucose and nothing else (other media, electricity, water, steam) (Chi *et al*., 2022). Furthermore, Sijtsma *et al.* (2010) calculated that DHA from heterotrophic microorganism *C. cohnii,* grown on ethanol, was 3-5 times more expensive than DHA from fish oil (Sijtsma *et al*., 2010).

To optimise the culture in fermenters, it is possible to change the carbon source. Generally, better productivities are obtained with glucose but acetic acid and glycerol can also be used (Griffith *et al*, 1960). The Table 7 below lists results obtained for the production of lipid and DHA when cultivating different strains on different carbon sources.

Table 7: Production of Biomass, lipid, and DHA by oleaginous microorganisms cultivated on different substrates (Patel et al. 2020).

Oleaginous microorganisms	Medium	Cell dry weight (g/L)	Lipid concentration (g/L)	DHA concentration (g/L)
Aurantiochytrium SW1	Fructose (70 g/L) and MSG (10 g/L)	19.0	9.13	4.75
Aurantiochytrium sp. YLH70	Fructose	15	7.77	2.5
	Glucose	14.5	7.55	1.98
Schizochytrium sp. S31	Glucose (20 g/L)	6.01	2.38	0.314
Schizochytrium limacinum SR21 (ATCC MYA-1381)	Sweet sorghum juice (50%); Fructose (61 g/L) Glucose (39.3 g/L)	9.4	6.9	2.5
Aurantiochytrium sp. SW1	Glucose (30 g/L)	5.8	2.12	1.12
	Fructose (30 g/L)	9.2	3.59	1.68
Schizochytrium limacinum SR21	Organosolv-pretreated spruce hydrolysate (60 g/L glucose)	26.87	12.87	5.86
Aurantiochytrium sp. T66	Organosolv-pretreated birch hydrolysate (30 g/L glucose)	10.39	4.98	1.29
Phaeodactylum tricornutum (CCMP-2561)	Food waste hydrolysates (3%)	–	510.9 µg/mg algae	≈17 µg/mg algae*
	Crude glycerol concentration of 50 mM and 100 mM	–	720 µg/mg algae	≈24 µg/mg algae*
An evolved diatom strain (E70) *P. tricornutum*	3% FW hydrolysate and 50 mM crude glycerol +3 mg/L butylated hydroxytoluene (BHT)	–	898.8 µg/mg algae	30.5 µg/mg algae
P. tricornutum SAG 1090-6	Organosolv-pretreated birch hydrolysate (glucose, 2 g/L; C/N 60)	3.23	1.26	0.054
	Organosolv-pretreated spruce hydrolysate (glucose, 2 g/L; C/N 60)	3.31	1.29	0.063
Aurantiochytrium sp. T66	Post-consumption food waste hydrolysate; glucose (30 g/L) Fructose (9.89 g/L)	14.7	6.34	2.15

* Data derived from the graphs, (–) not available.

The producing strains of DHA could be isolated from nature and the DHA productivity could be improved by metabolic regulation (Sun *et al*., 2018), fermentation process optimization (Guo *et al*., 2018), gene modifications by metabolic engineering (Ren *et al*., 2015) and genome editing technologies (Sun *et al*., 2019). As well as the source of carbon study, the nitrogen, phosphorus and other nutrient limitations or starvations lead to lipid accumulation in microalgae (Heggeset *et al*., 2019; Sun *et al*., 2014). Two nitrogen feeding strategies were compared for the heterotrophic cultivation of *C. cohnii*, the results showed that continuous-feeding with a medium solution containing 50% (w/v) yeast extract at 2.1 mL/h during 12-96 h was the optimal nitrogen feeding strategy for the fermentation process (Liu *et al*., 2018). More challenges need to be overcome to improve PUFA production by microorganisms.

2.3.3. Production challenges

While Labyrinthulomycetes production is exhibiting significant growth, the industry is also still facing a number of challenges:

- Productivity
  - Highly productive strains attain a dry biomass concentration exceeding 100 $g.L^{-1}$ in 96 h (Da Silva et al. 2021). Fed-batch fermentations generally lasting from 48 to 96 h (Du et al. 2021) are most commonly used for biomass production. The lipid productivity ranges widely, but some of the highest reported (Table 7) values are up to 535 to 700 ($mg.L^{-1}.h^{-1}$) (Chang *et al*., 2013; Magoni *et al*., 2022).

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- Scalability
  - To be competitive with fish oil, alternative sources of ω3-oils should be able to provide in the order of 100 000 tons oil annually for the feed industry. This corresponds to 25 000 tons EPA/DHA. Production of 25 000 tons microbial DHA will require one or more production plants with a total of 20 fermenters of 350-400 m^3 (Kleivdal Hans *et al*., 2013).
  - The heterotrophic microorganism production has advantages compared to phototrophic production like the use of (relatively) proven technology (fermenters have been used for decades in biotechnological industries), higher biomass growth rates and higher oil and PUFA contents of the cells.

- Source of carbon
  - The most important nutrient for the production of lipids is obviously the source of carbon. Glucose represents a major share of the costs: 1 kg of algae DM biomass requires input of 2-3 kg of glucose and is contributing to around 80% of total cultivation cost *(Harel et al*., 2002; Oliver *et al*., 2020).
  - Glycerol is another carbon source that has been used as a carbon source for heterotrophic microalgae growth (Kujawska *et al*., 2021). It is generally a cheap by-product from the biodiesel industry (Da Silva *et al*., 2021). However pure Glycerol is rather preferred because of impurities still present in biodiesel by-products.
  - Other substrates: *C. cohnii* can produce considerable amounts of DHA when grown on wastes such as carob pulp syrup (45.2 mg/g), rapeseed meal + crude waste molasses, cheese whey + corn steep liquor (5 mg/g), and sugarcane molasses and crude glycerol (5.5 mg/g and 6.6 mg/g, respectively). *Schizochytrium* has also been grown on food waste to produce 85.5 mg DHA /g (Da Silva *et al*., 2021).

- Biomass stabilization
  - The microalgal biomass has a very high-water content from the culture medium (which can be more than 90% of the total) and so once lipid-rich biomass has been produced with all the desired parameters the first step of crude oil recovery is often a reduction in water content. The biomass must be separated from the liquid culture by filtration, centrifugation, or by using rotary vacuum filtration and then spray-drying.
  - For example, prior to the oil extraction, *Crypthecodinium* sp. cells are broken by mechanical shear forces and enzyme degradation, and the resulting biomass is then spray-dried and crude oil extracted with hexane using standard industrial oil extraction protocol (Harel *et al*., 2002; Yin *et al*., 2018).
  - Processes often have to be performed under nitrogen, and antioxidants are also frequently used prior to extraction.

- Oil extraction
  - A variety of methods can be used to disrupt the microalgae cells, such as solvent extraction, ionic liquids, direct saponification, high-pressure homogenization, hydrodynamic cavitation, ultrasound/microwave/pulsed electronic field and ozone treatments, and hydrolytic enzymes.
  - Use of enzymes : some types of cells can be lysed with just proteases, for example oil may be extracted from *Schizochytrium sp.* using an alkaline protease (3%), at 55 over 9 h (Lin *et al*., 2018).
  - Solvent extraction is the most used at lab-scale, with the mixtures chloroform–methanol, hexane, and hexane–isopropanol being the most used solvents (Da Silva *et al.*, 2021). However physical disruption methods have been favoured at industrial scale, while enzymatic methods are becoming more frequent over the years. Physical disruption methods, as well as downstream processing for oil recovery/refining also remain cost intensive (equipment, energy, …).

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2.3.4. World key players

The main world suppliers of algae oils are:

- Corbion: AlgaPrime DHA (corbion.com)
- DSM: DHAgold™ - Solutions - Products - DSM
- Alltech :Alltech's Coppens International replacing fish oil DHA with algae | Alltech
- ADM: Onavita™ Omega 3 Oils | ADM
- Heliae Technology via Syndel laboratories: Syndel and Heliae announce algae distribution partnership - Hatchery International
- Veramaris: Omega-3 EPA + DHA for sustainable animal nutrition - Veramaris

Corbion whose factory is located in Brazil, uses sugarcane to produce *Schizochytrium* microalgae, which is commercialized as a whole algal biomass and used in the aquaculture feed industry, such as in the AlgaPrime DHA product. The facility uses sugarcane waste as an energy supply for the process.

DSM is a Dutch company that produces a variety of commodities pertaining to health and nutrition. It utilizes algae to produce some of its nutritional lipid products, primarily those which incorporate Omega-3. In 2010, DSM acquired Martek, a company which produced DHA using *Schizochytrium* DHASCO, and oil rich in DHA, used in the food industry is also produced by DSM, and is obtained from *C. cohnii* microalga. More details are given about world key players in section 3.4.5 Omega-3 oils.

2.3.5. Key companies in Europe

There is currently a growing number of companies active in the PUFA algal oils sector in Europe. They are relying on different strains (*Schizochytrium* sp, *Aurantochytrium* sp, *Crypthecodinium* sp, *Ulkenia* sp), and include a number of large and smaller companies.

While some European companies are producing abroad, in particular in Brazil for an improved access to low-cost sugar, other companies are producing locally in Europe (UK, France, ….

A more detailed presentation of the companies is outlined in section 3.6.4 of the report.

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3. Algae Uses in Europe and side-streams generated

3.1. "Direct" Algae use in Food

3.1.1. Global market

3.1.1.1. Uses

Japan, China, and Korea have maintained the tradition of consuming seaweeds as food since ancient times.

Japanese eat approximately 2 kg per capita/year (dry basis) in approximately 21% of their meals. Seaweed is used to flavour dishes such as noodles or soups or as an ingredient in vegetable mixtures, but is also consumed as such, for snacks, salads or even condiments. 21% of Japanese dishes include seaweed and the average consumption per capita is estimated around 1.1 kg of dry seaweed (General Food Policy Bureau, Ministry of Agriculture, Forestry and Fisheries, Japan). Around 21 seaweed species are used in everyday cooking in Japan, the most important being *Undaria, Ecklonia, Hizikia, Laminaria* (Kombu), *Eisena, and Pyropia* (Nori). Among them, the most popular and valuable Japanese seaweed is Nori. The biomass is at first crushed, dried into thin flexible sheets and finally used to wrap the sushi, maki and onigiris. It can also be eaten as seasoned "chips" (with sesame, chili, soy sauce), as an appetizer, or dried flakes to sprinkle on vegetable dishes and salads. Its marine aromas, similar to grilled sardine skin, are immediately noticeable once in the mouth, while its crunchy texture melts progressively. Most of the other seaweed are consumed in soups, salads, toppings mixed with other vegetables, or pickled. The brown seaweed Wakame is sold mainly as dried leaves, to be rehydrated in salads or soups, such as in Miso soup. Another brown kelp seaweed, named Kombu, is the basic ingredient to make dashi (Japanese stock), but can also be used to wrap fish (papillote) or pickled as a seasoning. The Japanese chemist Mr Kikunae Ikeda described for the first time the umami flavour by studying Kombu broth, umami meaning "delicious" or "tasty" in Japanese. The molecule delivering this flavour was identified as sodium glutamate, which is naturally present in seaweed. Nevertheless, the Japanese consumption of seaweed is slowly eroding and tends to decrease notably among younger generations who are turning towards Western type diets. For instance, people over 70 years old consume 4 times more Kombu (616 g / year) than those under 29 (Nagataki 2008).

Chinese diet comprises 74 species of edible algae, the widest collection for any ethnic group in the world. The main seaweed species consumed in China are *Undaria, Laminaria, and Pyropia*. The Chinese are used to cook their seaweeds : fast frying followed by simmering in water), stir-frying, steaming of the dried seaweed or simply dried seaweed added after simmering to the main dish (Xia Bangmei and Isabella A. Abbott 1987).

Koreans consume around 14 kg of seaweed per capita/year (around 2.1 kg dry weight) in soups and salads as well as in snacks and pickled form. Main seaweeds consumed in South Korea are *Undaria, Laminaria, and Pyropia*. Dried seaweed is traditionally used in rice rolls and as a pressed, roasted and oiled sheet of Nori like in Japan eaten as a crunchy snack (kim-nori) (Figueroa *et al.* 2021).

Microalgae are largely used as food supplement in different countries around the world with Spirulina and Chlorella the most popular for food application. Since the late 1970s, Spirulina has been extensively produced around the world (Hawaii, California, China, Taiwan, Japan) using open raceway ponds. Spirulina is used in food and feed supplements, due of its high protein content and its excellent nutritive value, such as high iron supply and γ-linolenic acid (GLA; 18:3ω6) presence. Spirulina is also the main source of phycocyanin, authorized as a natural colouring foodstuff.

Chlorella has been used as an alternative medicine in the Far East since ancient times and it is known as a traditional food in the Orient. The commercial production of Chlorella as a novel health food commodity started in Japan in the 1960s and nowadays, Chlorella is widely produced and marketed as a health food supplement in many countries, including China, Japan, Europe and the US.

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3.1.1.2. Volumes and market value

In 2019, the world global production of algae was estimated by FAO at more than 35 million tons of algae (34.7 million tons of farmed seaweed and 1.1 tons of wild-harvested seaweed, about 3.1% of the total) with a value of US$14.7 billion in direct-sales based on individual prices of the seaweed species considered (Cai *et al.* 2021). From this global volume and based on species and discussions with stakeholders around 38% are eaten in recognisable culinary formats, and usually sold at higher prices than seaweed sold for other applications, representing a significant part of the market.

Although this production volume is likely significantly overestimated, the overestimation mostly relates to hydrocolloid bearing seaweed (see for example section 3.3.2.1) rather than food-grade seaweed, and the actual share of food might be even higher.

It remains difficult to assess actual market values for seaweed and seaweed products. A number of market studies include a very broad spectrum, going far down the value chain and markets of downstream applications. For example a market study published in 2021 by Global Market Insights estimated the market for seaweed-based products, at €41 billion in 2020 due mainly to hydrocolloids for food and packaging, soil fertilisers, soil remediation and higher-value streams (food uses should be included) with 20% of this market in Europe. (Global Market Insights 2021).

EABA estimates that global production of microalgae biomass is about 130,000 tons dry weight per annum worth about €2.6 billion, with more than 75% coming from China. European output is limited and represents less than 0.5% of global production (EUMOFA 2023).

3.1.2. European market

3.1.2.1. Seaweed

European (EU, Norway, and United Kingdom) total seaweed production in 2019 represented around 300,000 tons (FAO 2021). This production volume has been stable for more than 20 years (McHugh 2003; ValgOrize - Interreg 2021) but mostly directed to non-food applications for the species representing the largest volumes. Most of the production were harvested from the wild (294,744 tons), while 1,450 tons of seaweed were obtained through cultivation (FAO 2021).

In 2016, the EU imports of seaweed products were almost twice the size of its exports (178,467 tons vs. 101,594 tons), making the EU the world's second-largest importer in terms of volume, valued at EUR 506 million. Seaweed for human consumption represented 8.5% of imports and 4.5% of exports) (Mendes *et al.* 2022). Currently, more than 50% of the companies concentrate on human food and animal feed applications.

In total, seaweed species (harvested from the wild or cultivated) directly used for food applications might represent 3,000 to 4,000 tons (Table 25 and Table 26) and a first-sale market of 9 to 12 million euros using an average price of € 3 / kg (ranging from € 0.5/kg for wild *Himanthalia elongata* to € 5-6/kg for cultivated organic kelp). If secondary transformation is included to also take into account sales of processed seaweed (whole dried seaweed, seaweed flakes, salted or brined seaweed, frozen seaweed, etc.), this may reach 12-20 million euros.

3.1.2.2. Seaweed-based food products

The European seaweed food market was estimated to be worth US$ 1.02 billion (€ 0.84 billion) in 2018 representing 10% of the global market (Vincent *et al.* 2020). This market is projected to grow in the future years to reach € 1.30 billion in 2030 according to the most conservative scenarios, or up to € 2.84 billion in the most ambitious scenario in the report made by the coalition Seaweed For Europe and illustrated in the Interreg ValgOrize project (Figure 30). The higher growth linked to the most ambitious

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scenario combines several significant changes, including favourable policy environments, considerable economies of scale, further cost efficiencies from technological innovations, and strengthening of advantageous consumer trends. In this high ambition scenario European cultivated seaweed should be able to cover 24% of this demand (Vincent *et al.* 2020).

There are numerous opportunities for the application of seaweed in food products. It has potential to further grow and innovate to meet European consumer demands. The market of seaweeds as sea vegetables is growing around 7-10% per year following demand from catering and foodservice companies, retail market and food processors (Organic Monitor 2014).

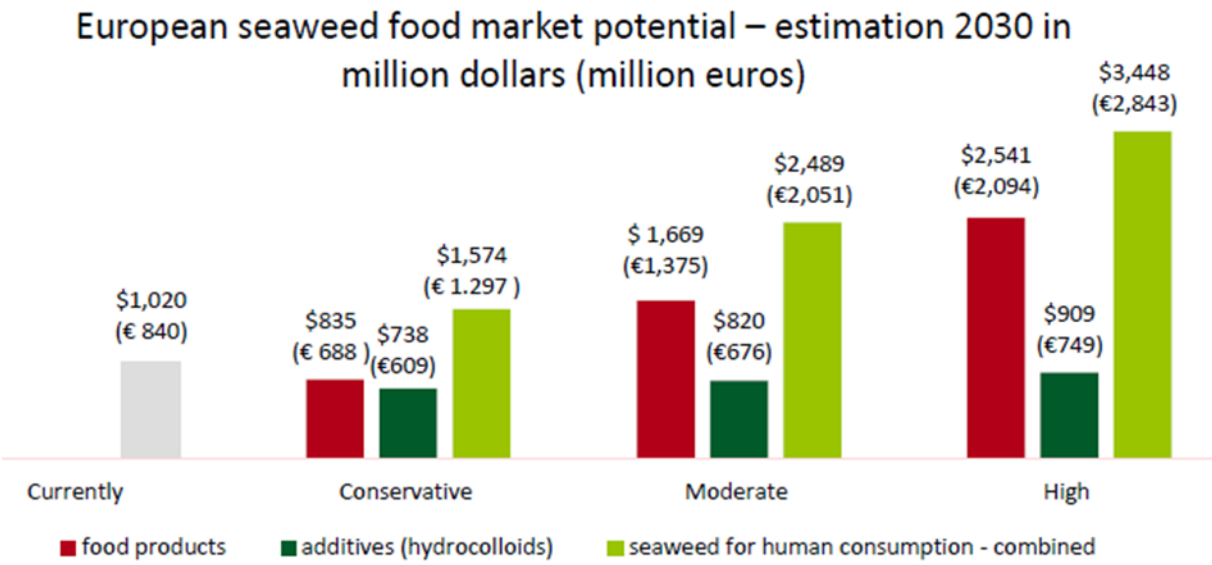

Figure 30 : Estimated growth of European seaweed in different scenarios (ValgOrize - Interreg 2021)

In the Western countries, the traditional use of seaweed in food is scarce, and very localised. Indeed, seaweed consumption is only seldomly reported in Ireland, Iceland, Nova Scotia and Norway (Mouritsen *et al.* 2013). The first hermit monks in Ireland, who landed in Brittany in the 7th century, consumed the red algae Dulse (*Palmaria palmata*). In the 10th century, in Northern Europe, the Vikings also ate dried algae during their long journeys across the oceans, as far as Greenland. In Ireland, from the 18th century the red seaweed Dulse was chewed. In Brittany, the traditional use of seaweed in food was based on extraction of gelling agents to prepare custard or flan, and this by boiling the "pioca" (*Chondrus crispus*) harvested on the shore.

In the last 3 decades, there has been a sharp increase in interest in seaweed throughout Europe, due to the growing popularity of Far Eastern cuisine, mainly Japanese (sushi), and to the development of seaweed harvesting for food in France, Ireland and Portugal in the 1990s.

France was a driving force for the food sector: harvested volumes, implementation of regulations, food products, networking with specialized retailers, collaborative projects. Since the 1990s, the different opinions established by the official French Food Surveillance Authorities have enabled this sector to progress.

The consumption of seaweed in France, as plain vegetable or seasoning, was initially driven by holistic approaches promoted by macrobiotic practices. This initial trend has now broadened in the Western countries involving new consumers which are concerned about their diet, seeking for "natural" foods produced in sustainable conditions and are open to innovation.

The negative connotations associated to the word “algae” have literally disappeared to give way to a new image of algae which is not only edible but also healthy and tasty. According to the latest consumer studies, 58% of the French population has already consumed seaweed, compared to only 30% ten years ago (Le Bras *et al.* 2014). This development is mainly explained by the presence of Asian

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restaurants offering products including seaweed such as (ranked from the most to the less consumed), sushi (93%), soups (62%) and Asian salads (sesame-seasoned wakame salads) (36%). As many as 34% of consumers declare that they "could try to eat" seaweed food products.

More recently the current consumption of seaweed products in the French population has been evaluated via an on-line survey where 780 adults participated. The percentage of people who had consumed seaweeds in the previous 12 months was 89% and then higher than the previous study of Idealg 8 years earlier. However, the authors stressed that the sample used in their study, which is not representative of the French population, could include more consumers of seaweed foods than the general population.

The authors determined that consumption of seaweeds in food was on average equal to 293 mg/day (Ficheux *et al.* 2022). Even if the percentage of population eating seaweed is in progress, the consumption of seaweeds by the French population was still much lower than that of Asian populations who consume on average 10.4 g of seaweeds per person per day.

The type of products consumed over the past 12 months mainly referred to Asiatic cuisine (sushi, soups) but also integrated French cuisine seaweed products cooked in a "French way": tartare, rillettes, seaweed as vegetables, ….

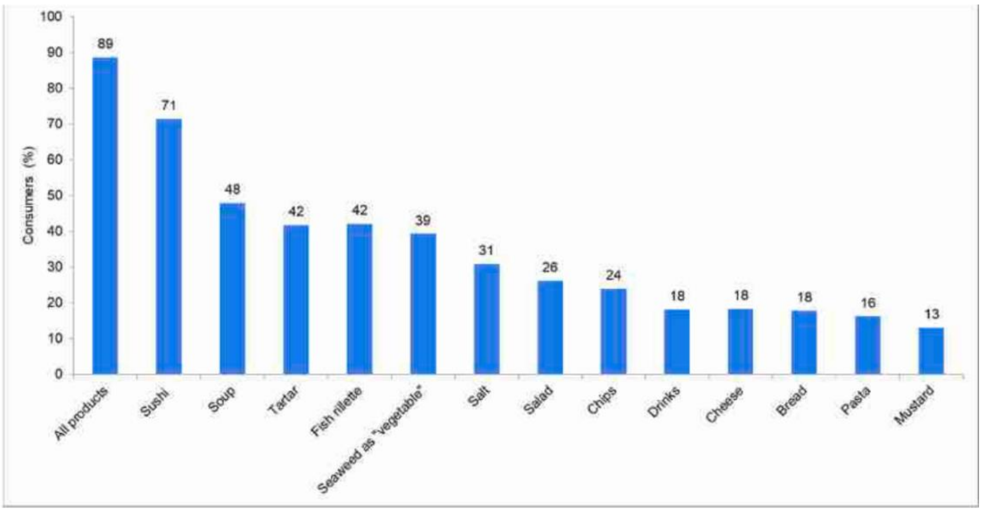

Figure 31 : Type of seaweed products consumed over the past 12 months (in %) (Ficheux et al. 2022)

Currently, seaweed products are appearing more and more often on the market in the retail market (retail chains, organic food stores, fish stores and specialist health food stores, on-line). The seaweed tartare, which is the most popular ambassador of seaweed cooking, has evolved for more than 20 years now. In 2016, seaweed tartare was even released under a retail brand!

Renowned chefs are now keen in using the textures, colors, flavors, in particular making broths (Dashi) from seaweed. Seaweeds also appear as an essential ingredient to introduce in vegetarian diets. Algae can be consumed as food or as ingredients in prepared foods, in a fresh, fermented, dried, or frozen format, either whole or milled into differently sized flakes, granules, or powders. By moving away from the traditional Japanese cuisine and by introducing more Western type food codes, new products are now emerging, such as vegetarian algae burgers, seaweed salads, pasta, soups, ready-to-eat prepared meals, mayonnaise and drinks. There is also a wide availability of dietary supplements based on seaweed.

Seaweed-flavoured food and drink launches increased by 147% in Europe between 2011 and 2015 (MINTEL 2016). This growth means Europe is now the second most innovative region globally when it comes to seaweed-flavoured food and drink launches.

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The main edible algae for food market are presented in Figure 32 below.

Figure 32 : Main edible algae found in Europe (Spirulina, Dulse, Sea lettuce, Atlantic wakame, Sea spaghetti, Royal kombu, Wakame, Nori and Chlorella)

However, in his annual review of the seaweed industry, Steven Hermans (Phyconomy.net) stressed in 2023 that there is a gap between seaweed species market demand and uses (*Ulva, Palmaria, Porphyra*), and cultivated seaweed species in Europe (*Saccharina, Alaria*) (Hermans 2023a). A similar reading was made in the Valgorize project (Figure 33).

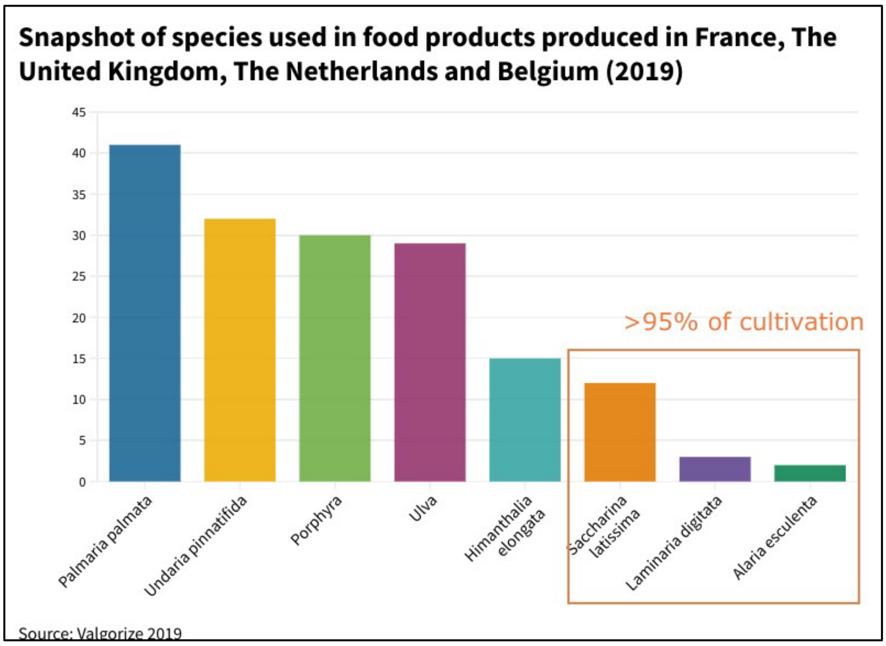

Figure 33 : Species used in food product in France with focus on European cultivated species

3.1.2.3. Microalgae and cyanobacteria

In Europe, 420 companies, distributed over 23 countries, are producing microalgae and seaweed: 46% of which produce Spirulina, 36% seaweed, and 10% microalgae. The remaining 8% produce both Spirulina and microalgae (Mendes *et al.* 2022).

Estimates provided by the European Algae Biomass Association (EABA) underline that the microalgae sector generated a turnover of more than 350 M € in 2018, by considering both companies and jobs, and reached more than 400 M € when including equipment companies and R&D companies.

European production for microalgae is estimated to be less than 0.5% of global production which represents less than 650 tons dry weight (EUMOFA 2023). According to our calculations (Table 27),

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total production might be lower than this estimation, with autotrophic production of microalgae (including *Chlorella*) in the range of 210 tons, and *Spirulina* close to 140 tons.

However, it is difficult to convert it to a market value. Microalgae and cyanobacteria produced in Europe are usually sold at a premium over a number of producing countries, as food supplements or after further downstream processing for higher value ingredients (with final ingredients partly re-entering the food and food supplements market).

3.1.2.4. Uses

One of the major uses of microalgae and cyanobacteria in food applications is in the nutraceutical market as food supplement. They can supply valuable sources of proteins, omega 3 lipids (chlorella), minerals (iron for Spirulina) and antioxidants compounds.

In Europe, dietary supplements accounted for EUR 30 billion in 2020, with an expected growth of 50.6% by 2026 (Mendes *et al.* 2022).

Spirulina thus contributes to the fight against malnutrition and anaemia in children and women in certain developing countries: international programmes distribute it (about 5 g/day for 3 months) mixed with traditional dishes or as energy bars (Habib *et al.* 2008).

Besides using microalgae as supplement, microalgae has already been used in various food products, e.g., pastas, snacks, biscuits, candies, gums, yoghurts, drinks, and bread (Batista *et al.* 2013; Grahl *et al.* 2020).

3.1.3. Processing

Once harvested seaweed are washed and then processed according to the desired end-product. Typical processing strategies to preserve seaweeds are outlined in Figure 5 (Blikra *et al.* 2021). In food applications, the nutrient content, physico-chemical and sensory properties as well as product safety are of prime importance.

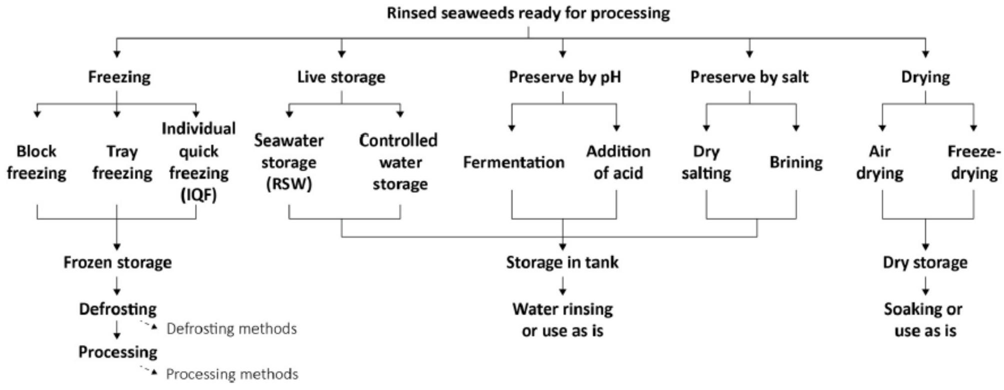

Figure 34 : Processing and preservation methods used for applications of seaweeds for food (Blikra et al. 2021)

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3.1.4. By-products

The different sources of by-products have been evaluated by interviews with seaweed producers and primary transformers. The main outputs are represented in the figure below.

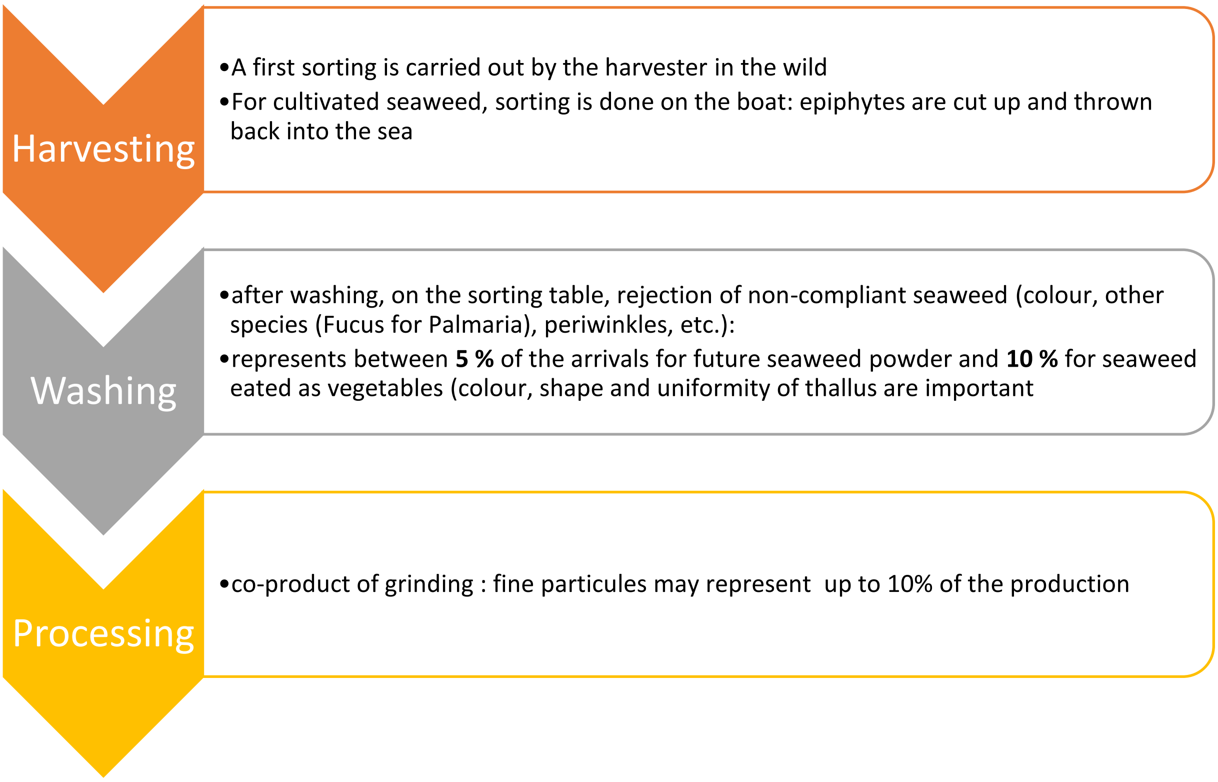

Figure 35 : Main sources of by-products during treatment of seaweed for food application

Type of by products and estimation of volumes

- After the washing step, by-products are not only composed of seaweeds but also contain sand, little rocks, broken shellfish.
- They represent a quantity which seems not so important for edible seaweed produced as powder. It is more important for seaweed eaten as vegetables.
- At this moment, they are valorised/given as fertilizers in gardens and fields. Producers do not get any money back from these by-products.
- Estimation of total volume in France: they could represent up to 200 tons (fresh) distributed among 15 seaweed processors for food.
- Estimation of total volume in Europe: 600 tons to 800 tons, if we assume the same losses occur in Portugal, Ireland, Scotland, Norway and Iceland.

