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Sustainability Analysis of Cultivated Seaweed Valorisation Concepts

Macro Cascade - Project

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Sustainability Analysis of Cultivated Seaweed Valorisation Concepts

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1 Summary

The Macro Cascade production platform covers the full valorisation chain starting with sustainable cultivation of macroalgae biomass up to the production of value-added products. This report presents an assessment of the sustainability of concepts developed within Macro Cascade. The analysis is based on the results from underlying techno-economic, environmental and social analyses studies performed in the Macro Cascade project. The sustainability assessment is presented in the form of a structured discussion supported by assessment tables. It addresses the three pillars of sustainability: *environment, social and economic*. Hereby it considers the principle of meeting today's needs while allowing future generations to meet their needs. Given that the impact of each of these pillars is very much determined by the technical characteristics of the concept, the latter has also been assessed.

The relevant routes are illustrated in Figure 1. The three stages of the seaweed to products chain are considered separately. For cultivation, a seaweed farm based on a rope-based cultivation concept is assessed. Preservation and storage are considered either by drying, baling and warehouse storage, or through ensiling and tank storage. Three valorisation routes are considered. The first option is co-fermentation of (dried only) seaweed with canola meal to functional feed or food. The second option is a cascading fractionation scheme of brown seaweed towards multiple products (alginate, mannitol, laminarin and fucoidan) aiming at making optimal use of all the components present in brown seaweed. The third option is an enzymatic process for the production of prebiotic oligosaccharides from red seaweed.

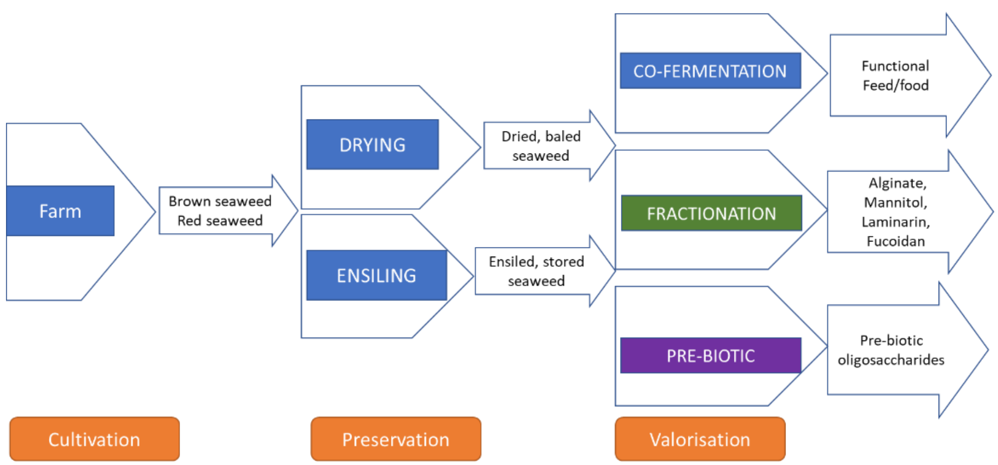

Figure 1: Routes for seaweed cultivation, preservation and valorisation.

The technical assessment of seaweed cultivation gave that, though seaweed cultivation could be considered complex, a good rating was obtained for the technical status. Preservation and storage through drying gave high product yields but with a very high energy use. Furthermore, a lack of knowledge on upscaled design procedures and loss of thermosensitive components was identified. Preservation through ensiling was rated superior in terms of energy use but has some uncertainties in the products yield and control of the ensiling process.

The technical assessment of co-fermentation of seaweed for functional feed and food gave very positive ratings given the high stage of development and low number of operations. The cascading scheme towards multiple products makes good use of all seaweed constituents but the scheme is very complex, with a significant heat demand. The valorisation of red seaweed to prebiotic oligosaccharides has a high product yield, but the heat demand is high for the coagulation agent recovery step.

The technical characteristics are reflected to a large extent in the economic aspects of sustainability. The economic assessment using a bottom-up approach in the project gave that seaweed costs contributions of both the capital costs as well as of operating costs are important. The seaweed costs found were very high when compared to prices of most products considered in the project, so further reduction of seaweed costs is required for economic feasibility. It is noted that when a top-down cost projection is used, the seaweed costs are estimated to be significantly lower.

In the fermentation towards feed and food products has good economic prospects, this because of the to the relatively simple process involved and limited share of seaweed in the total feedstock used. Though processing towards food-grade products has a lower market volume and higher costs, the prospects for the fermented food route are excellent because of the high anticipated product market value. The cascading scheme towards multiple products optimizes revenues but investments are relatively high because of the many process steps. Furthermore it was found that, compared to alginate-only production, the co-production of mannitol, laminarin and fucoidan using with the current scheme does not improve economics, so process simplification is advised. The energy and investments costs for pre-biotic oligosaccharides make the product costs high compared to the market price for pre-biotics. Economic viability for this route will depend on process improvements and the specific pre-biotic functionalities to be determined that would justify a high price.

The environmental assessment of seaweed cultivation showed that, in the cultivation, the steel as well as polymer use contributes to greenhouse gas (GHG) emissions whereas polymer contribute to other emissions. For drying the energy use is dominant. For preservation through ensiling the emissions are related to the steel mainly, but emissions are much lower than for drying given the negligible energy demand associated with ensiling. Comparison of greenhouse gas emissions of the chain for making seaweed derived products proved difficult because often there are no direct equivalent products. Results indicate that the GHG footprint of seaweed derived feed and food product is in the range of plant-based products and lower than of animal-based products (based on the protein content). GHG emissions resulting from drying with fossil energy are the main burden in terms of environmental impact of the seaweed products. In the pre-biotic oligosaccharides, the process heat gives a significant GHG emission contribution. The impact of heat use can be only partly mitigated with the implementation of renewable energy. Additionally, emissions associated to chemicals used in the cascading scheme can be also significant. The very low impact on land use of seaweed derived products is to be highlighted. Finally, it is important to mention that benefits from functional feed and food product as well as for the pre-biotic oligosaccharides in the form of benefits for animal and human health can be important positive impacts but are difficult to quantify.

Finally the prospects of the cascading use of seaweed for multiple products is evaluated. It is concluded that there are options for significant improvement of the technology in all three elements of the value chain, which can lead to improvement of all three aspects of sustainability.

The social and regional analysis consisted of a social life cycle assessment (s-LCA) to highlight the defined categories and indicators that were set to assess potentially negative as well as positive social effects of Macro Cascade. The s-LCA showed that social impacts on local communities and society in general are expected to be positive, some of them even highly positive, once sustainability criteria for seaweed biorefinery are met and seaweed cultivation is performed based on best practice and sound site selection. Highlights of positive social impacts are economic growth and development, market pull for seaweed, climate change mitigation, nutrient uptake, enrichment of biodiversity, coastal erosion mitigation, revival of rural areas and regional development. However, a few social risks remain even when best practice scenarios are chosen and sustainability of production chain and product is proven such as health and safety risks, competition over ocean space, the loss of positive environmental impact due to the wrong site selection, unsuccessful integration of non-local workers and negative public perceptions. Mitigation measures can help to lower those risks.

Contents

2 Abbreviations and terms

1-D	1-dimensional (rope based)
BBI-JU	Bio-Based Industries Joint Undertaking public/private parntnership
CAPEX	Capital expenses
CO_2	Carbon dioxide
Cost-plus	Cost price plus surcharge for return on equity
DoA	Description of Action
GHG	Greenhouse gas
IMTA	Integrated multi-trophic aquaculture
IPA	Isopropyl alcohol
LCA	Life cycle analysis
OPEX	Operational expenses
pH	Measure for acidity
R&D	Research and development
SDGs	United Nations Sustainable Development Goals
s-LCA	Social life cycle analysis

3 Introduction

The objective of this report is to present a case-based evaluation of the sustainability of seaweed cultivation and valorisation based on the results of the Macro Cascade project. Macro Cascade focusses on open water seaweed cultivation and valorisation towards functional feed and food, prebiotic oligosaccharides and cascading evaluation towards various chemicals and ingredients, including mannitol, laminarin, fucoidan. The analysis is based on the techno-economic evaluations, life cycle analysis and social analysis results from Macro Cascade. This report first presents the specific valorisation routes defined for Macro Cascade, followed by a discussion of the overall sustainability performance based on the results of the technical assessment of each of the steps in the process chain and results from the full chain sustainability assessment. The future and general prospects of seaweed cultivation and biorefineries are also discussed, putting the results of the sustainability assessment in perspective considering uncertainties, potential improvements and development of future markets.

3.1 Sustainable development and the blue economy

The United Nations have set the 17 main sustainable development goals (SDGs) in the timeframe up to 2030, outlining a plan of action for people, planet and prosperity (Desa, 2016). The SDGs cover diverse aspects of sustainability including the end of poverty, the building of a strategy for a strong and stable economic growth. They also address a range of social needs including education, health, social protection, and job opportunities, while tackling at the same time climate change and environmental protection. The goals cover a wide range of topics as illustrated in Figure 2.

Figure 2: United Nations sustainable development goals.

Fulfilling these goals will call for new resources, new technologies and new products, amongst which biomass can play an important role. At the same time, there is much need for a focus on coherent environmental policy, better connection among global bioeconomy policies and efficient public dialogue (BBI-JU, 2019).

Marine biomass, especially cultivated seaweed, is of specific interest given that is a new, relatively unexplored and underexploited resource that could open up interesting novel solutions to address some of the goals and their underlying objectives. Seaweed, or macroalgae as they are also referred to, could contribute to multiple SDGs, amongst them climate action, good health and wellbeing, zero hunger, decent work and economic growth. Given that novelty, the level of impact and potential benefits or negative effects on other goals need to be explored.

Seaweed has been used as a resource for food, feed and source for chemicals, fuels, consumer products such as cosmetics, and for promoting human and livestock health for centuries. Recently, novel developments in seaweed cultivation and biorefinery processing have opened up the interest in using cultivated seaweed as a novel resource for these products, providing potentially a vast supply and not competing with land use for food production.

