GENIALG

GENETIC DIVERSITY EXPLOITATION FOR INNOVATIVE MACRO-ALGAL BIOREFINERY

BIOREFINERY MANUAL

BENEFITS AND SUSTAINABILITY OF SEAWEED BIOREFINERY

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INTRODUCTION

Marine biomass has the potential to offer a wide range of biobased products. Generating these products in an economically feasible way requires a biorefinery approach.

A biorefinery is a set of cascading technological operations used for sustainably processing biomass into a spectrum of bio-based products.

Seaweed biorefinery is the complete process of refining sustainably cultivated or wild harvested seaweed biomass into value-added end products. Seaweed is sustainably converted into a spectrum of valuable substances which can be used for food, animal feeds, pharmaceuticals, fertilisers, aquaculture, biofuels, nutraceuticals, cosmetics, bioremediation, biopolymers and bio-based chemicals, to name but a few!

This manual is based on outputs and insights from the EU-funded **GENIALG** project, whose overall objective was to make seaweed biomass production more economically and environmentally sustainable by designing high-yielding seaweed cultivation systems that optimise the crops for biorefinery. **GENIALG** focused on seaweed biorefinery of *Ulva* spp. and *Saccharina latissima*.

Seaweed Biorefinery

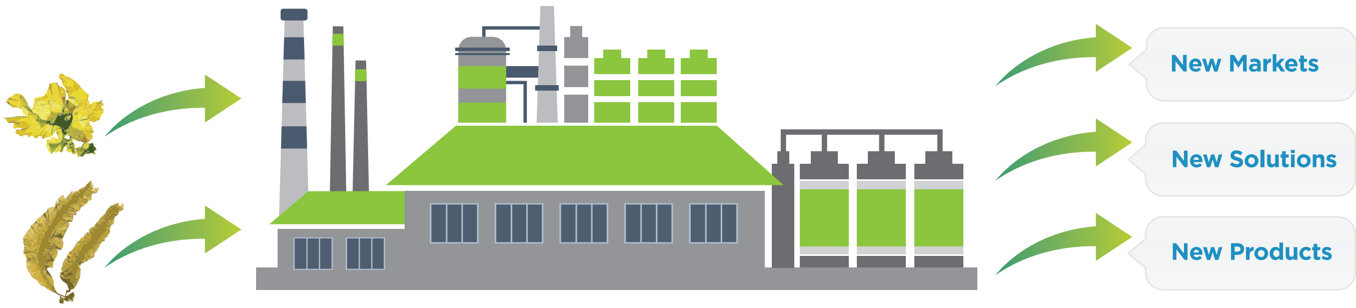

Figure 1 GENIALG seaweed biorefinery of *Ulva* spp. and *Saccharina latissima*. Graphic designed by AquaTT

CONTEXT

Seaweed cultivation and industry in Europe

In comparison to the extensive seaweed farms of Asia, seaweed aquaculture in Europe is still in its infancy, with most activity involving harvesting and exploiting natural populations for the colloid and plant biostimulants industry. Each year, approximately 250,000 tonnes fresh weight (FW) of European seaweed is collected from wild populations with a trade value between €50 and €100 per ton FW for brown algae and more than €1,400 per ton FW for smaller total amounts of *Ulva* and edible red algae.

European countries with seaweed cultivation include Norway, Ireland, France, Spain, Denmark, Portugal, United Kingdom, Germany, the Netherlands, Sweden and Belgium. Seaweed farms range from established, small production, to pilot/ research demonstration scale.[1]

A report[2] published by PEGASUS in 2019 provided an estimate of European seaweed aquaculture of 1,450 tonnes and market value of approximately €237,000 (based on FAO data). Discussions with industry contacts and collation of various non-FAO datasets suggest the production of cultivated seaweed biomass in Europe could be closer to 500 wet tonnes in any one year.