3.1.5. Regulatory status

The suitability of algae species for human food consumption in Europe is governed by the so-called “Novel Food” Regulation (Regulation (UE) 2015/2283), which applies to food and ingredients which were not consumed to a significant degree in Europe before May 15th 1997.

France was the first European country to establish a specific evaluation of the use of seaweeds and spirulina for human consumption as non–traditional food substances before 1997.

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In the beginning of 2024, EFSA updated the Novel Food Catalogue to clarify the uses of these new foods in Member States (traditional versus novel food), with the addition of 6 seaweed species or genera and 11 micro-algae in particular.

Overall, to date, 44 different genera of algae can be used as food in Europe, in most cases with a specification of the authorized species: 43 genera and/or species of macroalgae and 26 genera and/or species of microalgae. More information is provided in the EABA paper "Update on the Novel Food Catalogue/EU Novel Food State-of-the-art-10 years later" available from EABA website.

The regulatory status of edible seaweed and microalgae in France and Europe, along with the requirements in terms of contaminants, is also monitored and regularly updated on CEVA website.

Two synthesis tables are presented below to cite all the genus and species that are authorized to use in food and food supplements (whole biomass).

Table 8: List of authorized whole seaweed in food or food supplement (CEVA - 04/2024)

	Scientific name	France	France	Europe	Europe
		CSHPF opinions, DGCCRF	"arrêté plantes", DGCCRF "Liste algues"	Novel Food Catalogue "not novel"	Novel Food Catalogue "not novel"
		Food	Food supplements	Food	Food supplement
Brown	***Ascophyllum nodosum***	x	x	x	
	Alaria esculenta	x	x	x	
	Durvillaea antartica		x		x
	Ecklonia cava				x
	Eisenia bicyclis		x	x	
	Fucus vesiculosus	x	x	x	
	Fucus serratus	x	x	x	
	Fucus spiralis			x	
	Himanthalia elongata	x	x	x	
	Laminaria digitata	x	x	x	
	Laminaria hyperborea		x	x	
	Macrocystis pyrifera		x		x
	Padina pavonica		x		
	Saccharina japonica *(Laminaria japonica)*	x	x	x	
	Saccharina latissima *(Laminaria saccharina)*	x	x	x	
	Saccharina longicruris *(Laminaria longicruris)*		x	x	
	Sargassum fusiforme *(Hizikia fusiformis)*		x	x	
	Undaria pinnatifida	x	x	x	
Red	***Alsidium helminthochorton***		x		x
	Chondrus crispus	x	x	x	
	Corallina officinalis		x		x
	Euchema horridum		x		x
	Euchema denticulatum		x		x
	Euchema spinosum		x		
	Gelidium corneum		x	x	
	Gelidium amansii		x	x	
	Gelidium sesquipedale		x		
	Gracilaria gracilis		x		x
	(Gracilaria verrucosa)	x		x	
	Gracilariopsis longissima		x	x	
	Mastocarpus stellatus		x		x
	Palmaria palmata	x	x	x	
	Porphyra umbilicalis	x	x	x	
	Pyropia tenera *(Porphyra tenera)*	x	x	x	
	Pyropia yezoensis *(Porphyra yezoensis)*	x	x	x	
	Porphyra dioica	x	x	x	
	Porphyra purpurea	x	x	x	
	Porphyra laciniata **(= Eryrhroglossum laciniatum)**	x	x	x	
	Neopyropia leucosticta *(Pyropia leucosticta, Porphyra leucosticta)*	x	x	x	
	Phymatolithon calcareum *(Lithothamnion calcareum)*	x	x	x	
Green	***Monostroma nitidum***			x	
	Ulva sp.	x			
	Ulva lactuca		x	x	
	Ulva sp *(Enteromorpha sp .)*	x			
	Ulva intestinalis *(Enteromorpha intestinalis)*		x	x	

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Table 9: List of authorized whole microalgae in food or food supplement (CEVA - 04/2024)

Scientific name	France	France	Europe	Europe	Europe
	CSHPF opinions, DGCCRF	"arrêté plantes", DGCCRF "Liste algues"	Novel Food Catalogue "not novel"	Novel Food Catalogue "not novel"	Novel Food dossier
	Food	Food supplements	Food	Food supplement	Food/Food supplement
Aphanizomenon flos aquae		x		x	
Aphanizomenon flos-aquae* var. *flos-aquae			x		
Arthrospira sp. *("Spirulina sp")*	x				
Limnospira fusiformis *(Arthrospira fusiformis)*		x	x		
Limnospira indica *(Arthrospira indica)*		x		x	
Arthrospira major *(Spirulina major)*		x	x		
Limnospira maxima *(Arthrospira maxima)*		x	x		
Arthrospira platensis		x	x		
Chlorella sp.	x				
Chlorella vulgaris		x	x		
Heterochlorella luteoviridis *(Chlorella luteoviridis)*		x	x		
Jaagichlorella luteoviridis			x		
Auxenochlorella pyrenoidosa *(Chlorella pyrenoidosa)*		x	x		
Chlorella sorokiniana		x	x		
Parachlorella kessleri		x	x		
Auxenochlorella prothecoides		x	x		
Euglena gracilis					x (specified categories)
Graesiella emersonii		x	x		
Dunaliella salina		x		x	
Haematococcus lacustris				x	
Haematococcus pluvialis		x			
Nannochloropsis oculata		x			
Odontella aurita		x			x (specified categories)
Scenedesmus vacuolatus		x	x		
Ulkenia sp.		x			
Tetraselmis chuii					x (specified categories)
Schizochytrium sp.		x			

3.2. "Direct" Algae use in Feed

3.2.1. Market, type of actors and potential co-products

3.2.1.1. Market

In animal feed, the use of algae differs between animal species.

The terrestrial animal market (ruminant, poultry, pig, horses, and pets) still makes relatively little use of algae, although some applications developed decades ago as for instance brown algae meals for ruminants (Chapman and Chapman 1980).
In the meantime, microalgae use in aquaculture feed is a well-established application. However, the fact that a number of hatcheries are directly producing their own microalgae, rather than purchasing it from microalgae producers also complexifies the quantification of the market size.

Overall, it remains difficult to determine the market currently represented by these applications.

Regarding microalgae, some authors estimate that 30% of the world production might be destined to the feed market, firstly for aquaculture (Kusmayadi *et al.* 2021; Voort *et al.* 2015). Still, with an average production cost around $ 25,000 per ton of biomass, for five main taxa, production of microalgal biomass remains much more expensive than many other feedstocks (Saadaoui *et al.* 2021). Besides, the market value of microalgal biomass varies according to parameters such as production system, production costs, geographical origin, and step in value chain. As example, for *Nannochloropsis* sp., one of the most relevant species for feed, B2B price values are in the range of 30–110 €/kg and B2C market value (as marine phytoplankton) can go up to 1,000 €/kg (Araújo *et al.* 2021).

Similar conclusion can be made for macroalgae if direct nutritive properties are sought. A recent study (Emblemsvåg *et al.* 2020) compares how seaweed protein product can compete against soy protein concentrate as a protein ingredient for fish feed. They concluded that seaweeds rearing still needs

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substantial investment in cultivation and processing infrastructure to reach an estimated break-even scale of 65,000 tons, on a surface of several thousand hectares.

The main limitations in terrestrial animal market are then cost and volume compared to “normal” animal feed. Consequently, the use of algae is often restricted so far to niche animal feed applications, where they can bring specific benefits either directly or via the extraction of higher value compounds of interest (specific period of animal’s life, source of pigment or omega-3 ingredient-based products) (Shields and Lupatsch 2012).

Scalability of algae production and optimization of the processing methods is one of the key points of feed sector to place algae in a better market position (Araújo *et al.* 2021). Co-products from biorefinery, if available in suitable quantities, would enable greater availability of the source and lower price of algae and therefore a more widespread use for feed market in the future.

3.2.1.2. European companies active in algae-based feed

At European scale, 10% of the seaweeds compagnies and 19% of the microalgae companies (Araújo et al. 2021) direct their biomass production (or a part of it) to feed.

Most of the microalgae companies producing feed ingredients target aquaculture (Fitoplancton Marino, Spain; Greensea, France; Tomalgae, Belgium, …), while others, as well as seaweed companies often cover both aquaculture and terrestrial animals (Olmix, France; Ocean Harvest technology, The United Kingdom; Algea - the artic company, Norway/Italy; Phycom, The Netherlands; Allmicroalgae, Portugal, …).

Some compagnies also propose products only for terrestrial animals (LDC / LLDC Algae, France, …).

3.2.1.3. Co-products

Current generation of co-products remains limited.

When used as feed, microalgae are usually consumed as whole cells (either dried or as paste or diluted “green water”) and do not generate co-products.

In the case of seaweeds, most companies sell them as seaweed meals, e.g. milled seaweeds or combinations of species. In this case, co-products are similar to the ones also produced by food companies (Figure 35).

Only a limited number of companies are actually preparing complex seaweed extracts for feed applications (section 3.7.3), which would be more susceptible to generate side-streams, except for the preparation of specific ingredients already covered in sections 3.3.4 and 3.5).

3.2.2. History of use of algae in feed applications

Algae have been used to feed livestock for centuries especially during scarcity times where seaweeds were grazed by ruminants on the beaches sometimes during several weeks. During the 19th and beginning of the 20th centuries, seaweeds were used, occasionally or systematically, as feed livestock (dried and stored or even fermented in silage) in France (Brittany), the Scottish islands and Scandinavia (Gotland, Norway, Finland), mostly to ruminants (including calves) and pigs (Chapman and Chapman 1980). However, having a poor nutritive value for livestock, their use was limited. It is only more recently that interest for algae as active ingredients in animal feed has increased and so did the researches on their potential impact on livestock (Kusmayadi *et al.* 2021; Makkar *et al.* 2016).

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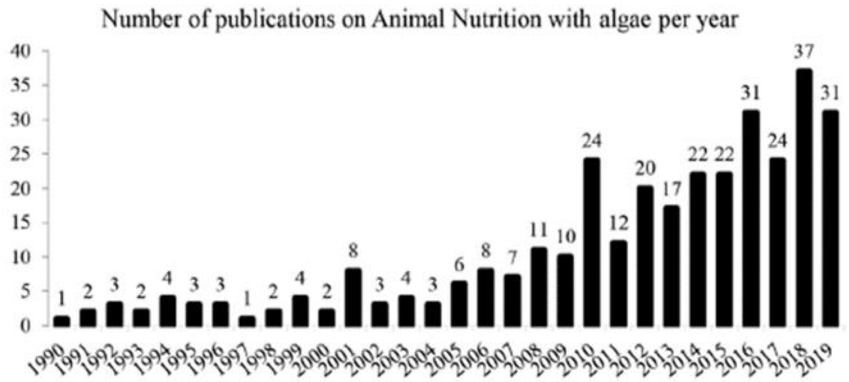

Figure 36 : Number of publications with "algae" in "animal nutrition" and/or 'animal-health" from 1990 to 2019, according to Web of Knowledge (Coudert et al. 2020)

The use of algae as livestock feed greatly depends on the species and their nutritional composition. Moreover, the animal adaption to the ingredient is another important factor. Quite different studies and reviews claims the benefits of algae and the challenge is now to support these claims. Indeed, results from experimental studies can be difficult to interpret as several compounds in algae can have confounding effects. Globally, the effects of algae in animal feed are: improved immune system, lipid metabolism, antiviral and antibacterial action, improved gut function, and stress resistance besides providing a source of protein, amino acids, fatty acids, vitamins and minerals, and other biologically active phytochemicals having an impact on productivity and/or product quality (Kusmayadi *et al.* 2021; Makkar *et al.* 2016; Shields and Lupatsch; Shields and Lupatsch 2012). The positive effect of some macroalgae to reduce enteric methane emissions in ruminant have also made the spotlight in the past years (Wasson *et al.* 2022).

The protein content of algae, especially microalgae and cyanobacteria, have been highlighted as an alternative protein source mainly for fish meal replacement in aquaculture and soy replacement in terrestrial production. The first drawback is the digestibility of the protein, which varies depending on species: it is expected that ruminants are among the most suitable recipients, since they ought to be able to break down even unprocessed algal cell walls due to their unique digestive system. The second drawback is the cost. If a source of protein-rich or lipid-rich algal meal came onto the market at an affordable price, the animal feed industry would certainly consider using it based on existing evidence of the nutritional value of algal biomass. However, all categories of algal products are currently much higher in cost than the commodity feedstuffs used in animal feeds, and their use requires additional benefits beyond protein replacement.

The interest of fatty acids from algae are mainly related to polyunsaturated fatty acids (PUFA) such as arachidonic acid (AA, 20:4n-6), eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3). Indeed, PUFA play a major role in human health by their actions in the prevention and treatment of coronary heart disease, hypertension, diabetes, arthritis, and other inflammatory and autoimmune disorders. As most of the microalgae producing these PUFA are not suitable for human consumption, their inclusion in animal feed, mainly aquaculture, might indirectly boost their nutritional values for humans.

The high content in certain vitamins and high mineral content of both macro- and microalgae can position them as an alternative of inorganic minerals salts, as mineral additives, that are used widely used in the animal feed industry. The main argument is that the natural forms are more bioavailable than the inorganic forms as they form complex with polysaccharides. However, the high variability of the vitamins due to algal species, growing season, culture conditions, and processing methods is a major drawback. However, some seaweeds (mostly brown) have been widely used since the 1970s for cattle.

Pigments (carotenoid essentially xanthophylls as fucoxanthin, lutein, and zeaxanthin and carotene as β-carotene) are of particular interest as they can only be produced by microorganisms, fungi, algae and higher plants and animals depend on their diet to meet their requirements. Poultry and aquaculture are particular in need of these molecules.

In livestock feed, the most commonly used algae (outside aquaculture) are *Ascophyllum nodosum*, *Laminaria sp.*, *Lithothamnion sp.*, *Macrocystis pyrifera*, *Sargassum sp.*, *Ulva sp.*, *Chlorella vulgaris*, and *Spirulina platensis* (Coudert *et al.* 2020; Kusmayadi *et al.* 2021; Makkar *et al.* 2016). Algae can be used in different forms as livestock feed (raw material fresh, frozen, or dried; oil obtained by extraction; or extracts used as a supplement in formulated diets). Mainly, the whole algae is used when incorporated in feedstuffs for cost considerations. However, there is a growing interest in algal extracts as they contain biologically active compounds likely to improve animal health and product quality (Coudert *et al.* 2020)

3.2.3. Different algae and uses depending on animal species targeted

3.2.3.1. Aquaculture feed

<u>Phytoplankton for hatcheries</u>

Aquaculture is the main field where microalgae are used as they are at the bottom of the aquatic food chain.

Microalgae provide an important direct or indirect feed source for early developmental stages of many farmed finfish, shellfish, and invertebrate species. Microalgae are responsible for the production of valuable nutritional compounds such as omega-3 fatty acid and some amino acids which accumulate afterwards in the food chain. It appears difficult to replace microalgae with substitutes to grow fish larvae and juveniles (Voort *et al.* 2015).

In hatcheries, the most used species are *Chlorella*, *Nannochloropsis*, *Tetraselmis*, *Tisochrysis lutea* (T-iso, formerly *Isochrysis galbana*), *Pheaodactylum*, *Thalassiosira*, *Pavlova*, *Chaetoceros* and *Skeletonema*. Live feeds are also used. They are a combination of several microalgae species which deliver a balanced diet to improve growth and survival rates at higher rate than one individual specie.

Their main uses are:

- Bivalve molluscs depend on microalgae at all development stages.
- Gastropod molluscs and sea urchins need a transition phase before juvenile macroalgae diet which is ensured by benthic diatoms. *Navicula* sp., *Nitzschia* sp. and *Amphora* sp. are some of the cultivated diatoms used, although challenges exist in optimising their methods of cultivation and deployment.
- Crustaceans (e.g., rotifer, shrimps) eat zooplanktonic live prey in their planktonic larval stage. These preys are fed on microalgae prior their distribution. These steps have been studied to improve nutritional quality of zooplanktonic prey, in particular to enhance omega-3 fatty acids. Commonly used microalgal strains for this purpose are *Nannochloropsis* sp., *Tetraselmis* sp., *Pavlova lutheri* and *Tisochrysis lutea.*
- Marine finfish species and some freshwater fish species larvae also receive live prey fed on microalgae. Depending on the presence of microalgae directly in the tanks of fish larval, the process is referred as “green water” or “pseudo green water” rearing technique. Commonly used microalgal strains for this purpose are *Nannochloropsis* sp., *Tisochrysis* sp. and *Tetraselmis* sp.

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Table 10: Non-exhaustive list of most commonly used strains and their uses in aquaculture (Shields and Lupatsch 2012)

Group	Genus	Species	Area of application
Cyanobacteria	Arthrospira	platensis	FFI
Chlorophyta	Tetraselmis	suecica, chui	B, CL
	Chlorella	sp., vulgaris, minutissima, virginica, grossii	R, FFI
	Dunaliella	sp., tertiolecta, salina	FFI
	Haematococcus	pluvialis	FFI
Eustigmatophyceae (Phylum Heterokontophyta)	Nannochloropsis	sp., oculata	R, GW
Labyrinthulea (Phylum Heterokonta)	Schizochytrium	sp.	RAD
	Ulkenia	sp.	RAD
Bacillariophyta (diatoms)	Chaetoceros	calcitrans, gracilis	B, CL
	Skeletonema	costatum	B, CL
	Thalassiosira	pseudonana	B, CL
	Nitzschia	sp.	GU
	Navicula	sp.	GU
	Amphora	sp.	GU
Haptophyta	Pavlova	lutheri	B
	Isochrysis	galbana, add. galbana "Tahiti" (T-iso)	B, GW
Dinophyta (dinoflagellates)	Crypthecodinium	cohnii	RAD

Key: FFI formulated feed ingredient; B bivalve molluscs (larvae/postlarvae/broodstock), C crustacean larvae (shrimps, lobsters); R rotifer live prey; RAD rotifer and Artemia live prey (dry product form); GU gastropod molluscs and sea urchins; GW "green water" for finfish larvae

Different effects have been reported on the use of microalgae in aquaculture which vary with microalgal strains, fish species, experimental conditions, and observational/analytical techniques. Globally, research show an effect on nutritional status of live prey and fish larvae, feeding behaviour of fish larval, larval digestive function and microbial community composition in the rearing water and the larval digestive tract (Shields and Lupatsch 2012).

The production of microalgae represents a significant cost to aquaculture farms. Algal culture cost is estimated to be on average 30% of hatchery cost, and up to 60% which represent between USD 50 to USD 400 per kg of dry weigh depending on the applied scale (Global Seafood Alliance 2020). Yet, fish aquaculture is dependent on forage fisheries from the adult life stage. The diminution of wild stock induced a push-up of fishmeal and fish oil prices. The growth of aquaculture fish production should lead to better market opportunities for algae to replace aquaculture feeds.

Fish and Shellfish aquaculture

Seaweeds are also increasingly used in aquaculture. They are for example used for sea urchin's production as these animals prefer this type of feed in nature. *Ulva* sp. and *Gracilaria* sp. Are the main species used as they are source of carotenoid needed to enhance the colour of the gonads (Shields and Lupatsch 2012).

Seaweeds are also increasingly used for fish (Wan *et al.* 2019) or shrimp feeding, allowing improve immunity, resistance to viruses and parasites (e.g. sea lice) or overall health ang growth performance.

Seaweed are also cultivated for the feeding of abalone, for example in South Africa or France (*Ulva* sp, but also red and brown species) (Kirkendale *et al.* 2010; Shuulaka 2011). But the largest developments in this field occurred since 2005 in Korea and China, with a booming abalone industry, intricately linked with seaweed aquaculture. In Korea, Abalone are fed on fresh *Undaria pinnatifida* and *Saccharina japonica* and it is estimated that at least 600,000 tons of these 2 species are currently used annually for abalone feeding (Hwang *et al.* 2022; Hwang and Park 2020). In parallel, the flourishing Chinese abalone and sea cucumber industry is relying on *Saccharina japonica*. In 2018, 30-40% of annual cultivated kelp production in Shandong and Dalian, and 60% of the production in Fujian was directly used as feed for

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abalone and sea cucumber aquaculture (Zhang 2018), a major shift from an historical production targeting food and alginates production.

Lastly, beyond the direct uses of microalgae in early growing stages discussed above, microalgae and Labyrinthulomycetes are also used for the extraction of compounds of interest as omega-3 fatty acids and pigments used in aquaculture. We will discuss them directly in dedicated sections of the report.

3.2.3.2. Poultry

Among terrestrial animal, incorporation of algae into poultry rations offers the most promising prospect for their commercial use in animal feeding (Kovač *et al.* 2013; Makkar *et al.* 2016). In poultry, algae can be used as a partial replacement for conventional proteins with the incorporation of 5-10%. In several countries, they are officially approved as chicken feed. More specifically, a dietary incorporation rate of 2% for microalgae or a range between 1% and 5% for macroalgae is suitable for both laying hens and broiler chickens, even though these ranges greatly depend on the type of algae used and the expected benefits for poultry production (Coudert *et al.* 2020). The use of enzyme cocktails might help to enhance the nutritional value which could be reduce by polysaccharides contains in algae (Makkar *et al.* 2016).

The effects of algae in poultry nutrition concern egg productivity, egg quality (York colour), egg composition (lipids in particular omega-3), hen and broiler health (prebiotic, gastrointestinal health, absorption of nutrients), growth performance, meat production and quality (proximate composition or colour). The increase in laying rate and egg weight can reach +4.0 to 8.6 percentage points and +1.3 to 1.5 g, respectively. The increase in body weight of broilers and decrease in feed conversion ratio can vary from 5% to 22% and from 4% to 15%, respectively (Coudert *et al.* 2020). It also appears important to evaluate their potential effect as a source of calcium (Makkar *et al.* 2016).

Brown seaweed appear to be the main species studied among them *Ascophyllum nodosum*, *Sargassum* sp. *Undaria pinnatifia* and *Ulva* sp. For microalgae and cyanobacteria, *Chlorella* sp. and Spirulina are the main species studied. Results vary among algae species, and type of production (Makkar *et al.* 2016).

3.2.3.3. Ruminants

Due to their polygastric digestive tract and the presence of the rumen and its micro-organisms, ruminants may be expected to be the most suitable terrestrial animal production to use algae as they can digest even an unprocessed algal cell wall. They can also utilize the non-protein nitrogen contain in algae among other constituents such vitamins and minerals. (Costa *et al.* 2022; Kovač *et al.* 2013). Yet, large-scale algae-livestock feedstuff value chains have not been established due to the high cost of production, processing and transport logistics, shelf life and stability of bioactive compounds and inconsistent responses by animals under controlled experiments. One opportunity to enhance the inclusion of algae in ruminant nutrition is the inclusion of by-products from other industries such as biofuels and biorefinery (Costa *et al.* 2022).

Studies performed in ruminant nutrition showed variable results as the nutritional value of seaweeds varies depending on algal species, their composition (protein, minerals, polysaccharides, phlorotannins), and the adaptation of the animal to this particular feed (Costa *et al.* 2022; Makkar *et al.* 2016). An exception to the previous sentences is the use of *Ascophyllum nodosum* which has been used as a feed additive for decades. Indeed, the algae is a source of minerals which could correct mineral deficiency in milk production. *A. nodosum* meal and its extracts have been shown to enhance immunity and antioxidative status in cattle, sheep and goats and reduce pathogenic microorganisms. The other species studied are *Laminaria* sp., *Saccharina* sp., *Macrocystis pyrifera*, *Phytomalithon calcareum*, *Sargassum* sp., which mainly have an impact on water consumption and pH buffer in the rumen, and some red seaweeds such as *Palmaria palmata* which have a potentially high nutritive value as a source of protein. Regarding microalgae and cyanobacteria*, Chlorella* sp. and Spirulina have been

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the most studied one with positive impact on ruminal population with higher fatty acid compositions and the production of microbial protein (Kusmayadi *et al.* 2021; Makkar *et al.* 2016).

Another recent interest is focused on bioactive compounds present in red seaweed, such as bromoform, that directly affects methanogenesis and by extent the production of methane by ruminants. Recent studies have highlighted the role of bromoform molecules which inhibits the production of methane contained in red algae especially those belonging to the *Asparagopsis* species (Wasson *et al.* 2022). Yet, some limits need to be pushed before these algae can be used on a large scale to reduce enteric methane emissions: heterogeneity in *in vivo* results, the fate of bromoform in products and in the environment, production of these algae and price competitiveness which may need the intervention of a low emission scheme (Costa et al. 2022). Some compagnies are currently developing the culture of *Asparagopsis* (Futurfeed, and Sea Forest in Australia and Blue Ocean Barns in Hawaii). One European company Volta Greentech in Sweden is also currently developing an ingredient based on *Asparagopsis* to reduce methane.

3.2.3.4. Swine

Nearly all the pig-feeding studies indicate that microalgal biomass in general is a feed ingredient of acceptable nutritional quality and suited for rearing pigs. In the same way, seaweeds have an impact on growth performance, digestibility, prebiotic antibacterial, antioxidant and anti-inflammatory functions in swine. The studies mainly include brown seaweeds (*A. nodosum*, mix of brown seaweeds, *Ecklonia cava*, *Laminaria* sp., …). Seaweeds can also be a source of iodine for regions where part of the population suffers from iodine deficiency. As for the others animal production, the price and scale-up of the algal production are the main sticking points (Corino *et al.* 2019; Makkar *et al.* 2016).

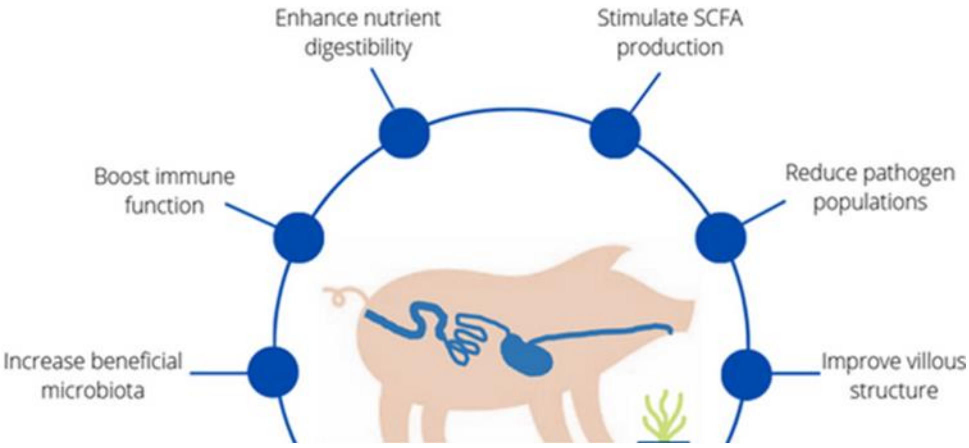

Figure 37 : Benefits of seaweeds on piglet gut health (Al-Soufi et al. 2022)

3.2.3.5. Pets and horses

Few scientific studies have been performed to study the effect of algae on nutrition of pets (cats, dogs, rabbits) and horses. The main effect reported are on gut health and prebiotic effect to reduce the use of antibiotic and welfare of the animals. Some studies concluded to avoid algae for pets until their harmlessness and nutritional value have been proved (Al-Soufi *et al.* 2022; Makkar *et al.* 2016).

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At the same time, the petfood and horse market is a niche market for algae in which price is less a barrier than in other land-based production.

3.3. Production of phycocolloids and other polysaccharides

Polysaccharides, and particularly the three main phycolloids (alginates, agar, carrageenans) play a major role in the global seaweed sector. This is also the case in Europe, with a number of companies holding significant shares of the global market, using a combination of local and imported seaweed.

While the 3 major phycocolloids are representing the largest share of the algae polysaccharides market, a number of other polysaccharides are also emerging (industrially or still in a research phase), often for more specific markets.

We will review them individually.

Volumes and market values expressed in this review are built from various sources (public sources, market reports, country statistics, industry interviews), combined with our own interpretation of the market and values. It should be noted that depending on sources, the numbers provided may relate directly to the “pure” carbohydrates, or are based on formulated products, as colloids are often blended for standardization of physico-chemical and rheological parameters, or to adjust their properties. This can also impact the variability of the values provided.

3.3.1. Alginates

3.3.1.1. Description and source

Alginates are polysaccharides extracted from brown seaweeds, which are composed of mannuronic acid (M) and guluronic acid (G) monomers. Alginates properties (and applications) are depending on the proportion and distribution of M:G monomers in the polymer, which is often directly related to the seaweed species used. In particular, a higher G content leads to strong and rigid gels.

Market is progressively shifting towards “high G” products, made from *Laminaria hyperborea* (Norway + Northern Europe) and *Lessonia* sp. (South America, processed locally (limited production in Chile) and in Asia-Pacific (mostly China + Japan) and Europe (France, Norway)). *Laminaria digitata* is also widely used in France, while other species are also imported from South America. Production from locally cultivated kelp species is also still important in China.

3.3.1.2. Global Market

Significant variations are observed in the evaluation of the global alginates market depending on sources.

Table 11: Global alginate market according to various sources and market reports

Market value	Year	Market volume	CAGR	Source
$ 750 M	2020	44,000 tons	5 %	(Grand View Research 2020b)
$ 610 M	2020		3.3 %	(Global Market Insights)
$ 390 M	2021		4.5 %	(Data Bridge Market Research 2021)
$ 345 M (Food, Pharma, PGA only)	2015	48,000 tons Incl. 25,000 tons (Food, Pharma, PGA)	-	(Porse and Rudolph 2017)
-	2022	45,000 tons	-	(Industry interviews 2023)

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A consensus value might then be a global volume of ~45,000 tons, with a CAGR around 4%, but a more realistic growth rate might be closer to 2-3% (Bixler and Porse 2011; Industry interviews 2023; Porse and Rudolph 2017), although recent inflation of energy costs and raw materials, might push it to much higher levels.

Market value estimates show much larger variations. This is likely due to the use of high prices in some estimations (e.g. an average price of 25-30$/kg for food and pharma grades according to Grand View Research).

A more realistic estimate might be a total sales volume of € 525 M including:

- 20,000 tons premium grade alginates (Food, Pharma, PGA) at an average price of 15 €/kg
- 25,000 tons technical grade alginates at an average price of 9 €/kg

3.3.1.3. Alginates production in Europe

European producers mostly focus on Food/Pharma grades, with PGA mostly produced in the Asia-Pacific region and technical grades mostly produced in China.

EU total alginate production according to (Porse and Rudolph 2017) was 13,500 tons in 2015 but this value might be overestimated , and actually closer to 12,000 tons (Industry interviews 2023). With an average selling price in Europe around 13 €/kg (Industry interviews 2023; United Nations 2023), this would represent € 156 M in sales.

The production is currently mostly split between three main factories in France (Algaia and JRS) and Norway (Dupont). JRS also announced on March 23rd, 2023, the purchase of Algaia, reducing the number of active companies to two.