The European Union and the BBI-JU have acknowledged this potential in the funding programme topic 'BBI.VC3.R9-2019' targeting the valorisation of aquatic biomass. Within this call, the use of 'blue' biomass such as macroalgae, for high value applications such as food ingredients, feed proteins, pharma and nutraceuticals is recognised as a promising means of reducing Europe's dependence on imports (e.g. fish, vegetable oils, proteins for animal feed) and diminishing the pressure on land resources. The *Macro Cascade* project aims at developing a cascading marine macroalgal biorefinery platform that covers the whole technological chain for processing sustainable cultivated macroalgae biomass to highly processed value-added products. The project also aims at making an impact on European entrepreneurship and industry through a "Blue Print" for a marine macroalgal biorefinery with competitive business models that include life cycle analysis and socio-economic impact assessment along the whole value chain.

The Macro Cascade production platform covers the whole valorisation chain starting from cultivation of sustainable cultivated macroalgae biomass up to the production of highly processed value-added products (Figure *3*). For this purpose, a range of mechanical and physicochemical pre-processing techniques are applied, combined with enzymatic or microbial techniques for product extraction aiming to make use of all high-value components in seaweed. The concept is a novel contribution to the blue economy, in which all economic activities are related to oceans, seas and coasts. Furthermore, the concept opens up an additional, sustainable resource for novel products in food, feed, nutraceuticals, chemicals and cosmetics.

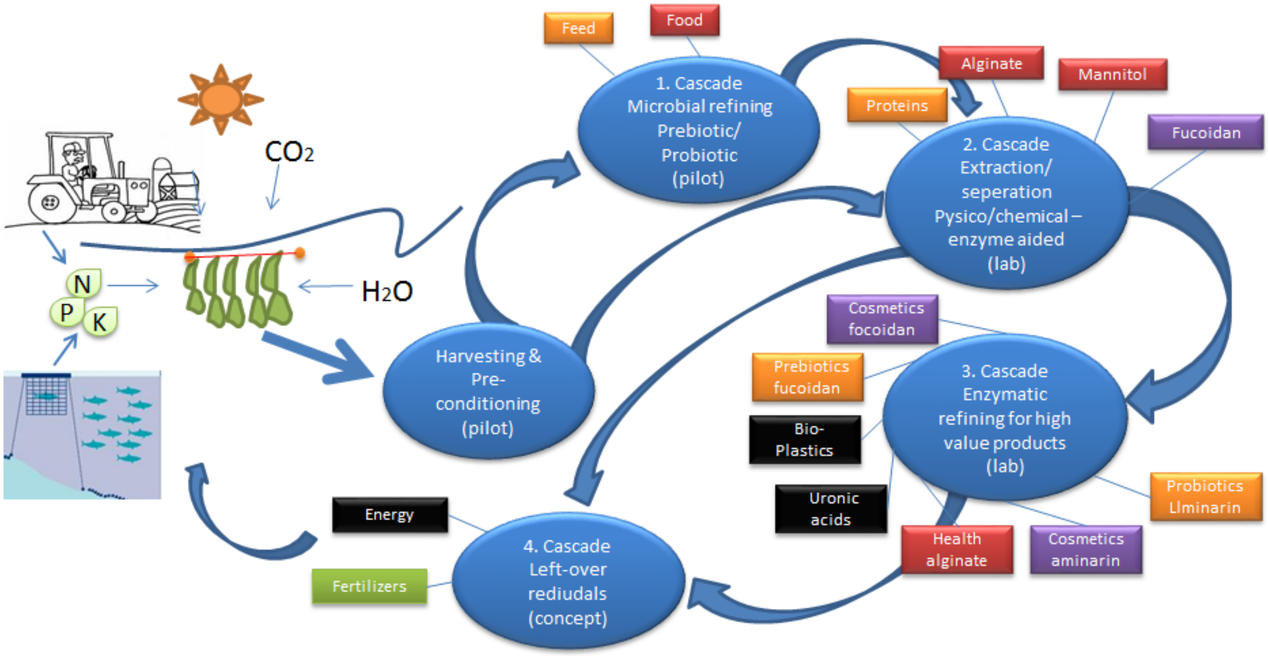

Figure 3: Overview of the integrated marine macroalgal biorefinery, converting the macroalgae into intermediates and final products in four cascading steps.

Given the novelty of the concept, it is necessary to assess the impact of the potential positive and negative effects including the drivers behind these contributions, any uncertainties and further developments required. A sustainability analysis aims to assess the potential impact of a novel concept. It uses therefore the three pillars of sustainability: *environment, social and economic*, see Figure 4. Hereby it considers the principle of meeting today's needs while allowing future generations to meet their needs. The impact on these three pillars is very much determined by the technical characteristics of the concept in consideration and therefore this report will also elaborate on the results of the technical assessments made within Macro Cascade.

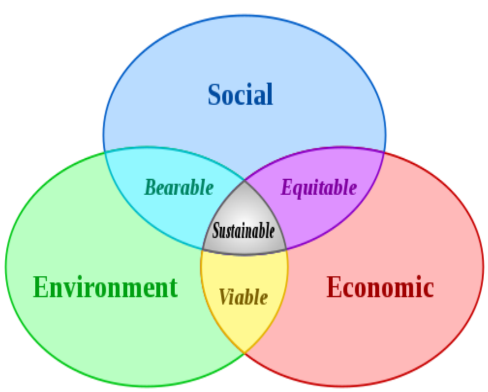

Figure 4: Three pillars of sustainability (Adams, 2006).

3.2 Objective, scope and methodology

The objective of this report is to present a case-based evaluation of the sustainability of seaweed cultivation and valorisation based on the Macro Cascade concepts. A sustainability analysis addresses the three main aspects of sustainability, which are economy, environment and social aspects. The analysis is done for the value chains evaluated in Macro Cascade. This includes the open water seaweed cultivation on 1-D systems, preservation and storage through drying or ensiling and the three valorisation routes towards functional feed and food, prebiotic oligosaccharides and cascading fractionation (alginate, mannitol, laminarin and fucoidan).

The analysis builds on the results of the techno-economic evaluation, life cycle analysis (Deliverables D6.2 and D6.3, public summary available) and social and regional analysis (Deliverable D6.4) performed in the Macro Cascade project. The sustainability consists of two elements being a structured discussion on the elements of sustainability and a semi-qualitative rating of sustainability indicators for each of the routes, on which the discussion will be based. The discussion will cover the underlying issues including assumptions, critical issues and uncertainties. Future prospects, knowledge gaps and development needs are addressed. Though not being direct input for this work, the results from the business case development in the project will be taken into account also, primarily in the section 6.2.

Semi-qualitative indicators are used to interpret or translate numerical/quantitative results from the techno-economic evaluation, life cycle and social analysis of the Macro Cascade concepts. Indicators and results that have been identified as relevant for the decision process were collated in overview tables and interpreted. More qualitative methods are available which typically apply weighing factors to indicators to render single scores indicative of the degree of sustainability (Cinelli, Coles, & Kirwan, 2014; Cinelli, Coles, Sadik, Karn, & Kirwan, 2016; Sadok et al., 2008). However, the approach of a structured discussion is preferred to a more mathematical approach. The latter approach may appear more 'scientific', but it depends on subjective value-based choices that may not seem apparent. In addition, transparency is lost in such an approach. Therefore already during the definition phase of the project it was defined to not to use such (semi) quantitative methods, as laid out in the description of action, DoA, of the Macro Cascade project.

Though being very important part of sustainability, assessment of ecological aspects of seaweed cultivation is excluded from this report since these were not within the scope defined for the project. The reader interested in this aspect is referred to results from other projects that have recently brought valuable information on environmental risk and knowledge gaps (Bruhn et al., 2020; Campbell et al., 2019) or on guidelines for sustainable seaweed growth (Barbier et al., 2019).

After this introductory chapter, chapter 4 first presents the specific routes defined for Macro Cascade. In Chapter 5, it will then present the methodology and starting points used. Chapter 6 presents the results of the sustainability assessment including the underlying technical assessment. Chapter 7 presents the findings of the social and regional assessment. In Chapter 8, the future and general prospects of seaweed cultivation and biorefineries are discussed putting the results of the previous chapter in perspective considering uncertainties, the improvement potential and development of future markets. The report ends with conclusions and recommendations in Chapter 9.

4 Routes for cultivation, preservation and valorisation

The value chains for seaweed valorisation considered in Macro Cascade can be divided into three main stages, see Figure 5. The valorisation routes included here were selected as the most promising and representative. The first stage is seaweed cultivation, which yields fresh seaweed delivered on land. The second stage is preservation and storage, where seaweed is stabilized through two alternative technologies to allow year-round processing. The final stage is valorisation to products, where three different routes are followed to produce either:

- Functional feed/food via co-fermentation of seaweed with canola meal using dried brown seaweed
- Multiple products (alginate, mannitol, laminarin and fucoidan) via a cascading biorefinery using dried or ensiled brown seaweed
- Pre-biotic oligosaccharides using dried or ensiled red seaweed.