Norway is Europe's top producer of seaweed with more than 120,000 fresh tonnes from wild harvesting of kelps and rockweed, and is the only country producing in the hundreds of tonnes range by cultivation. Industries elsewhere in Europe are typically in the 10-200 tonne range.[3]

France is Europe's second largest seaweed producer, with 55,000 to 65,000 wet tonnes of wild and up to 150 wet tonnes of cultivated seaweed harvested recorded in 2019.[4]

Global value of seaweed industry

32 million metric tonnes of seaweed collected and traded in 2018, valued at 8 billion US.[5]

The Americas and Europe contributed, respectively, 1.4 percent and 0.8 percent of world seaweed production in 2019. Seaweed production in these two regions was primarily fulfilled by wild collection, and cultivation only accounted for 4.7 percent and 3.9 percent of total seaweed production, respectively.[5]

Drivers for increasing demand in seaweed biomass

As an important part of the global biobased economy, demand for seaweed biomass is driven by:

- Popularisation of using seaweed ingredients in foods and products for health and wellbeing
- Increasing global population
- Increasing demand in proteins from alternative sources/crops
- Increased competition for land to produce food/ limitations of land for agriculture
- Seeking alternatives to high greenhouse gas practices associated with traditional agriculture
- Shift towards more sustainable industries

Overview of seaweeds' key components

Commercially grown seaweed species are rich sources of commercially interesting compounds. This manual focusses on two European seaweed (macroalgae) species, *Saccharina latissima* (sugar kelp) and *Ulva* spp. (sea lettuce).

Ulva is currently used as an edible food or for animal feed and its extraction provides many products, including soluble extracts used as plant biostimulants and feed additives rich in minerals and fibers, as well as solid material rich in polysaccharides such as ulvan. Unlike other anionic polysaccharides from brown and red seaweeds, Ulvan is not extracted as a single ingredient.

On the contrary, many compounds from kelps are already exploited and commercialised or are under development:

- **Alginate** is currently the main target compound. It is an acidic polysaccharide with thickening and jellifying properties, widely used in everyday products in the food sector, textile industry, cosmetics, and pharmaceutical products such as plasters and stomach antacids.
- **Fucans** or **Fucose-Containing Sulphated Polysaccharides** display well-documented promising biological activities and some commercial products are sold in Asia, Australia, Norway and France.
- **Laminarin** is a small glucose polymer with applications in plant defence stimulation, animal and human care.
- **Fucoxanthin** is a carotenoid pigment also found in diatom microalgae with many biological activities under study, including anticancer activity.
- **Mannitol** is a sugar-alcohol, a small molecule already used in medicine and as food additive (seaweeds not being the major source of mannitol so far).
- **Phlorotannins** are a family of seaweed-specific tannins (phenolic polymers) displaying many biological activities, presently valorized in the cosmetic and well-being sector.

It is interesting to note that both *Saccharina latissima* and *Ulva* species display a nutritionally interesting lipid content, being rich in biologically active lipids, including poly-unsaturated fatty acids such as omega-3.

Figure 2 GENIALG's focus seaweed species. Graphic designed by AquaTT.