Surprisingly, several other exporting countries are listed in Europe with significant volumes. This is much likely related to distribution of ingredients and blends. It is in particular the case for United Kingdom (even exceeding French exports in 2020), which is at least partially related with the presence of Dupont blending facility in Girvan (Scotland).

Table 12: Trade balance of the 3 main alginates exporters in Europe (2019 – pre-COVID values)
Source: https://oec.world/en/profile/hs/alginic-acid-its-salts-esters

Country	Export (M€)	Import (M€)	Balance (M€)
Norway	59.0	0.24	58.7
France	33	10.5	22.6
UK	24.6	11.7	12.9

The 2 French factories of JRS in Lannilis (Algaia, former Cargill factory) and Landerneau (JRS, former Danisco factory) process a large proportion of the *Laminaria digitata* harvested in France (45,000 to 55,000 tons/year), *Laminaria hyperborea* harvested in France (15,000 to 20,000 tons/year) as well as imported species (in particular from South America) which may represent 20% of the volume processed. Their combined production is likely close to 3,000 tons, for a total turnover in excess of € 40 M for the 2 companies.

In the meantime, Dupont in Norway (former FMC factory) processes 150,000 tons of *Laminaria hyperborea* harvested on the Norwegian coast (corresponding to 5,000-6,000 tons alginates, using a 3% conversion ratio, in line with other sources (Harmsen 2014)) and also imports seaweed from other countries as Iceland, Chile and Tasmania.

Other newcomers are also joining the alginates market, but often based on new biorefinery processes targeting a range of diverse products. It is for example the case of Alginor in Norway (current pilot facility abler to process 10,000 tons of seaweed/year, plans for a second factory able to process 100,000 tons), or Origin by Ocean in Finland (R&D/scale-up).

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Another project of factory was led by Marine BioPolymers (MBL) in Scotland but is currently on hold, following restrictions on kelp harvesting in the area. The company initially requested a 30,000 tons/annum harvesting license (Greenhill *et al.* 2021).

3.3.1.4. By-products, co-products and effluent streams

Other seaweeds can be harvested along with the targeted *Laminaria* species, either because they share the same habitat (e.g. *Saccorhiza polyschides* for *Laminaria digitata*), or because they grow as epiphytes of the *Laminaria* (e.g. *Palmaria palmata* for Norwegian *Laminaria hyperborea*).

In particular *Saccorhiza polyschides* is another alginate-bearing brown seaweed, but tends to degrade seaweed processability and alginate quality. It is present in limited quantity either naturally, or by implementing limits in the quality specifications for harvesters, and *Saccorhiza* is not separated before processing.

Palmaria palmata is also present as an epiphytic species on *Laminaria hyperborea* harvested in Norway (up to 5%). While not valorized to date, this represents a significant source of this seaweed currently in high demand across Europe for food applications, but also triggering interest for its relatively high protein content (Aasen *et al.* 2022).

Subsequently, several side-streams and co-products are generated in the alginate processing. They are described in Figure 38 and detailed below.

<u>Lixiviation effluents</u>

Strongly diluted fraction (~20g/L), which may represent 35% to 50% of initial seaweed weight (Bojorges *et al.* 2022; France Agrimer 2021). 35% seems a more realistic estimation at industrial-scale, although higher levels can be reached at lab-scale.

This fraction can contain (Bojorges *et al.* 2022):

- High mineral content: ~40-50%
- Carbohydrates including mannitol (seasonal and depending on species), laminarin (seasonal and depending on species) and fucoidans/fucose-containing polysaccharides: 40-50%
- Minor protein content: ~5%
- Minor soluble polyphenols content

The lixiviation in acid conditions might also lead to partial desulfation of fucose-containing polysaccharides (Bojorges *et al.* 2022), as well as denaturation of proteins.

Presence of traces of formaldehyde are also possible in these effluents, as formulation can still be used to improve seaweed stability during storage and downstream processing, including insolubilisation of the phlorotannins, which remain in the solid residues (Hernández-carmona *et al.* 1998).

<u>Precipitation and purification effluents</u>

Effluents in this second stage are dependent on the process applied to recover and purify the extracted sodium alginate (alginic acid or calcium alginate process), as well as downstream treatment (bleaching, conversion to sodium alginate or other forms as calcium or potassium salt or PGA, etc.) (McHugh 2003).

However, the effluents from alginate separation are again diluted and largely composed of minerals (up to 80% (Bojorges *et al.* 2022)), although still containing some carbohydrates and alkali-soluble proteins. They are usually sent directly to the wastewater treatment installations, and are less likely to generate significant amounts of compounds of interest.

<u>Solid-coproducts</u>

The residues from sodium-alginate extraction (usually referred to as flotation cellulose, or cellulosic cake) are mostly composed of polysaccharides (~60%), proteins (~15-25%) and minerals (~15-25%) (CEVA unpublished data; Fleury and Lahaye 1993). The polysaccharides fraction contains a

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combination of insoluble polysaccharides (mostly cellulose and insoluble fucose-containing polysaccharides) and soluble polysaccharides (mostly residual alginates).

While these residues are theoretically rich in organic matter, they are industrially separated by filtration using significant amounts of filtration aids (30-50%) (Industry interviews 2023). The filtration aids are mostly inorganic materials (perlite, bentonite, diatomaceous earth) although smaller amounts organic media can be added (e.g. cellulose).

As a consequence, the solid co-products are composed of over 50% minerals, with significant amounts of insoluble materials, which makes downstream processing more complex.

They are usually obtained with a dry matter of ~25% but can be further dried or stabilized (composting), to stabilize them and valorize them in other areas (e.g. in agriculture), depending on composition and local regulations.

Sewage sludge

Wastewater treatment units of the alginates factories also generate significant amounts of sewage sludge, which are usually disposed by spreading on farms (can require significant surfaces) or are handled as waste (cost).

Sludge volumes might represent in average 1 ton biological sludge / ton of alginate produced according to information from producers and regulatory dossiers for spreading plans.

Process waste material

Material losses also occur during the process and some waste material is recovered during cleaning of reactors (liquid + solid residues) and downstream powder processing (alginates). Their volumes are limited and they are currently handled as waste. They likely represent <1-2% of the total raw material processed.

Valorization of the by-products

Most alginates producers are already in a process of valorizing their co-products and effluents, or developing solutions to do so.

As mentioned above, agricultural uses of the solid co-products are the most developed (although associated revenues are often limited).

Companies (established or start-up) are also working on biorefinery approaches, either by pre-extraction of the raw materials before entering the main alginates extraction process, or by extraction of compounds of interest from the lixiviation effluents.

While the volumes processed remain limited to date, successful developments have been performed by alginates companies. For example, Algaia is developing a range of specialty extracts and plant biostimulants. FMC (now Dupont-IFF) was also the first European processor to develop a food-grade fucoidan to be sold as food supplement in the USA (US Food and Drug Administration 2013), which was purified by ultrafiltration, likely from exudates of freshly harvested/cut seaweed (e.g. patent EP2643356).

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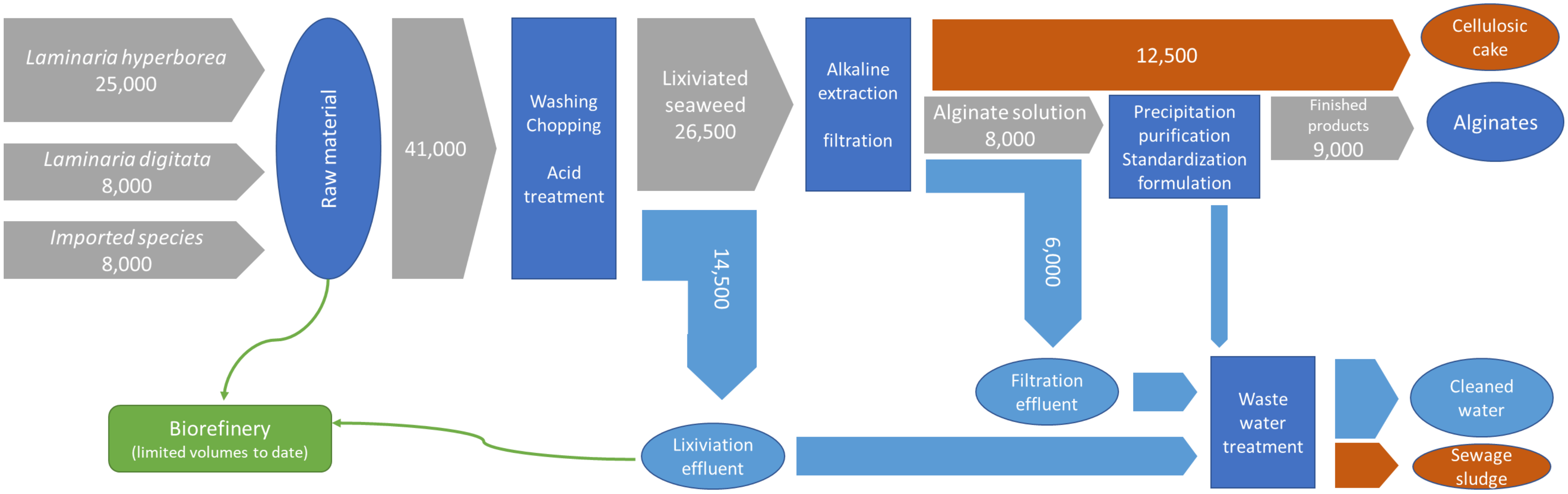

Figure 38 : Alginates processing (traditional industrial process) – putative mass balance, expressed as tons of dry matter (from seaweed) – CEVA calculations

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3.3.2. Carrageenans

3.3.2.1. Description and source

Carrageenans are a family of sulfated polysaccharides extracted from red seaweeds, which are used mostly in the food industry for their gelling, thickening, and stabilizing properties (van de Velde and Ruiter 2002). Other markets are also growing, and cosmetics might represent a significant contribution to future growth (Coherent Market Insights 2022b; Industry interviews 2023).

They are composed of alternating 3-linked β-D-galactopyranose and 4-linked α-D-galactopyranose or 3,6-anhydro-α-D-galactopyranose units, with varying degrees/positions of sulfation and anhydro content.

There are three main commercial classes of carrageenans:

- Kappa carrageenan forms strong, rigid gels in the presence of potassium ions, and reacts with dairy proteins. It is sourced mainly from *Kappaphycus alvarezii* also known as "Cottonii".
- Iota carrageenans forms soft gels in the presence of calcium ions. It is produced mainly from *Eucheuma denticulatum* also known as "Spinosum"
- Lambda carrageenans do not gel, and are used to thicken dairy products.

Two types of carrageenans can also be distinguished, depending on the process used for their production:

- Refined Carrageenans (RC) are purified using the alcohol or gel-press process. They are used in dairy, beverages, protein drinks, salad dressings, as well as in Cosmetics and Pharmaceutical applications.
- Semi-refined carrageenan (SRC) or Processes Eucheuma Seaweed (PES) are less refined products used, among others, in applications that do not need gel clarity or can handle insoluble particles: petfood, meat applications, …

Market is dominated by cultivated Cottonii and Spinosum (Figure 39), mostly cultivated in the Philippines and Indonesia where an increasing part of the processing is taking place, but also in the Indian Ocean (Zanzibar, Madagascar, …) (Neish 2021; Porse and Rudolph 2017). China is also a major player in their processing, using raw material form South East Asia (Porse and Rudolph 2017).

In the meantime, seaweeds harvested in South America and Europe (*Gigartina sp*, *Chondrus crispus*, *Sarcothalia crispata*, *Chondracanthus chamissoi*, *Mazaella laminarioides*), often see their volumes stagnating or even decreasing and face significant price increases. For example, the average price of these five species exported from Chile to Europe increased by 117% between 2020 and 2022 (Industry interviews 2023).

However, these cold water species are still of importance for specific carrageenan-grades, or to be used to adjust technical properties and performance in commercial products (Industry interviews 2023).

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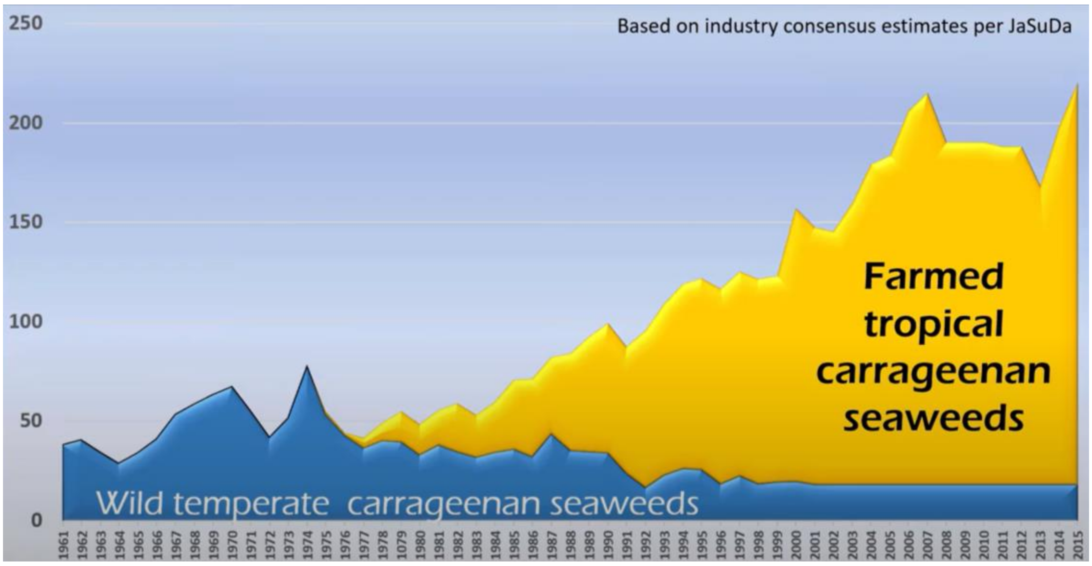

Figure 39 : Thousands of tons of dry carrageenan seaweeds 1961-2015 (Neish 2021)

It is difficult to establish the true volumes of carrageenan-bearing seaweed cultivated. Values commonly referred to are published by the FAO (Cai *et al.* 2021) report a total production of *Kappaphycus* sp. and *Eucheuma* sp. around 12 million tons (fresh weight). However, they rely on national statistics from producing countries and appear to be significantly overestimated.

A more realistic approach would be to consider a production in 2021 in the range of 250,000 to 340,000 tons dry weight (Industry interviews 2023; Neish 2021), equivalent to less than 2 million tons fresh weight. Of these, 80-85% are *Kappaphycus* sp, and 15-20% *Eucheuma sp*.

This production alone is equivalent to around € 400M, using an average price of 1200-1500 €/T in 2020, but twice that amount in 2022 with prices that doubled over the last 2 years (Industry interviews 2023).

3.3.2.2. Global Market

As for alginates, significant variations are observed in the evaluation of the global carrageenans market depending on sources.

These variations might, among others, be related to differences between total amounts of carrageenans produced, and volumes sold. Indeed, carrageenans are almost never sold as pure ingredients, but are usually standardized and/or blended with other ingredients.

Table 13: Global carrageenans market according to various sources and market reports

Market value	Year	Market volume	CAGR	Source
$ 850 M	2021	54,000 tons	3.4 %	(Grand View Research 2020a)
$ 882 M	2021		4.4 %	(Coherent Market Insights 2022b)
$ 518 M	2015	57,800 tons	2%	(Porse and Rudolph 2017)
	2022	84,000 tons	3%	(Industry interviews 2023)
	2022	Close to 100,000 tons		(Industry interviews 2023)

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A consensus value might then be a global volume of ~80,000 tons (formulated products), with a CAGR around 3% (in volume), although recent inflation of energy costs and raw materials, will push growth rate in value to much higher levels.

Market value estimates also show larger variations related to average prices used. Porse and Rudolph use a 9$/kg average price (although in 2015), while Grand View Research uses 15.4$/kg.

Using an average price of 10-15 €/kg, the global market might represent € 800 M to € 1200 M.

3.3.2.3. Carrageenans production in Europe

European producers focus on Refined Carrageenans (at least for their productions in Europe).

EU total carrageenan production according to (Porse and Rudolph 2017) was 7,500 tons in 2015 (6,400 tons gel-press and 900 tons alcohol process), while (Neish and Msuya 2013) provided higher volumes with 10,250 tons in 2015, although this might include production from the Philippines.

There are currently three producers operating in Europe:

- CP Kelco (Denmark)
  (also operating in the Philippines as Marcel Food Sciences (RC) /Marcel Trading Corp (SRC))

- Cargill (France)
  (sold its stake in Philippine Bio-Industries (RC facility) to W Hydrocolloids Inc. in 2020)

- Ceamsa (Spain)
  (also operating in the Philippines with CEAMSA Asia (SRC))

Overall, these 3 companies might currently process 20,000 tons of dry seaweed (Industry interviews 2023). However, this is difficult to convert to carrageenan volumes for several reasons:

- Extraction yields are different for cultivated warm water species (20-30%) and harvested cold-water species (30-50%)
- Carrageenan content in end-products can be highly variable due to standardization and blending.

The 7,500 tons reported by (Porse and Rudolph 2017) are quite consistent with an average extraction yield of 30% and additional blending. With a current average selling price approaching 15 €/kg in Europe (Industry interviews 2023; United Nations 2023), this would represent € 112 M in sales for European production.

3.3.2.4. By-products, co-products and effluent streams

After an initial cleaning process (to remove sand, shells, plastic residues, …), the (usually dried) seaweed are directly integrated in the process, and do not generate side-streams at this stage.

As mentioned earlier, two different types of products with distinct processes and different effluents / co-products can be prepared from the seaweed (Figure 40), but no production of SRC/PES is performed in Europe.

- PEC/SRC process: full-processing, no solid by-products. Liquid effluents from alkaline cooking (containing salts, proteins, …) are generated.
- RC process: solid residues, rich in cellulose are isolated during the filtration(s) after alkaline cooking. Liquid effluents are also generated, especially after precipitation stage

RC process for Europe and streams generated is further illustrated in Figure 40.

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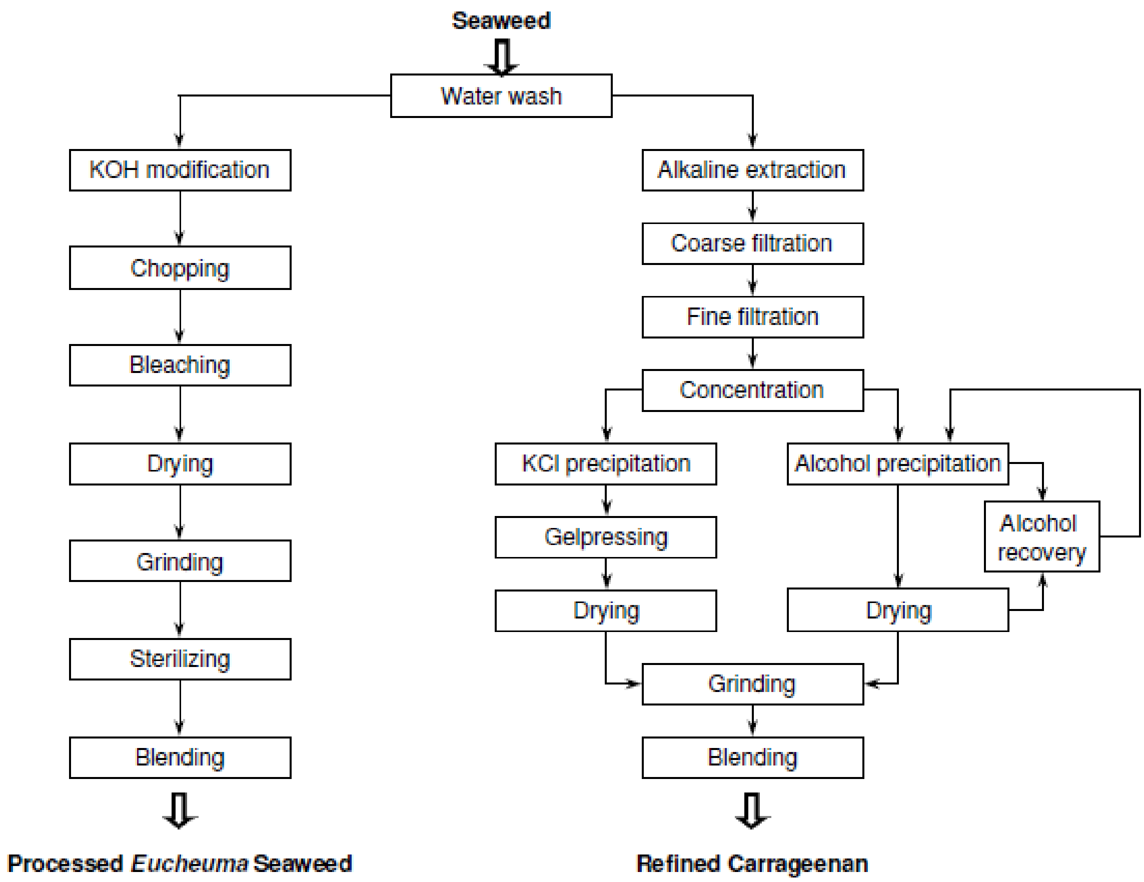

Figure 40 : Carrageenan processing
(van de Velde and Ruiter 2002)

Solid residues

Solid residues from extraction are mostly composed of residual cellulose and some "hemicellulose and lignins" (Gontiñas *et al.* 2019), as most soluble compounds are extracted during the prolonged alkaline cooking and extraction.

Their exact composition depends on the seaweed used in the process and the alkali treatment applied, although the producers do not separate them according to the raw materials used (Industry interviews 2023).

However, as for the solid residues from alginates processing, they are often industrially separated by filtration using significant amounts of filtration aids (mostly perlite and possibly additional cellulose (Industry interviews 2023). As a consequence, the solid co-products are composed of over 80% minerals, with significant amounts of insoluble materials, which makes downstream processing more complex.

They are usually obtained with a dry matter of 20-30% but can be further dried or stabilized (composting), to stabilize them and valorize them in other areas (e.g. in agriculture), depending on composition and local regulations. They are currently partially valorized (directly or after stabilization) as soil fertilizers, or for soil structuration or pH adjustment, but a large part is supplied to the farmers without generating revenues.

An alternative method is to use a preliminary coarse filtration (or centrifugation), prior to the fine filtration using perlite. In this case, a perlite-free product can be obtained with a much higher organic content. This seaweed by-product is partly valorized by CP Kelco (biogas production and agricultural uses), but mostly incinerated due to excessive cadmium content. (CP Kelco 2021).

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The quantity of solid residues can be estimated to be around 75,000 tons wet weight for Europe, which include around 10,000 tons of organic matter (mostly cellulose), and equivalent amounts of perlite (mixed or not with the seaweed residue).

Liquid effluents

Liquid effluents from carrageenan processing exist in two forms:

- Effluents from gel pressing, after KCl precipitation (main process in Europe)
- Vinasses obtained after alcohol recycling from alcohol precipitation.

They can contain a variety of compounds including proteins (potentially denaturated by the alkaline process), or small carbohydrates, but their organic matter is very low and they also contain significant amounts of minerals from the seaweed and from salts used in the process (alkaline treatment, neutralization, potential KCl addition, …).

Significant volumes are sent directly to the factories' water treatment plants.

Water (and alcohol when used) are recycle to the maximum extent, but significant volumes of effluents are sent directly to the wastewater treatment plants of the factories (Industry interviews 2023).

Sewage sludge

Wastewater treatment units of the carrageenan factories also generate significant amounts of sewage sludge, which are usually disposed by spreading on farms (can require significant surfaces) or are handled as waste (cost) (Industry interviews 2023). It can also be considered for biogas production, but it is not currently the case.

Note: the three European producers are processing different ingredients, (pectins, xanthan) and are using shared water treatment facilities, so the sludge does not only result from seaweed residues treatment.

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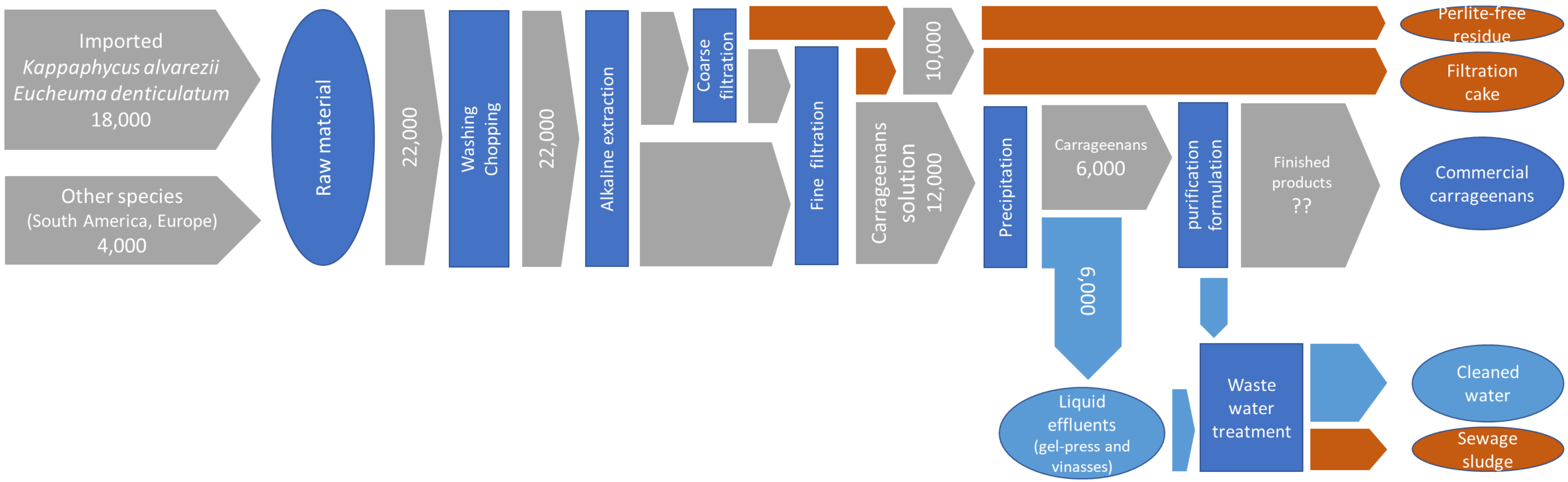

Figure 41 : Carrageenan processing and by-products in Europe – putative mass balance, expressed as tons of dry matter (from seaweed) – CEVA calculations

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3.3.3. Agar

3.3.3.1. Description and source

Agar is a polysaccharide, which forms very strong gels, and was the first seaweed hydrocolloid utilized at large scale. It is composed f alternating units of D-galactose and 3,6-anhydro-L-galactose, with few variations, and a low content of sulfate esters (Armisén and Gaiatas 2009).

It can be extracted from a limited number of red seaweed species (*Gelidium* sp, *Gelidiella* sp and *Pterocladia* sp), and can also be prepared from *Gracilaria* sp, *Gracilariopsis* sp or *Ahnfeltia* sp, usually after an alkaline treatment allowing to improve its properties (desulfation, and formation of the anhydrogalactose unit).

There are two main types of commercial agar (Porse and Rudolph 2017):

- Bacteriological agar, used for pharmaceutical and biotech applications is extracted from *Gelidium* sp, which provides a higher yield and improved performance (including a lower gelling temperature). It represents a small portion of the market in volume, but is sold at a significant premium. It is also relying on declining stocks, and occasional quotas / bans on harvesting, which triggers significant price fluctuations.
- *Gracilaria* agar-agar is mostly used in food applications, but also other markets even if they remain limited. The largest part of the market is relying on cultivated *Gracilaria* sp.

Wild *Gelidium* sp are mostly harvested in Morocco (80% of the global landings), as well as in Southern Europe (Spain, France and Portugal), South America (Chile, Mexico) and Asia (mostly Korea currently). Total Gelidium production is currently estimated to be around 14,000 tons dry weight, with prices ranging from 1,000€/ton (dry weight) for beach-cast seaweed, to 3,000 €/ton for high quality material (hand-picked by divers).

With landings decreasing in most historical countries and severe restrictions on *Gelidium* exports as of 2015 triggered a global crisis. Even though the situation has eased out since that date, global *Gelidium* production is still relying largely on Moroccan seaweeds, and the situation remains fragile (Santos and Melo 2018).

Gracilaria sp, is a less sensitive raw material as it is relatively easily cultivated, with Indonesia and China as the leading countries. Estimates of *Gracilaria* production for the agar industry vary between 110,000 and 130,000 tons dry weight (Industry interviews 2023; Neish 2021; Paravano 2015; Porse and Rudolph 2017). Its price varies significantly but can be estimated to be 700€/ton for South-East Asia material.

3.3.3.2. Global Market

When compared to alginates and carrageenans, market estimations for agar are relatively consensual (Table 14).

This might be related to the fact that agar is mostly sold in pure form. Some standardization also occurs but it is not required from a technical aspect: limited amounts of "excipients" are added, and only in less than 10% of the market concerned (Industry interviews 2023; Paravano 2015).

Table 14: Global agar market according to various sources and market reports

Market value	Year	Market volume	CAGR	Source
$ 276 M	2021		4.7%	(Coherent Market Insights 2021a)
$ 324 M	2021		5.1 %	(Mordor Intelligence 2021)
$ 221 M	2016		5.5 %	(Future Market Insights 2016)
$ 246 M	2015	14,500 tons	7 %	(Porse and Rudolph 2017)
	2014	16,000 tons		(Paravano 2015)
	2022	13,000 tons		(Industry interviews 2023)

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Gelidium agar represents around 1,500 tons, currently sold around 30 €/kg, although significant fluctuations have been observed over the recent years, especially during the global shortage in 2016-2017.

Gracilaria agar, might represent between 11,000 and 13,000 tons, with a current average price around 15€/kg (Industry interviews 2023; Paravano 2015; Porse and Rudolph 2017).

In total, the agar market might be estimated around € 225 M (€ 45 M for *Gelidium* agar, and € 180 M for *Gracilaria* agar).

3.3.3.3. Agar production in Europe

There are currently three producers operating in Europe, all located in Spain:

- Roko Industrial
- Hispanagar
- Agar de Asturias (microbiological agar only)

The three companies process mostly *Gelidium* sp, with *Gelidium* agar representing 70% of the European output (Industry interviews 2023).

Total European production was estimated to be in a range of 800-1,000 tons in 2015 (Paravano 2015; Porse and Rudolph 2017), which would correspond to € 20 M to €25 M in sales, using an average selling price of 25€/kg.

However, the three companies cumulated a turnover of around €50M in 2016/2018, which might indicate that these volumes/prices are underestimated, or could also indicate that some of the companies also trade agar. Still, their total production might actually be closer to 1,200-1,300 tons for a market of € 35M.

3.3.3.4. Agar production process, by-products, co-products and effluent streams

After an initial cleaning process (to remove sand, shells, plastic residues, …) of the (usually dried) seaweed, the seaweed is subjected to a pre-extraction treatment depending on the genus used (Armisén and Gaiatas 2009; McHugh 2003).

Gelidium can be pre-treated in a mild acidic bath, before being subjected to hot water extraction.

Gracilaria is subjected to a hot alkaline treatment to improve its gel-strength and then rinsed.

Both seaweed types are subsequently extracted in hot water.

As *Gelidium* is more resistant, it can be subjected to higher temperatures, possibly under pressure to reach 105-110°C (McHugh 2003). But this higher resistance also allows a better conservation of seaweed structure, and improves subsequent filtration which does not require filtration aids, while it is required for *Gracilaria* (Industry interviews 2023).

Finally, the products are let to gel by cooling, and the gels are subsequently concentrated either by freeze-thaw cycling (up to 10-12% agar), or by syneresis (up to 20% agar) (Armisén and Gaiatas 2009). By expelling a higher amount of water and dissolved salts and molecules, the second technique allows higher agar purity and is more energy efficient, and is now the preferred process.