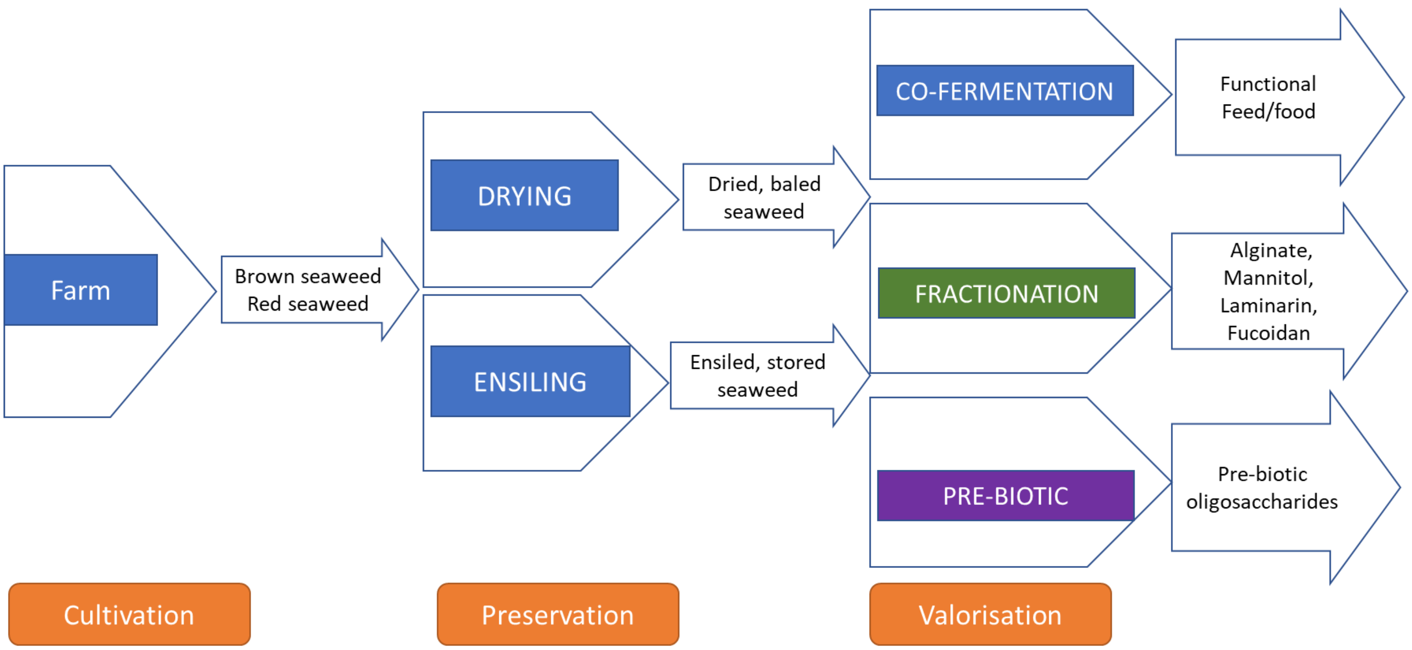

Figure 5: Routes for seaweed cultivation, preservation and valorisation. Different combinations of the seaweed, preservation and valorisation are possible, see text below.

4.1 Cultivation

The cultivation concept selected for the assessment is a modified version of the 1-dimensional (1-D) system as published by (Bak, Mols-Mortensen, & Gregersen, 2018) and is depicted in Figure 6. Operation of this system has been proven under nearshore exposed conditions. The system is a rope-based system consisting of polymer growth fixed lines connected to large marker buoys on both ends, which are connected to a mooring system. The sporophytes are directly brought onto the growth lines offshore. The growth lines are connected to a polymer fix line of 500 m length and a floater to keep the growth line vertical. The mooring system consists of a chain and a steel scoop anchor that holds the system in place at an average depth of 75 m. All connections are made with stainless-steel shackles. Transport to shore is done by rental barges assuming an average distance of 20 km and is included in the cultivation phase. The cultivated seaweed is brown seaweed, *Saccharina latissima*. Currently, the cultivation of red seaweed (i.e. *Palmaria palmata*) is considered very difficult. To evaluate the potential of this seaweed for the case of production of prebiotic oligosaccharides it was assumed that its cultivation has the same yield as brown seaweed *Saccharina latissima.*

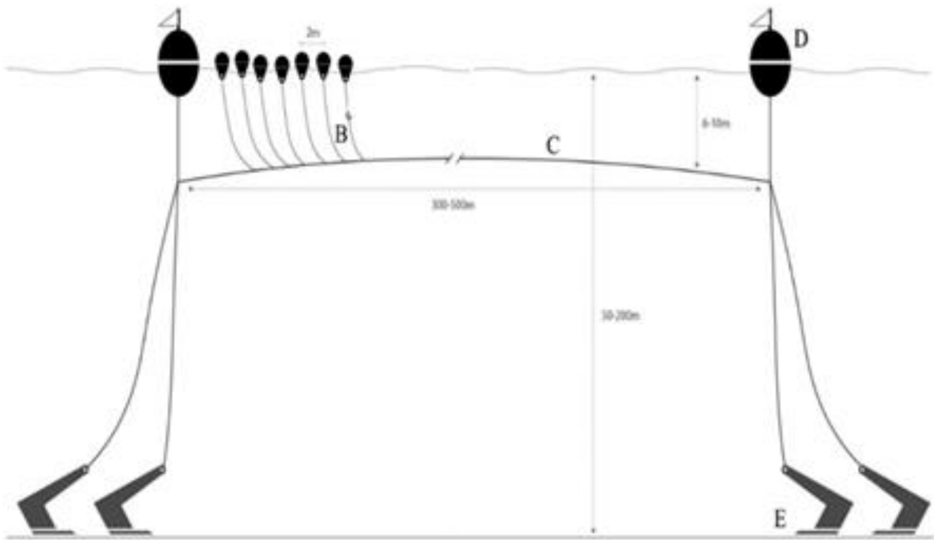

Figure 6: Seaweed cultivation system. Figure adapted after (Bak et al., 2018).

4.2 Preservation and storage

Fresh seaweed will deteriorate if stored wet at room temperature, thus preservation is required to prevent this from happening. At the same time, preservation allows to operate a seaweed processing plant throughout the year, which limits plant capacity and investments. Preservation of seaweed can be done by either air drying or ensiling, see Figure 7. For drying, seaweed is transported from the ship to air dryer operating at low temperature. Drying is followed by baling of the seaweed and on-site storage in a warehouse. Alternatively ensiling can be done with a much lower energy demand than air drying. Here, seaweed is transported to large storage tanks where it is mixed with lactic acid bacteria. These bacteria convert part of the sugars in seaweed into lactic acid, which generates an acid environment in which microorganisms cannot grow. The seaweed is then stored under oxygen free conditions within the same storage tank until processing throughout the year.

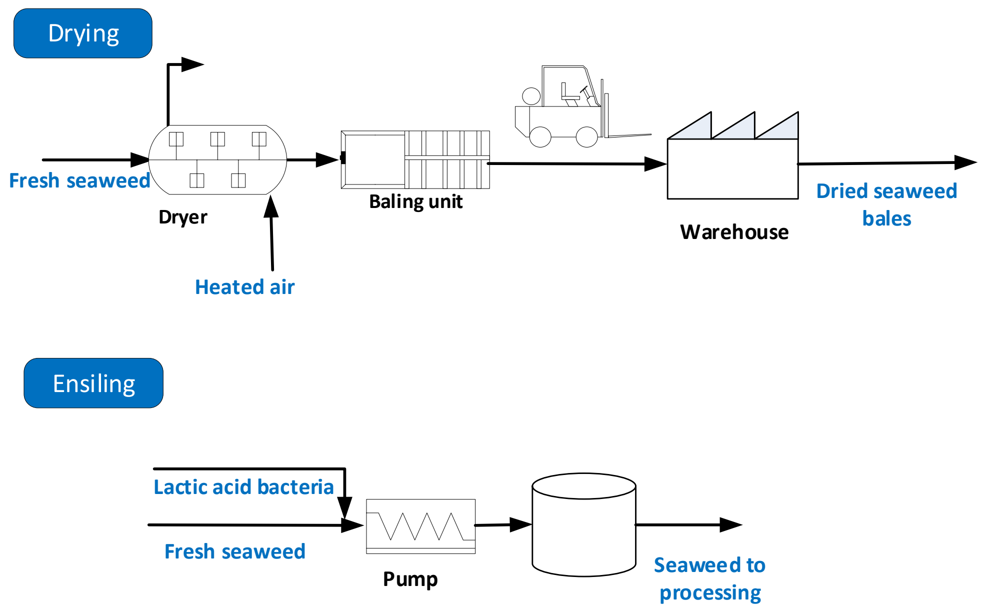

Figure 7: Schematics of seaweed preservation by drying or ensiling.

4.3 Technologies for the valorisation of seaweed to products

Simplified schemes of the process flow diagrams of the technologies implemented for the conversion of seaweed to the selected products are depicted in Figure 8. The first option is **co-fermentation** of seaweed with canola meal to produce **functional feed or food**. Here, the brown seaweed is cut and mixed with canola meal and water. Canola meal, also called rapeseed meal, is the by-product from rapeseed oil. It has a high protein content and is widely used as feed for all kinds of livestock. Lactic acid bacteria are added after which the mixture is allowed to ferment. The co-fermentation of the seaweed and canola meal improves the digestibility of the seaweed and allows (additional) functional components (prebiotics, probiotics and bioactive components) to be formed. The product from the fermentation is dried, after which is exported as the functional feed for livestock. The functional food product alternative for human applications is produced following the same process. The mere difference is in the certification of canola meal as feed- or food-grade, the use of food-grade equipment and food-grade procedures during production, and the lower plant size required for food grade given that the anticipated market size is lower for functional food. The product has comparable anti-microbial and anti-inflammatory properties as functional feed. In the framework of the Macro Cascade, tests are being performed at Silkeborg Hospital investigating the benefits of using this functional food product on patients with intestinal problems.

The second option is a **cascading scheme** towards **alginate, mannitol, laminarin and fucoidan**. Here, seaweed undergoes a series of processing stages at increased severity to extract a range of products. The first stage is cold water extraction, where the liquid extract contains mannitol and (low branched) laminarin. These are separated, purified and precipitated by crystallization or (spray) dried, to yield respectively mannitol and laminarin, thus obtained as two separate solid product streams. The second stage is hot water extraction which extracts (high branched) laminar and fucoidan. These are separated by membrane filtration, purification and spray drying and obtained as two solid phase product streams. The final stage is alginate production from the seaweed stream remaining after cold and hot water extraction. Here, the alginate is dissolved using sulphuric acid. The alginate is further purified using precipitation, reacidification and final precipitation as sodium alginate, which is then dried to the final product. The final by-product consisting of the wet residual seaweed stream could be valorised either as low value feed ingredient (it contains proteins, but also quite some minerals) or as a feedstock for anaerobic digestion to produce biomethane. The latter can be used for heating purposes in the biorefinery.

The third scheme is the **production of pre-biotic oligosaccharide**s from red seaweed. Here, *Palmaria palmata*, rich in xylans, is considered for the assessment. The xylans are taken from the seaweed by water extraction and coagulated by admixing with isopropyl alcohol (IPA). The water and IPA are removed by evaporation (drying). Then, the resulting xylans are milled and fed to the enzymatic transglycosylation and precipitation section where they are derivatised using enzymatic glucose addition. The product is purified and concentrated using a two-step membrane filtration. The final step is spray drying after which the final product are pre-biotic oligosaccharides obtained as a solid stream. Recent experimental results indicate that also the xylans have pre-biotic functionality. A simplified process considered is then to omit the transglycosylation step and to export the xylans as the final product.