ULVA

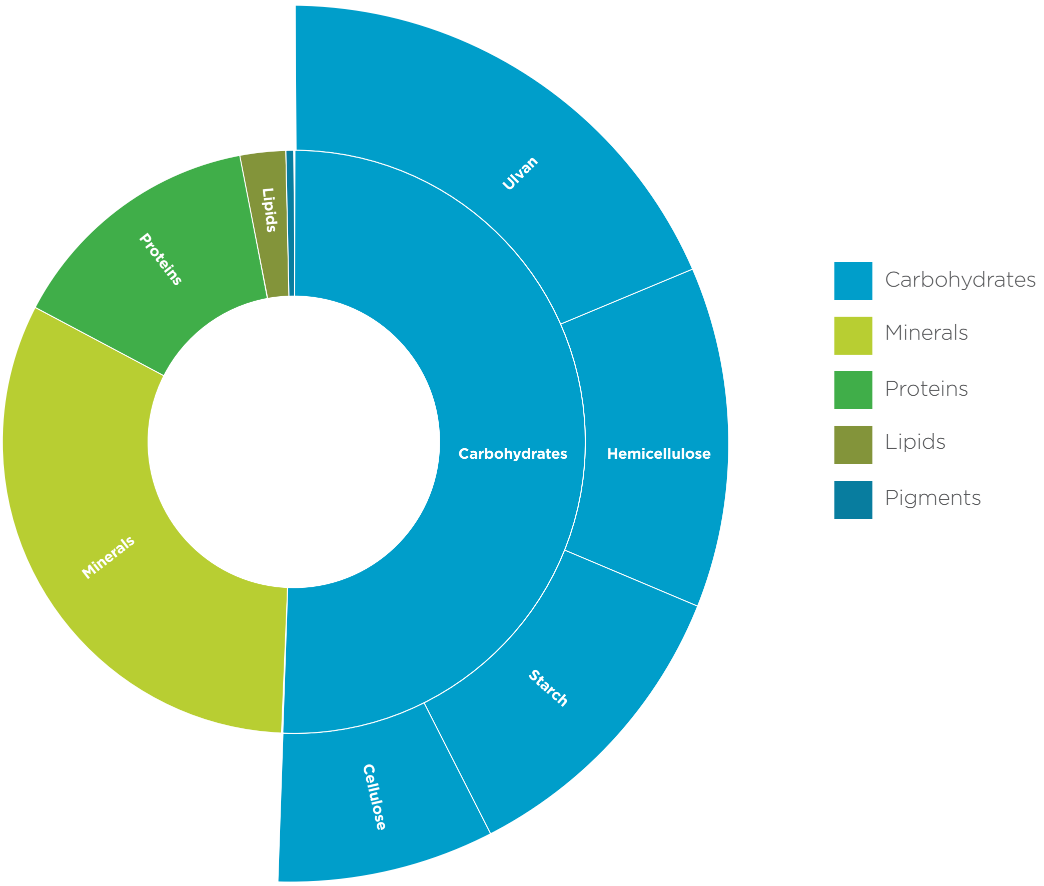

Figure 3 Average biochemical composition of sea lettuce (*Ulva* spp.)