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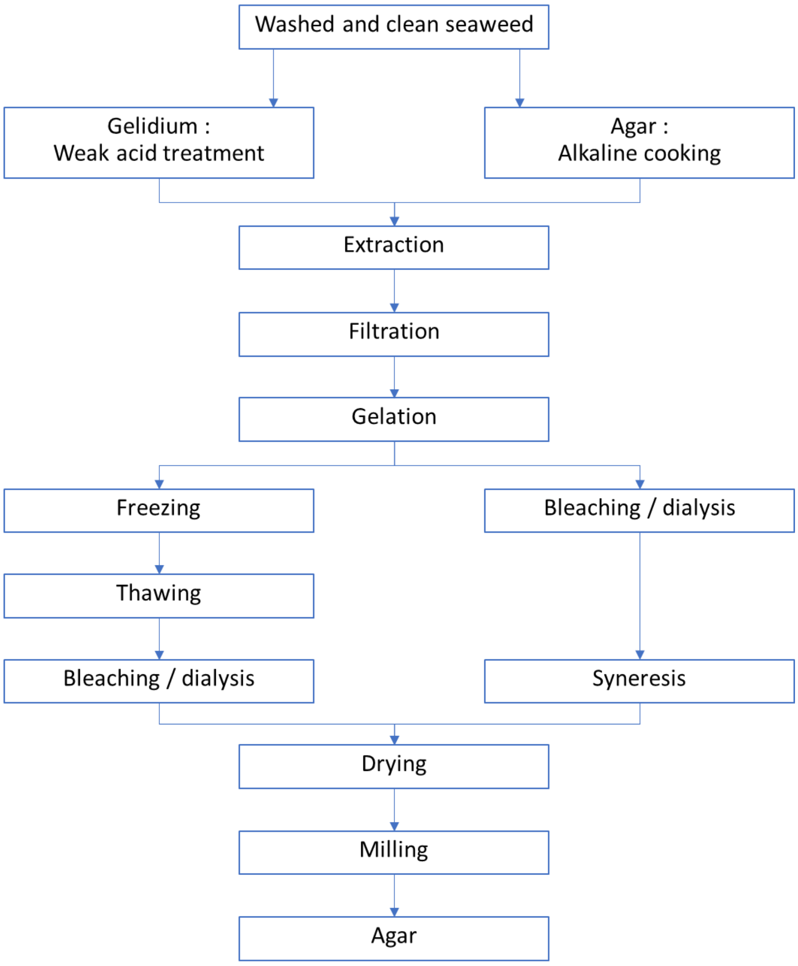

Figure 42 : Agar fabrication diagram
(Armisén and Gaiatas 2009; McHugh 2003)

Process and co-products from *Gracilaria*:

During alkaline cooking and extraction of *Gracilaria*, the seaweed is disintegrated. Filtration aid is mandatory as a consequence, and is usually performed with perlite.

Solid residues

- Contain high level of perlite
- More or less the same amount of dry material after processing (1 kg of filtration aid added for 1 kg of seaweed processed)
- No filtration cellulose added.

The residues can be composted for agriculture (direct supply for use by farmers is not allowed anymore in Spain) but are sold to composting companies (limited value but no destruction costs)

Liquid residues

- Little information on composition is available. Composition also depends on gel concentration process.
- Water is recycled as much as possible and usually sent to wastewater treatment afterwards.

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Process and co-products from *Gelidium*:

Seaweed is generally only “soaked” for extraction and is easily removed afterwards. The addition of filtration aid is then not required if the process is performed properly.

Solid residues:

- Can consist of seaweed only (can make a very good material for further processing).
- Currently composted but good candidate for further processing.

Liquid residues:

- Little information on composition is available. Composition also depends on gel concentration process.
- Recycled as much as possible and usually sent to wastewater treatment afterwards.

Both processes also lead to sewage sludge, associated with the downstream treatment of the liquid effluents.

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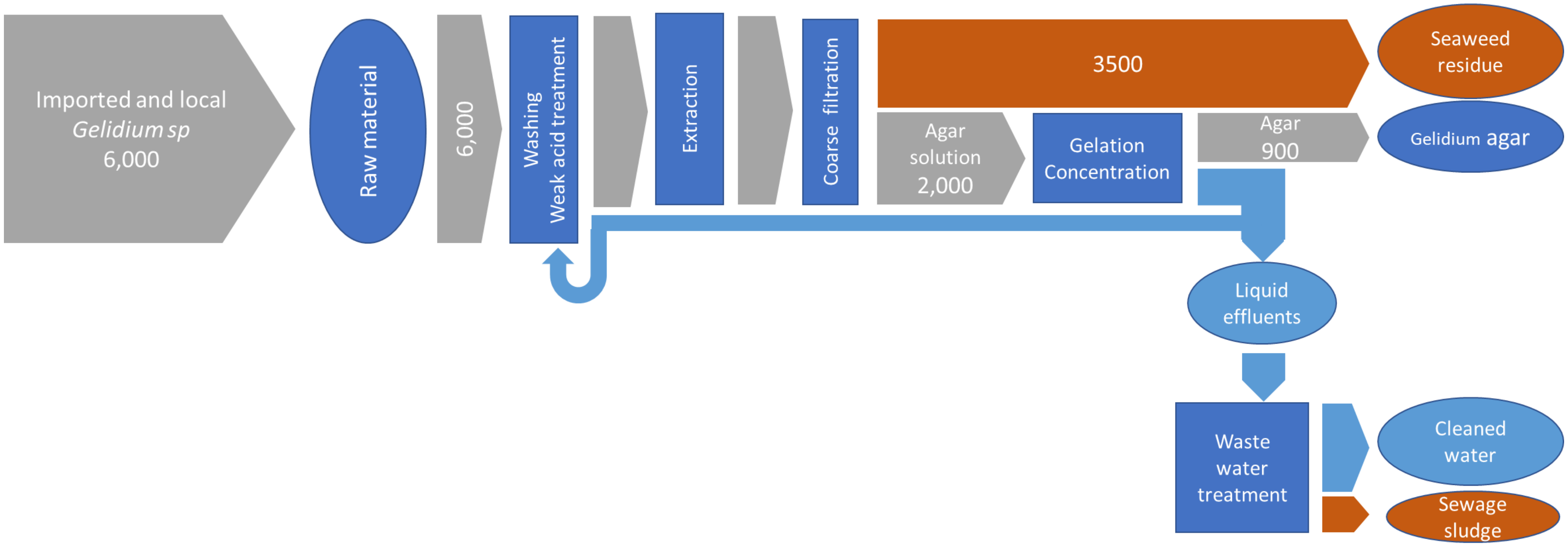

Figure 43 : Gelidium agar processing and by-products in Europe – putative mass balance, expressed as tons of dry matter (from seaweed) – CEVA calculations

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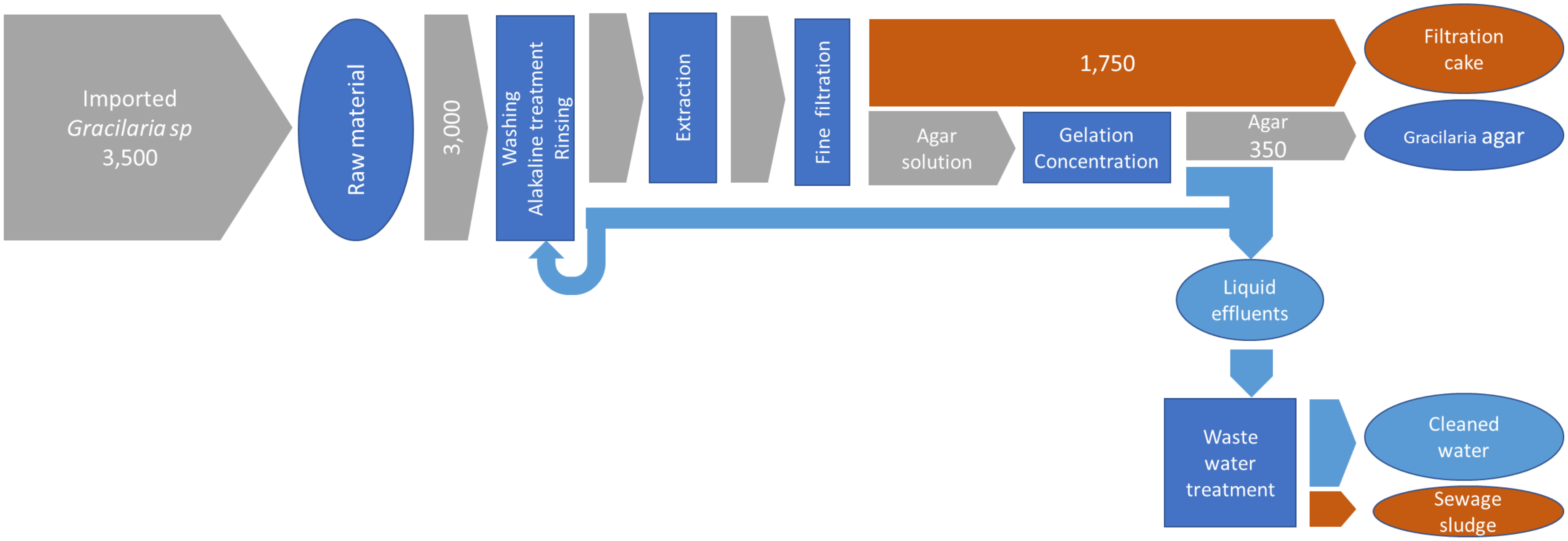

Figure 44 : Gracilaria agar processing and by-products in Europe – putative mass balance, expressed as tons of dry matter (from seaweed) – CEVA calculations

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3.3.4. Other polysaccharides

3.3.4.1. Furcellarans

Description and source

Furcellarans are sulfated anionic polysaccharides extracted from the red algae *Furcellaria lumbricalis*, which possess properties reminiscent of both agar and carrageenan (Marangoni Júnior *et al.* 2021).

While initially described as "Danish agar" due to their capacity to form hard and brittle gels, furcellarans are actually closer to (kappa-)carrageenans and are classified in the same E407 category of food additives (Phillips and Williams 2009). They are traditionally found in nature as a mixture of sodium, potassium, magnesium and calcium salts of a linear polymer, composed of alternating units of 3-linked partially sulfated β-galactopyranose and 4-linked α-anhydro-d-galactopyranose (Marangoni Júnior *et al.* 2021; Phillips and Williams 2009).

Market and current European industrial players.

Furcellarans have a limited market and are currently mainly produced by the Estonian company Est-Agar AS.

The company mentioned in 2019 that it had a plan to process 1500 tons fresh in 2019 (300 tons harvested from a 2000 tons harvest quota, + 1200 tons beach-cast) (Pau 2019). In 2020, the company processed similar levels of beach-cast seaweed, with 300 tons dried seaweed purchased from local harvesters (€ 350/ton).

Furcellaran extraction yield might reach 20%-40% based on dry weight at lab-scale, with lower levels in drifting seaweed compared to attached seaweed (Marangoni Júnior *et al.* 2021). According to other sources, yields of 5-6% of the fresh weight are reached at industrial scale (Aldag S. *et al.* 2021; Senstad 2021).

Assuming the processing of 1500-2000 tons fresh weight annually, this might represent 75-120 tons of furcellaran.

Assuming a market of ~75-100 tons, and a selling price of 8 €/kg (similar to carrageenans), the market of furcellaran might represent € 0.60-0.80 M (Est-Agar plant declared an average turnover of ~ € 0.7 M over the last years).

Newcomers

No other company currently producing furcellarans was identified, which mis at least partially related to the fact that there are limited raw materials available.

Estonian start-up Vetik is focusing on pigment (phycoerythrin) extraction and plans to valorize carrageenans (furcelarans) as co-products (BlueBio Project TACO Algae). Est-Agar themselves are also developing new biorefinery approaches.

Co-products and effluent streams

Co-products of furcellaran processing depend on the process used (Figure 45), with solid residues obtained during the initial filtration step (likely mixed with filtration aid), and subsequent liquid effluents from the washing steps in the case of roll-dried furcellarans, or from the gel-press process.

As a first estimate, co-product to extract ratios could be considered in similar proportions compared to other hydrocolloids (40-50% solid residues (150-200 tons), and 20-30 % in liquid effluents (~100 tons).

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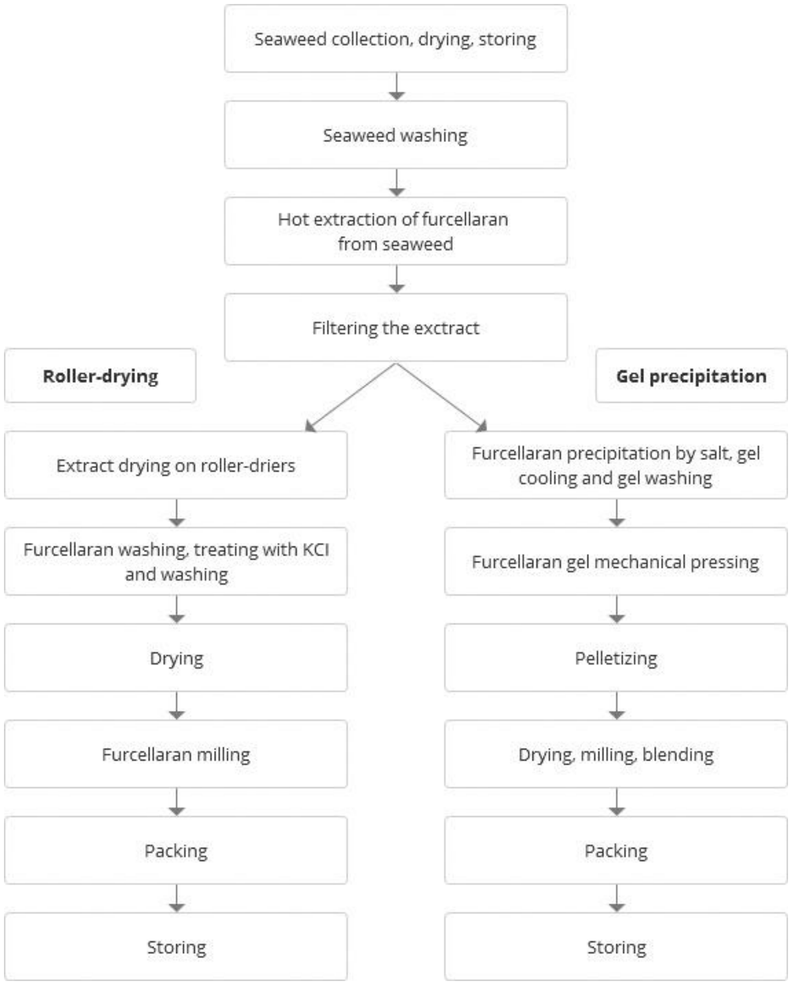

Figure 45 : Furcellarans production process (Estagar website 2023)

3.3.4.2. Ulvans

Description and source

Ulvans are complex polysaccharides extracted from certain green seaweed and in particular from *Ulva* sp.

Market and current European industrial players.

There is still no established market in Europe (or worldwide) for purified ulvans, although they are increasingly explored for their biological properties (Kidgell *et al.* 2019) or through the potential biorefinery of *Ulva sp* (Andrade *et al.* 2022). Their properties are also exploited in a number of end products for various applications, as for example in feed and agricultural products (Olmix, France), or in cosmetics extracts for example.

They are currently not authorized for food applications in Europe (Novel Food status), even if prepared from edible species.

Newcomers

New start-up companies are also investing in ulvans processing and testing. It is for example the case of Investalga AHTI, in Spain, or Seprosys in France which started as a process development company but now also offers cosmetic ingredients from *Ulva* sp.

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Co-products and effluent streams

Co-products and effluents streams from established companies using *Ulva* sp as a raw material (cosmetics, agriculture) are already covered in other sections.

Volumes generated in the context of specific ulvans extraction and purification by dedicated companies are still negligible (pilot-scale at best).

3.3.4.3. Fucoidans

Description and source

Fucoidans is a general term, often used to describe a broad range of fucose-containing sulfated polysaccharides extracted from brown seaweed, and in particular from Fucales (Deniaud-Bouët *et al.* 2017).

Market and current European industrial players.

Fucoidans market is not very documented to date, and market reports refer to a market in the range of $ 30-70 M (Market reports World 2023; Straits Research 2022), which might be strongly relying on retail prices of food supplements, rather than direct sales of the ingredient itself in Business to Business operations.

Fucoidans can be found in a broad range of brown algae, and algae extracts, but purified fucoidans are not as common. Fucoidans have historically been produced mostly in Asia, as well as in Australia. They are mainly used in food supplements, although they have been extensively studied for their human and animal health benefits (Saeed *et al.* 2021), as well as for cosmetics or agriculture for example. Their complex structure and variability in composition (not only related to differences between species), as well as complex purification (e.g. polyphenols co-extraction) might be one of the limiting factors for health applications.

Similarly, fucoidans use in Europe remains limited and has been mostly based on imports of food supplements.

Some European productions exist, but remain limited in volumes, and are rather focused on extracts, and not purified fucoidans. For instance, the French company Algues & Mer (Solabia group) has been producing an extract containing a combination of fucoidans and polyphenols (Fitalga™), used on food supplements (export markets) and feed. Various cosmetic extracts are also capitalizing on the bioactivity of the fucoidans they contain.

One counter-example is the production of purified fucoidans (Protasea®) by FMC (now Dupont-IFF), already mentioned earlier in this report (paragraph 3.3.1), for export markets. New biorefinery approaches also logically on fucoidan valorization, from alginate-bearing seaweed.

It should also be noted that fucoidans are still considered as Novel Food in Europe. To date, only two fucoidan extracts from *Fucus vesiculosus* and *Undaria pinnatifida*, produced by the Australian company Marinova, are listed on the Union List of Novel Foods (European Commission 2017). Another request is pending for fucoidans from *Cladosiphon okamuranus* manufactured in Japan and submitted by H. Holstein GmbH & Co in Germany (EFSA 2020).

Newcomers

Some established companies are developing biorefinery approaches and starting to develop fucoidan or fucoidan-containing products and extracts (e.g. Algaia in France). In parallel, more recent companies and start-ups, focusing on biorefinery of brown seaweed, are also investing in this field, as Alginor in Norway or Origin by Ocean in Finland.

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Co-products and effluent streams

Co-products and effluents streams from fucoidans production in Europe are still very limited (pilot-scale or industrial development). And while fucoidans volumes are expected to increase in coming years with the upscaling of several processes, they are likely to be integrated in existing biorefinery and/or alginate production process, and may not generate specific side-streams.

3.3.4.4. Laminarin

Description and source

Laminarin is a beta-glucan extracted from kelp species (linear β(1,3)-glucan with β(1,6)-branches). Its existence and biological properties have been long known (Kadam *et al.* 2015), in particular as an efficient plant defense elicitor (Klarzynski *et al.* 2000). Still, laminarin current industrial uses are still limited, although it is exploited in agricultural products (in particular by Goemar (FR), subsidiary of UPL, for its Vacciplant product).

Market and current European industrial players.

There is no known current market (nor producers) in Europe for purified laminarin sold as an ingredient, except at laboratory scale. And its use, through seaweed extracts, is covered in other sections of this report (as well as the associated co-products and effluents). Laminarin is currently mostly produced in China, with a relatively small market of € 2M (Business Research Insights 2022).

3.3.4.5. Paramylon / Microalgal Beta-Glucan

Description and source

Paramylon is a beta-glucan (linear β(1,3)-glucan) that can be extracted from microalgae species and in particular *Euglena gracilis (Gissibl et al. 2019)*. It is increasingly used for human and animal nutrition, especially for immunity. Nevertheless, despite initial work on extraction, products are currently sold mostly as whole-cell microalgae, although some purified forms are still present on the market (e.g. Kemin Betavia Pure).

Market and current European industrial players.

Global beta-glucan market is estimated to be around $500-550 M in 2022 (Coherent Market Insights 2022a; Straits Research 2022), but algal beta-glucan only represents a small fraction of the market, led by yeast and oat bet-glucans.

The current form authorized in Europe (Novel Food dossier filed by Kemin, US production) is whole-cell *Euglena gracilis*. Another request is pending for paramylon (Kemin).

The production capacity by fermentation at Kemin's facility was ~300T/y in 2016 (25 T/month whole algae, and 1.5T/month of purified beta-glucan). Solabia-Algatech (French group, production located in Israel) recently acquired a license on technology from the US company F3 Platform Biologics to produce β(1-3)-glucans. Its production capacity has not been communicated and they probably still have limited market shares pending regulatory approvals.

Co-products and effluent streams

BioGlena produced by Solabia-Algatech is also sold as whole microalgae, leading to the absence of co-products in Europe.

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3.3.4.6. Cellulose

Seaweed cellulose is not commercialized in Europe as such, but is involved in a number of seaweed-based materials currently developed (packaging, insulation, paper, …). It could, among others, be prepared from seaweed industry co-products, which are currently used in agriculture (spreading) or discarded.

3.3.4.7. Algae exopolysaccharides

While their use remains relatively limited, exopolysaccharides (EPS) excreted by microalgae and cyanobacteria can present very interesting structures, physico-chemical properties and bioactivity (Borjas Esqueda *et al.* 2022; Laroche 2022; Pierre *et al.* 2019).

Often seen as potential disturbances for the cultivation step (viscosity, foaming, …), and complex to isolate (high dilution, complex purification), their presence in spent culture medium can be worth investigating.

The most representative example is the valorization of *Porphyridium* sp exopolysaccharides in the cosmetics sector.

3.4. Production of carotenoids

3.4.1. Overall carotenoids market

3.4.1.1. Description

Carotenoids are a family of pigmented compounds which are synthesized by plants, algae, fungi, and microorganisms, but not animals. They are the most important pigments in nature that are responsible for various colours of different photosynthetic organisms by concentration in the food chain (crustaceans, fish). Carotenoids can be classified into carotenes (β-carotene), which are unsaturated hydrocarbons, and xanthophylls (astaxanthin, fucoxanthin, lutein and zeaxanthin), which present one or more functional groups containing oxygen (Ngo *et al.* 2011).

As natural pigment, microalgae have been used as a source of carotenoids for over years. Mainly, commercially important carotenoids sourced from algae are β-carotene from *Dunaliella salina*, astaxanthin from *Haematococcus pluvialis* and fucoxanthin from macroalgae and more recently microalgae, especially diatoms (Voort *et al.* 2015).

3.4.1.2. Applications

Various effects of carotenoids have been reported in scientific literature mainly link to beneficial properties in preventing human diseases including cardiovascular diseases, cancer and other chronic diseases. The main application concerned their antioxidant properties by virtue of their highly unsaturated nature, which enable them to lend themselves to oxidation instead of other molecules. Especially, fucoxanthin and astaxanthin are known to be major ingredients of marine carotenoids and have also been recognized to possess excellent antioxidative potential (Galasso *et al.* 2017; Ngo *et al.* 2011).

3.4.1.3. Global market

Some estimations have been made about the global carotenoids market. In 2016, the global market was estimated to be USD 1.24 billion (Novoveská *et al.* 2019; Saadaoui *et al.* 2021), it was expected to reach USD 2.0 billion in 2026 with a CAGR of 4.2% during 2021-2026 (Kusmayadi *et al.* 2021).

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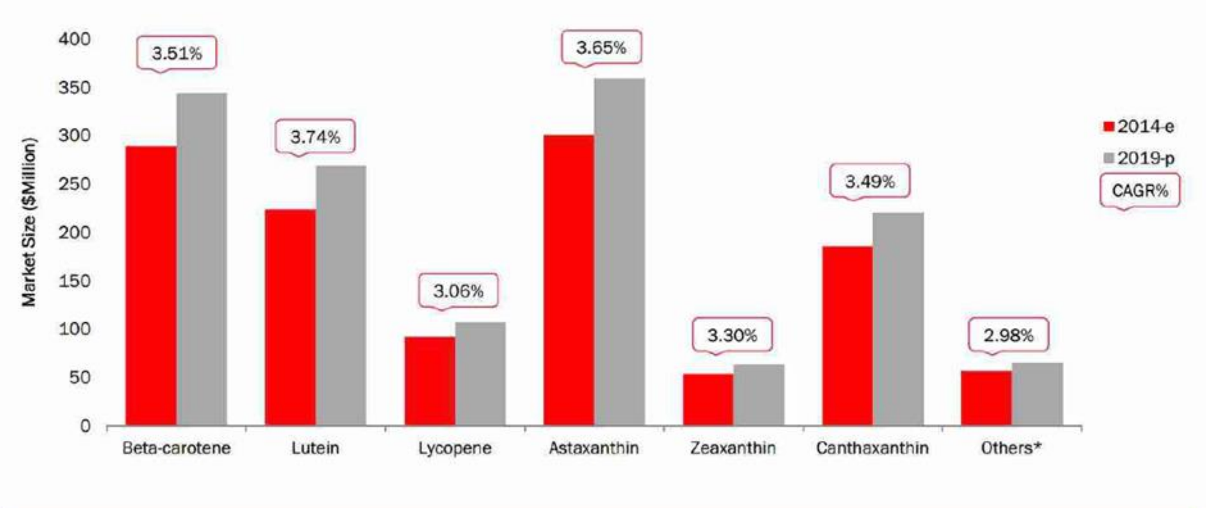
Regarding algae, the market is led by astaxanthin and β-carotene which are considered as the most relevant due to their established applications (Novoveská *et al.* 2019). Yet, the amounts of natural carotenoids produced from plants, animals, and micro-organisms remain limited as they are in competition with their synthetic forms.

Even the highest producing strains of microalgae synthesize less than 10% of carotenoids (dry weight). Carotenoids can be rapidly produced synthetically using low-cost labour and inexpensive chemicals, negating the need for the presence of a living organism and subsequent harvesting and extraction costs. Yet, while synthetic carotenoids are faster and cheaper to produce, they can be less effective in terms of their health-promoting properties, due to the formation of less active configuration isomers, and are hence less valuable and desirable as a product (Cuellar-Bermudez *et al.* 2015; Novoveská *et al.* 2019).



Note: Others include annatto, capsanthin, fucoxanthin, and trans-β-apo-8'-carotenal*

CAGR has been taken up to two places of decimal

e – Estimated; p – Projected

Figure 46 : Astaxanthin and β-carotene, two largest markets for the next five years (Boussiba 2016)

3.4.1.4. European market

In Europe, estimations from 2016 announced a global market (synthetic and natural) value of $466 million in a growing sector. The main reason is that Europe is a home base for leading carotenoid manufacturers exporting worldwide (Novoveská *et al.* 2019). Another aspect is the awareness regarding health and diet in European society.

The German company BASF SE, which is the largest chemical producer in the world leads the production of synthetic carotenoids under the brand names Lucantin® and Lucarotin®. Second to this is DSM, a Dutch company that produces synthetic carotenoids under the brand name Carophyll®. Regarding algae, several smaller compagnies are invested in the carotenoids production (Algalif, BDI-BioLife Science) although the main producers are in the USA (Cyanotech) or in Asian countries.

3.4.1.5. Downstream processes and co-products

The first step to extract carotenoids is cell lysis which can be achieved using several methods (and their combinations) including physical grinding, milling, ultrasound-assisted extraction, microwave-assisted extraction, freeze-thawing, etc. this step is used to rupture the cell wall to increase biomolecules extraction efficiency (Silva *et al.* 2020). Traditionally, for commercial purposes, algal carotenoids have been extracted using organic solvents (e.g., acetone, methanol, ethanol, hexane, dodecane) at a higher

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temperature and pressure are the most popular and are standardized to meet commercial specifications (Novoveská *et al.* 2019).

Yet, these methods suffer several, inherent limitations, including low efficiency (extraction yield), selectivity (purity), high solvent consumption, and long treatment times, which have led to advancements in the search for innovative extraction technologies (Poojary *et al.* 2016). This is why novel technologies have been developed for efficient extraction such as enzyme-assisted extractions, use of green solvents (environmentally safe and non-toxic solvents), subcritical water extraction and super-critical CO_2 extraction (non-toxic, non-flammable method) (Kadam *et al.* 2013; Novoveská *et al.* 2019). They are becoming increasingly prevalent.

In all cases, residual biomass presents interesting levels of fibers, proteins and residual carotenoids and lipids.

3.4.2. Beta-carotene

3.4.2.1. Description and source

β-carotene is the most prominent carotenoid which is involved in photosynthesis. The natural form of β-carotene comprises a mixture of two isomers (all-trans and 9-cis-trans), which are hard to obtain synthetically (Silva *et al.* 2020).

Table 15: Content and isomeric composition of β-carotene by source (Harvey and Ben-Amotz 2020)

β-Carotene content and isomeric composition.

Source	β-Carotene content % AFDW	β-Carotene composition (%)	
		All trans β-carotene	*9-cis* β-carotene
Synthetic	100	> 98	< 2
Carrot	0.01–0.06	50	2
Palm oil	0.06–0.07	36	24
Dunaliella	6–14	50	> 40

The main algal source of β-carotene is *Dunaliella salina*, a halotolerant green microalga and the richest microalgae source of β-carotene. *Dunaliella salina* can yield more than 10% of the product when cultivated in proper conditions, such as hyper saline water, warm climate, and minimum cloudiness. Its production is divided in two steps. The first stage is known as the “greening stage,” where adequate conditions for *D. salina* growth are provided. After cells concentration reaches a certain level, stress conditions are trigger accumulation of carotenoids, turning the colour of microalgae from green to orange (reddening phase) (Hexa Research 2018; Marino *et al.* 2020; Silva *et al.* 2020).

Other strains of algae that are rich in β-carotene include *Chlorella* and *Spirulina platensis*.

3.4.2.2. Applications

Natural β-carotene has shown anticancer and antioxidant properties with a direct application in protection of human skin against photoaging. It is also implicated in the decrease of risk of cardiovascular diseases. This lipid-soluble pigment is also known as a vitamin A precursor, which is biosynthesized by the human body. β-carotene is transformed enzymatically into retinal and then into retinol (vitamin A). These properties are linked to a specific form (9-cis form), almost absent in the synthetic form, and a better absorption in the human body (Galasso *et al.* 2017; Silva *et al.* 2020).

Currently, β-carotene is extensively used as a natural colouring agent in the food industry (e.g., soft drinks, baked foods, and margarine), as well as an active ingredient in antioxidant supplements.

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3.4.2.3. Global market

The global market of β-carotene is estimated to be more than 500 tons of which natural β-carotene (algae & plants) represents between 5 to 8% i.e. around 25 to 50 tons (Boussiba 2016; Global Market Insights 2020). The estimated global market value shows a regular increase in the last decade to reach USD 720 million in 2027. The natural market is more difficult to estimate.

The major producer of *Dunaliella salina* for natural β-carotene production is BASF based in Germany, which accounts for around 40-50 tons but produces in Australia. Other producers are Nature Beta Technologies (NBT) based in Israel (2–3 tons per year), and the Indian company E.I.D Parry (1–3 tons per year). European multinational DSM also proposes natural β-carotene via its brand CaroCare® (Boussiba 2016; Marino *et al.* 2020; Silva *et al.* 2020).

Table 16: Estimated market values of β-carotene according to different sources (Borowitzka 2013; Boussiba 2016; Global Market Insights 2020; Hexa Research 2018; Silva et al. 2020)

Year	Natural market (USD million)	Global market (USD million)	CAGR (%)
2013	50 to 80	270	
2016	60		
2020		480 to 520	6 (2021 – 2027)
2026 (p)		619	3.8 (2018 – 2026)
2027 (p)	40	720	

p: projected

3.4.2.4. European production

There is currently no significant algal β-carotene production in Europe.

Dunaliella salina is produced in small volumes by a number of European companies, which might totalize a production of 2T/y (cf section 0), as well as by NBT in Israel with larger volumes. It is only partly extracted for β-carotene, and also sold as fresh or dried biomass, with very limited amounts of biomass available.

3.4.2.5. Process and co-products

Several processes are used to extract β-carotene which are mentioned in the general section on carotenoids. The emergence of new processes such as super-critical CO_2 extraction and their diversity has been little studied.

Extractions using petrochemical solvents and supercritical CO_2 were compared (Harvey 2017; Harvey and Ben-Amotz 2020) with the aim to valorise several components such as water-soluble and liposoluble fraction (Figure 47 and Figure 48). For super-critical CO_2 extraction, the oily extract typically represented 16-17% by weight of total algal biomass. Around 30 % of this extract was made up of carotenoids, of which >87% are hydrophobic carotenes. However, ~50% of the oil remains in the defatted powder, and includes xanthophylls. On the other hand, extracts prepared using petrochemical solvents typically represented ~ 35% by weight of the total material and contained ~14% total carotenoids.