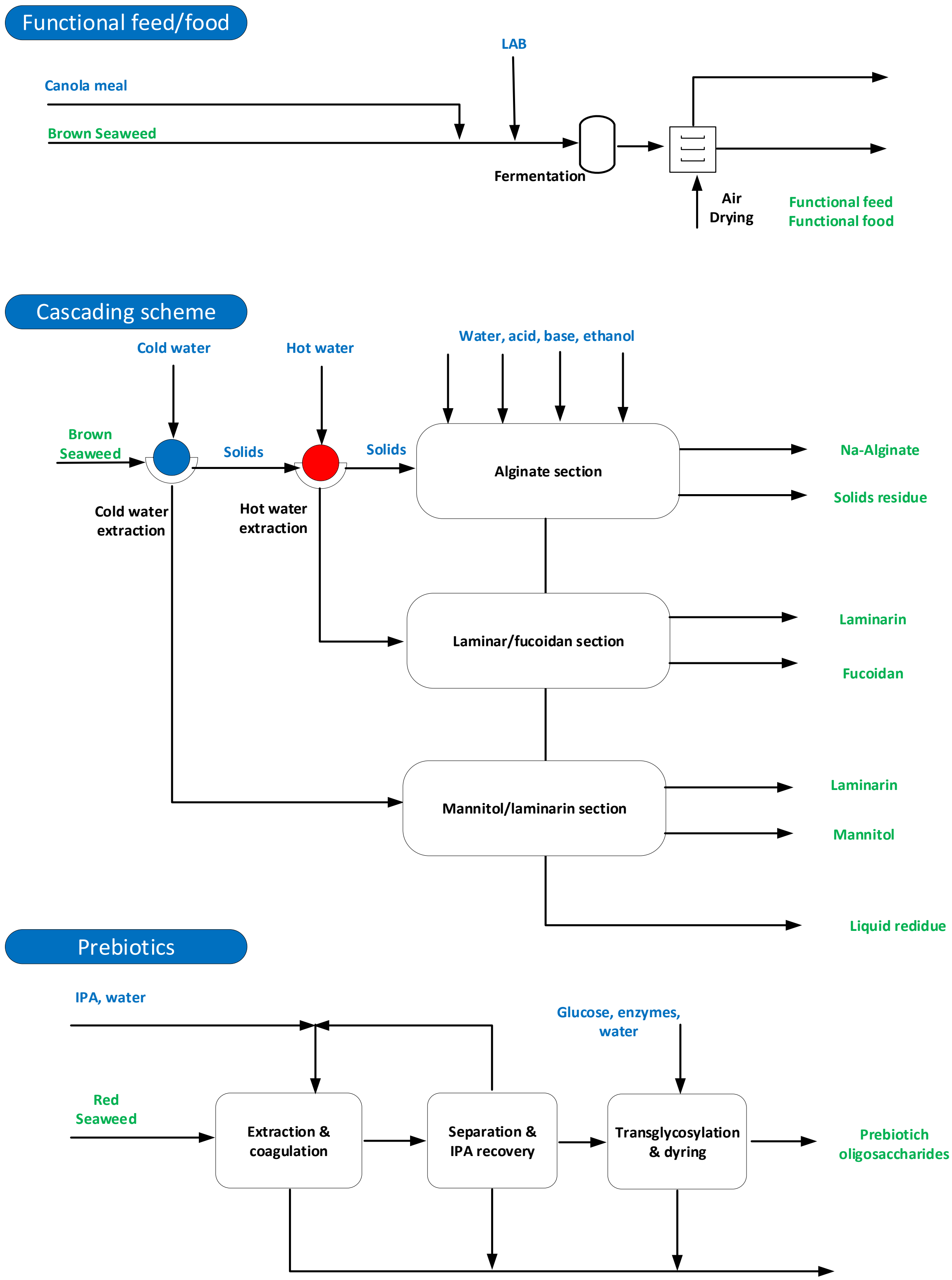

Figure 8: Schematic of valorisation routes. LAB: Lactic acid bacteria; IPA: Isopropyl alcohol.

5 Assessment methodology and starting points

5.1 Methodology and representation

The working method for the sustainability assessment is illustrated in Figure 9. The basis for this assessment is the results from the techno-economic evaluation, the life cycle analysis and the social analysis. A selection and definition of the indicators was made from these results. Scoring indicators were developed for each of these indicators, where a 5-scale rating --/-/0/+/++ was applied, indicating whether the rating is respectively very positive (++), positive (+), neutral (0), negative (-) or very negative (--) for the indicator. The final integrated sustainability assessment results then have two elements: (1) the assessment table with the indicator and rating, and (2) a structured discussion that relates to the table as well as to the underlying assessments.

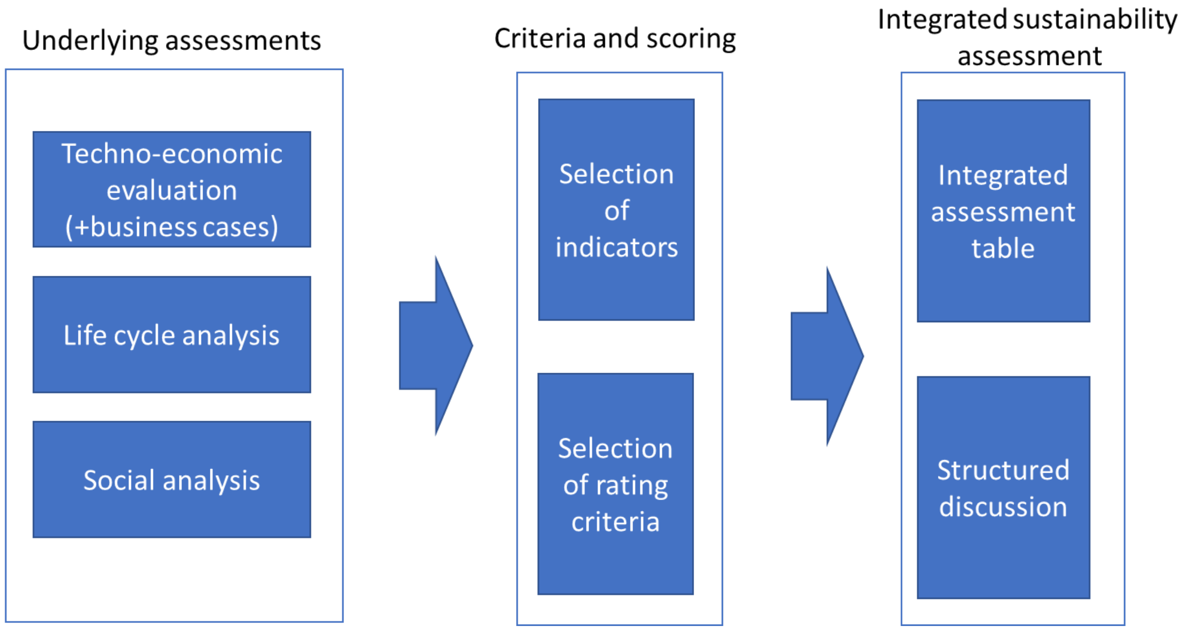

Figure 9: Working method for the sustainability assessment.

The rating results are presented throughout the report using a template as listed in Table 1. The upper part lists the definition of the indicators selected, which are based on information resulting from the underlying assessments and have been selected to give a concise representation of the technological options. The second part of the table gives the actual rating results of a technology option, as is indicated by a green fill of the selected rating field. The first column lists the definition of the indicator. Within the 2nd and 6th column, there is a rating scheme which is used for the rating on a five points scale.

Often there were no absolute (legal or rule-of thumb) indicators available. The indicators have therefore been based on relative values, either as a relative contribution for the specific technology, or a relative value to a reference technology. On one hand, this reflects that the numerical value of indicators selected is not always equally sensitive to the sustainability. On the other hand, this was also used to better reflect the different characteristics of the technologies and thereby support the structured discussion. The resulting overall assessment table is presented in Appendix 1. The table will be discussed in detailed in each corresponding section in this Chapter. The ratings are based on the current concepts of the technology, assuming that these technologies are fully developed and assuming. Other assumptions are listed in the next section.

Table 1: Assessment template, indicators definitions, rating limits and rating results as indicated by the green fill of the rating field.

Section/sustainability aspect	**++**	**+**	**0**	**-**	**--**
	Very positive	Positive	Neutral	Negative	Very negative
Indicator 1 definition	Rating limits for ++	Rating limits for +	Rating limits for 0	Rating limits for +	Rating limits for --
	e.g. <25% of reference	e.g. 25%-75% of reference	e.g. 75-125% of reference	e.g. 125-175% of reference	e.g. >175% of reference
Indicator 2 definition	Rating limits for ++	Rating limits for +	Rating limits for 0	Rating limits for +	Rating limits for --
	e.g >200% of reference	e.g 100%-200% of reference	e.g 100-50% of reference	e.g 50-25% of reference	e.g <25% of reference
Results for indicator 1 (green)	++	+	0	-	--
Results for indicator 2 (green)	++	+	0	-	--
Etc	++	+	0	-	--

5.2 Starting points and methodology of the underlying assessments

The technical design of the cultivation stage involved setting up an inventory of all parts and operations required for cultivating the specified amount of seaweed. This involved setting up mass and heat balances for the preservation and storage as well as valorisation stages. For this part, Macro Cascade laboratory results were translated into a in a full-scale plant design, with subsequent sizing of the main dimensions of process equipment. Feasibility was then assessed based on the results and assumptions made for each technology.

Seaweed cultivation, preservation and most of the valorisation routes were evaluated for a production capacity of 10 ktonne/yr dry weight (equivalent to 77 ktonne/yr fresh weight), which is the capacity of a typical alginate plant. Only for the functional feed and food (where canola meal is mixed with seaweed and where seaweed is only a small contribution) different plant capacities are used: 25 ktonne/yr and 8 ktonne/yr total product (incl. moisture) respectively.