SACCHARINA

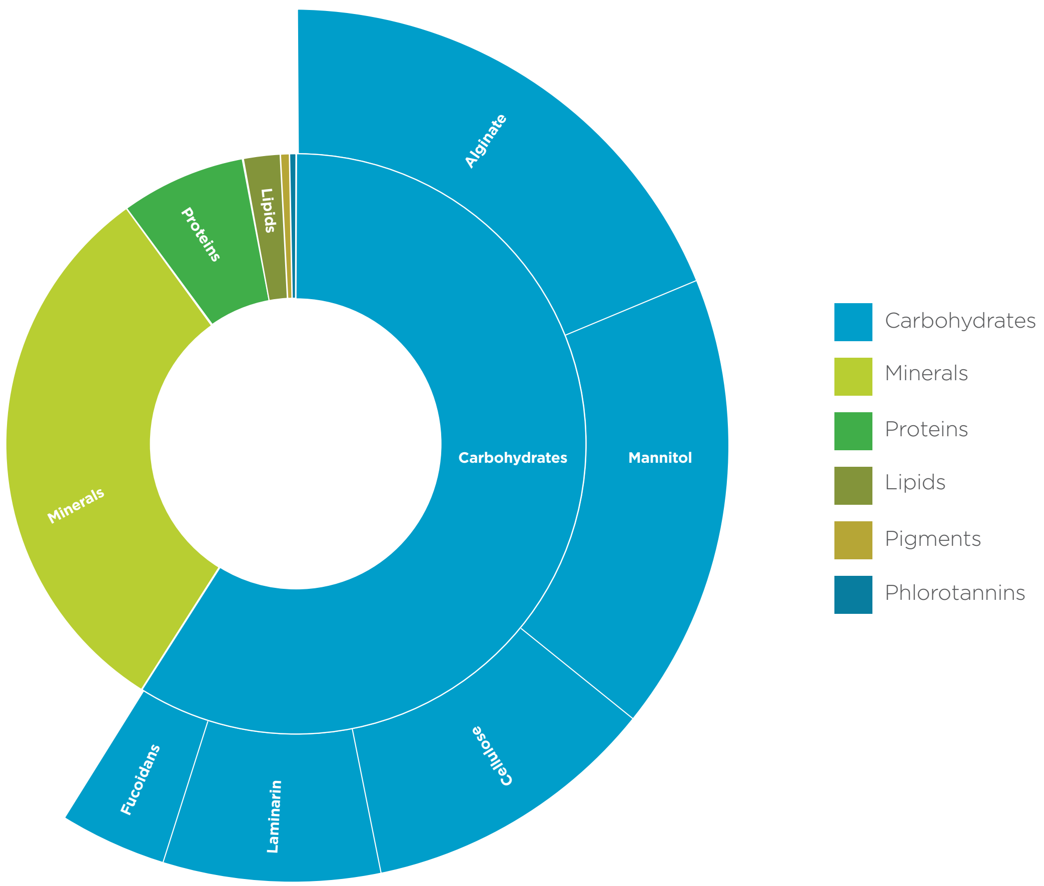

Figure 4 Average biochemical composition of sugar kelp (*Saccharina latissima*)

Current and future applications

The food sector is currently the main application of seaweeds, where seaweeds are eaten as sea vegetables, or used as ingredients to change the texture or enhance the taste of a product. The sugar polymer alginate is for example found in dairy products.

Seaweed useage is also widespread in human health and wellbeing, with dietary supplements, care products such as toothpaste, or biomedical applications such as plasters among the numerous applications. Many cosmetic products also contain seaweed ingredients, including alginates.

Seaweed products are also found in the animal nutrition, health and wellbeing sector. In aquaculture, seaweeds are used as feed supplement for fishes and shrimps, but products have also been developed specifically for pork, ruminants and poultry farms.

Seaweeds have long been used in coastal areas for soil fertilization, which is still the case. As well as this direct use of seaweed biomass, a range of seaweed-derived products are also used for growth stimulation, stress tolerance, and plant defence boosters.

The growth potential of these markets is equally important, and we have already witnessed the development of novel seaweed applications such as in the material sector, for paints and bioplastics. Due to the well-documented and promising biological activities of many seaweed components, we can expect to see development of pharmaceuticals of algal origin, as shown recently in China.[6]