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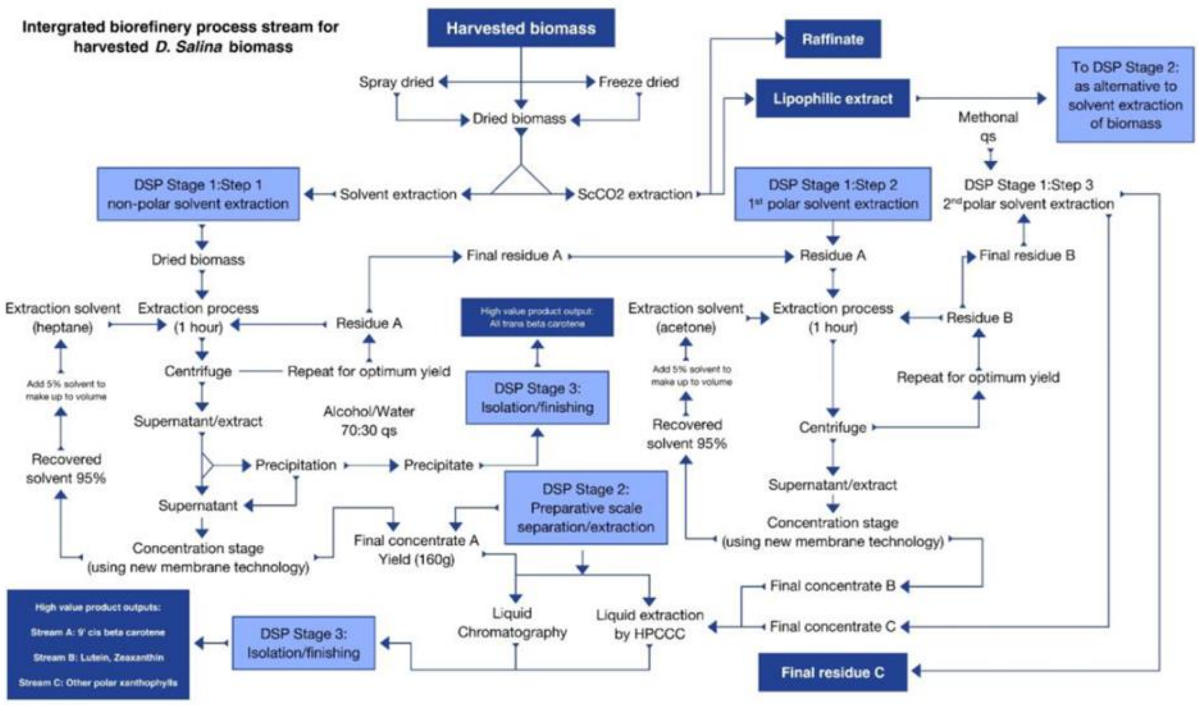

Figure 47 : Integrated biorefinery process stream for harvested Dunaliella salina powders (Harvey 2017)

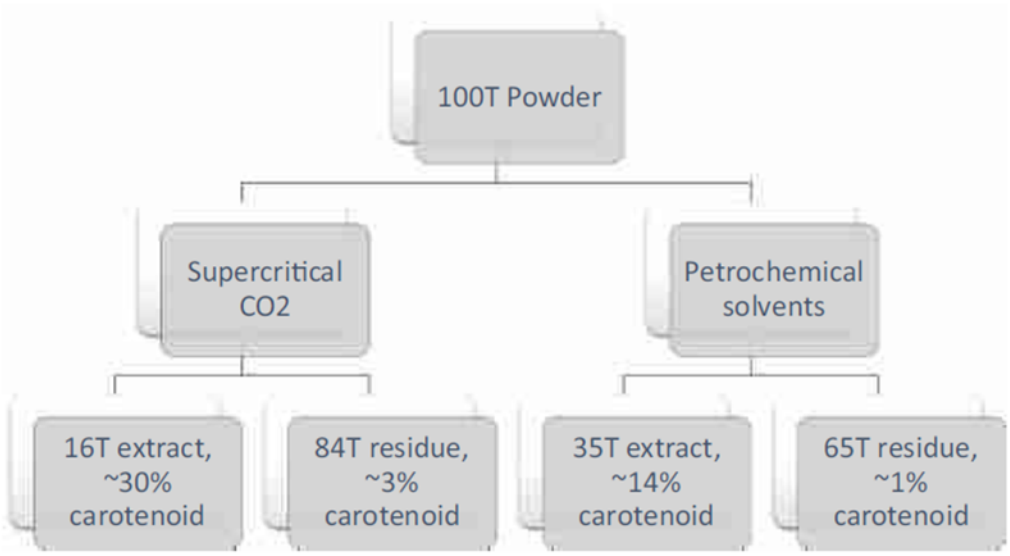

Figure 48 : Illustration of the effect of extraction with scCO2 compared to the use of non-polar and polar petrochemical solvents on the yields of extract and defatted powder (residue) and concentration of carotenoids (Harvey and Ben-Amotz 2020)

3.4.3. Astaxanthin

3.4.3.1. Description and sources

Astaxanthin is a secondary carotenoid which is synthesized by some plants, algae, and bacteria. It can be also found in some fishes, crustaceans, and birds by accumulation due to food chains in nature. Therefore, the main source of natural astaxanthin is krill. Astaxanthin is available from chemical sources

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(synthetically produced) and from natural sources (extracted from microalgae, yeast, and crustaceans). Synthetic astaxanthin has a 20-fold lower antioxidant capacity than the natural form and corresponds to 95% of the astaxanthin available in the market. Only natural astaxanthin is approved for human consumption by the FDA (Silva *et al.* 2020).

In algae, astaxanthin is mainly obtained from the microalgae *Haematococcus pluvialis* in which it represents around 90% of total carotenoids. As for *Dunaliella salina*, the production is performed in two phases: the first phase ("green phase") where cellules multiplicate mainly in photobioreactor and second phase ("red phase") mainly in open ponds where cellules transform in cistus link to environmental modification (light, salinity, minerals, etc.) and produce/store astaxanthin up to 3.8-5% of the microalgae dry weight (Panis and Carreon 2016; Silva *et al.* 2020).

3.4.3.2. Applications

Aquaculture was one of the first applications for this pigment where it was applied as a feed additive to give the red colour to the flesh and shell of salmon, trout, shrimps, and langoustines. Especially, natural form is used in organic farms. Astaxanthin is also used in dietary supplements due to health benefits such as anticancer, anti-inflammatory, and anti-ageing effects. Astaxanthin is considered the most potent antioxidant in nature, with an antioxidant activity 10-fold stronger than the ones of other carotenoids such as lutein, zeaxanthin, β-carotene, and canthaxanthin. It is referred as the most powerful antioxidant in commercial literature (Silva *et al.* 2020). Synthetic and natural form differ from their isomers which have different benefits. For food supplement, only the natural form is authorised (extracted form krill and *Haematococcus pluvialis*) (Galasso *et al.* 2017).

3.4.3.3. Global market

The global market is estimated to have reached USD 600 million in 2019 and USD 800 million in 2026 with a CAGR of 3.5% during this period. Yet, there is a discrepancy in price between synthetic and natural form from *Haematococcus pluvialis*: synthetic form is estimates around 1000 – 2000 $/kg and natural form from *Haematococcus pluvialis* around 7000 – 10000 $/kg (Araújo *et al.* 2021; EUMOFA 2023; Global Market Insights 2019, 2022; Government of Iceland - Ministry of Food, Agriculture and Fisheries 2023; Silva *et al.* 2020). Synthetic astaxanthin is produced from petrochemical sources, which raises the issues of food safety (potential toxicity in the final product), pollution, and sustainability. In fact, to date, synthetic astaxanthin can only be used as an additive to fish feed for pigmentation purposes and has not been approved for direct human consumption in food or supplements (Panis and Carreon 2016). Society's desire for more natural products can be a lever to increase the growth of the natural astaxanthin market although specialists of the market are more cautious with a potential saturation of the human market. The demand to natural products in aquaculture could also be a driver of the market.

3.4.3.4. European production

Main historical producers are not located in Europe but in the USA (Cyanotech), Japan (Fuji), or Israel (Algatech) with some new players in China or India (Global Market Insights 2022).

In Europe, the company Algalif in Iceland is the largest producer but significant production also occurs mostly in Austria and Sweden, as well as in Israel (see 0).

3.4.3.5. Downstream processing and co-products

Several processes are used to extract astaxanthin which are mentioned in the general section on carotenoids. The emergence of new processes such as supercritical CO_2 extraction have demonstrated their efficiency (Cuellar-Bermudez *et al.* 2015), and are largely present in the industry. Most of the

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European producers are currently using supercritical CO_2, which also presents the advantage to allow the production of a solvent free ingredient.

With a production in Europe and Israel of 120-150 T, one could estimate that a potential deposit of 90-130 T of residual biomass rich in fibers, proteins and residual lipids and carotenoids are available (around 50 T if Israel is excluded).

To our knowledge, they are currently often valorized in feed applications.

3.4.4. Fucoxanthin

3.4.4.1. Description

One of the commercially valuable carotenoids present in microalgae is fucoxanthin. Fucoxanthin, an orange-colored pigment, is one of the most valuable and abundant carotenoids found in the marine environment. Fucoxanthin is a non-provitamin A xanthophyll that is mostly present in marine brown seaweeds and microalgae along with chlorophylls a/c protein.

Historically, mainly extract for brown algae used in the alginate industry but the small content induced a limited cost-effectiveness and costly extraction methods. Brown algae producing fucoxanthin include *Hijikia fusiformis*, *Undaria pinnatifida*, *Sargassum sp*., *Laminaria* sp. and *Fucus* sp.

Fucoxanthin has been also isolated for bioactivity studies from other marine seaweeds such as: *Alaria crassifolia*, *Cladosiphon okamuranus*, *Cystoseira hakodatensis*, *Eisenia bicyclis*, *Hijikia fusiformis*, *Ishige okamurae*, *Kjellmaniella crassifolia*, *Myagropsis myagroides*, *Padina tetrastromatica*, *Petalonia binghamiae*,

Undaria pinnatifida is the seaweed species containing the highest fucoxanthin content (0.5%) compared to others species (0.01–0.1% of dry cell weight).

Interest for microalgae is raising as they have higher contents of fucoxanthin (1.0–2.5% of dry cell weight) (Pocha *et al.* 2022). Indeed, fucoxanthin is also found in the diatoms *Chaetoceros* sp., *Cylindrotheca closterium*, *Odontella aurita*, and *Phaeodactylum tricornutum* (Galasso *et al.* 2017), triggering new developments at lab and industrial scale.

3.4.4.2. Applications

Fucoxanthin belongs to the class of xanthophylls and is a common carotenoid in brown seaweeds. The molecule is used for its antioxidant, fights against cellular damage, anti-cancer, anti-inflammatory and anti-obesity effects (Galasso *et al.* 2017; Peng *et al.* 2011).

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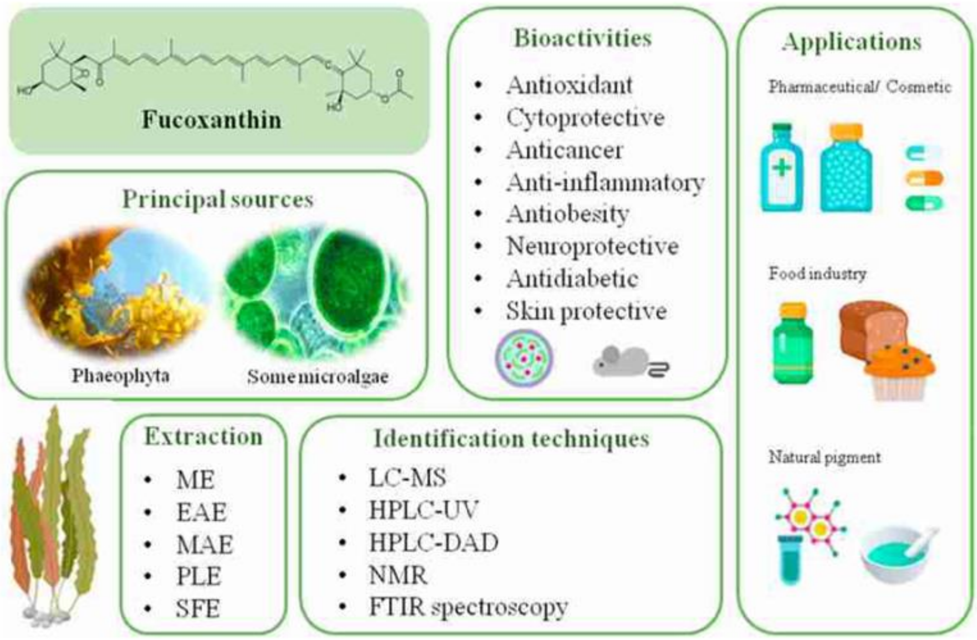

Fig. 2. The main sources of fucoxanthin are brown algae (Phaeophytes) and some microalgae. Several techniques have been employed to extract this compound, such as maceration extraction (ME), enzyme assisted extraction (EAE), microwave assisted extraction (MAE), pressurized liquid extraction (PLE) or supercritical fluid extraction (SFE). Following the extraction, the identification step has been carried out using different chromatographic and spectroscopic techniques. Fucoxanthin has gained attention in the last decades, due to the wide variety of attributed beneficial activities, such as antioxidant, anti-inflammatory, anticancer or neuro-protective effects. These bioactivities are interesting for its diverse applications in the industry, including the development of innovative pharmaceutical, cosmetic and food products. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Figure 49: Sources, bioactivities and applications of fucoxanthin and extraction and identification techniques (Lourenço-Lopes et al. 2021)

3.4.4.3. Global market

High variability is reported in different studies about fucoxanthin market value. In 2019, the value varies between USD 64 million and USD 99 million with a projection of USD 140 million in 2024 and a CAGR of 2.7% (2021 – 2024). The price of fucoxanthin also shows high variety between 15,000 and 80,000 USD / kg depending on sources (Algae-UK 2020; Algatech 2018; Boussiba 2016; Lourenço-Lopes *et al.* 2021; Pocha *et al.* 2022). The proportion of microalgae in growing in a market occupied mainly by macroalgae historically. Yet, it is reported that the potential applications of this pigment are very promising; however, they are limited because the commercialization of fucoxanthin is almost non-existent (Lourenço-Lopes *et al.* 2021).

3.4.4.4. European production

In Europe, Microphyt is a French company currently marketing fucoxanthin extracted from *Phaeodactylum tricornutum* accepted by FDA in 2019 for its fucoxanthin extract PhaeoSOL from *Phaeodactylum* with clinical trials in process for age-related cognitive decline.

Solabia, a French company also acquired the Israeli company Algatech, which produces an ingredient Fucovital form *Phaeodactylum* cultivated in photobioreactors, which is authorized in USA and Japan for reduction of metabolic syndrome linked to obesity and for hepatic health.

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3.4.4.5. Process and co-products

The common way of obtaining fucoxanthin from macroalgae like seaweeds yields very low content after going through ineffective and costly extraction methods. Its suffer from high production costs, scarcity of biocompatible solvents, and complications in scaling up (Pocha *et al.* 2022).

The processes used for microalgae are like those used for β-carotene and astaxanthin and with the same limits.

Time-saving and innovative extraction methods such as enzymes assisted extraction, ultrasound extraction, microwave extraction, supercritical-fluid extraction, co-solvent extraction, pressurized liquid extraction, and aqueous two-phase system (ATPS) have been frequently researched for bioactive compounds extraction from algae (Pocha *et al.* 2022). The new processes tested show improvement in the extraction yield of fucoxanthin. For example, the enzyme-assisted extraction increase by 50% the extraction yield (Kadam *et al.* 2013). Some researchers also focus on the co-extraction of fucoxanthin and omega-3 possible on the non-calcifying *Haptophyta Tisochrysis lutea*, and the diatom *Phaeodactylum tricornutum* in organic solvent (ethanol, methanol, ethyl acetate) (Delbrut *et al.* 2018).

However, the extraction yield of fucoxanthin has been found to be very variable depending on the selected species and the recovery technique. Moreover, the extraction and purification of biomolecules is also a time-consuming and expensive process that can account for up to 70% of the total cost of biological products (Pocha *et al.* 2022).

Future and innovative studies regarding efficient, quick and fast extraction methods can speed up the progress towards its commercialization and the valorisation of the co-products of extraction (Lourenço-Lopes *et al.* 2021).

But with a current European *Phaeodactylum* production estimated to be 4T/y, available co-products remain very limited, although possibly valuable. They will also grow in the coming years, following current industrial developments.

3.5. Production of phycobiliproteins

Phycobiliproteins are a group of coloured proteins present commonly not only in cyanobacteria (blue–green algae) but also in other species as for example eukaryotic red algae or cryptomonads. Phycobiliproteins are brilliant-coloured and water soluble antennae-protein pigments organized in supramolecular complexes called phycobilisomes which are assembled in the outer surface of the thylakoid membrane (Cuellar-Bermudez *et al.* 2015).
Phycobiliproteins absorb energy in portions of the visible spectrum (450-650 nm) and function as accessory pigments in photosynthetic light collection. Four main classes of phycobiliproteins are produced (Table 17). The absorption maxima are predominantly determined by the extension of conjugated double bonds in the chromophores (Cuellar-Bermudez *et al.* 2015, 2015; Sekar and Chandramohan 2008).

Table 17: Characteristics of the main phycobiliproteins

Pigment		Color	Major absorption	Emission light	Subunit structure of stable form
allophycocyanin	APC	bluish green	λ_{max} : 650-655 nm	660 nm	$(\alpha\beta)_3$
phycocyanin	PC	blue	λ_{max} : 610-620 nm	637 nm	$(\alpha\beta)_3$, $(\alpha\beta)_6$
phycoerythrin	PE	purple	λ_{max} : 555-565 nm	577 nm	$(\alpha\beta)_3$, $(\alpha\beta)_6$
phycoerythrocyanin	PEC	orange	λ_{max} : 568>590 nm	607 nm	$(\alpha\beta)_6$

In general phycobiliproteins are made up of chromophore-bearing polypeptides containing low molecular weight α unit (MW : 12-19 kDa) and large β subunits (MW : 14-21 kD) (Abalde *et al.* 1998).

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Allophycocyanin occurs as a trimer (α3β3) whereas C-phycocyanin is found as a complex solution of trimers (α3β3), hexamers (α6β6) and other oligomers and its molecular weight ranges from 44 to 260 kDa (Chaiklahan *et al.* 2010) .

3.5.1. Production of Phycocyanin

3.5.1.1. Description and sources

Phycocyanin (or c-Phycocyanin or PC), a blue pigment, is the major phycobiliprotein of *Spirulina* and constitutes up to 20% of its dry weight but varies between 5 to 25% depending on cultivation parameters (CEVA, Internal database). Allophycocyanin is a minor component compared with c-phycocyanin. From our internal database, Spirulina contains the two phycobiliproteins approximately at a ratio ranging from 1.4 to 3.5 depending on species, strain and cultivation conditions.

Phycocyanin is produced by different organisms. In Kuddus & al (2013), 23 organisms producing C-phycocyanin are reported (Kuddus *et al.* 2013)

- *Anabaena marina*
- *Aphanizomenon flos-aquae*
- *Arthronema africanum*
- *Coccochloris elabens*
- *Cyanidium caldarium*
- *Galdieria sulphuraria*
- *Gracilaria chilensis*
- *Lynghya sp.*
- *Mastigocladus laminosus*
- *Microcystis*
- *Nostoc, Phormidium*
- *Oscillatoria quadripunctulata*
- *Phormidium fragile*
- *Spirulina fusiformis*
- *Spirulina maxima*
- *Spirulina platensis (Arthrospira platensis)*
- *Spirulina sp.*
- *Synechocystis sp.*
- *Synechococcus elongates*
- *Synechococcus lividus*
- *Synechococcus vulcanus*
- *Synechococcus sp.*

Depending on the species, the production of phycocyanin includes four different options (Kuddus *et al.* 2013):

- Photoautotrophic
  - Outdoor method of C-PC production in open ponds predominantly at tropical and subtropical locations. *Arthrospira platensis* selected due to its ability to be grown in open ponds without being outcompeted by contaminating organisms (although contaminants are present).
- Mixotrophic
  - Enclosed reactor. Specific growth rate of mixotrophic cultures grown on glucose corresponds to the sum of the photoautotrophic and heterotrophic growth rate. Higher growth rate in the mixotrophic indoor cultures than in the photoautotrophic outdoor cultures of *A. platensis*.
- Heterotrophic

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  - Production is not limited by incident light intensity. The unicellular rhodophyte *Galdieria sulphuraria* is a candidate for heterotrophic production of C-PC, producing major amount of C-PC and minor amounts of allophycocyanin. It exhibits optimal growth at temperature > 40°C and is able to utilize a variety of carbon sources. Heterotrophic production of *Arthrospira platensis* (on glucose and fructose) leads to low specific growth rate and pigment contents.
- Recombinant production
  - Quite challenging: complete synthesis of recombinant proteins depends on coexpression of α- and β- chains as well as parallel synthesis and insertion of the correct phycobilin chromophores. Has been produced in photoautotrophic *Anabaena* species which naturally synthetize and insert phycocyanobilin into C-PC.

Spirulina/*Arthrospira*/*Limnospira* remains the preferred species because it is well known and widely produced and commercialized at a relatively low cost across the globe.

3.5.1.2. Global market

Even though Spirulina is commercially cultivated in many countries, the exclusive production of proteins and c-phycocyanin is still low and estimated to represent only 5% of Spirulina production. Based on an extraction yield of 10 % (optimistic) this would lead to 75-150 tons of phycocyanin at world level.

The market is growing strongly but there are great disparities in market reports, with an estimated CAGR depending on the source ranging from 7-10% (Market Data Forecast 2022) to 30% according to Meticulous Research, which is very optimistic.
The global phycocyanin market might be valued at $155.3 million in 2020 with an expected market value of $ 409.8 million by 2030 according to Allied Research (Allied Market Research 2022) . However, according to Meticulous Research, the Phycocyanin market is expected to reach $245.5 million by 2027, at a CAGR of 28.5% during the forecast period of 2020 to 2027 (Meticulous Research 2020), which would mean around $40 million in 2020. Market Growth report also reports a market of $ 50 million in 2021. The latter numbers might be relatively consistent with a global production of 100 tons, and an average price of 500 $/kg across categories.
But the growth of the market leaves no doubt as world leaders in that field, especially in the food color market, are investing million dollars in production lines (Fact.MR 2022).

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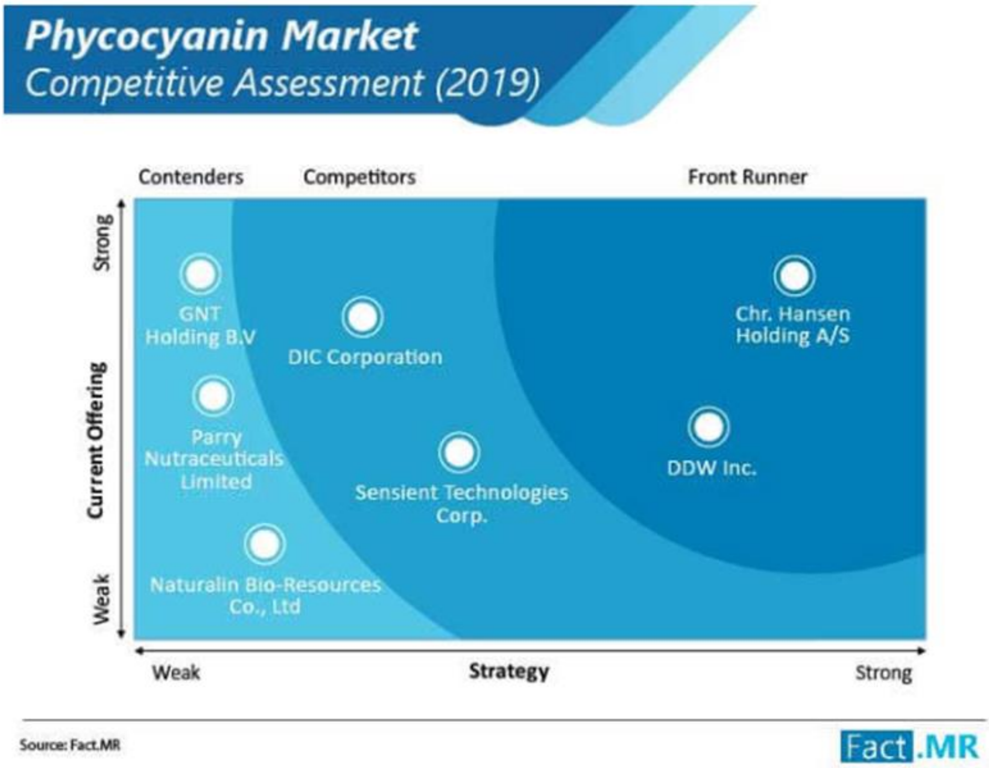

Figure 50 : Positioning of the key players in phycocyanin according to Fact.MR (Fact.MR 2022)

The phycocyanin market is segmented on the basis of form, grade, application and region. The grades of phycocyanin are based on purity, defined by a ratio between absorbance at 620 nm (maximum absorption of phycocyanin) and 280 nm (absorbance of the total proteins) (Borowitzka 2013).
On the basis of this purity criteria, the market is divided into food grade, pharma grade and reagent and analytical grade.

Phycocyanin divides into different grades depending on its purity (Guan 2016)

- Grade 1: A620/A280 0.50-1.50 (Food level) (Used only as a Dye);
- Grade 2: A620/A280 1.50-2.50 (Cosmetic level) (Used only as a Dye);
- Grade 3: A620/A280 2.50-3.50 (Regent level) (Used as Dye and Biomarker);
- Grade 4: A620/A280 Above 4.00 (Analytical level, Antibody level) (Used in Therapeutics, Biomarker, and Treatment)

Alternatively, commercial phyocyanin can also be rated according to colour density, based on the optical density of a 1% solution at 618 nm (usually ranging from E6 to E30).

The price of phycocyanin may depend on its purity and intended use. Most C-PC sold by companies in the market is as a natural food colorant (A620 /A280: 0.75-1.50), whose price is $100-500 per kilogram (Guan 2016) depending on quality and concentration. However the commercial price of C-PC increases with its purity and consequently, the price of reagent -grade C-PC is estimated to reach $ 1000 – 5000.g^{-1} and analytical grade more than $ 15 000.g^{-1} (Manirafasha *et al.* 2016).

3.5.1.3. Uses

The main phycocyanin applications are found in pharmaceutical industries and analytical reagents as fluorescent probe, in food supplements and in natural food color ingredient.

Spirulina C-PC has been approved by Food and Drug Administration (FDA) as a natural blue food colorant in 2013 (FDA 2013).

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It should also be noted that the company Fermentalg has recently filed a dossier in the United States (self-affirmed GRAS) for the authorization of phycocyanin extracted from another species, *Galdieria sulphuraria* (GRAS Notice 1000 2021). This species, produced by fermentation with greater efficiency, could possibly provide a more stable phycocyanin, which is particularly interesting for the beverage market.

In Europe phycocyanin extract can be classified as extracts/concentrates with colouring properties if the extraction is considered as non-selective, depending on enrichment factor. This enrichment factor is determined by the ratio of the content of the pigment in the primary extract to that of the nutritive constituents and should be non-significantly different from that present in the source materials (animal food chain)
If the ratio of the content of the pigment to that of the nutritive in the primary extract is significantly different from that present in the source material as a result of physical and/or chemical extraction, the extraction is considered as selective and phycocyanin extract might be classified as a food additive (falling under Regulation (EC) No 1333/2008). Because EFSA has banned the use of synthetic colors in food products, it has boosted the demand for natural colouring foodstuff and therefore the demand for phycocyanin.
This blue-pigment from Spirulina is already used in the food/cosmetic industry, for instance in beverages and confectionery (e.g., Bloo Tonic®, B-blue Spirulina drink, Blue Spark Innocent smoothie and M&Ms® chocolates).

In the context of food supplement, AlgoSource (www.algosource.com), a French company, produces phycocyanin as a liquid extract (Spirulysat® concentration of phycocyanin : 5000 mg /L) that is sold in ampoules (10 mL) (Araújo *et al.* 2021; Silva *et al.* 2020).
Numerous studies have shown phycocyanin as a functional metabolite due to its antioxidant, neuroprotective, anti-inflammatory, and hepatoprotective properties. However, up to now there is no functional and health claims authorized in Europe. Some claims related to Spirulina or extracts of spirulina are in pending process related to tonus/vitality, amino acid supplementation, glycemic health.

The phycocyanin use in cosmetic application is also in progress, as a blue coloring but also for its free radical scavenging and anti-inflammatory properties.

3.5.1.4. European production

The world key players for phycocyanin are Bluetec Naturals Co (China), DDW Inc (US), DIC corporation (Japan), Earthrise Naturals LLC (USA), Japan Algae Co (Japan), Parry Nutraceuticals (India), but several production sites are also located in Europe (Table 18).

Table 18: Main European phycocyanin producers

	Country	Production	Product	website
Laboratoires Phyco-biotech	France	Limited	Powder form (freeze-dried) (purity index: 3.7)	https://www.phyco-biotech.com/fr
Naturex (part of Givaudan since 2018)	France	? they have announced to triple the phycocyanin production through a new extraction line at Avignon (Silva *et al.* 2020)	Vegebrite® Ultimate spirulina	https://www.naturex.com
Fermentalg	France	In 2022: first revenues from the industrial production between the beginning of November 2022 and January 2023, represents a turnover of 250 K€ (Agromedia 2022)	Blue Origins® Galdieria Blue Extract.	https://www.fermentalg.com

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		Technology developed in partnership with DDW, a Givaudan subsidiary since June 2020		
Green tech	France	1 ton? Pilot line capable of producing 1-2tons/year. Objective: production of 10 tons/year which will require the production or purchase of 100 tons/year of spirulina. During a recent SpiralG project they produced up to 10 tons of spirulina.		https://www.greentech.fr/en/
AlgoSource	France	?	Spirulysat®	https://algosource.com/produit/spirulysat/
PhycoFarming project MIAL (MicroAlgen)	Germany	Aims to develop a process for extracting phycocyanin directly on the production site (project completion initially announced in 2022).		https://www.awi.de/en/science/special-groups/aquaculture/aquaculture-research/projects/phycofarming.html

3.5.1.5. Extraction process and co-products

The general extraction process of phycocyanin comprises 3 stages and is illustrated in Figure 51. Each step may be carried out using various techniques

- Cell disruption
- Extraction ("salting-in") and cell debris removal => crude extract. Purity up to 0.7-1.0
- Purification ("salting-out"). Purity up to 4-5

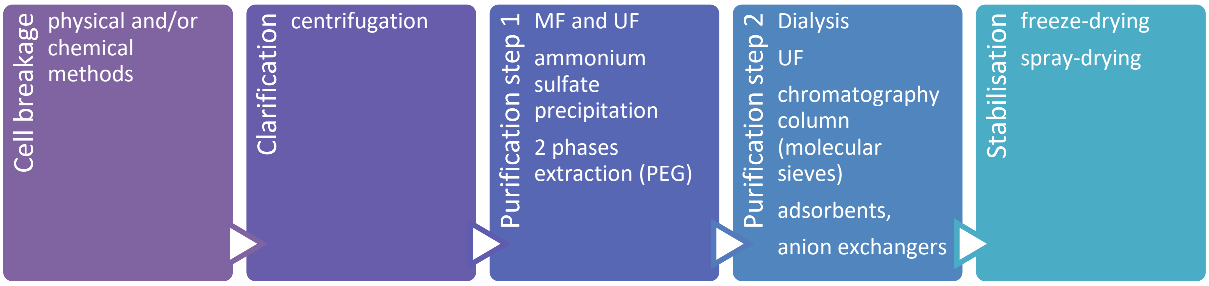

Figure 51 : General process of phycocyanin extraction (CEVA, based on literature review)

<u>Production challenges</u>

The production of phycocyanin requires two main consecutive processes : upstream process including microalgae biomass production/metabolites accumulation and downstream processing (including harvesting, extraction and biorefinery methods). The downstream processing generally requires high-cost techniques used for the extraction and purification of products.

<u>Potential biomass side streams</u>

Depending on the extraction buffer solvent, the method of cell disruption, the method of clarification the % of dry biomass left can vary. Based on literature review the spirulina residual biomass after phycocyanin extraction is comprised between 48 % and 70% (Guan 2016).

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We have limited data available about the European production of phycocyanin. We estimated the world production to be in the range of 75-150 tons. This field is emerging in Europe with new players and new processes. If we assume that the European phycocyanin production represents currently 10% of the world production, it would translate into 7.5 to 15 tons phycocyanin (which is a quite optimistic hypothesis), and lead to a potential residual biomass after phycocyanin extraction of 3.6 to 10.5 tons (equivalent dry biomass).

Due to the purification processes, and frequent use of buffers, effluents from the process are heavily loaded with minerals, and might be challenging to valorize.