The economics addressed both capital and operational costs. The starting points for capital investments were framed again assuming a fully developed technology and the common n^{th} plant which means that any extra investments, or reduced performance for the first set of plants build for a technology are not accounted for. Capital investments for the preservation and storage and for valorisation were based on purchased equipment costs or part costs. Surcharges were added as a percentage of these equipment costs for indirect costs and facilities using a literature method for the economic evaluation of chemical processes (AACE, 2003). For the cultivation, the same method was used, while reassessing all surcharge percentages. The main indicator used was the cost-plus price. The cost-plus price differs from the cost price with respect to the 10% return on equity added for the cost-plus price. The cost-plus price is made up of operational costs (OPEX), and capital costs (CAPEX) which consists of all depreciations plus and the assumed return on equity. In addition, the results from the business case analysis were used, which use extrapolation of current small-scale operations.

The environmental impact assessment was performed using the mass and heat balances obtained in the technical analysis. In this life cycle analysis (LCA), the inventory of the plant equipment for preservation and storage and for the valorisation stage were omitted because their contribution is known to be very little. For the cultivation stage, however, the inventory of the cultivation system was included. The analysis was cradle-to-gate assessment aiming at identifying the hot-spots and providing an order-of-magnitude assessment against a comparable product. The analysis used the *ReCiPi* method with 18 midpoint indictors for environmental impact, such as greenhouse gas emissions, fossil fuel depletion, aquatic ecotoxic, land use etc.

6 Sustainability assessment results

6.1 Technical assessment results

A sustainability assessment generally involves discussion of economic, environmental and social impacts and does not necessarily involve a technological assessment. However, the performance on these aspects is often dictated by technology factors. Since the Macro Cascade project assessed these technologies in detail, the opportunity is taken to discuss these technological aspects in their relation to overall sustainability.

6.1.1 Technical assessment of seaweed cultivation

Seaweed can be obtained from wild harvest or from cultivation. Important producers of seaweed harvested from the wild are Chile, China and Norway. Cultivation of seaweed is predominantly employed in shallow and shielded waters in China, Indonesia, Republic of Korea and the Philippines (Ferdouse, Holdt, Smith, Murua, & Yang, 2018). In Europe, seaweed is predominantly obtained from wild harvest. The large amount of labour and sea conditions that are required in cultivation concepts from other continents cannot be used in European operations. Recently, innovative seaweed cultivation systems are being developed for the European context. Ocean Rainforest has operated such an innovative system as presented in section 4.1 since 2011 in both sheltered but also semi-exposed sea conditions suitable for the production scale required for 10 ktonne/yr dry weight. The development status has therefore been rated as "demonstrated in environment". For even larger-scale operations, further demonstration in even more exposed conditions is still required.

Table 2: Technical assessment of cultivation (1-dimensional system).

Cultivation	++	+	0	-	--
Development status	Proven in environment	Proven in demo	Development required	R&D required	Further basic research required
Supply potential	> 400% of wild harvest	400-200%of wild harvest	50-200% of wil harvest	50-25% of wild harvest	<25% of wild harvest
Yield	>9 kg/m2	4-9 kg/m2	2-4 kg/m	2-1 kg/m	<1 kg/m2
Direct energy use	<25% of wild harvest	<50% of wild harvest	50-200% of wil harvest	> 200% of wild harvest	>400%of wild harvest
Technical complexity	Fundamentally simpler	Practically simpler	Equal to wild harvest	Practically more complex	Fundamentally more complex
Supply potential	++	+	0	-	--
Development status	++	+	0	-	--
Yield	++	+	0	-	--
Direct energy use	++	+	0	-	--
Technical complexity	++	+	0	-	--

The supply potential has been rated against the supply of natural harvest. Currently the largest producer in Europe is Norway with a yearly wild-harvest production in 2015 of 145 ktonne/yr fresh weight (Ferdouse et al., 2018). The production capacity of wild harvest is limited by environmental constraints, the number of suitable sites and concerns of negative impacts on sea ecology, which will limit further expansion at some point in time. For Macro Cascade, a cultivation site size of 10 $ktonne_{dw}$/yr was considered. The potential for seaweed cultivation with this concept, however, is much larger since the concept developed can be deployed multiple times at various sites across Europe. It must be noticed that there are competing activities in open waters but careful planning and combined operation such as in Integrated multi-trophic aquaculture (IMTA) and combination of wind turbine parks with seaweed cultivation will ensure that the potential can be large and have a significant positive environmental impact.

Yield is defined as the production of fresh seaweed per meter of line deployed. High yields are crucial for economic feasibility, but also to reduce the environmental impact since the environmental burden of cultivation and preservation and valorisation is always considered relative to the amount of seaweed produced. In that respect, a better yield of seaweed is always important to increase performance. Current yields (for *Saccharina latissima*) are sufficient for the target markets envisaged for early deployment, but it is recognised that yield improvement is an important factor in cost reduction to improve economic feasibility.

Direct energy use is related to wild harvest operations. Here, the only direct energy use is in the energy for ship transport during the harvesting operation. For seaweed cultivation, there are additional ship movements for deployment of the cultivation system, seeding, cleaning of lines and maintenance. Therefore cultivation has a much larger direct energy use than wild harvest. It is however important to mention that the absolute contribution of this energy use not very significant compared to that of the rest of the value chain.

Technical complexity of seaweed cultivation is again compared to that of wild harvest. Undoubtably, technical complexity is much higher given the infrastructure that needs to be put in place, and knowledge that is required for operation thereof. Even compared to current cultivation methods which are predominantly employed in Asia, the technical complexity in the European context is higher. Because of higher labour costs in Europe, European seaweed technology needs to rely on much higher level of mechanisation. For example, the mechanised harvesting which was further developed in the Macro Cascade project has proven to significantly increase the speed and reduce the costs of harvesting, but this will be a more complex operation than manual harvesting in small boats, since not only the seaweed but also the grow-out unit needs to be handled. Much knowledge has been gained the past years on construction, operation and further development thereof to allow for cost reduction and better environmental performance of seaweed cultivation.

6.1.2 Technical assessment of seaweed preservation and storage

The result of the technical assessment of the two routes for seaweed preservation and storage is listed in Table 3.

Drying of seaweed with subsequent baling and warehouse storage

Drying is successfully employed by several seaweed producers. Open-air drying as employed outside Europe is not feasible in the (Northern) European climate and labour cost context. Instead, seaweed drying can only be done using either fossil energy, or renewable or waste heat sources. Some examples exist for successful drying of seaweed for small-scale operations using air drying rooms where seaweed is in place in trays/shelfs. Some operators have proprietary knowledge on other types of small-scale seaweed drying. Generally spoken however, the knowledge for design and operation of seaweed dryers, especially at larger scale, is very limited. It is specific for each seaweed type. In the techno-economics, but also in the Macro Cascade task on seaweed drying, it was found that open literature for selection and design of drying units for seaweed was found to be very limited. It was found that dryers, especially in the case of a short harvesting season, can become very large both in terms of mass throughput and thermal input. Importantly, the current scale of operation is relatively small compared to the anticipated biorefinery, and upscaling to the required throughput is not straightforward. It is therefore found that, building on the successful operation of small-scale operations, further R&D is required for seaweed drying.

Baling is selected to limit storage volume and costs. It is a conventional technology that can readily be adapted for seaweed. If not, alternative methods such palletisation may also be applied. Warehouse storage is conventional technology.

The product yield of drying is so that the full dry weight content of the seaweed is present in the preserved product. However, care must be taken for the various thermosensitive components that are in the seaweed. This limits operating temperature, which negatively affects energy efficiency and equipment costs. Depending on the targeted components, these might be partly lost, and the rating will be lower.

For the heat balance, the theoretical heat of evaporation of the water in the seaweed was chosen as a reference. For seaweed drying, the heat demand is higher given that, due to the low drying temperature applied, the heat lost with the moist hot air in the stack is quite significant. Given the large water content of the seaweed (87% water), the heat for drying is significant in absolute terms also.

Technical complexity is rated low because drying is a simple, single, physical operation for which various types of equipment are available. However, it must be noted that, as discussed above, the basic knowledge for design of such equipment at the scale required is currently very limited. Also there are lots of practical challenges which may be specific to the seaweed species. Therefore, though it may be a low complexity operation, in the end, the design approach may still require further development.

The baling, transport and warehouse storage are assessed to be not very complex and can be done with minor modifications of existing equipment.

Seaweed preservation and storage trough ensiling

Whereas ensiling is a reliable and established method for preservation of food and feed (maize, grass), ensiling of seaweed is in an early stage of development. Successful trials have been conducted, demonstrating the feasibility and potential of the technology. Scale-up and industrial application, required very good control of the process. The process design assumed natural ensiling, (which gave better results than chemical ensiling) using only lactic acid bacteria inoculum. Additional addition of sucrose and nutrients could be considered. Here especially the risk of severe seaweed deterioration during storage needs to be minimized. Further research into the operational factors that determine the development of pH during ensiling and other factors that are relevant in the risk for deterioration.

During ensiling, lactic acid is produced from sugars present in the seaweed. Macro Cascade results showed that predominantly mannitol and glucose are converted. Data on sugars loss in literature however differs significantly. The relation between final pH and sugars loss is also still poorly understood. Protein seems not too little affected. The effects on the content of high-value components and their extractability are largely unknown, and especially for these components a separated assessment closely related to the valorisation route of the seaweed is required. Given these uncertainties no rating was given for this indicator. Most experiments are conducted with dried seaweed and additional experimental work on the impact of using ensiled seaweed in the downstream processes considered is advised.

The ensiling process takes place at ambient conditions therefore energy consumption is limited. Temperature adjustment by heating could potentially better control the process but heating of seaweed was judged to be unfeasible. The only but minor energy demand is therefore for transport and cutting.

The technical complexity of ensiling is relatively low. It is a single-step biochemical process that uses conventional large storage tanks as the main equipment. On the other hand, the control of this single step to avoid seaweed deterioration is not well understood and the underlying biochemistry may be very complex, therefore requiring further fundamental research and development.