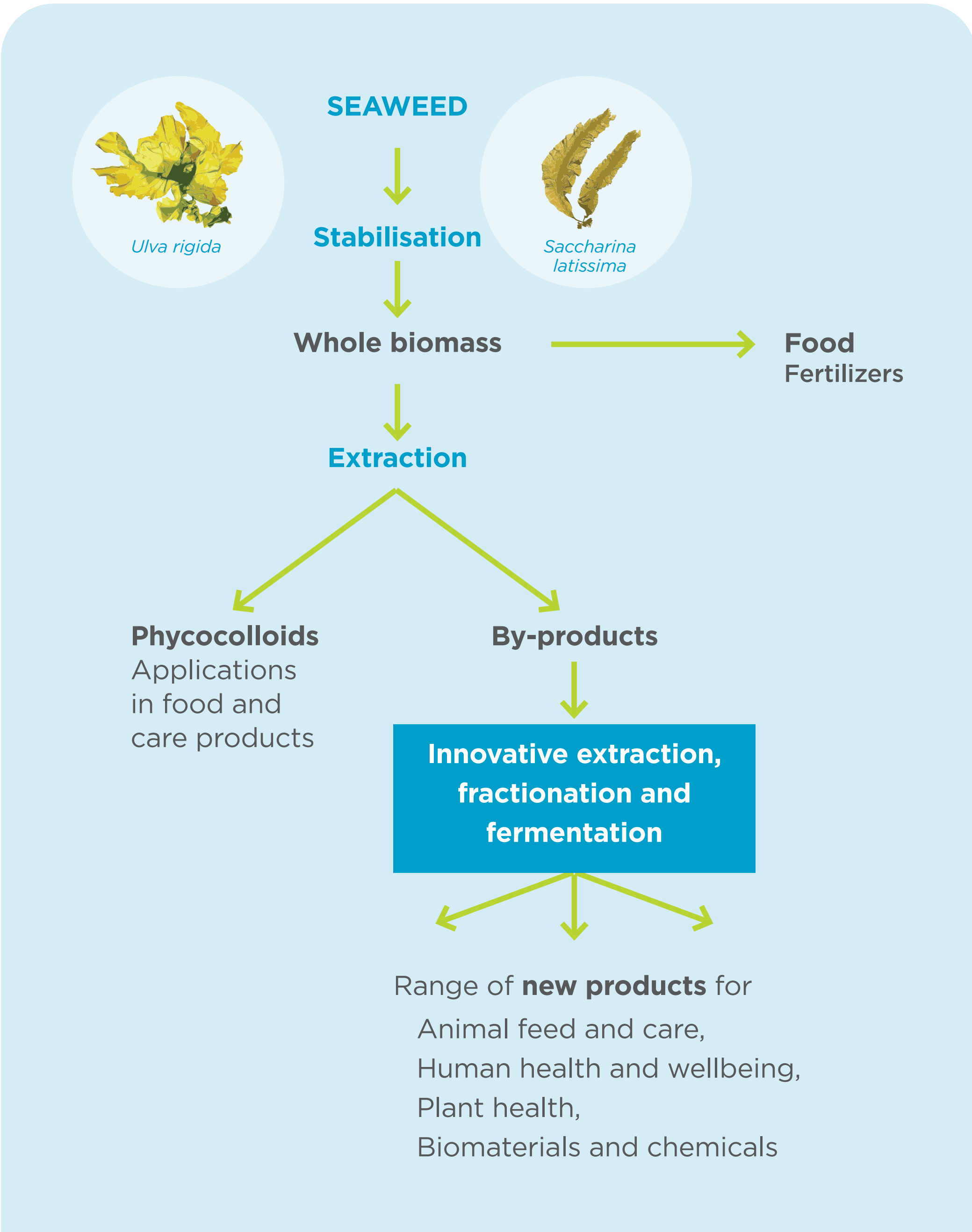

Figure 5 Processes and products of seaweed biorefinery. Graphic designed by AquaTT.

METHODOLOGY

Biorefinery set up and success are highly dependent on the context (geographical, industrial, biomass availability).

It is important to identify the first product on which biorefinery should be based, together with its extraction process. Minor modifications of the initial process can then be implemented in order to extract secondary compounds from by- or co-products.