The residual biomass of *Spirulina* following the extraction of proteins and C-PC can be further valorized through different biorefinery routes. As for many current uses of residual algal biomass, applications in agriculture can be considered (biofertilizer), as well as energy conversion (e.g. biogas). But further processing could also be considered (e.g. extraction of PHA/PHB) as well as direct uses in food/Feed applications (Thevarajah *et al.* 2022).
For food and feed uses, the utilization of food-grade chemicals in the extraction and purification stage of proteins and C-PC needs to be examined thoroughly to ensure consumer safety and economic viability. The residual biomass should be purified and tested for harmful toxins, heavy metals, etc. to ensure consumer safety before its utilization as human food and animal feed (Thevarajah *et al.* 2022). However, the residual biomass after phycocyanin extraction from Spirulina showed great potential, with high levels of proteins maintained, and an antioxidant activity, which is even higher compared to whole spirulina biomass (Fratelli *et al.* 2022).

Table 19: Composition of Spirulina and residual biomass after protein and C-Phycocyanin extraction (Parimi et al. 2015)

	Original A. platensis biomass	Residual biomass after protein extraction	Remaining biomass after phycocyanin extraction
C (%)	50.1	35.3	
H (%)	6.4	5.5	
N (%)	11.0	7.6	
O (%)	25.9	31.3	
Ash (%)	6.7	20.3	3.2
Protein content (%)	68.8	47.5	61.1
Lipid content (%)			2.6
Carbohydrate			32.8
Ref	(Parimi *et al.* 2015)	(Parimi *et al.* 2015)	(Fratelli *et al.* 2022)

3.5.2. Production of Phycoerythrin

Phycoerythrins are another type of phycobiliproteins found in a number of red seaweed (*Grateloupia* sp., *Palmaria palmata*, *Porphyra* sp, …), as well as microalgae (*Phormidium* sp, *Porphyridium* sp, …) and cyanobacteria (*Anabaena* sp., *Nostoc* sp., *Spirulina* sp., …).
They can be divided into four classes: R-phycoerythrin (R-PE), B-phycoerythrin (B-PE), C-phycoerythrin (C-PE) and B-phycoerythrin (B-PE), based on their origin and absorption spectrum. R-PE are the most abundant in red algae and marine unicellular cyanobacteria, while B-PE is found in microalgae (Munier *et al.* 2014).

As for phycocyanin, various purities can be obtained, but phycoerythrin use as food colouring agent did not develop. The phycoerythrin market is centred around high-purity products, mostly use as fluorescent markers for biological applications.

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The global phycoerythrin market is difficult to assess, as it is mostly composed of niche products sold at very high prices. Values from market reports are completely erratic and range from $5 million to several billion dollars. It seems reasonable to consider that this market, much more limited than the phycocyanin market, represents a few million dollars.

Volumes of algae processed in Europe, and associated co-products, are expected to be very limited although some European companies are active in the sector (e.g. Phyco-biotech in France).

Phycoerythrin is also targeted in the biorefinery of *Furcelaria lumbricalis* developed by Vetik in Estonia, including as a colouring agent for the cosmetic industry.

3.6. Production of Omega-3 oils

3.6.1. Description and sources

Omega-3 fatty acids are a group of essential fatty acids for human. They are necessary for the development and functioning of the retina, brain and nervous system. Adequate intake of omega-3 is therefore essential for women of childbearing age, pregnant and breastfeeding women, and children.

The precursor of the group of omega-3 fatty acids is alpha-linolenic acid (ALA). It is regarded as essential because it is necessary for the development and proper functioning of the body, which cannot synthesise it by itself. From this compound the body synthesises other omega-3 fatty acids, especially eicosapentaenoic (EPA) and docosahexaenoic (DHA) acids. However, the rate of conversion of ALA to DHA is too low to cover the body's needs in DHA, and therefore DHA is also regarded as essential and must be supplied in the diet. The foods richest in omega-3 are derived from terrestrial plants (walnuts, rapeseed oil, soybean oil, linseed oil, etc.) containing ALA and marine animals (oily fish such as salmon, tuna, mackerel, herrings, sardines, anchovies, etc.) and marine microalgae that contain EPA and DHA (ANSES, 2022).

The omega 3 market offers diversification of sources and products. Growing demand for omega 3 coupled with rising pressure on anchovy fisheries to extract fish oil has increased the demand from non-fish sources including flaxseed, walnuts, algae, and krill oil.

- It is dominated by fish oil concentrates: 39.31% of the market (Fortune Business Insights 2020)
- These concentrates are obtained by various chemical processes from fish oil and contain 2-3 different fatty acids.
- The second most abundant source of omega 3 is fish oil (raw material for concentrates). The composition of fish oil is more complex than concentrates and consists of over 50 different fatty acids.
- algae oil and kill oil represent together around 30% of omega 3 market. The demand of non-fish source from consumers in parallel of rising pressure on anchovy fisheries to extract fish oil has increased and segment of algae oil and krill oil is in constant progression.
- At last, the plant sources such as walnuts and flaxseed play a minor part with less than 10% of the global omega 3 market.

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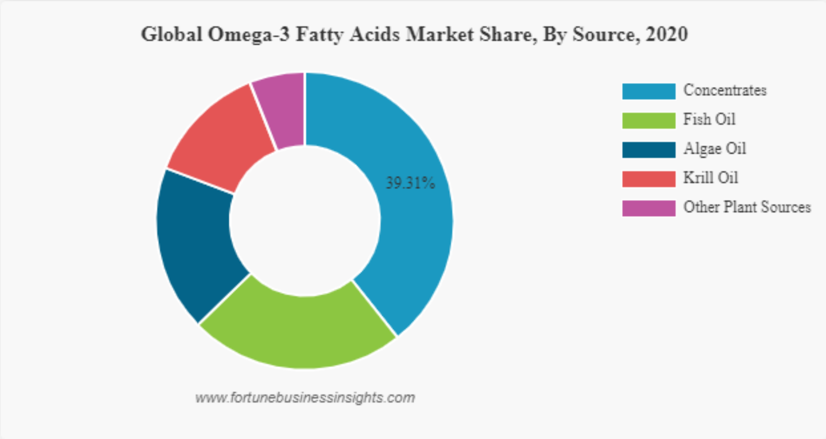

Figure 52 : Global omega 3 fatty acids market in 2020 by source (Fortune Business Insights 2020)

Wide variety of species are known to be able to produce n-3 LC PUFA and to have or almost have a development at industrial scale : Diatoms, Eustigmatophytes (Sehl *et al.* 2022), Dinoflagellates and Thraustochytrids.

Diatoms like *Phaeodactylum* and *Nitzschia* are microalgae with photosynthetic capacities, but which often also have the capacity to feed on organic matter. They are known for their low DHA and high EPA content, which can represent on average around 30% of total fatty acids (Perdana *et al.* 2021). For example EPA levels of 22.4 ± 1.7% up to 31.4 ± 1.7% with 7.1% DHA were obtained in Genetically Modified Diatom *Phaeodactylum tricornutum* (Hamilton *et al.* 2015).

Eustigmatophytes such as *Nannochloropsis* and *Trachydiscus* are obligate phototrophs and must gain their energy from light. These too produce little to no DHA and their predominant LC-PUFA is EPA. It is described EPA levels of 12.74 ± 1.84% in *Nannochloropsis salina* CCMP1176 and 10.93 ± 1.84% in CCMP537 on total fatty acids (Oliver *et al.* 2020).

Dinoflagellates and Thraustochytrids respectively represented by *Crypthecodinium* and *Schizochytrium/Aurantiochytrium* are known for their higher DHA and their relatively low EPA contents. Indeed, DHA level can reach up to 60% of total fatty acids (Chang et al. 2013)

- Thraustochytrid biomass may have a total lipid content of 36–84% with the average being 62% (Du *et al.* 2021; Patel *et al.* 2021)
- The DHA content of total fatty acids in *Schizochytrium* spp. may approach nearly 40% by weight (Metz *et al.* 2009)
- *Crypthecodinium cohnii*: DHA is almost exclusively the only PUFA present in its lipid and can be as high as 65% of the total fatty acids (Mendes *et al.* 2009)
- *Crypthecodinium cohnii* and *Schizochytrium* sp. are two microorganisms historically used for the commercial production of PUFAs by Martek Biosciences.

Up to now only heterotrophic production of *Crypthecodinium* and *Schizochytrium/Aurantiochytrium* has succeeded in producing products that compete with fish oils on both quality and price. Therefore, they are predominant in current n-3 LC-PUFA production processes.

3.6.2. Global market

The global omega-3 FAs market size was valued at 2.43 billion USD in 2022 and is expected to expand at a Growth Rate (CAGR) of 7.8% over the period 2023–2030 (Grandviewresearch.com).

The worldwide production and consumption of omega-3 FAs is governed by the food, beverage and food supplementation market, covering almost 75% of the market volume of EPA + DHA with a value of 54% of world revenues of sale (Voort *et al.* 2017) From the association of long chain omega-3 producers

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GOED, the global EPA and DHA omega-3 market was globally valued at 1.58 billion USD in 2021 with volume at 115,758 metric tons (Schutt Ellen 2022)

Within this market, **algae oils accounted for approximately 2034 tons:** 1.8% of the volume of the world n-3 LC-PUFA market and 15% of its value (Sehl *et al.* 2022). Algae oil is expected to witness the fastest growth in the sources segment of long chain omega-3.

Between 2018 and 2019, the world volume of algae oils increased from 2009 to 2109 metric tons, an increase of 5%, and market players indicate that this trend is accelerating.

The leading players in the Omega-3 market include Aker Biomarine Antarctic AS, BASF SE, BioProcess Algae, LLC, Croda International Plc, EPAX, GC Reiber Oils, Koninklijke DSM N.V., Lonza, Omega Protein Corp., Orkla Health amongst others.

Oils extracted from microalgae are still relatively expensive to produce compared to fish oil. Historically, the price of algae oil was 40-100 €/kg depending on the concentration and the production method for human nutrition.

Currently decreasing with the increase of the offer, in particular the specific fish feed offer (remains still 2x higher than the price of an equivalent DHA/EPA concentrate from fish). The biomass itself (DHA-rich algal dry biomass (*Crypthecodinium* sp. or *Schizochytrium* sp.)) was estimated to be worth US $25 kg^{-1} in 2002 (Harel *et al.* 2002).

(Chi *et al.* 2022) have made a comparison of price of DHA extracted from fish oil and price of DHA from *Schizochytrium.* On average, fish oil has around 16% DHA and fish oil price during 2015–2019 averaged U$1744 per metric ton. If this oil contained the usual average of 16% DHA, and all of it could be recovered, 6.25 tons of oil would be required to obtain 1 ton of DHA. The total cost of purchasing the required oil would be US$ 10,900 per ton of DHA, resulting in a minimum production cost of US$10.90 per kg DHA, ignoring the cost of recovering the DHA from the oil and other contributing factors (Chi *et al.* 2022). For the cultivation and production of DHA from *Schyzochytrium* the authors estimated that if fermentation is conducted on glucose the cost of substrate per kg of DHA would be 12.56 US$ therefore 15% higher than price of DHA fish oil (considering glucose and nothing else (other media, electricity, water, steam)).

Sijtsma calculated that DHA from heterotrophic microorganism *C. cohnii*, grown on ethanol, was 3-5 times more expensive than DHA from fish oil (Sijtsma *et al.* 2010).

In a techno-economic analysis of industrial production of marine microalgae as a source of EPA and DHA-rich raw material for aquafeed, Chauton et al determine that the cost for the phototrophic production of EPA and DHA is 39 USD per kg of EPA/DHA equivalents, when produced in flat panel reactors in high irradiance regions (cultivation of phototrophic microalgae species : *Isochrysis galbana, Phaeodactylum tricornutum or Nannochloropsis spp*.) (Chauton *et al.* 2015).

3.6.3. Applications

In terms of uses of omega 3 in 2021, dietary supplements made up the largest share of the market, accounting for 58% of the volume at 67 000 metric tons followed by pet food supplementation (37%), infant formula (5.3%) and the remaining are fortified foods and pharma products. Demand remained strong in 2021 and into 2022 (Schutt Ellen 2022).

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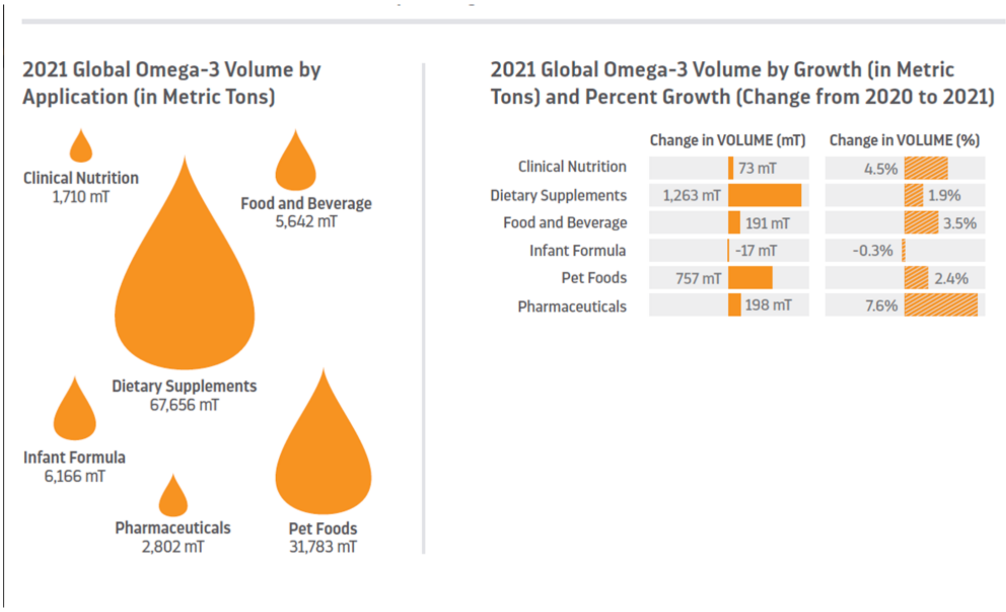

Figure 53 : Global omega3-volume by application and by growth in 2021 (Schutt Ellen 2022)

Concerning the use of algae oil, the distribution is not the same: majority of DHA algae oil volume (75%) is going into infant formulas (GOED, 2020). This market is expected to grow from USD 265.58 million in 2020 and to reach USD 506.33 million by 2028 (Stone Mark 2022).

The volume of dietary supplement is dominated by Asia-Pacific (34.5%), followed by United States (29%) then Europe (21%) (Schutt Ellen 2022).

The market in Europe is projected to significant growth due to expanding EPA and DHA market in UK. According to the Coherent Market Insights analysis, the United Kingdom EPA and DHA market were valued at USD 66.5 million in 2021. It is projected to reach USD 84.2 million by 2027, registering a CAGR of 4.26% during the forecast period, 2022-2027 (Coherent Market Insights 2021b).

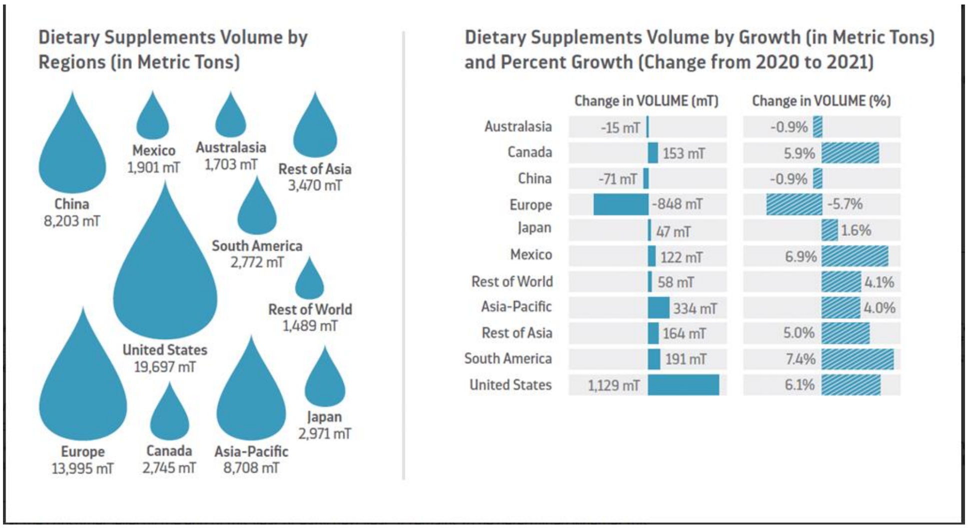

Figure 54 : Dietary supplements volume by regions and by growth (Schutt Ellen 2022)

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World key players

The main world suppliers of algae oil are:

- Corbion
- ADM Alltech
- Alltech
- DSM / Veramaris
- Lonza

Corbion whose factory is located in Brazil, uses sugarcane to produce *Schizochytrium* microalgae, which is commercialized as a whole algal biomass and used in the aquaculture feed industry, such as in the AlgaPrime DHA product. The facility uses sugarcane waste as an energy supply for the process.

ADM, the Archer Daniels Midland Company, is a health and nutrition company. In 2014, ADM and Synthetic Genomics, Inc entered into a joint venture, which explored the use of microalgae to produce omega-3 fatty acids. Synthetic Genomics works with a number of algal species, including Chlorella, to create their products. in June 2019, ADM unveiled a new line of DHA/EPA blends containing omega 3, 6, and 9, which offer benefits that can help support cognitive, heart, immune system, or eye health. Called "Onavita Algal DHA" and "Almega EPA," the new blends were created in collaboration with Qualitas Health, a marketer in algae cultivation.

DSM is a Dutch company that produces a variety of commodities pertaining to health and nutrition. It utilizes algae to produce some of its nutritional lipid products, primarily those which incorporate Omega-3. In 2010, DSM acquired Martek, a company which produced DHA using *Schizochytrium* and now commercializes products like Life'sTM OMEGA, Life's DHATM products. In May 2020, DSM launched life'sDHA SF55-O200DS for maternal and early life nutrition solutions. The algae-derived ingredient contains a minimum of 550 mg/g of natural triglyceride DHA. DHASCO, an oil rich in DHA, used in the food industry is also produced by DSM, and is obtained from *C. cohnii* microalga.

DSM also collaborates with other companies, such as Evonik Nutrition and Care GmbH and Sanofi to produce other algae related products. Veramaris is a joint-venture of DSM and Evonik, focusing on the production of omega-3 oils for feed applications.

Alltech is another company focusing on omega-3 oils obtained by fermentation for uses in the feed and aquaculture sector (whole celles and oil). Initially based in the USA, the company moved its production to Brazil.

Lonza is one of the historical players of the omega-3 market, producing omega-3 oil from *Ulkenia* sp (Switzerland and Czech Republic) for health and nutrition applications.

A number of newcomers have also emerged and reached significant production volumes as for instance Mara Renewables (Canada/UK) and Fermentalg (France).

3.6.4. Key companies in Europe

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Table 20: Key omega-3 oils operators in Europe

Country	Company	Species	Type of cultivation	Production	Turnover	Website
Netherlands	Veramaris	*Schizochytrium*	Fermentors Joint venture Evonik-DSM ***Production in USA (Nebraska)***	Announced a capacity to meet 15% of the global omega-3 fatty acid demand for salmon aquaculture* (around 18,300 tons)		https://www.veramaris.com/what-we-do-detail.html
Netherlands	Corbion	*Schizochytrium*	Fermentors ***Production in Brazil***		976.4 million (2019) Of which omega-3 oils represent only a fraction	http://www.corbion.com/algae-portfolio
France	Fermentalg	*Schizochytrium* *Ulkenia*	Fermentors, Mixotrophy Production in Spain (ADL Biopharma: fermentation production capacity of 2.4 million litres, including 8 x 225,000 litre fermenters)	Several hundred tons of DHA ORIGINS 550	Has recorded a 36% increase in turnover in 2022. It amounts to €7.7 million. Sales: North America: 30.3%, Europe: 67% and Asia: 2.6%	https://www.fermentalg.com Home - Fermentalg - Algae you can trust
France	Polaris	*Schizochytrium*	Production in Great Britain (Mara renewables)			OmegaVie Algae oils - Polaris
Switzerland	Lonza	*Ulkenia*	Fermentors		Lonza Group Ag annual revenue for 2021 was $5.9 billion, of which omega-3 oils represents only a fraction	https://www.lonza.com/
Great Britain	Algaecytes	*Euglena gracilis*	photobioreactor system (Phyco Flow) Pilot plant in UK and production plant in Germany The 2,000,000 litres plant (in Germany) will be the world's largest enclosed photobioreactor plant **(industrial site not in operation)**	Potential: 50MT/year EPA oils Potential: 300MT/year of algal biomass for agricultural biostimulants, β-carotene,…	< 5 M€	Home - Algaecytes
Canada	Mara Renewables	*Schizochytrium*	Production in England (AO3, Algal Omega 3 Ltd, Knowsley)	In 2021, supply of DHA equivalent to 7.36 billion fish (anchovies), i.e. 29,000 tons of anchovy => 876T omega-3 => ~3,000T algae (likely highly overestimated)	AO3: 6 M€ (2020) 2022: Partnership between Thai Union Ingredients and Algarithm's parent company, Mara Renewables	https://www.maracorp.ca/
Sweden	Simris Alg	*Phaeodactylum tricornutum*		EPA-rich oil,		simrisalg.se

n.b.: *Schizochytrium* is now *Aurantiochytrium* spp.

*Fish oil: In 2019, nearly 71% of fish oil consumption in aquaculture was used to feed salmon and trout (433,100 tons). Salmon uses 122,000 tons EPA + DHA ((EUMOFA 2023)

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3.6.5. Process and potential co-products

A variety of methods can be used to disrupt the microalgae cells, such as solvent extraction, ionic liquids, direct saponification, high-pressure homogenization, hydrodynamic cavitation, ultrasound, microwave, pulsed electronic field and ozone treatments, and hydrolytic enzymes, followed by extraction with or without solvent.

Solvent extraction remains the most used technique at lab-scale, with the mixtures chloroform–methanol, hexane, and hexane–isopropanol being the most used solvents (Da Silva *et al.* 2021).
However, industrially, mechanical disruption and heating, followed by direct phase separation if the most commonly used technique, either directly from the fresh fermentation broth or after drying. Isopropanol can also be added at this stage to form an emulsion before centrifugation of the oil (UK Food Standards Agency - Advisory Committee on Novel Foods and Processes 2011).
Use of enzymes can also be considered for cells lysis. For example oil may be extracted from *Schizochytrium sp.* using an alkaline protease (3%) as described by Lin *et al* (Lin *et al.* 2018) or in patent EP2958982B1.

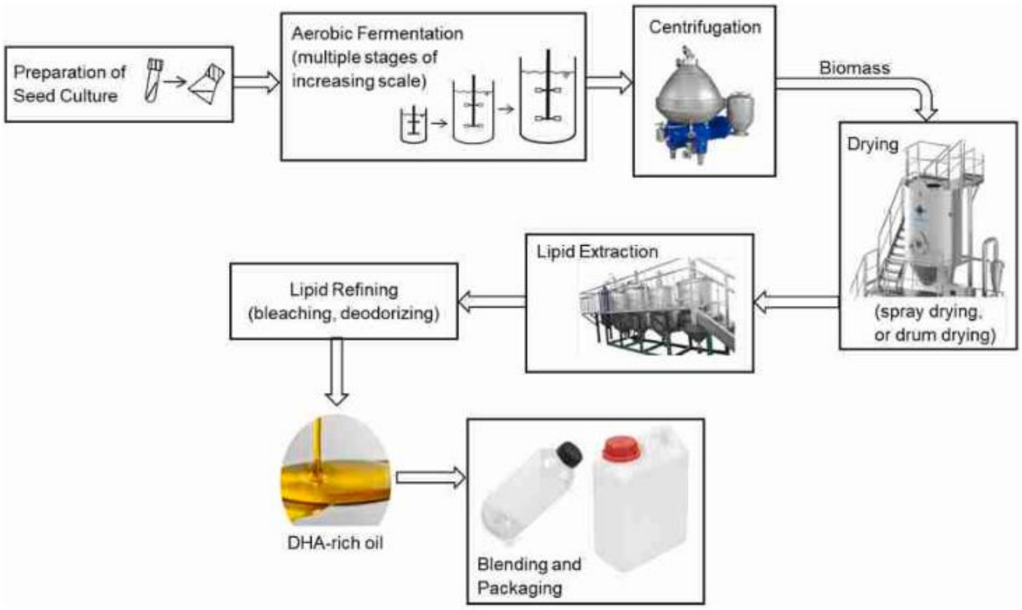

Fig. 2. The process for producing food-grade DHA-rich oil from *Schizochytrium* spp. Based on Winwood (2013).

Figure 55 : Typical process for producing food-grade DHA-rich oil (Chi et al. 2022)

3.6.6. Potential biomass side-streams

It is important to stress that microalgae lead to higher production yields than other sources (Finco *et al.* 2017):

- 1,000 kg of fish (anchoy) leads to 100 kg oil then to 30 kg omega 3 (at 30% PUFA)
- 1,000 kg of microalgae biomass (*Schyzochytrium*) leads to 600 kg oil then to 300 kg omega 3 (at 50% PUFA). In this case residual biomass could be estimated to 400 kg defatted cells.

If we hypothesize from the different european stakeholders communication, a european algae oil production around 500 tons, the potential residual biomass will be 333 tons.

The residual biomass (i.e. cell carcasses that remain after fatty acids have been extracted from lysed cells) can be used as an animal feed, containing as it does about 35–40% protein, 8–10% ash and 45–50% carbohydrates (Mendes *et al.* 2009). Other specific compositions of residual biomass after lipid extraction are presented in Table 15 below.

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Table 21: composition of residual biomass (after lipid extraction)

		Defatted *Crypthecodinium*	defatted *Nannochloris oculata*	Residual biomass (average)
Dry matter	%		88.8-94.3	
Carbohydrates				45-50%
Ash	%DW		24.2-49.7	8-10%
Crude proteins	% DW		21.9-38.1	35-40%
Lipids	% DW	12	<0.2-2.9	
DHA	% of total fatty acids	50		
EPA		<0.5		
AA		N.D.		
		(Harel *et al.* 2002)	(Bryant *et al.* 2012)	(Mendes *et al.* 2009)

Because of this high protein content and the elevated levels of DHA, the whole biomass is beneficial to animal growth, so which are widely used as an ingredient of livestock feed. They can be used for aquaculture (e.g., shrimp, oysters, fish) feed. For instance, it is possible to replace up to 10% of crude protein from fishmeal and soy protein concentrate with Lipid-Extracted Algae (LEA) from different microalgae species without causing significant reductions in fish red drum performance (Patterson and Gatlin 2013). However, the authors stressed that whole algae product without lipid extraction was more nutritious than LEA meals when fed to juvenile red drum.

Fermentation residues of thraustochytrids have been used as feed additives for a variety of aquatic animals, including Atlantic salmon parr and pacific white shrimp (Miller *et al*., 2007). When Schizochytrium biomass residue was added to pig feed, the serum triglycerides of the pigs significantly decreased, and the DHA content in subcutaneous fat increased 13 times (Jon Meadus *et al*., 2011). These studies indicate that feeding the fermentation residues of thraustochytrids can have unique positive effects on the physiological function of livestock, improving animal growth and product quality.

The residue of *Schizochytrium sp.* fermentation were also used to replace yeast extract for its own fermentation. (cf Figure 56). A 27.1 g/L of DHA yield was obtained when 80% of yeast extract nitrogen was replaced with the residues, which was 20.07% higher than that of the control. Re-using fermentation wastewater and algae-residue extract , the authors obtained a final cell dry weight of 110.15 g/L, with 63.63 g/L of total lipid and a DHA yield of 28.45 g/L (Yin *et al.* 2018).

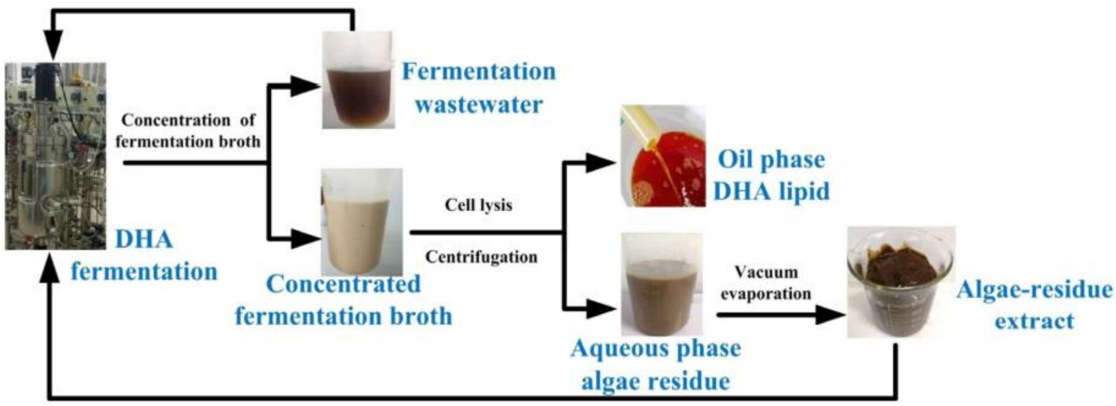

Figure 56 : Flow chart of the preparation and application of fermentation wastewater and algal-residue extract (Yin et al. 2018)

The residual microalgal biomass can also be mixed with a combination of brewer's yeast, or residues from spray-drying of yeast extracts. These ingredients are mixed with water to form a dough-like

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substance, and cooked to form a pleasant-smelling biscuit-type which dogs and cats find highly appealing (Mendes *et al.* 2009).

From the crude oil after process of DHA refining, it could potentially possible to extract some high value pigments such as carotenoids. In particular, astaxanthin productivity of 9.48 mg $L^{-1}d^{-1}$ was reported through the cultivation of *Aurantiochytrium sp*. mutant and astaxanthin yield of 162.14 µg g^{-1} from *Thraustochytrium sp*. S7 (Russo *et al.* 2021).

The lowest value application of the residual cake could be anaerobic digestion for the recovery of energy and mineral nutrients in the production process.

3.7. Production of extracts

3.7.1. Agriculture (biostimulants, biocontrol, fertilizers…)

3.7.1.1. Presentation and uses of algae extracts in agriculture

In coastal areas of Europe, macroalgae have a long history of use by farmers either directly or in composted form. A major advance in the use of algae in agriculture results from the work carried out by Dr. Reginald F. Milton in the 1940s, who developed the first practical method for liquefying seaweed for agricultural, based on a hot pressure alkaline process (GB664989A). This first seaweed « biostimulant » called Maxicrop, was marketed in the early 1950s and the production reached approximately 900,000 L in 1964 (Craigie 2011). Then in the 60-70s, other companies started producing seaweed extracts for agriculture, such as Algea (Norway, today subsidiary of Valagro) with an alkaline *Ascophyllum nodosum* extract similar to Maxicrop, Kelpak (South Africa) with an *Ecklonia maxima* extract produced by a patented mechanical pressure differential process called Cold Cellular-burst technology and Goëmar (France, now subsidiary of UPL Corporation) with seaweed preparation base on a patented process based on cryo-milling (US4023734A).

In the last decade, many scientific works have focused on the effects of the application of seaweed extracts on plants and soils, and have shown their numerous and diverse benefits on seed germination, vegetative growth, yields, flowering, fruit production, production quality, abiotic stress mitigation, soil properties and microbial activity (Battacharyya *et al.* 2015; Nabti *et al.* 2017; Pohl *et al.* 2019; Sharma *et al.* 2014; Sujeeth *et al.* 2022). In very recent years, there has also been a significant increase in scientific work dealing with the biostimulant properties of microalgae, cyanobacteria and their derived extracts (Chiaiese *et al.* 2018; Ronga *et al.* 2019).

At the same time, the precise mechanisms activated by seaweed biostimulants remain poorly understood, due to the complexity of their composition, the potential synergistic effects of the multiple compounds present in these products and the great diversity in plant responses. According to data from the scientific literature, a wide variety of molecules are potentially responsible for the effects of seaweed biostimulant measured on plants, including carbohydrates, polysaccharide and their derivatives, peptides and amino acids, phytohormones (or at least compounds with growth hormone ‐ like activity), osmolytes, polyamins, betains, phenolic compounds, vitamins or even microelements (Deolu-Ajayi *et al.* 2022; Kapoore *et al.* 2021; Sujeeth *et al.* 2022).

Over the past 20-25 years, a multitude of liquid seaweed extracts have been marketed with quite varied claims on their "physioactivating", "anti-stress", "phytostimulant" or "fortifying" effects on plant crops and have been commonly called "biostimulant" without this term having any regulatory value. Then, until recently, the approval and marketing of " biostimulants" was governed by EC Regulation 2003/2003 and national rules specific to each state.