Table 3: Technical assessment seaweed preservation and storage

Preservation and storage	++	+	0	-	--
Development status	Fully commercial	Proven technology	Development required	R&D required	Further basic research required
Yield	Loss of target components <5%	Loss of target components <15%	Loss of target components <25%	Loss of target components <50%	Loss of target components <75%
Energy use	<10% of heat of evaporation	10-80% of heat of evaporation	80-120 % of heat of evaporation	120-150% of heat of evaporation	>150% of heat of evaporation
Technical complexity	1-5 steps, physical	5-10 steps, or 1-5 biochemical	10-15 steps	20-25 steps	35+ steps
Drying and baling					
Development status	++	+	0	-	--
Product(s) yield	++	+	0	-	--
Energy use	++	+	0	-	--
Technical complexity	++	+	0	-	--
Ensiling					
Development status	++	+	0	-	--
Yield	++	+	0	-	--
Energy use	++	+	0	-	--
Technical complexity	++	+	0	-	--

6.1.3 Technical assessment of three valorisation routes for stored seaweed

The result of the technical assessment of seaweed preservation and storage is listed Table *4*. The first indicator used is the development status of the concept. This indicator combines an assessment of the technology readiness level, whether conventional equipment can be used and if there are development or further basic research is required. The second indicator is the product yield, that results from mass balance calculations, where the total yield of targeted products compared to the total feed organic matter is considered. The heat use was quite different for each valorisation concept. Rather than rating an absolute heat requirement, the heat demand of the valorisation routes was compared relative to the heat requirement for seaweed drying (as obtained from the technical design of seaweed drying), considering an equal amount of seaweed processed. The final indicator is the technical complexity. This indicator combines the number of main process steps, where biochemical steps are considered to be more complex and lead to a higher complexity score.

Table 4: Technical assessment of seaweed valorisation routes.

Valorisation	++	+	0	-	--
Development status	Proven in environment	Proven in demo	Development required	R&D required	Further basic research required
Product(s) yield	> 90% of organic mass	90-60% of organic mass	60-30% of organic mass	30-10% of organic mass	10% of organic mass
Energy use per unit of product	<20% of drying	0-75% of drying	75-150% of drying	150-400% of drying	>400% of drying
Technical complexity	1-5 steps, physical	5-10 steps, or 1-5 biochemical	10-15 steps, or 5-10 biochemical	15-30 steps	30+ steps
Fermenation feed/food					
Development status	++	+	0	-	--
Product(s) yield	++	+	0	-	--
Energy use per unit of product	++	+	0	-	--
Technical complexity	++	+	0	-	--
Cascading scheme					
Development status	++	+	0	-	--
Product(s) yield	++	+	0	-	--
Energy use per unit of product	++	+	0	-	--
Technical complexity	++	+	0	-	-
Oligosaccharides					
Development status	++	+	0	-	--
Product(s) yield	++	+	0	-	--
Energy use per unit of product	++	+	0	-	--
Technical complexity	++	+	0	-	--

Valorisation towards functional feed and food through co-fermentation

The seaweed fermentation for feed application is currently successfully deployed in the commercialization phase at the company *Fermentation Experts*. As such, it is a proven technology, and the remaining step is upscaling to the projected production volume. The seaweed is completely used in the process, where part of the sugars is converted into lactic acid. Lactic acid can be digested and is therefore part of the product and not a loss. The final product contains the bioactive components present in the seaweed or that are being formed during the co-fermentation process. As such, the product yield can be considered very good with marginal losses.

The main energy demand of the process is for drying of the final product, next to some minor energy use for heating, transport and mixing. A very large part of the feed is canola meal, and the fermentation is done at a water content that is low (11%) compared to the water content of seaweed (87%), and water addition during fermentation is limited. Consequently, the heat demand is significantly lower than required for seaweed drying.

The technical complexity of the process is limited, having only a few process steps of which one is biochemical. The fermentation process is temperature-controlled and the co-mixing of canola meal meaning that the variations in seaweed composition reduce risks of the processability or affect to a lesser extent the quality of the final product, unlike with ensiling of seaweed.

Valorisation through the cascading scheme

This concept for seaweed valorisation involves a complex scheme aimed at valorisation of all main seaweed constituents (see Figure 5). Though the scheme is based on experimental work, the experimental, most of the conversion and separation data was assumption based because experimental data was lacking or not yet judged representative for a fully developed technology. The current scheme philosophy is to have steps with increasing severity of the treatment. However, other schemes have been proposed, aiming at extracting high-value alginate first. Equipment used is mostly conventional. The extensive use of membrane filtrations requires experimental validation to investigate feasibility in terms of achievable product purity, losses and membrane fouling. This is the same for crystallization where the envisaged separations are yet to be further demonstrated with relevant seaweed-derived syrups.

The cascading scheme makes optimal use of all constituents in the seaweed by stepwise fractionation: hot water extraction, cold water extraction and acid-based alginate extraction. Projected yields give an appropriate product yield with relatively low losses. The energy use is lower than for seaweed drying. This is because alginate precipitation and mannitol crystallization are performed which avoid energy-intensive evaporation. Heat integration options were investigated but their benefits were limited given the low temperature throughout the process.

The technical complexity of the cascading scheme is high. The number of steps is large and consists of 25 sub-sections each having several unit operations. Each section has an impact on multiple downstream sections. However, most operations are physical processes. The membrane separations require special attention and possibly further R&D for selection of suitable membranes, demonstrating large scale, long term operation and avoiding membrane fouling. From experimental results, it is however known that proper control of the alginate product quality is complex and requires in-dept knowledge.

Valorisation of seaweed towards prebiotic oligosaccharides

For this system, the laboratory procedure was translated into an industrial process. The process has been demonstrated at laboratory scale and an assessment of its adaptation using industrial equipment has been made within the techno-economic evaluations of Macro Cascade. Most equipment is conventional and available. The key step in the process is the selective coagulation of extracted xylans. This is done using admixing IPA (iso-propyl alcohol) with the extract. After this, a very large stream of IPA and water needs to be separated via distillation which proves to be an expensive and energy intensive step.

The product yield of the process is very good. The red seaweed feed contains a high amount of xylans, and extraction and conversion efficiencies are good. Also, a separate analysis indicated that the waste stream could be further used in anaerobic digestion. The process design shows that the process has a very high energy demand, primarily for the IPA/water separation. The reason for this is the high mass flow of the water/IPA feed compared to the final product mass flow as well as the high energy demand of this separation.

The technical complexity of the concept is moderate. The process contains a limited number of steps, with two enzymatic steps that require special attention, and a limited number of conventional operations.

6.2 Economic assessment results

The results of the economic assessment are presented as those of seaweed cultivation, seaweed storage, and that of the three valorisation routes assuming a feedstock seaweed price.

6.2.1 Economic assessment of seaweed cultivation

The results of the economic evaluation of seaweed cultivation are presented in Table 5. These are based on the bottom-up economic evaluation performed in the project. Capital expenses (CAPEX) and operating expenses (OPEX) are assessed relative to each other. The results show that both are relevant and have a relatively equal contribution to the cost of cultivated seaweed. CAPEX includes capital investment for the different elements of the cultivation system (grow-out lines, buoys, mooring system and anchors), as well as indirect costs (installation, deployment, engineering, facilities, contingency). These are depreciated using element-specific depreciation periods. The OPEX includes costs of labour, ships rental and maintenance. In this evaluation, it was found that the contribution of the various elements in OPEX and CAPEX is not determined by a single element but consists of contributions of equal orders of magnitude of the different elements. This makes that the estimated cost does depend less on a single cost assumption. It however also has the consequence that reducing the costs of seaweed cultivation is not achievable by addressing a single cost element but needs reduction of various cost elements. Using this approach, the estimated overall interfacing costs of cultivated seaweed delivered on land for preservation and storage is 2 orders of magnitude higher than those of wild harvest seaweed. This means that the cost of seaweed feedstock is in the range of prices that are typical for food applications. Prices for existing market of functional ingredients for cosmetics, feed and chemicals are typically lower, with some exceptions for products with a low market volume. To be suitable for most non-food applications, therefore it is expected that the cost-price of cultivated seaweed needs to be further reduced.

Extrapolation of the current operational costs to larger scale was chosen as approach for the estimation of costs for seaweed cultivation in the business case canvas development task in Macro Cascade. This resulted in significantly lower costs of cultivated seaweed than estimated with the bottom-up approach in the techno-economic evaluation. Through this approach, the direct costs are lower, but the indirect costs are projected to be significantly lower. One important difference between the two approaches is that the economic analysis method is applicable to large corporate businesses, whereas the business canvas extrapolates from lean operated small and medium enterprises. As a result, the seaweed interfacing costs are closer to economic feasibility for the latter approach.

Table 5: Economic assessment of seaweed cultivation

Seaweed cultivation	++	+	0	-	--
Cutivation CAPEX contribution	<25% of wild harvest	25-50% of wild harvest	50-200% of wild harvest	> 200% of wild harvest	>400%of wild harest
Cultivation OPEX contribution	<25% of wild harvest	25-50% of wild harvest	50-200% of wild harvest	> 200% of wild harvest	>400%of wild harest
Cultivated seaweed interfacing costs	<10%	10-25%	25-75%	75-90%	>90%
Seaweed cultivation economics					
Cutivation CAPEX contribution	++	+	0	-	--
Cultivation OPEX	++	+	0	-	--
Cultivated seaweed interfacing costs	++	+	0	-	--

6.2.2 Economic assessment of seaweed preservation and storage

The results of the economic evaluation of seaweed preservation and storage trough either drying, baling and warehouse storage, or through ensiling are presented in Table 6.

For seaweed drying, followed by baling and warehouse storage, the main contribution to the total costs is in the OPEX, specifically for the energy required for drying. Depending on the time required for storage (related to the length of the harvesting season), the OPEX contributes half to three quarters of the costs. In the capital costs, both the investment in a dryer as well as the warehouse are as important.

On the other hand, the share in OPEX is very low for ensiling. The costs of ensiling are dictated by the investment in the storage tanks. The large storage volume required, in combination with the corrosion prevention required for the storage tanks, contribute to the large investment.

All in all, the costs of seaweed preservation, expressed in storage costs per dry matter of preserved seaweed, were found to be quite similar for both methods of preservation and storage. The contribution of preservation and storage to the seaweed costs is less than 10% compared to the costs of cultivated seaweed. However, this contribution will increase when seaweed cultivation costs are lowered.

Table 6: Economic assessment of seaweed preservation and storage.