Seaweed Biorefinery Process

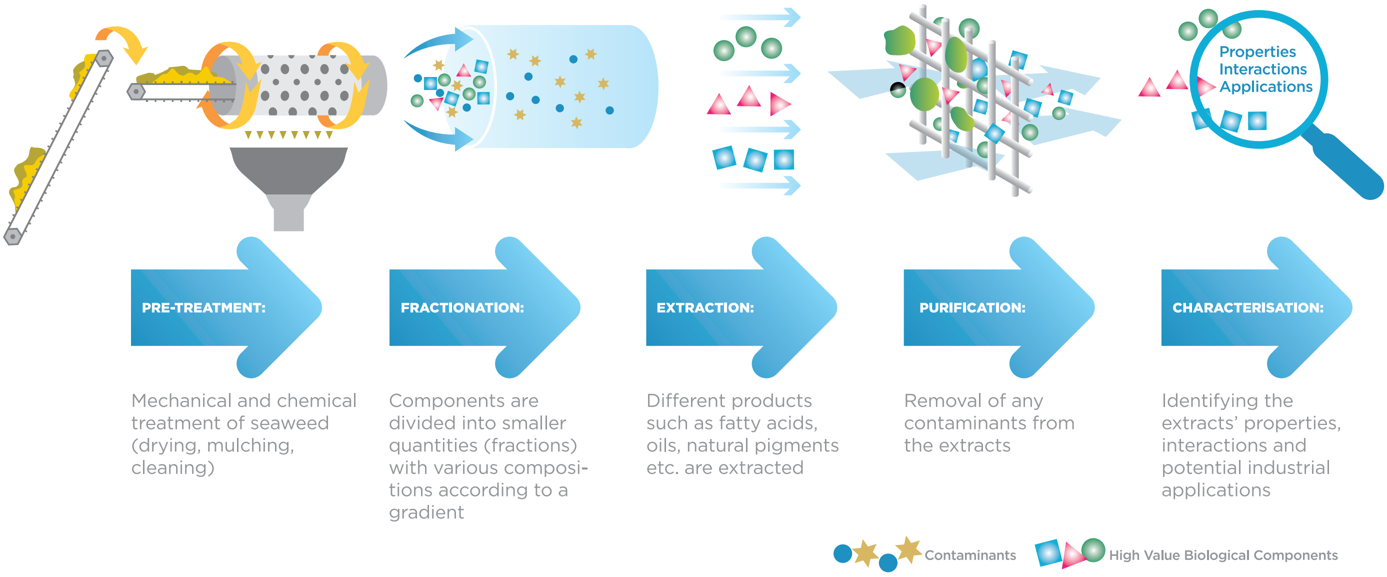

Figure 6 Steps of the biorefinery process. Graphic designed by AquaTT.

Biorefinery process

Seaweed biorefinery involves pre-treatment, fractionation, extraction, purification and characterisation of the commercially interesting substances.

Pre-treatment is a combination of mechanical treatments such as grinding and pressing of the fresh biomass. At the start of the separation process, fractionation divides the seaweed components into fractions of different quantities, compositions and physical state (solid, liquid), using mostly physical methods. During the extraction step, compounds are differentially solubilized in water or other solvents, using conventional or innovative methods such as enzyme treatments, or environmentally sustainable solvents like supercritical CO_2 or ionic liquids. These extracts are then put through a purification process whose severity depends on the applications targeted, with some applications requiring only a low degree of purity. The purified substances are characterised, and their properties are tested for potential industrial uses.

Benefits and sustainability

More than ever, we need to concentrate on a sustainable bioeconomy and a production system that decreases negative impacts on the environment. Seaweed biorefinery supports a minimal or zero-waste society, as any leftover residuals from the process have a use, for example as fertilisers, fermentation processes, or platform molecules in chemical processes.

The overall objective of the **GENIALG** Project was to make seaweed biomass production more economically and environmentally sustainable by designing high-yielding seaweed cultivation systems that optimise the crops for biorefinery.

Benefits of seaweed biorefinery include:

- Refining large amounts of seaweed which will give access to low abundance of valuable compounds which are already known to provide new applications and markets, such as pigments and lipids.
- Lower costs related to zero-waste retreatment and management.

- Increased economic growth and jobs in coastal communities where seaweeds are harvested or cultivated.
- Reduced energy and water consumption in seaweed processing.
- Reduced pollution by shifting from fossil fuel-based industries and compounds to sustainable, carbon-storing bio-based industries and products. This includes CO_2 mitigation, helping with the fight against climate change.

INNOVATION

Enzymatic processes improve extraction yields and compounds' purity, using mild thermal and chemical conditions

Seaweed cells are surrounded by an extracellular matrix, analogous to plant cell walls, which is a kind of jellified structure entrapping a large number of compounds. Selective destructuration of the extracellular matrix using specific biotechnological tools such as enzymes improves the extraction of these valuable compounds. The composition of this extracellular matrix being complex and unique, the use of various enzymes produces novel sugars in a very specific way.

Environmentally sustainable chemicals and solvents

Two types of innovative seaweed extractions using solvents have been shown to enable efficient recovery of seaweed compounds, namely supercritical carbon dioxide, and ionic liquids. Though these methods may be considered unsafe by the general public, they are in fact non-toxic and have many advantages, including high efficiency in the extraction of various valuable compounds from seaweeds and improved yields and purity. Ionic liquids are also environmentally friendly since they can be recycled, and supercritical CO_2 is harmless towards the environment and requires low operating conditions (temperature and pressure).