Since the adoption on June 5, 2019 of the new Regulation (EU) 2019/1009 laying down rules on the making available on the market of EU fertilising products ((EU) 2019/1009), "plant biostimulant" products are now clearly defined. Thus, according to the European Commission, a « plant biostimulant » shall be an EU fertilising product the function of which is to stimulate plant nutrition processes independently of

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the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: (a) nutrient use efficiency, (b) tolerance to abiotic stress, (c) quality traits, or (d) availability of confined nutrients in the soil or rhizosphere. Plant biostimulants products are thus well distinguished from phytosanitary products, which are regulated separately (Regulation (EC) No 1107/2009).

3.7.1.2. Global and European biostimulant markets

According to different estimates from market analysts, the global biostimulants market is estimated to be worth USD 3-3.5 Bn in 2022 and is expected to register a CAGR of 10-12% over the next 5-10 years. It is projected to reach USD 6.2 Bn by 2027 according to Markets and Markets or even USD 9.5 Bn by 2032 according to Global Market Insight.

Most market analysts report that the European biostimulants market accounts for roughly half of the global market. Estimates of the value of the European market range around USD 1.5-2 billion in 2022. (Market Date Forecast, Market and Markets and Dunham Trimmer). The CAGR reported is 10-12% (European Biostimulants Industry Council 2022).

Figure 57: Biostimulants market by region in 2021 (Transparency Market Research 2021)

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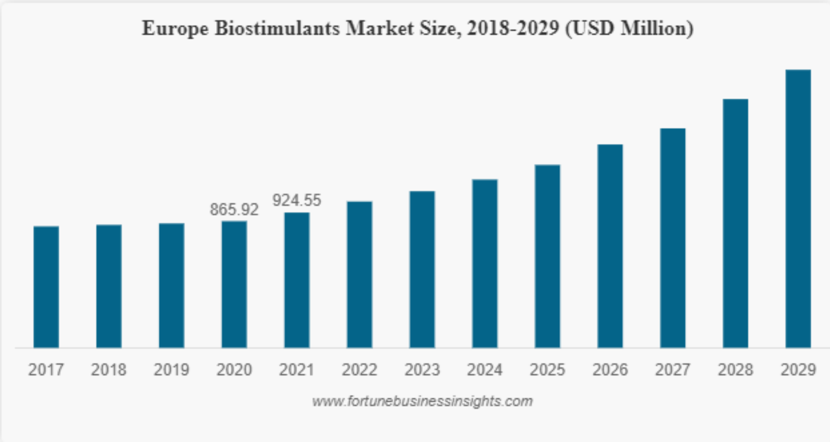

Figure 58: European Biostimulants Market Size (Fortune Business Insights 2021)

Seaweed extracts segment

Most seaweed extracts used worldwide for their biostimulatory properties are produced from brown algae, usually harvested from wild populations. The vast majority of seaweed biostimulant extracts are derived from *Ascophyllum nodosum* and *Laminaria sp.*, especially in Europe (*Ecklonia sp*., *Sargassum sp.* and *Durvillaea sp*. are also used in another part of the world).

According to the market analyses carried out in the Bio4safe project in 2016, seaweed extracts were estimated to account for the largest share of the global biostimulant market (> 30%), which also includes for the main other categories humic acids, protein hydrolysates / amino acid, microorganisms and trace elements. The same study also revealed that Europe accounted for approximately 40% of the global seaweed-based biostimulants market (i.e. €194 million) (North Sea Farm Foundation 2018).

3.7.1.3. European production and algae species used

In Europe, the main players in the seaweed-based biostimulants industry are listed below, with the main species used by these companies (to our knowledge).

Table 22: Main European producers of algae-based biostimulants

Company name (country)	Main algae species used
Agrimer (France)	*L. digitata*
Algaïa (France)	*L. digitata, L. hyperborea*
Arramara (Ireland, subsidiary of Acadian Seaplant)	*A. nodosum*
BioAtlantis (Ireland)	*A. nodosum*
Bio3G (France, subsidiary of Elephant Vert Group)	*Laminaria* sp and other brown seaweeds
Goëmar (France, subsidiary of UPL Corporation)	*Laminaria* sp.*, *A. nodosum*
Olmix (France)	*Ulva sp., Solieria chordalis*
OGT (Ireland), part of **Rovensa Next** (Spain)	*A. nodosum*
Timac Agro (France, Roullier group)	*A. nodosum, Fucus vesiculosus, Fucus serratus, Arthrospira platensis*
Valagro (Italy)	*A. nodosum*
AlgaEnergy (Spain)	microalgae
BIORIZON Biotech (Spain)	*Arthrospira sp., microalgae and cyanobacteria*

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LLDC Algae (France)	*Chlorella sp.*

* for extraction of laminarin, active ingredient (elicitor) of IODUS® a phytosanitary product

The share of microalgal biostimulants is still negligible today. However, many projects of phytoremediation of industrial effluents using microalgae are under development, with a planned use of biomasses in the sector of biostimulants.

Recently, many industries in Spain (Agroplasma, AlgaEnergy, Agrialgae, Allgrow and Biorizon biotech), Turkey (Mikroalg Inc. and MCT Tarim Ltd.), USA (AgroValley Inc.), Hungary (Natur Agro) and India (Soley Biotech, Hindustan bioenergy Ltd.) advanced their research and investments in commercialising microalgal biostimulants and biofertilizers, where mainly *Arthrospira*, *Chlorella*, *Scenedesmus*, *Haematococcus* and *Nannochloropsis* extracts have been explored so far (Kapoor *et al*., 2021).

3.7.1.4. Process and co-products

As mentioned in section 3.7.1.1, a range of diverse processes are applied to algae for the preparation of these extracts.

A number of products, sometimes referred to as "creams", are actually directly containing the finely ground seaweed, and do not generate any by-products. This is also usually the case for microalgae and cyanobacteria-based products for which no downstream filtration is applied.

A number of other products are "true" extracts, which undergo a solid/liquid separation. In this case, as for other extraction industries, the co-products obtained are wet (usually 20-30% dry matter) residual biomass, containing various compounds as fibers and insoluble proteins, and possibly some filtration aids. Nevertheless, their composition and quality also vary according to the process applied (e.g. strong alkaline treatments that may degrade a number of compounds). These co-products are usually further valorized in agriculture (potentially after composting) or integrated into other products. Their amount is difficult to assess, but they may represent several thousand tons of dry matter.

Lastly, a few ingredients can be purified, and also generate liquid effluents (e.g. laminarin), but they represent only a small fraction of the total agricultural market.

Besides co-products, seaweed discards are also generated by some producers after harvesting. For example, Rovensa next recently launched an innovation call for the use of 180-280 tons of *Fucus* sp separated each year from their Ascophyllum nodosum raw materials by their subsidiary OGT in Ireland.

3.7.2. Cosmetic extracts

3.7.2.1. Rationale for the use of algae ingredients

The cosmetics industry is a competitive market, constantly in search for new and innovative active compounds from green and natural sources, since consumer preference towards eco-friendly, safe but also effective cosmetic products is rapidly expanding.

Algae are considered a widely available and promising source of unique and active compounds and are gaining increasing attention in recent years for the production of cosmetic ingredients. Their use for this type of application is also linked to the number of scientific studies demonstrating the potential skincare properties of algae.

A broad range of bioactive compounds are often associated to the biological properties of algae, such as polyphenols / phlorotannins, pigments, sterols, polysaccharides / sulfated polysaccharides and their oligomeric derivatives, exopolysaccharides, proteins, peptides, amino acids, mycosporine-like amino acids, lipids / fatty acids, vitamins, minerals and various secondary metabolites.

The benefits of algal compounds for skin care are based on various activities as antioxidant / radical scavengers, anti-inflammatory, moisturizing, UV protection, enzymes inhibition (e.g. matrix

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metalloproteinases, tyrosinase), tissue growth stimulation, slimming, anti-acne or even antibacterial properties (Jesumani *et al.* 2019; López-Hortas *et al.* 2021; Martínez-Ruiz *et al.* 2022; Pereira 2018; Pimentel *et al.* 2018; Yarkent *et al.* 2020)(Jesumani *et al.* 2019cff557e339f3487a911b237e5e4901a1" \o "Jesumani V, Du H, Aslam M, Pei P, Huang N (2019) Potential Use of Seaweed.

Algal extracts can also be used as technical ingredients to improve texture (e.g. thickening or gelling properties of phycocolloids), color (e.g. phycobiliproteins and carotenoids) or stability (antimicrobial and antioxidant properties of phlorotannins for example) of cosmetics.

In Europe, 17 % of the seaweeds companies and 24 % of the microalgae companies direct their biomass production - or a part of it - to cosmetics and wellbeing production (Araújo et al. 2021).

3.7.2.2. Species used

CEVA has carried out an inventory of algae-based active cosmetic extract commercially available (marketed in BtoB). The data - including algae species, main cosmetic claims, *in vitro* and/or clinical objectification - were collected through different sources, mainly the merchant sites of cosmetic ingredients producers or suppliers, free databases (*e.g.* SpecialChem) or specialized journals. The objective was to be as exhaustive as possible but all the ingredients currently on the market are probably not listed. Although the search for information was carried out on a global scale, the ingredients from European companies are more represented (data from Asian companies in particular are less accessible). Finally, the data allows to give an overview of the species used in cosmetic ingredients and the main claims associated.

Currently, we have found about 500 active cosmetic ingredients based on algae, including both seaweeds, microalgae and cyanobacteria (about 3% of the ingredients were excluded from the graphical analyses because the type of algae was not found or is not communicated). According to our database, brown seaweeds are most often used in active cosmetic ingredients, followed by microalgae and cyanobacteria, red and green seaweeds, the latter being found in only 6 % of the products analysed. It should be noted that the share of microalgae / cyanobacteria is constantly increasing, representing 27% of the species used for the production of cosmetic active ingredients, *vs* 23% in 2018.

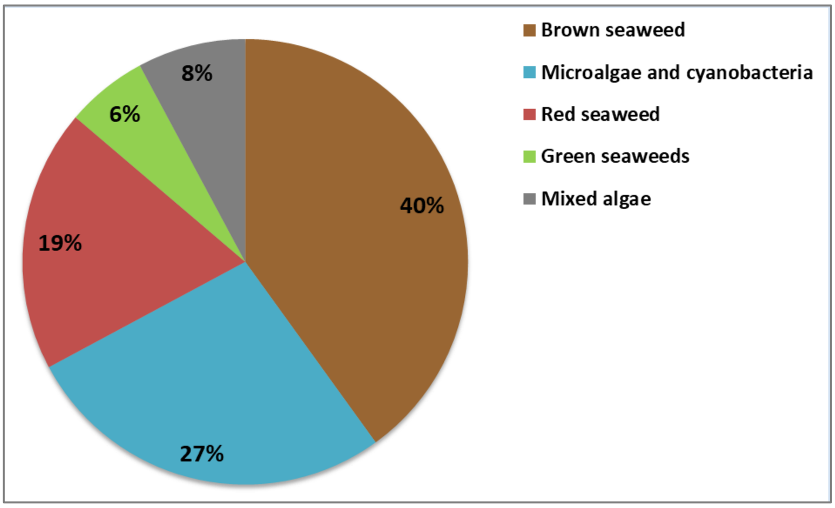

Figure 59: algae-based active cosmetic ingredients by type of algae (CEVA)

Seaweed-based cosmetic ingredients

The vast majority of seaweed extracts for cosmetics are from a single species (93% of the ingredients reviewed). More than half of the seaweed-based cosmetic ingredients are brown species extracts (> 35

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species). Among them, 24% are from *Laminaria* species (*L. digitata*, *L. japonica*, *L. hyperborea* and *L. ochroleuca*), 22 % from *Fucus* species (*F. vesiculosus* and *F. serratus*), 11 % from *Undaria pinnatifida*, 7% from *Ascophyllum nodosum*, 4% from *Himanthalia elongata*, 4% from *Marocystis pyrifera* and 3% from *Saccharina latissima*. The last quarter is represented by a greater diversity of seaweeds, including *Alaria esculenta*, *Pelvetia* sp., *Sargassum* sp., *Padina* sp., *Cystoseira* sp., *Bifurcaria bifurcata, Lessonia* sp. and *Ecklonia cava*.

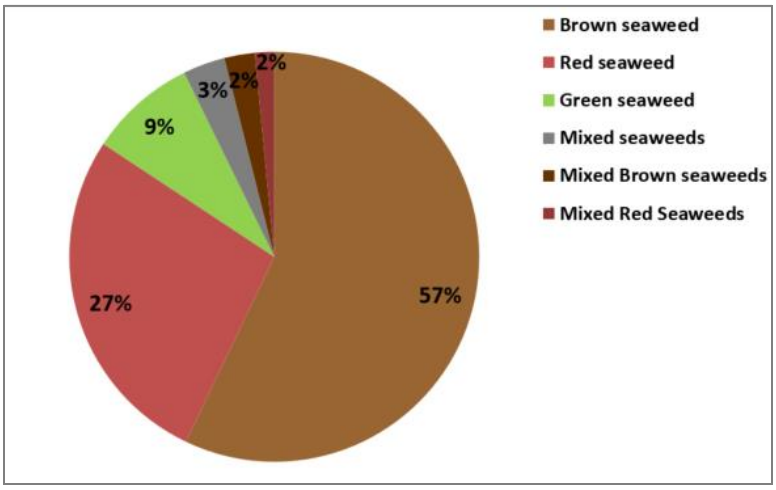

Figure 60: seaweed-based active cosmetic ingredients distribution by type (CEVA)

About 30 different species of red seaweeds are used for the production of cosmetic ingredients, the four main species being *Chondrus crispus* followed by *Palmaria palmata*, *Corallina officinalis* and *Porphyra umbilicalis,* for half of the products. Then we also find *Phymatolithon calcareum* (formely *Lithothamnium calcareum*), *Kappaphycus alvarezii, Jania rubens, Gelidium spp., Gigartina stellata, Hypnea musciformis, Calliblepharis jubata, ...*

Only 3 genera of green seaweeds have been found in cosmetic ingredients from our database, including *Ulva* sp. (62%), *Caulerpa lentillifera* (19%) and *Codium* (19% with *C. tomentosum* and *C. fragile*).

Microalgae and Cyanobacteria based cosmetic ingredients

More than a quarter of the products listed in our database come from microalgae or cyanobacteria (relative shares of 73% and 27 % respectively). Spirulina, *Chlorella* and *Haematococcus* represent more than 10% (respectively 5, 3.5 and 3%) of all ingredients in our algae-based cosmetic ingredients.

Table 23: Distribution of microalgae and cyanobacteria species in cosmetic ingredients (CEVA)

Microalgae species	% of occurrence in microalgae-based active cosmetics
Chlorella spp. (mostly *C. vulgaris,* and *C. sorokiniana, C. emersonii)*	21
Haematococcus pluvialis	19
Dunaliella salina	12
Porphyridium cruentum	11
Phaeodactylum tricornutum	5
Nannochloropsis spp. (N.oculata, N. oceanica, N. granulata)	5
TIsochrysis lutea (formely *Isochrysis galbana*)	4
Others	23
Cyanobacteria species	**% of occurrence in cyanobacteria-based active cosmetics**
Spirulina / *Arthrospira*	80
Aphanizomenon Flos Aquae	10
Aphanothece sacrum	3
Phormidium persicinum	3
Anacystis nidulans	3

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Cosmetic claims of algae-based cosmetic actives

Depending on the groups of algae considered, between 38 % and 60% of the ingredients in the database have been tested *in vitro* and/or *in vivo* (clinical study) to support their cosmetic claims. Regardless of the algae species, the objectified actives *in vitro* mainly claim anti-aging and moisturizing effect for almost half of them.

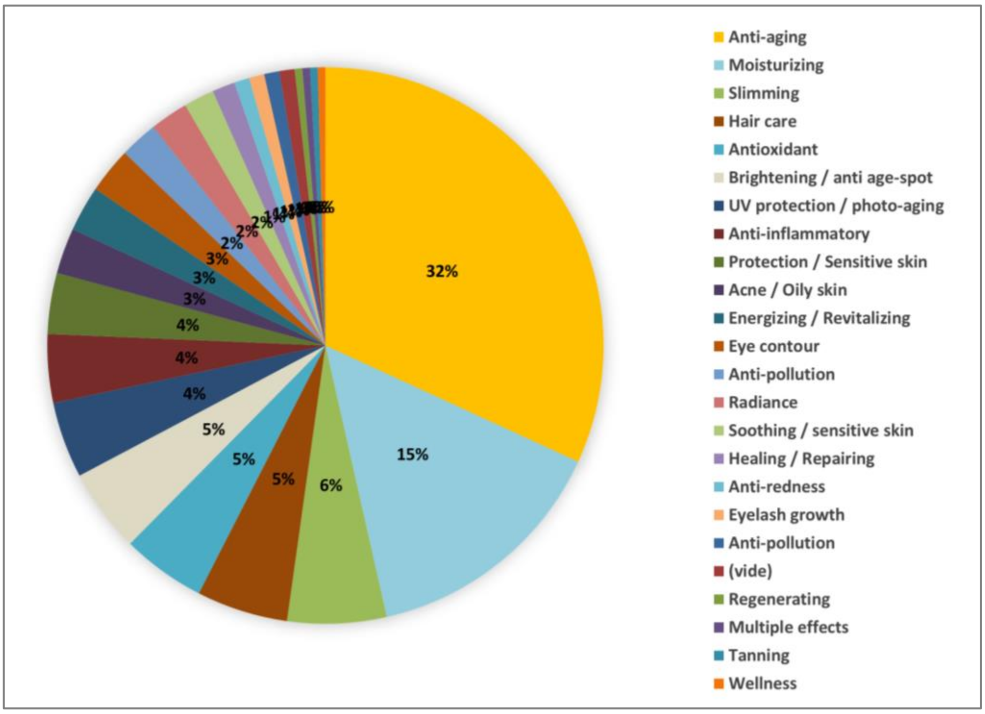

Figure 61: distribution of algae-based cosmetic actives according to their target (CEVA)

There are fewer objectified extracts among brown seaweed ingredients (40%) and more generic products claiming skin benefits based solely on literature data (potential bioactivities related to the chemical composition). But there is a greater proportion of brightening / whitening active ingredients (about 12 % of objectified ingredients from brown algae *vs* < 2 % from other groups of algae). This is an example highlighting the link between claims and unique chemical features of algae, several scientific studies have indeed shown the properties of phlorotannins and fucoidans to reduce the synthesis of melanin (Azam *et al.* 2017).

Among cyanobacteria extracts, spirulina products are often generic extracts (only 24% tested for their activity). On the other hand, ingredients based on microalgae have been subjected to more efficacy tests (60%). We also note that a greater proportion of the tested extracts from microalgae and cyanobacteria target anti-aging effects (36 % and 42 % respectively).

3.7.2.3. Global Market

According to a market research study by Meticulous Market Research Pvt. Ltd. (Meticulous Research) in collaboration with European Algae Biomass Association, the algae (seaweeds and microalgae) products market for cosmetics is expected to reach $305.3 million by 2029, at a CAGR of 7.3% during the forecast period 2022–2029 (from slightly under $ 200 M to date). However, this report gathers all algae-based ingredients used in cosmetics (including texturizing compound among others), and not only active cosmetic ingredients. The CAGR is expected to be greater for Chlorella, seaweeds (especially brown seaweeds) and spirulina based actives (Meticulous Research).

This report also stresses that the growth of this market is mainly attributed to the growing cosmetics industry, increasing demand for vegan skincare products, and rising awareness about the health

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benefits of organic cosmetic products. Additionally, emerging markets in Asia-Pacific and Latin America provide significant growth opportunities for cosmetic algae product manufacturers in the coming years. However, the lack of R&D activities in underdeveloped countries and the complex production of algae products have restricted the growth of this market to some extent.

Future Market insights predicts that the overall market for microalgae *(including cyanobacteria such as Spirulina)* in the personal and cosmetics sector will reach US$ 76.5 M by 2031, growing at a CAGR of 4,2% over the 2021-2031 period (Future Market Insights 2021). The demand for microalgae in the personal care and cosmetics sector in Europe will rise at 4% CAGR through 2031.

3.7.2.4. European players

Numerous European companies are producing algae extracts for cosmetic applications. And a large share of the algae-based cosmetics ingredients is produced by European companies.

However, it is often complex to categorize them and assess the share of algae-based cosmetic ingredients in their portfolio. Indeed, some algae companies are covering various markets including cosmetics, which may represent a small share of their activity in volume, but non-negligible contribution to their turnover. In parallel, other companies are specialized in cosmetic ingredients, but only occasionally produce algae-based ingredients, among other plant-based and/or synthetic ingredients.

Nevertheless, a number of companies with their main focus (or a significant share of their activity) on algae-based cosmetic ingredients can be listed, many of them located in France:

- Agrimer (France)
- BiotechMarine (subsidiary of Air Liquide/SEPPIC) (France)
- CODIF (France)
- Gelyma (France)
- Greenaltech (Spain)
- Greensea (France)
- Lessonia (France)
- Odycea (France)

Overall, the European production of algae-based ingredients might represent a market in the range of 50 to 100 million euros, although providing a precise estimation is challenging.

3.7.2.5. Co-products

This general overview of seaweed extracts intended for the cosmetics market shows the great diversity of algae currently exploited to produce cosmetic extracts, with (at least) 75 species of seaweeds and 30 species of microalgae / cyanobacteria.

Moreover, for a same species, different extraction processes can be applied depending on the targeted compounds. For example, ingredients from *Undaria pinnatifida* can be obtained with various type of methods: fermentation of the seaweed with probiotic *Lactobacillus* (Myferm-WP by The Garden of Naturalsolution), enzymatic hydrolysis (Wakame Extract H.GL.-M.S. by Provital Group), supecritical CO_2 oil (Wakapamp by CODIF), microwave-assisted extraction (Phytessence Wakame by Croda), liposoluble extract of cultured gametophytes (EPHEMER™ by Biotechmarine – SEPPIC) or even highly purified fucoïdans (Maritech® Reverse by Marinova or Fucoidans serie by Haerim).

However, cosmetic extracts are rarely purified, and co-products generated are mainly the algae residues left after extraction. Limited volumes of liquid effluents can be expected.

The volumes of seaweed processed are generally low for a given commercial extract, the size of the production batches most often approaching the pilot scale. Except for a few specific, very successful products, volumes of a single seaweed processed are rarely exceeding a few tons fresh weight each

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year. Also, many companies are processing different algae types, and co-products, which are not segregated are mixtures of various species and their processing is spread across the year.

Taken together, these elements suggest highly fragmented co-product deposits, with small volumes and changing chemical compositions.

It should nevertheless be stressed out that some companies also supply "algae water" recovered from the drying process of fresh seaweeds to replace pure water in cosmetic formulas and to increase the naturality and organic content of the products (e.g. Lessonia, with its range of Aqualgae products).

3.7.3. Feed extracts

As mentioned earlier in the algae feed section of the report (3.2), Most companies are currently using whole algae directly as feed ingredient.

Some purified extracts are also produced, sometimes from seaweed but mostly from microalgae/Labyrinthulomycetes: marine omega-3 oils for example are increasingly used in fish feed and animal feed (section 3.6), as well as some pigments or polysaccharides like beta-glucans used for their potential to support immunity (section 3.3.4).

Still some companies are exploring the potential of seaweed for the development of specific extracts with beneficial properties for growth performance and health. It is for example the case of the French company Olmix, which processes several thousand tons of beach-cast/drifting *Ulva* sp. and *Solieria* sp. for a range of extracts used as feed additives. However, there are limited co-products available from this processing, as the company is further processing the co-products internally for agricultural products.

3.8. Algae Biomaterials

3.8.1. A very active sector

Over the last few years, significant interest emerged for algae-based solutions across all categories of biomaterials: bioplastics, packaging, textile, … In this field, algae are indeed perceived as a promising alternative to plastics derived from fossil resources, but also land-based agricultural resources.

As for the field of biomaterials made from land-based/agricultural resources, several technical approaches are being followed. They lead to a diverse range of products, fully or only partially algae-based, and which can be biodegradable, compostable, recyclable or reusable.

The Phyconomy database (Hermans 2023b), which lists over 1,000 companies worldwide active in the algae sector, identified almost 60 companies focusing (fully or partly) on algae-based materials.

Of those companies, almost 30 are located in Europe, but only 10 existed before 2019. Several companies also recently announced significant investment deals, with close to 45 million euros raised by 6 companies (NOTPLA, Eranova, Oceanium, one • five, Biotic and Kelpi).

But while some products might be already established for pioneering companies, many companies are still at the research & development stage, or are implementing pilot units. Current markets are then relatively limited, and are difficult to assess, as most company turnovers are unpublished or still rely largely on income from collaborative research programs and grants/seed money.

Table 24: List of European companies active in algae-based materials – adapted from Phyconomy database (Hermans 2023b)

Name	Headquarters	Industry (Applications)	Founding year
Smartfiber	Germany	Textiles	2005
Algopack	France	Biomaterials	2010
Notpla	UK	Biomaterials, Paper/cardboard	2014
Pyratex	Spain	Textiles	2014
Eranova	France	Biomaterials	2016
Biopaxium	UK	Biomaterials	2017
B'zeos	Norway	Biomaterials	2017
Inland Sea	UK	Textiles	2017
BlueBlocks	Netherlands	Biomaterials, Construction	2018
Oceanium	UK	Biomaterials, Ingredients & extracts	2018
Futuralga	Spain	Biomaterials	2018
Searo (prev. SoluBlue)	UK	Biomaterials	2018
Mercel	UK	Biomaterials	2019
Oimo	Spain	Biomaterials	2019
Sargasse Project	France	Paper / cardboard	2019
squiish	UK	Biomaterials	2019
Biotic	Israel	Biomaterials	2020
one • five	Germany	Biomaterials	2020
FlexSea	UK	Biomaterials	2020
Kelpi	UK	Biomaterials	2020
Marea	Iceland	Biomaterials	2020
Marinatex	UK	Biomaterials	2020
Plantsea	UK	Biomaterials	2020
Uncommon Alchemy	UK	Textiles	2020
Metalchemy	UK	Bioplastics	2021
mujō	Germany	Biomaterials	2021
Noriware	Switzerland	Biomaterials	2021
Pit Seal	Ireland	Biomaterials	2021
Vyld	Germany	Biomaterials	2021
Zeefier	Netherlands	Textiles, Pigments	2021
Seaweedfoam	Lithuania	Biomaterials	2023

3.8.1.1. Raw materials sources

Companies in the algae-base materials sector are taking different approaches and use a broad range of raw materials:

- Extracted ingredients, especially commercial seaweed hydrocolloids (carrageenans, agar, alginates).
- Co-products from the algae-processing industry.
- Unprocessed seaweed: harvested locally, cultivated (e.g. red seaweed from South-East Asia) or beach-cast seaweed from algal blooms and storms (*Ulva* sp., *Sargassum* sp.).
- Microalgae from eutrophicated water bodies (freshwater lakes/ponds), although this is not commonly practiced in Europe.

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While co-products are being increasingly explored as cheaper raw materials for more competitive materials, the development of new biorefineries increasing the value obtained from these co-products might in the end, limit their potential use in biomaterials applications.

3.8.2. Typologies of products

3.8.2.1. Blends

A commonly used approach to increase the share of bio-based resources in materials is to incorporate algae powder directly in the materials to play a role of charge / reinforcement the material. Various raw materials can then be used: dried microalgae, ground seaweed, algae processed to improve their technical properties, or industry co-products (extraction residues, cellulosic co-products from agar or carrageenan extraction, …).

Algae do not exhibit thermoplastic properties, or melting properties, but can be compatibilized with different materials (thermoplastic or thermos-compressible materials, various polymers,…), which can be bio-based or fossil-based (Schmidtchen *et al.* 2022). Inclusion rates of 10-30% are not uncommon, and can even be higher, even if the biomaterial properties can be impacted, and regulatory aspects should also be considered.

Selection of the raw materials is also important and should focus on algae/algae products composition (e.g. high starch and protein content for plasticity), as well as absence of mineral residues (sand, shells, filtration aids, …) which are not compatible with plastic processing technologies (injection, extrusion, …).

AlgoPack company in France was a pioneer in this field, focusing on brown seaweed and industry co-products, and more recently on beach-cast *Sargassum* sp. An industrial pilot was also implemented in 2021 by Eranova in Port Saint Louis du Rhône (France) to process *Ulva* sp., and Eranova is currently preparing a new significant investment to move to full industrial-scale.

Seaweed can also be incorporated into other non-plastic materials as for example paper (e.g. Premium papers AlgaCarta of the Italian company Favini, incorporating *Ulva*), cardboard, or molded cellulose, sometimes with very high incorporation rates can be reached for molded / thermo-compressed materials (e.g. patents for 2nd generation of Algopack products, or from the Korean company Marine innovation). The French start-up Sargasse Project also focuses on 100% algae-based paper/cardboard alternatives, prepared from *Sargassum* sp..

A similar approach can also be found in textile, with for example cellulose fibers enriched with seaweed powder (Seacell™, developed by the German company SmartFiber AG), and produced since almost 20 years using a modified Lyocell process.

By tuning the processing conditions and algae material preparation (chemical treatment, formulation), leather alternatives can also be obtained as illustrated by Uncommon Alchemy and Oceanium in the UK, or Studio Tomatis in France.

Lastly, construction materials incorporating algae are also being developed (raw bricks, insulation materials, …) in order to improve their bio-based content, but also to build up on their mechanical and technical properties (high mineral content reducing flammability, …). These developments, although often relatively artisanal (e.g. Sargablock in Mexico), are also being explored on industry co-products as one of the solutions to handled co-products loaded with mineral filtration aids as Perlite (e.g. ESITC engineering School in Caen).

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3.8.2.2. Algal biopolymers

Various algal biopolymers can also be used for the production of biomaterials: they include both parietal and reserve polysaccharides, which are the most widely used to date, but other compounds as proteins could also be considered.

Starch (found in green seaweed and some red seaweed, as well as in microalgae) and cellulose (present across the algae range) are often sourced from land-based plants, and many companies are focusing on the use of commercial seaweed hydrocolloids (alginates, carrageenans and agar).

These phycocolloids present significant advantages. They are indeed already available commercially, and rely on seaweed species with well-established harvesting and cultivation routes. They can also present regulatory benefits, as their "*quantum satis*" authorization in foods facilitates their incorporation in the production of food-contact materials, or even edible packaging (Patel 2019). And they are also considered biodegradable.

Nevertheless, their cost can be relatively high (8-20€Kg for purified hydrocolloids) and several companies also investigate the possibility to use whole seaweed, co-products, or partially refined hydrocolloids.

The field of algae biomaterials exhibiting the highest activity is probably packaging and disposable tableware, with a multiplication of start-up companies in Europe, USA, Asia or Oceania (NotPla, B'Zeos, Kelpi, Biopac/Evoware, Loliware,…).

Most of these applications are based on their texturizing properties, and their ability to form gels and films, whose formulation and downstream treatments depend on the polysaccharide used. In particular, films can be obtained by casting/drying (mostly carrageenan or agar-based (Phan *et al.* 2005; Sedayu *et al.* 2019), but also alginates (Kontominas 2020; Senturk Parreidt *et al.* 2018)). Some materials (films and larger pieces of materials) can also be molded or wet-extruded (Schmidtchen *et al.* 2022).

But while packaging is often the main target, other types of materials can also be obtained. For examples, extrusion of alginate fibers has been used for decades in the pharmaceutical industry for wound dressings and haemostatic swabs (Chen *et al.* 2021), but are now being explored for the production of textile fibers. Industrial productions exist in China (SFM, Dezhou Hengfeng), but start-up companies are also entering this market (AlgiKnit).

3.8.2.3. New algae-based biomaterials obtained by chemical or biotechnological conversion

Another approach to convert algae into biomaterials is to convert their carbohydrates (polysaccharides after chemical or enzymatic hydrolysis, sugars, polyols, …) to biopolymers by biotechnological routes, although these developments are still mostly at an R&D stage. These approaches include fermentation to lactic acid and subsequent production of polylactic acid (PLA), or direct production of polyesters (PHA, PHBV) by microorganisms fed on algae-sugars. PHB polyesters can also be directly produced by certain cyanobacteria strains (Özcimenc *et al.* 2017).

Glucose-based algae polysaccharides (starch, cellulose, laminarin) are the most used to date for these conversions, as glucose is the most readily fermented/metabolized, but other sugars and polyols (galactose, mannitol, …) can be considered by selecting appropriate microorganism strains.

However, algae polysaccharides often present very complex structures and uncommon sugars, compared to land-based plants. As a consequence, a limited number of commercial enzymes active on seaweed polysaccharides are available, which may restrict large-scale production, and many yeasts/bacteria are not able to metabolize their sugars.