Seaweed preservation & storage	++	+	0	-	--
CAPEX contribution	<10% of pres/storage costs	20-33% of pres/storage costs	33-66% of pres/storage costs	33-90% of pres/storage costs	>90% of pres/storage costs
OPEX contribution	<10% of pres/storage costs	20-33% of pres/storage costs	33-66% of pres/storage costs	33-90% of pres/storage costs	>90% of pres/storage costs
Cultivated seaweed interfacing costs	5% of seaweed cost	5-10% of seaweed cost	10-25% of seaweed cost	25-40% of seaweed cost	>40% of seaweed cost
Seaweed drying, baling					
CAPEX contribution	++	+	0	-	--
OPEX contribution	++	+	0	-	--
Cultivated seaweed interfacing costs	++	+	0	-	--
Seaweed ensiling					
CAPEX contribution	++	+	0	-	--
OPEX contribution	++	+	0	-	--
Cultivated seaweed interfacing costs	++	+	0	-	--

6.2.3 Economic assessment of seaweed valorisation routes

Various indicators were selected for the economic assessment of the valorisation routes. The first indicator of economic performance is the contribution of the biorefinery cost to the total costs, corresponding to the ratio of CAPEX plus OPEX (excluding seaweed feedstock) to the total production costs (including feedstock). Within the biorefinery costs, the shares of capital costs (CAPEX) and operational costs (OPEX) of the are listed as CAPEX contribution and OPEX contribution, respectively. The final indicator is the comparison of the total final product cost-plus price (see section 5.2 for a definition) to the market price of the products equivalent to those manufactured with in the Macro Cascade routes evaluated. Here all seaweed costs are assumed 10 €/kg and a return on equity of 10% is used in the cost-plus price.

For the seaweed valorisation towards fermented feed product, the feedstock costs are the most important cost factor. In fermentative routes, other cost associated to biorefining have a limited contribution, though not negligible. Within the biorefinery costs, the largest contribution of the biorefinery routes is in the OPEX, with a limited contribution of CAPEX. Most importantly the final cost-plus price of the functional fermented feed product is in the range of the market price which can be obtained for equivalent products. This gives a positive but limited profitability.

For the fermented food case, the feedstock costs of canola meal and the biorefinery costs are higher than for the fermented feed case. This effect is much more pronounced making the contribution of biorefinery costs about 50% larger. Within the biorefinery costs, it is seen that the main contributor is the CAPEX since food grade equipment is required. Also, the plant size is smaller because the market volume for functional food is much smaller than for functional feed. The final product costs of fermented food are therefore higher than for fermented feed. However, market prices are higher for functional food than for functional feed, so a high profitability is projected for fermented food.

In the cascading scheme, the biorefinery costs are limited to 28% of the total costs. Both CAPEX and OPEX are relevant, given the complex scheme with many operations as well as the extent of drying and large amount of chemicals required. CAPEX is in the end the most important contributor corresponding to 2/3 of the total costs. Revenues, using literature market prices, were highest for alginate due to the larger production of this component. Laminarin and mannitol also contributed and despite the fact that fucoidan had a relatively low product yield per unit of dry weight seaweed, its contribution to revenues its large given its high specific price.

Assuming market prices for all co-products and then calculating the effective costs of main product alginate, it was concluded that the resulting cost-plus price for alginate is larger than the current market price for alginate. The main reason here is that the seaweed feedstock, which is the main cost factor, is much more expensive via cultivation as evaluated herein than via wild harvesting, as currently used for European alginate production. Furthermore, it was found that the complex multi-product fractionation scheme proposed herein does not improve the economics when compared to a reference scheme of alginate-only production without cascading production of mannitol, laminarin and fucoidan. The additional CAPEX and OPEX of the co-production of these chemicals do not compensate for their extra revenues. It is seen however that further optimization of such a scheme may bring improvements as will be discussed further in Chapter 8.

The production of prebiotic oligosaccharides suffers from the technical difficulties identified earlier in Section 6.1.3. The IPA/water separation step is both very energy intensive as well as capital intensive leading to high biorefinery costs. This makes that the cost-plus price per unit of mass of product is very high compared to common prebiotic oligosaccharides such as inulin, or other prebiotic oligosaccharides. However, there is a large variance in prices for pre-biotics and when assuming the market price of different higher-value prebiotic oligosaccharides, the gap with the cost-plus price is much lower. The market price is likely be very dependent on the specific pre-biotic functionalities. If functionalities are very specific and of high value, this could translate in a higher market price and reduce the gap between cost-plus price and market price.

Table 7: Economic assessment of seaweed valorisation routes.

Valorisation economics					
Biorefinery contribution to total costs	<10%	20-33%	33-66%	33-90%	>90%
Biorefinery CAPEX contribution	<10%	20-33%	33-66%	33-90%	>90%
Biorefinery OPEX contribution (excl feedstock)	<10%	20-33%	33-66%	33-90%	>90%
Profitability: costplus/market price ratio	<25%	50-100%	75-125%	125-200%	>200%
Seaweed to fermented feed					
Biorefinery contribution to total costs	++	+	0	-	--
Biorefinery CAPEX contribution	++	+	0	-	--
Biorefinery OPEX contribution (excl feedstock)	++	+	0	-	--
Profitability: costplus/market price ratio	++	+	0	-	--
Seaweed to fermented food					
Biorefinery contribution to total costs	++	+	0	-	--
Biorefinery CAPEX contribution	++	+	0	-	--
Biorefinery OPEX contribution (excl feedstock)	++	+	0	-	--
Profitability: costplus/market price ratio	++	+	0	-	--
Seaweed to fractionated products					
Biorefinery contribution to total costs	++	+	0	-	--
Biorefinery CAPEX contribution	++	+	0	-	--
Biorefinery OPEX contribution (excl feedstock)	++	+	0	-	--
Profitability: costplus/market price ratio	++	+	0	-	--
Seaweed to prebiotic oligosaccarides					
Biorefinery contribution to total costs	++	+	0	-	--
Biorefinery CAPEX contribution	++	+	0	-	--
Biorefinery OPEX contribution (excl feedstock)	++	+	0	-	--
Profitability: costplus/market price ratio	++	+	0	-	--

6.3 Environmental assessment results

The results of the environmental assessment are presented as those of seaweed cultivation, seaweed storage, and that of the full chain of cultivation, preservation/storage and either of three valorisation routes.

6.3.1 Environmental assessment of seaweed cultivation

The results of the environmental assessment of seaweed cultivation are depicted in Table 8. The reference chosen is wild harvest of seaweed. The environmental impact associated with materials use for the cultivation system and the GHG emissions and other life cycle impacts are larger than for wild harvest seaweed. Here especially the steel used in the cultivation system had a large impact on the CO_2 footprint. Polymers such as polyurethane used in the buoys had a significant impact on other impact categories (such as e.g. eutrophication categories). As stated earlier, ecological impacts have not been assessed in in the project. It is however worth mentioning that the ecological impact of harvesting in wild harvest is avoided. Knowledge so far in literature is quite limited regarding ecological impacts but first results indicate that some negative but also some positive effects of seaweed cultivation can be expected, such as positive effect on biodiversity.

Table 8: Environmental assessment of seaweed cultivation routes.

GHG emissions (LCA) per kg of product	<20% of wild harvest	20-75% of wild harvest	75-125% of wild harvest	125-200% of wild harvest
Other life cycle impacts	Predominantly positive	Positives with minor negative	Positives with minor negative	Negative with minor positive
Indirect effects	Significant positive effects	Positive effects	Positive and negative effects	Some negative side effects
Environmental: cultivation				
GHG emissions (LCA) per kg of product	++	+	0	-
Other life cycle impacts	++	+	0	-
Other and Indirect effects	++	+	0	-

6.3.2 Environmental assessment of seaweed preservation and storage

No separate environmental assessment was done for seaweed preservation and storage in the project, but for this report an assessment was made based on the difference between seaweed cultivation and cultivation and storage combined. The technologies were assessed against each other to highlight the relative difference. Results are presented in Table 9.

Because of the large heat demand of drying, and absence thereof in ensiling, the ensiling is far less harmful in GHG emissions impact. For other life cycle impact, the steel used in the ensiling storage vessel has some impact, yet here also ensiling is much better than drying because the steel has only a minor contribution compared to the heat for drying. Other and indirect effects are listed to align with the assessment of other parts of the chain, but no significant effects can be expected.

Table 9: Environmental assessment of seaweed preservation and storage

Preservation and storage	**++**	**+**	**0**	**-**	**--**
GHG emissions (LCA) per kg of product	<20% of alterative	20-75% of alternative	75-125% of alternative	125-200% of alternative	200% of alternative
Other life cycle impacts	Predominantly positive	Positives and negative	Positives with minor negative	Negative with minor positive	Predominantly negative
Indirect effects	Predominantly positive	Positives with minor negative	Positive and negative effects, or no significant effects	Negative with minor positive	Predominantly negative
Environmental: drying and bailing					
GHG emissions (LCA) per kg of product	++	+	0	-	--
Other life cycle impacts	++	+	0	-	--
Other and Indirect effects	++	+	0	-	--
Environmental: ensiling					
GHG emissions (LCA) per kg of product	++	+	0	-	--
Other life cycle impacts	++	+	0	-	--
Other and Indirect effects	++	+	0	-	--

6.3.3 Environmental assessment of full chain of cultivation, preservation and valorisation routes

The results of the full chain environment assessment are presented in Table 10. These are for the full chain from seaweed to products for the various valorisation routes and assume drying with fossil energy. It must be noted that the LCA comparison proved to be quite difficult. In some of the cases, the products produced from seaweed are often not directly replacing existing established products but are rather novel with a similar function. Furthermore, results from the LCA were obtained on a mass allocation basis, meaning when assessing the impact of the multiple product cascading scheme, the impact was divided over the products based on their share in product mass flow rate. This might not be a good comparison approach for all components. Especially for health-related applications, allocation based on equivalent key health activities per unit of seaweed-based product would be the optimal approach for comparison. However, the specific health effects are yet to be fully studied and quantified per mass dose.

The results in Table 10 are for the full chain. The main contributor to the CO_2 emissions of the seaweed production is from the material inventory of the cultivation unit (environmental depreciation of equipment parts), rather than the operation itself, as mentioned in Section 6.3.1. As discussed earlier, here especially the use of steel was responsible for around half of the greenhouse gas effect associated with cultivation. Preservation by ensiling has a small contribution to the greenhouse gas emissions. However, preservation by drying can have a high impact, making up to 88% of the contribution of greenhouse gas emissions from cultivation and preservation/storage. When fossil energy is used. Using a renewable energy scenario can reduce the impact of drying by a factor of 4, where solar energy is the main contributor to (electric) drying. Even in such renewable energy scenario, the greenhouse gas footprint of the drying is 3 times that of ensiling.