CONSTRAINTS AND CHALLENGES

Variability

The growth of seaweeds like *Saccharina latissima* and *Ulva* species in the wild is highly marked by seasonality, which generates a high variability in algal supply for seaweed processors along the year. The biochemical composition of seaweeds also follows a seasonal variation.

Development and improvement of seaweed cultivation, through progress in strain selection and controlled culture conditions in land-based systems, help addressing these issues, while lowering the pressure on wild seaweed stocks.

Storage and Transport

Seaweeds have a high water content, and as for many types of crops, wet biomass transport is expensive. Overcoming this constraint can be achieved by installing biorefinery plants close to the seaweed farms, or at least the first steps of biorefinery processes should be performed close to the harvesting sites.

Stabilisation of seaweeds by freezing or freeze-drying is very energy intensive and thus highly expensive. This solution is therefore rarely implemented at industrial scale, but mainly for research and development purposes.

Air drying seems to be the most favourable option, but its efficiency and energy cost vary depending on geographic and climatic parameters: a correct drying level can be achieved through a natural ventilation in southern European countries, whereas correct drying needs additional heating in northern countries.

The potential of ensilage for seaweeds is also a solution for long term storage. Even if it does not preserve the structural integrity of all content such as sugar-based products, it can provide valuable protein and mineral sources for animal feed.

Storage methods can be deleterious for some target compounds: freezing affects the molecular weight, and therefore the rheological properties of alginates; dewatering, like belt pressing, may lead to the loss of valuable ingredients; ensilage generates modifications of the biochemical composition and especially the carbohydrate content.

Biomass supply and demand are not adequate for product development

Seaweed producers and biorefiners have not yet been able to adjust their production, because these two sectors are in their development phase. The development of new products needs sustainable supply, through the development of aquaculture, while aquaculture needs increasing demand, through the development of new products, to grow.

Knowledge gaps

Unlike terrestrial crops that have been cultivated and improved by selection for millennia, seaweed domestication has only recently begun in Europe. Although progress is considerable, driven by technologies developed for other organisms, genotyping, phenotyping and selective breeding still need to be studied, developed and improved.

Although seaweed composition is well documented, methods for biochemical analysis of seaweeds are only starting to be standardized. Thus, variations and fine structural variations of components are still not well understood and need to be more exhaustively described.

Regulatory issues

There is a lack of commonly accepted methods of analysis for seaweed compounds/composition. The authorized contaminants thresholds in particular can vary from one country to the other, which makes trading seaweed products difficult.

Consumption of seaweeds in Europe, as a vegetable, an ingredient or food additive, is ruled by the 'Novel food' regulation, in which only about 15 species are authorized, which includes both *Sacharina latissima* and *Ulva* species. However, regulation about seaweed consumption depends also on EU State members' specific recommendations.

New coalitions were recently launched such as Seaweed for Europe and the Safe Seaweed Coalition to address such issues for the European and world seaweed industry, respectively.

GOOD PRACTICES

The success of a biorefinery implementation will be aided by:

1. Choosing a plant location close to cultivation sites or harvesting sites, to reduce problems related to transport. This will have a positive impact on stabilisation and creation of jobs for coastal populations.
2. Avoiding focus on single high-value products: the production of two low- or mid-value products ensures a more rational utilisation of the biomass than the extraction of only one high-value product generating significant waste and thus additional costs.
3. Taking care of designing a process that matches with regulations of the targeted sector (related to GMOs or chemicals, in the food, pharma, or cosmetics sectors for example).

CONCLUSIONS

An increased awareness of our daily use of seaweed products, mostly phycocolloids in food or care products, together with an increased consumption of seaweed as sea vegetables, should improve social acceptance of novel seaweed based products such as biopackaging or pharmaceutical products. Therefore, promoting seaweed consumption might foster the success of seaweed biorefineries' implementation and sustainability and reciprocally, biorefineries will help to improve the contribution of seaweed in our future food systems as protein-rich, omega-3, or anti-oxidant rich fractions in processed food.

CITATION

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