Examples of these approaches are illustrated in several European projects:

- PLA production from microalgae residues after lipid extraction (Eclipse project (Cordis 2023b))

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- PLA production from seaweed polysaccharides as for example from *Ulva* sp. starch (SeaBioPlas project (Cordis 2023c))
- PHA production by cyanobacteria grown in mixed microalgae/bacteria/cyanobacteria cultures fed on wastewater (InCover project (Cordis 2023a))

But start-up companies are also exploring this field, as for example Biotic in Israel, which targets the production of PHA/PHBV from microorganism fed on seaweed sugars (Ghosh *et al.* 2019).

3.8.2.4. Waste streams end effluents

As mentioned above, the biomaterials market is still in an early phase, with a very limited number of companies active at full-scale, and consequently, limited amounts of available co-products and effluents.

Many are also formulating seaweed ingredients from the hydrocolloids industry, which does not generate any specific streams beyond those already existing.

It should also be noted that companies developing algae-base materials are very much focused on using co-products, or re-using their own co-products for other materials, which will probably limit the available solid residues stream in this field in the future. However, they are likely to generate liquid effluents, especially if the chemical/biotech route further develops.

3.9. Emerging uses and markets

3.9.1. New biorefineries

Biorefinery routes are increasingly taken up by established companies, in a move to valorize their co-products, and increase the value generated from their raw materials. However, the development of new processes in existing installations can be challenging, and they may also lack experience in new markets, beyond their core business.

Some companies nevertheless invest in new production lines, and R&D capacities, to diversify their product ranges and use of co-products, as for example Algaia in France. Partnerships are also sought by many companies to valorize co-products, but increase logistical constraints (co-product stabilization and/or drying, transportation…).

In parallel, an increasing number of start-ups are emerging, and progressively moving to pilot and industrial-scale, by completely designing their equipment/installations to accommodate biorefinery processes.

Some of these new companies in Europe are (non-exhaustive list):

- Alginor (Norway)
- Oceanium (UK)
- Origin by Ocean (Finland)
- Vetik (Finland)

Interestingly, these new biorefinery companies are mostly located in Northern Europe, and working from seaweed.

But multiple initiatives also arise in Southern Europe around the biorefinery of microalgae, with a number of European projects (D-Factory, Sabana, multi-str3am, Scale, …) and platforms and associations like the Collaborative Lab for Biorefineries in Portugal.

While the number of operating biorefineries is still limited at this stage, their growth will necessarily trigger new uses of raw materials, new ingredients, and create emulation across the market.

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3.9.2. Water treatment

Water treatment is also another topic where algae will take up a growing share in the coming years. Microalgae use for water treatment (Mohsenpour *et al.* 2021; Valchev and Ribarova 2022) and effluents mitigation (Salazar *et al.* 2021) has been extensively studied and is increasingly explored at larger scale. This is well illustrated by Circalgae's sister project Realm, which combines greenhouses effluents treatment and microalgae production to generate sustainability and economic benefits for both parties.

Seaweed are less present in this field but new approaches like integrated multitrophic aquaculture at-sea or on-land (Buck *et al.* 2018; Shpigel 2013) are also growing.

While these concepts are still facing a number of challenges, including from a regulatory perspective when it comes to using the algae produced in effluents, they will definitely open up the way to new sources of raw materials, likely cheaper too, and new product developments. Additional work will also be required to fully assess their environmental benefits and the associated value.

3.9.3. Environmental services, carbon capture and climate-change mitigation

Over the last few years, the place of seaweed cultivation in a changing world, facing rising atmospheric CO_2 levels and global warming, has been very high on political and mediatic agendas and raised a lot of controversies (Gallagher *et al.* 2022; Krause-Jensen *et al.* 2018).

Seaweed can exhibit high productivity and are one of the main carbon sinks in the global ocean, both as biomass standing stock and as vectors of carbon export through detritus pathways (although depending on species and geographies) (Ould and Caldwell 2022; Sato *et al.* 2022). And they also provide ecosystem services (coast protection, nursery habitats,…) (Hasselström *et al.* 2018), contribute to coastal economies, and can be used for a wide variety of products (although this might in the end recycle a large part of the carbon to the atmosphere).

It then seems logical to consider the algae as a potential candidate for carbon sequestration and climate-change mitigation (Ould and Caldwell 2022). But there is still a significant amount of research needed to quantify those aspects, and fully understand the mechanisms involved, or cultivate them at the scale required for a significant impact on climate-change.

Still, algae cultivation can, and will, certainly contribute to these benefits. And Blue Carbon investments in the scale-up and optimization of technologies, as well as incentives for algae production, should also contribute to the supply of increased volumes of seaweed that will enter the seaweed biorefinery.

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4. Synthesis

4.1. Summary tables / graphs

It is very difficult to establish an exhaustive picture of the European algae industry. While some countries are publishing national statistics, a lot of data is still missing, or is scattered across many sources. Confidentiality aspects in a competitive market also limit communications from companies and volumes produced/processed and associated turnover.

The following tables are providing a summary of the information that we collected, supplemented when feasible with extrapolations based on our knowledge and industry interviews.

Table 25: Wild seaweed resources collected in Europe and their uses

Species	Approximative volume harvested (tons fresh weight)	Food and supplements	Feed	Colloids and polysaccharides	Bioactives, high value ingredients	Agriculture	Cosmetics	Biomaterials
Laminaria hyperborea	150,000-170,000			⬤			•	
Laminaria digitata	40,000-50,000	•		⬤		●	•	
Ascophyllum nodosum	65,000-75,000	•	●	•	•	●	•	
Hand-harvested kelp species (*Laminaria spp., Undaria pinnatifida, Saccharina latissima)*	500-1,000	●				●	●	
Fucus sp, *Himanthalia elongata*	2,500-5,000	●	•			●	•	
Palmaria palmata	500-1000	⬤					•	
Chondrus crispus / Mastocarpus stellatus	250-500	●		⬤			•	
Ulva sp.	100-200	●					•	
Ulva sp. (beach-cast/drifting)	5,000-10,000		●	•		●		•
Gelidium sp. (beach-cast/drifting + harvesting)	5,000-10,000			⬤			•	
Furcelaria lumbricalis (beach-cast/drifting + harvesting)	1,000-2,000			⬤	•		•	
Solieria sp. (beach-cast)	5,000-10,000		●			⬤		

Legend:

⬤	> 50%	●	20-50 %	•	< 20 %

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Table 26: Main seaweed resources cultivated in Europe and their uses

Species	Approximative volumes cultivated (tons fresh weight)	Food (+ supplements)	Feed	Colloids and polysaccharides	Bioactives and specialty ingredients	Agriculture	Cosmetics	Biomaterials	Others
Saccharina latissima	500-1,000	⬤	●				•	•	•
Alaria esculenta	200-500	⬤					•		
Ulva sp.	50-100	●	●	•	•		•	•	
Undaria pinnatifida	50-100	⬤			•		•		

Legend:

⬤	> 50%	●	20-50 %	•	< 20 %

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Table 27: Microalgae and cyanobacteria cultivated in autotrophic conditions in Europe and their uses

Species	Approximative volumes cultivated (tons dry weight)	Food / supplements	Feed / Aquafeed	Omega-3 oils	Phycobiliproteins	Carotenoids	Cosmetics	Agriculture	Others
Spirulina / Arthrospira sp.	140	⬤	•		•			•	
Chlorella spp.	80	⬤	•					•	•
Nannochloropsis spp.	20	●	●	●					
Haematococcus pluvialis	100	●	•			⬤			
Tysochrysis lutea	< 1		⬤						
Dunaliella salina	2 (+35 tons in Israel)	●	●			●			
Phaeodactylum tricornutum	4 (+ Israel)	●	●	●		●	•		
Tetraselmis spp.	5	●	⬤						
Porphyridium spp.	< 1				•		●		
Scenedesmus spp.			●					•	

Legend:

⬤	> 50%	●	20-50 %	•	< 20 %

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Table 28: Microalgae, cyanobacteria and Labyrinthulomycetes cultivated in heterotrophy in Europe and their uses

Species	Approximate Volumes cultivated (tons dry weight)	Food	Feed / Aquafeed	Omega-3 oils	Phycobiliproteins	Carotenoids	Cosmetics	Agriculture	Others
Chlorella spp.	10s tons	⬤	•						
Schizochytrium / Auranthiocytrium spp. *Crypthecodinium* spp.	< 1,000 tons			⬤					
Ulkenia sp.	100s tons ?			⬤					
Galdieria sulphuraria	*confidential*				⬤				

Legend:

⬤	> 50%	●	20-50 %	•	< 20 %

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Summary of the markets

Table 29: European biorefinery - main markets for seaweed/seaweed products produced or processed in Europe

Product	Estimated Volume (tons dw)	Estimated Market value (€ M)	Comments
Spirulina sp.	180	13-18	See section 2.2.3 Using an average price of € 75-100 / kg combining direct BtoC sales, and BtoB activities (average price in France at € 130 / kg)
Autotrophic *Chlorella* spp.	80	2-3	See section 2.2.2 Using an average price of € 30/kg
Haematococcus pluvialis and astaxanthin	120-150	24-30	Including Israel See section 2.2.2 and 3.4.3
Labyrinthulomycetes	-	-	*Almost no direct sales see Omega-3 oils*
Other microalgae for food, feed and aquafeed applications	20-30	4-6	Using an average price of € 200/kg
Seaweed for food applications	500-700	12-20	See section 3.1.2.1 Including only first-sale and first transformation products
Seaweed for feed applications	*Not determined*	*Not determined*	See Section 3.2
Alginates	12,000	150	See section 3.3.1.3
Carrageenan	7,500	110	See section 3.3.2.3
Agar	1,250	35	See section 3.3.3.3
Furcellaran	75-100	0.7	See section 3.3.4.1
Other polysaccharides	*Not determined*	*Not determined*	See section 3.3.4 Limited volumes and markets for purified molecules
Fucoxanthin	*Not determined*	*Not determined*	See section 3.4.4.4. Limited market, but growing.
Phycocyanin	7.5-15	3.75-7.5	See section 3.5.1.4 Assumption that it is mostly produced from imported *Spirulina*
Phycoerythrin	*Not determined*	*Not determined*	See section 3.5.2 Limited market to date
Omega-3 oils	500	50	See sections 2.3 and 3.6
Cosmetic extracts	*Not determined*	50-100	See section 3.7.2 Small volumes of seaweed processed but higher added value.
Agricultural extracts	*Not determined*	200	See section 3.7.1
Feed extracts	*Not determined*	*Not determined*	See section 3.7.3 Limited market to date.
Biomaterials	*Not determined*	*Not determined*	See section 3.8 Limited market to date.

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Table 30: Main co-products identified in European algae biorefinery

Industry	Co-product stream	Co-product type	Characteristics (Dry matter, …)	Approximate "Algae" material content (tons dry weight)	Composition (compounds of interest)	Current fate	Constraints
Alginates	Lixiviation effluent	Liquid effluent	High dilution (~20g/L) Acidic (pH ~4)	14,500	- Mannitol, laminarin and fucoidans/FCSP (40-50%) - Minerals (40-50%) - Proteins (~5%) - Polyphenols (minor)	Mostly waste water treatment Some refining (UF, …) for production of polysaccharides	- Large volumes / low concentration - Potential partial desulfation of fucoidans - traces of formaldehyde - heavy metals and arsenic
Alginates	Filtration effluent	Liquid effluent	High dilution Alkaline (pH ~10)	6,000	- Minerals (up to 80%) - Soluble Proteins - Carbohydrates	Waste water treatment	- Low organic content - Proteins possibly denaturated
Alginates	Cellulosic cake	Solid residue	25% dw	12,500 (~20,000 including mixed perlite)	- Polysaccharides ~60% (cellulose, alginates, insoluble FCSP) - Insoluble proteins (15-25%) - Minerals (15-25%)	Agricultural spreading + limited sales	- High insoluble perlite content (30-50%)
Alginates	Sewage sludge	Solid residue		9,000		Destruction or agricultural spreading	- Waste status - Arsenic and heavy metals
Carrageenans	Perlite-free residue	Solid residue	20-30% dw	10,000 (+ 10,000 perlite mixed or not)	- cellulose - Residual polysaccharides / carrageenan - Insoluble aromatics - Insoluble proteins (low content)	Biogas production Incineration	Cadmium content can limit downstream applications (biogas)
Carrageenans	Filtration cake	Solid residue	20-30% dw		- Mostly cellulose - Residual polysaccharides / carrageenan - Insoluble aromatics - Insoluble proteins (low content)	Agricultural applications	- Very high insoluble perlite content (Up to > 80% Mineral content) - can contain non-seaweed cellulose (filtration aid)

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Industry	Co-product stream	Co-product type	Characteristics (Dry matter, …)	Approximate "Algae" material content (tons dry weight)	Composition (compounds of interest)	Current fate	Constraints
Food-grade seaweed	Harvesting and cleaning residues	Solid residue	12-20% dw	several dozen tons	Depends on species	Returned to sea during harvesting or treated as waste	- Poor quality (degraded, epiphytes, shells, …) - very dispersed (in time and space)
Food-grade seaweed	Grinding / Milling residues (fine particles)	Solid residue	90% dw	tons	Depends on species	Sold at significant discount	- fine particles not directly usable for food applications - - often inadequate for extraction (complex solid / liquid separation)
Carrageenans	Gel-press effluents and vinasses	Liquid effluent	High dilution	6,000	- depends on raw materials (not segregated) - high mineral content - Soluble proteins - Small metabolites - Pigments	Waste water treatment	- Large volumes / low concentration - Proteins can be denaturated by the alkaline treatment (+ alcohol processing)
Carrageenans	Sewage sludge	Solid residue		> 10,000		Biogas Incineration	
Agar	(*Gracilaria*) Filtration cake	Solid residue	20-30% dw	1,750 (+ equivalent amount of perlite)	- cellulose - Residual polysaccharides / agar - Insoluble proteins (low content)	Composted for agriculture	- High insoluble perlite content - potentially degraded by alkaline treatment
Agar	(*Gelidium*) seaweed residues	Solid residue	20% dw	3,500	- cellulose - Residual polysaccharides / agar - Proteins	Composted for agriculture	
Agar	Liquid effluents	Liquid effluent	High dilution	3,000	- Minerals - Proteins - Pigments - Small metabolites (floridoside, …)	Waste water treatment	- Large volumes / Low concentration Low organic content - Proteins possibly denaturated by alkaline treatment

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Industry	Co-product stream	Co-product type	Characteristics (Dry matter, …)	Approximate "Algae" material content (tons dry weight)	Composition (compounds of interest)	Current fate	Constraints
Agar	Sewage sludge	Solid residue		?		Waste	
Furcellarans	Filtered seaweed	Solid residue		100-200	- cellulose - Residual polysaccharides	?	
Furcellarans	Liquid effluents	Liquid effluent	High dilution	100	- Depend on purification process - Minerals - Proteins - Pigments - Small metabolites	Waste	- Low concentration - Low organic content
Ulvans (purified)				Non-significant			
Fucoidans (purified)				Limited, and often integrated with alginates processing			
Laminarin (purified)				Non-significant			
Paramylon				No co-products (whole cells)			
Astaxanthin (*Haematococcus*)	Residual biomass	Solid residue	Depending on process ($scCO_2$, solvent)	90-130	- fibers - proteins - residual lipids and carotenoids	Feed	
Phycocyanin	Residual biomass	Solid residue		3-10	- Proteins (60%) - Lipids (low) - Carbohydrates	Feed	
Phycocyanin	Liquid effluents	Liquid effluent		300			- Low organic content - Very high mineral content (buffer solutions)
Omega-3	Residual biomass	Solid residue			- Carbohydrates - Proteins - Residual lipids	Feed	
Cosmetic extracts		Solid residues		Small volumes	Extremely diverse	Waste / composting	- Highly dispersed over time and geographies

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Industry	**Co-product stream**	**Co-product type**	**Characteristics** (Dry matter, …)	**Approximate "Algae" material content** (tons dry weight)	**Composition** (compounds of interest)	**Current fate**	**Constraints**
Agriculture extracts / biostimulants	Extraction residues	Solid residues	20-30% MS	Up to several thousand tons	- cellulose - insoluble carbohydrates (alginates, …) - insoluble proteins	Agriculture	- Composition might be significantly different depending on processes applied - not stabilized / dried unless already re-used
Agriculture extracts / biostimulants	Discarded raw materials	Fresh seaweed (e.g. *Fucus* sp)		Hundreds of tons	- carbohydrates (alginates, fucoidans,…) - polyphenols - minerals	Agriculture	- not stabilized / dried

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4.2. Analysis

4.2.1. Gaps

4.2.1.1. Knowledge gaps on volumes and quality of co-products and liquid effluents streams

Many companies, and particularly the ones processing large quantities of algae, are well aware of the volumes of solid co-products produced and have implemented tools to handle them. They have also already explored the composition of their solid co-products, and possible ways to valorize them. This valorization at industrial scale often remains limited to direct spreading on agricultural fields, composting, or possibly biogas production, due to a number of constraints. It usually provides limited economic benefits, beyond the reduction of cost of not having to have them incinerated/treated as waste, and these co-products still represent a largely untapped resource for the development of new biorefineries.

However, in-depth knowledge of the volumes and composition of liquid effluents remains more limited. A particular focus is put on recycling water (and possibly chemicals) as much as possible to reduce the impact, but liquid effluents are in most cases directly sent to a water-treatment facility (on-site for large companies, or in shared installations with neighboring companies, while smaller companies are often discarding the effluents, after a preliminary treatment, to municipal waste waters).

While this is true for liquid effluents from the (macro)algae processing, very similar questions can be raised for cultivation effluents (spent cultivation medium). While these cultivation media tend to be recycled to a maximum extent, they are in most cases treated as waste as a last resort, while they might still contain various compounds of interest (Liu *et al.* 2016).

Confidentiality on volumes and composition of effluents (chemicals or contaminants present, composition information disclosure that may provide information on confidential process steps, …) can also be a limiting factor for potential downstream use by third parties.

4.2.1.2. Presence of contaminants and undesirable processing aids

A number of companies working on the valorization of their side-streams also report challenges related to the presence of contaminants, which might be hindering downstream uses.

It can be the case for example for arsenic, especially for brown seaweed species, which can be present in non-negligible amounts in a number of side-streams, while many potential products that could be produced from this side-streams are covered by regulations restricting arsenic content.

It can also be the case for cadmium for example, in brown or red seaweed, which can limit downstream applications, as illustrated by the difficulties to use solid residues from carrageenan production for biogas production (section 3.3.2).

Residues of chemicals, as well as potential degradation of compounds of interest during the chemical process (e.g.acid or alkaline treatment), should also be considered.

Lastly, a number of processing aids can also generate difficulties to valorize co-products. The most common example is the use of mineral filtration aids (perlite, celite, …), which are broadly used to improve the filtration step after extraction of colloids and extracts. While inert, these filtration aid remain mixed with the solid co-products, reducing the concentration of the compound of interest in the residue. As they are not soluble, they can also generate numerous challenges during the downstream processing, either for further extraction or for direct uses (incompatible with a number of processes as extrusion, etc.).

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4.2.1.3. Presence of water – consequences for preservation and transportation

Another question raised when it comes to the valorization of the co-products, is their form.

Liquid effluents are usually highly diluted and have to be processed on site, at least to some extent. But solid residues are also in wet form in most cases (typically 20-30% dry weight) and removing this water represents a significant investment in terms of both energy and equipment.

Some co-products could be directly treated onsite for further valorization, but they often require transportation to partner sites, and transportation of wet products is costly. In parallel, leaving the products in wet form, until the quantity is sufficient for transport and further processing, raises additional challenges for preservation.

Some companies also introduced stabilization steps, such as composting, but this results in a significant loss of organic matter and compounds of interest, and the composted products are mostly used for agricultural applications.

4.2.1.4. Fragmentation of the supply of co-products

While a few industrial players are generating significant amounts of co-product streams (notably the hydrocolloids producers), the EU algae market is heavily fragmented between hundreds of companies, often SMEs, spread over the whole territory.

While many of them generate co-products, the volumes are often limited, and may also be themselves fragmented, with several species processed within a single company, for example in the food or cosmetics industry. The co-products are also usually not segregated to date (as no specific valorization routes are in place) and the co-products are usually mixtures of different species.

4.2.1.5. Challenges related to market access and market size

Biorefinery of algae can also be challenging for companies dedicated to a single ingredient or ingredient range. Beyond technical aspects of developing new processes and processing lines, the new products generated from co-product streams can be new for the company.

Companies may lack experience and market access to sell these ingredients/products in new markets, beyond their core business. For instance, expanding into plant biostimulants and packaging biomaterials, may not be straightforward for a food ingredients or cosmetic ingredients company. Beyond the commercial and marketing aspects related to market access, other parameters should also be taken into account as for example different regulatory frameworks, new characterization requirements, technical support needs, etc …

Finding an adequate balance between the different product streams of a biorefinery is also challenging. Co-products from small-sized processing facilities designed for high-value bioactives, may not be sufficient to develop a new product line for applications markets requiring large volumes of ingredients (feed, materials, …). Inversely, some bioactives value is intricately linked with their scarcity. Producing them at large-scale from a broadly available industrial co-product is obviously attractive, but implies further market development, and will also inevitably impact the selling price once their available in larger quantities.

4.2.1.6. A regulatory landscape still not always appropriate

Algae are still quite new in the European economic and regulatory landscape.

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While their production and use (e.g. in Food, feed, agriculture, …) is covered by an extensive range of regulations, these regulations are often sectorial and did not specifically consider algae. They can also vary significantly from one country to the other.

While this could be seen as a quite open field, it also sometimes induces limitations (e.g. inappropriate limits on contaminants), or leaves “grey zones” creating regulatory risks that companies are not willing to take.

The use of liquid effluents for algae cultivation, and the allowed downstream uses of the biomass produced, is also a case that warrants considering evolutions of the regulatory framework, as it would make sense from both environmental and economic aspects (see section 3.9.2).

Also, while the “end-of-waste” status is recognized under the Waste Framework Directive 2008/98 for specific applications and under strict conditions, there is still a very limited list of opportunities to valorize certain waste, although things are changing as illustrated by the case of sewage sludge (Capodaglio 2023).

A number of questions are also raised on the consequences of using “waste” CO_2 from various industries for algae production, and its consequences in terms of quality and regulatory status on the product. The origin of this CO_2 (biogenic, fossil, mineral, …) is also a topic currently discussed in the context of European standardization (CEN/TC 454 - Algae and algae products).

4.2.1.7. Uncertainties on future supply and price of seaweed

The crisis faced by the agar industry in 2016-2017 (section 3.3.3) is a good illustration of how sensitive an industry can be to fluctuations on raw material supply. In this case, quotas related to resource management were involved, but other factors are increasingly influencing raw materials availability and prices.

For example, over recent years, supply chain disruptions related to COVID-19 as well as a number of outbreaks of epiphytes and diseases have been impacting the production of tropical red seaweed used in the carrageenan industry. The latter have been associated with global warming, with increasing water temperatures, and possibly reduced salinity (Ward *et al.* 2022).

Closer to us, significant decline and move northwards of South European kelp forests have been identified, and led to OSPAR recommendation 2021/05 on furthering the protection and conservation of kelp forest habitat. They are related to a number of factors, including anthropogenic water quality changes, but warming water temperatures are putting an additional threat on these cold-water species (de Bettignies T. *et al.* 2021). While the main seaweed fields harvested by the algae industry have not seen a significant impact to date, a particular attention is required.

While no overly pessimistic assumptions should be made, these potential constraints on the supply, particularly related to anthropic impacts and global warming, should be taken into consideration. And in any case, proper resource monitoring and management strategies should be implemented to ensure sustainable management of standing stocks and ecosystems. This is generally the case in Europe, although usually handled directly at national or even regional level, with an absence of European-wide strategy and policies.

These constraints on seaweed supply also have a significant impact on price fluctuations for raw materials. Over the last few years, seaweed buyers have been facing significant prices increases (50 to 150%) for many species, whether harvested or cultivated, and produced in Europe or imported. This will also contribute to reshaping the algae industry.

4.2.1.8. Supply of species of interest and reduction of production costs

While seaweed cultivation is developing across Europe, the cultivated species are often not the ones facing the highest market demand.

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This is true for food applications, where some of the most sought-after species are challenging to cultivate, especially at sea (*Porphyra* sp, *Palmaria palmata*, …) or not allowed for cultivation in Europe (*Undaria pinnatifida*).

Concerning the species processed in larger volumes for the hydrocolloid industry, some are also not properly domesticated (*Gelidium* sp), not suitable for cultivation in European cold waters (*Eucheuma* sp, *Kappaphycus* sp), or not sufficiently productive and too costly when cultivated compared to harvesting from the wild (*Laminaria digitata* or *Laminaria hyperborea*).

Similarly, while EU microalgae, cyanobacteria and Labyrinthulomycetes production keeps progressing, with an increasing number of industrial players, these raw materials keep facing competition from countries with lower production cost.

For all those species, innovation at all levels (biology and ecophysiology, strain selection, cultivation parameters, infrastructure and equipment costs, downstream processing, …) will be required to reduce production costs, and offer a broader range of species and algae quality to match industrial needs.

4.2.2. Synergies and opportunities

4.2.2.1. A global move towards a Blue and Circular Bioeconomy

“We live in a world of limited resources. Global challenges like climate change, land and ecosystem degradation, coupled with a growing population force us to seek new ways of producing and consuming that respect the ecological boundaries of our planet. At the same time, the need to achieve sustainability constitutes a strong incentive to modernize our industries and to reinforce Europe’s position in a highly competitive global economy, thus ensuring the prosperity of its citizens. To tackle these challenges, we must improve and innovate the way we produce and consume food, products and materials within healthy ecosystems through a sustainable bioeconomy.” (European Commission 2018)

“The EU Algae Initiative will aim to unlock the algae potential in Europe by increasing sustainable production, ensuring safe consumption and boosting innovative use of algae and algae-based products. This will help to achieve the objectives of the European Green Deal, the transition to a green, circular self-sufficient and carbon neutral EU, post Covid-19 recovery and mitigation of economic crisis resulted by Russia’s military aggression against Ukraine.” (European Commission 2022)

These two citations from the European Commission are a perfect illustration of the importance and role that the biorefinery of algae can play in Europe, and the political and strategic support behind it.

But beyond political aspects, it is also a part of a societal move towards a more circular bioeconomy and a shift towards aquatic resources.

Many industries are increasingly considering marine and aquatic resources as alternative to fossil-based resources and traditional aquacultural resources, generating a new demand. And biorefining and full valorization of their raw materials is both an answer to an ever-increasing focus on Environmental and Social Responsibility, and an economic requirement in a context of increasing raw materials and processing (equipment, energy, …) costs.

Consumers are also increasingly eager to make a shift towards a more sustainable economy. Co-products are not a taboo or considered as waste anymore. Use of co-products and up-cycling has even become a selling argument, even in the cosmetics industry. This may not always translate in a willingness to pay (yet), but is definitely

4.2.2.2. A changing normative and regulatory framework

While current regulations are not always appropriate for algae and for bioeconomy/biorefinery in general, new regulations progressively take algae into account, and lift uncertainties for the industry.

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One could cite, for instance, the recent Regulation 2009/1009 for fertilising products, which provides a framework for (often algae-based) plant biostimulants, or Regulation 2023/121 which allows the use of new fertilizing sources for land-based cultivation of organic algae. The EU Seaweed Initiative also proposed, starting in 2023, to assess the market potential, efficiency and safety of algae-based materials when used in fertilising products and the need to amend Regulation (EU) 2019/1009 on EU fertilising products to include more specifically algae-based materials (European Commission 2022).

The EU Initiative also proposes to develop harmonized EU-wide strategies on spatial planning, licensing and access to marine space to support seaweed cultivation. Harmonized regulations on contaminants for edible algae are also currently considered.

In parallel, the European standardization committee CEN/TC 454 'Algae and algae products' was created in 2017. Numerous standards and technical reports are published or being elaborated in order to support broader and harmonized terminologies, methods and quality assessments across the industry.

4.2.2.3. A broad and diversified pool of co-products and effluents

As discussed in the previous section, the algae industry across Europe is relatively fragmented, with many companies involved (quite often relatively small ones), and a diversity of species processes.

Nevertheless, a number of solid co-products and liquid effluents available in significant quantities have been identified across the algae industries (Table 30) and could be exploited for new biorefinery approaches.

Additional effluents, as cultivation media (microalgae, Spirulina, Labyrunthulomycetes or land-based seaweed cultivation), should also be considered.

Further data collection on their composition, variability, and current stabilization, treatment and valorization pathways, will be required in order to maximize their potential value and orient future research on biorefining strategies and processes.

Also, interactions between algae processors could be sought in order to identify local opportunities to aggregate by-products in regions where algae industry is strong (Brittany, Ireland, …), and share downstream treatment or processing facilities (drying, …).

4.2.2.4. Technical innovation: optimized harvesting and cultivation targeting the biorefinery

Land-based production of algae, particularly in closed systems (microalgae, cyanobacteria, Labyrinthulomycetes) is also an efficient way to control algae composition. Beyond improvements in overall productivity and reduction of productions costs, optimization of strain selection and cultivation parameters should allow the production of biomass with optimized composition for downstream biorefinery. It should not only focus on maximizing the output of one specific constituent of the biomass, but also the content and accessibility of co-products.

Similarly, increased understanding of geographical and seasonal variations, as well as optimization of harvesting and cultivation practices, should allow a better valorization of seaweed ingredients and by-products. This is already happening, with a number of companies selecting geographical origin of seaweed and harvesting period to optimize composition (higher content in targeted molecules, lower level of contaminants, …). However, it can still be extended to a broader range of species, and optimized for improved co-products valorization. It should nevertheless be articulated with harvesting regulations and preservation of ecosystems and seaweed biomass recovery.

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4.2.2.5. Technical innovation: Process improvements to improve co-products usage and value

One of the potential routes to full algae biorefinery is to completely (re)design the process to preserve the quality of the different co-products and streams, and facilitate their downstream processing. Novel extraction technologies (preferably green and low-energy technologies) are one of the enablers of such process revisions that would allow a more efficient biorefinery of algae.

While very interesting from a theoretical point of view, this is not always simple to implement. One the main challenges of this approach is that it usually reduces the yields of the main product targeted. This could be compensated by novel value generation from the by-products, but may not be as straightforward, when new products require market development, while the first one is already established. A second challenge is that completely new processes can be difficult to fit in an existing factory where heavy equipment are in place and designed for a specific process. Therefore, such an approach of fully redesigned process fits well with the establishment of start-up companies covering multiple markets, or with the construction of new factories that will allow diversification of product ranges.

Alternatively, optimization of specific processing steps can be implemented in existing plants in order to improve handling and processing of specific by-products, or even to allow their industrial valorization.

For example, new green pre-treatments can be key to enabling easier extraction of compounds of interest, preserving co-products quality by allowing less drastic processes, or even generating new interesting by-products. This is also the case with a number of current industries adding a preliminary extraction step before re-injecting the raw material in their standard process.

Integration of new technologies for specific processing steps can also be valuable. As mentioned earlier (Table 30), the use of mineral filtration aids is generalized across the algae industry, but has significant consequences on the possibilities of reusing or processing the solid co-products. Alternative filtration or separation technologies, or new extraction technologies modifying the structure and behavior of the algae products to be separated, can open up new opportunities for the use of these co-products.

4.2.2.6. Industrial synergies

Biorefinery is often a question of optimizing product streams handling and processing, and integrating multidisciplinary approaches. As discussed earlier, it can also be challenging for companies lacking experience and human resources in specific markets or processes.

One option to raise barriers can be collaboration with other industrial players. While stabilization and transportation of co-products can be a challenge, they can be optimized to allow collaborations with companies located in a reasonable area around the co-product production facility. Improved communication and sharing of knowledge/best practices can only be beneficial to the development of such a collaboration network, as would be an improved understanding and mapping of co-products streams and composition.

New companies or cooperatives dedicated to the collection, processing and recovery of these by-products towards may be another solution. The challenge here is to find a win-win organization for all stakeholders.

Integrated biorefineries combining different companies are also developing. Most of them were initially based on agricultural/forestry resources, but many of them progressively integrate algae resources. And with future developments of the algae industry, new algae campuses could emerge, either regrouping various companies or pooling of equipment available for the stakeholders.

To complete this analysis and go deeper in the gap analysis of the algae derived market in Europe, the Circalcae document 5.1 provides an overview of a comprehensive market related to the European and international algae industry. In particular It highlights the strengths, weaknesses, opportunities, and threats within the algae market, and identifying critical gaps that need to be addressed for the industry to thrive and contribute to sustainability and economic growth in Europe.

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