Table 10: Environmental assessment of the full seaweed to products chains.

Entire chain including valorisation	**++**	**+**	**0**	**-**	**--**
GHG emissions (LCA) per kg of product	<20% of reference	10-50% of reference	50-100% of reference	100-150% of reference	>150% of reference
Other life cycle impacts	Predominantly positive	Positives with minor negative	Positives with minor negative	Negative with minor positive	Predominantly negative
Indirect effects	Predominantly positive	Positives with minor negative	Positives with minor negative	Negative with minor positive	Predominantly negative
Seaweed to fermented feed/food chain					
GHG emissions (LCA) per kg of product	++	+	0	-	--
Other life cycle impacts	++	+	0	-	--
Other and Indirect effects	++	+	0	-	--
Seaweed to fractionated products chain					
GHG emissions (LCA) per kg of product mix	++	+	0	-	--
Other life cycle impacts	++	+	0	-	--
Indirect effects	++	+	0	-	--
Seaweed to prebiotic oligosaccarides chain					
GHG emissions (LCA) per kg of product	++	+	0	-	--
Other life cycle impacts	++	+	0	-	--
Indirect effects	++	+	0	-	--

For the route of seaweed to fermented feed and food product, the contribution of CO_2 emissions from the feedstocks (seaweed and rape meal) and from processing are of equal magnitude, this in spite of the seaweed being only 10% of the total feedstock. This primarily is a result of the large impact of the fossil energy drying of seaweed. Comparison with equivalent products is rather complex. It requires clarity about the specific market application for which the product is intended or competing against. Considering the feed as a replacement of other food/feed products containing protein, a comparison can be made with other protein sources. In this case, the carbon footprint is calculated per unit of protein provided by the product. Through this comparison, the seaweed product had a carbon footprint in the lower range of most plant-based protein products and significantly lower than animal-based proteins. Considering the other impact categories of the environmental analysis, it is seen that the seaweed has a considerable contribution in the ecotoxicity impact and fossil fuel resource use, while having no contribution to land use. Indirect effects worth mentioning are the contributions to animal health in the case of feed and human health in the case of food.

For the cascading scheme of fractionated products, the specific energy use of the co-production of alginate, mannitol, laminarin and fucoidan is compared to the reference production of alginate only. Such a process has the advantage that makes optimal use of the seaweed by extracting all major components. It was found that the co-production scheme has typically more dilute streams than the alginate process, which results in a higher total energy demand per unit of product produced, and thus in GHG emissions of the whole process. For a fully fair comparison it should be compared against separate production of each component. In that case a reduction in specific energy use and GHG emissions can be expected. Considering the other impact factors, there is a contribution from the use of chemicals in the alginate production. This is however not different from conventional alginate production, so the impact is assessed as neutral. Indirect effects worth mentioning are positive health effects that can be expected from the use of fucoidan as an ingredient in nutraceutical products. The increased resource efficiency will also lower all types of indirect effects not directly covered by the study.

The fermented food/feed product and the fractionated products were used as reference for the analysis of the environmental impact of pre-biotic oligosaccharides since there is not data of a clear benchmark product being replaced in the market. It was found that the high energy demand of the process (see the technical evaluation in section 6.1.3) dominates the environmental impact. The greenhouse gas emissions per unit of product are large in absolute terms and compared to the other products obtained through the other routes considered in this study. A fully fair comparison would have been against equivalent products on a mass, or preferably at an equal prebiotic activity basis. However, this requires information on the equivalent components and their pre-biotic activity that was not available at the time of the assessment. For the other impact factors, there is an impact of the large fossil fuel use on relevant factors, as there is from the glucose use. No clear reference is viable, but given the magnitude of the fossil fuel use, this indicator was assessed as (-). Indirect effects worth mentioning are the positive effects on human health that can be obtained with the prebiotic oligosaccharides produced.

7 Social and regional assessment results

The following section presents the results of a social life cycle assessment (s-LCA) and highlights the defined categories and indicators that were set to assess potentially negative as well as positive social effects of the Macro Cascade concepts. The s-LCA covers the entire value chain of cultivation, preservation/storage and all three routes for valorisation. The results are based on the social and regional analysis performed in the project and are presented in Table 11. Here, the indicators are grouped in socio-economic, social-environmental, social-cultural and social-political indicators.

Overall, the Macro Cascade social impacts are positive, for some impact indicators even with the potential to be highly positive. The majority of social impacts are connected and dependent on the environmental, the economic and the overall sustainability performance of seaweed-based value-added products. Therefore, negative performances in each of these aspects can cause a shift towards negative results. This is true even for potentially highly positive social impacts. Underneath the summary table is a detailed description of each risk and it mitigation option.

First, highly positive impacts can be expected in terms of economic growth and development, based on a growing seaweed industry. The higher availability of biomass could also support the change towards a market pull for (value-added) seaweed-based products. As a result, more jobs will be created requiring varying levels of qualification and training. However, there is also a risk of creating a low wage sector, including seasonal work. Proper monitoring standards for seaweed farms operating at large scales will help to avoid such risks. This should include a thorough characterisation and hazard classification (REACH) to ensure health and safety of workplaces. Furthermore, there is potential competition over the regional ocean space. Co-use scenarios in which different forms of ocean usages are combined could mitigate this risk.

Second, there are highly positive effects for the socio-environmental indicators. The effects of seaweeds' CO_2 and nutrients uptake, their ability to release oxygen and their effect on ecosystems and biodiversity in large-scale cultivation systems could help to lower the societal burden to mitigate climate change. It also has the potential to dampen the wave energy that increases the extent of coastal erosion. However, these positive impacts of large-scale seaweed cultivation are strongly site-dependent, which means that potentially positive socio-environmental impacts can turn into negative effects when envisaged sites are not suitable for large-scale seaweed cultivation. Competition for nutrients can impact the health of local marine systems, invasive or non-native species may negatively impact the local biodiversity and too low wave energies could affect sedimentation and nutrient transport. To avoid these risks, site selection for large-scale seaweed cultivation must be based on smart decision-making systems and coupled hydrological-ecological modelling.

Table 11: Social and regional assessment of seaweed cultivation and valorisation.

Social and regional aspects	**++**	**+**	**0**	**-**	**--**
	Very positive	Positive	Neutral	Negative	Very negative
Socio-economic	Significant growth and workplace creation and/or market pull seaweed	Some growth and workplace creation and/or market pull seaweed	Neutral	Some creation of low wage and/or seasonal work, health and safety risks and/or competition over ocean space	Significant creation of low wage and/or seasonal work, health and safety risks and/or competition over ocean space
Socio-environmental	Significant effect on climate change mitigation, nutrient uptake, biodiversity and/or coastal erosion	Some effect on climate change mitigation, nutrient uptake, biodiversity and/or coastal erosion	Neutral	Some emissions, nutrient release, biodiversity loss and/or coastal erosion	Significant emissions, nutrient release, biodiversity loss and/or coastal erosion
Socio-cultural	Significant revival of rural areas, strong entrepreneurship , economic indepence and/or positive public perception	Some revival of rural areas, strong entrepreneurship , economic indepence and/or positive public perception	Neutral	Some resistance industrialisation, and/or influx of non-local workforces and/or changing public perception	Significant resistance industrialisation, and/or influx of non-local workforces and/or changing public perception
Socio-political	Very positive	Postive	Neutral	Negative	Very negative
Socio-economic					
Economic growth and development	++	+	0	-	--
Market pull for seaweed	++	+	0	-	--
Safety and health	++	+	0	-	--
Competition ocean space	++	+	0	-	--
Socio-environmental					
Climate change mitigation	++	+	0	-	--
Nutrient uptake	++	+	0	-	--
Biodiversity	++	+	0	-	--
Coastal erosion	++	+	0	-	--
Socio-cultural					
Revival of rural areas	++	+	0	-	--
Entrepreneurship	++	+	0	-	--
Public perception	++	+	0	-	--
Influx non-local workforce	++	+	0	-	--
Socio-political					
Regional development	++	+	0	-	--

Third, positive socio-cultural impacts follow by developing infrastructure due to the revival of rural areas and/or regions that lack other economic specialisation opportunities. Coastal residents could face new sources of income or opportunities based on a successful seaweed-based economy. In addition, an economically thriving region results in the need of a growing workforce and possibly the influx of non-local workers. Targeted training and qualification programmes for local workers and sound integration strategies for non-local workers can help to preserve social cohesion and local culture of communities. Public perception is also important to discuss as it can pose a significant threat towards upscaling. Coastal residents could have fears of visual and noise pollution and loss of recreational, touristic and property value. Consensus building processes and a focus on the sustainability aspect of seaweed cultivation can help to mitigate these risks.

Last, highly positive effects are assessed for a good financial status and diversified economic opportunities that are expected to lead to regional empowerment at political levels.

Overall, the social impacts on local communities and society in general are expected to be positive, some of them even highly positive, once sustainability criteria for seaweed biorefinery are met and seaweed cultivation is performed based on best practice and sound site selection. However, a few social risks remain even when best practice scenarios are chosen, and sustainability of production chain and product is proven. Mitigation measures can help to lower those risks.

8 Beyond the Macro Cascade cases: improvements for improved prospects of seaweed cultivation and valorisation

The results presented are for the concrete cases developed in the Macro Cascade project. This has the advantage that pros and cons become very specific, and that the analysis can be based on quantitative data. The limitation of such an approach is that many choices need to be made. These include the starting points, system boundaries and assumptions, working out the design, data used in all calculations and a choice of indicators. Uncertainties are an inherent element of these. The most important factors have been addressed in sensitivity studies in the project. Though several iterations were part of the technical design, still the outcome gives input for further improvements.

Firstly it is concluded that the cost of cultivated seaweed is key to further development of a seaweed biorefinery. The results from the techno-economic analysis indicate that here both the operational costs as well as the investments for the cultivation unit need to be reduced. Importantly, reductions in investments for cultivation must also lead to reductions in operating costs (seeding, harvesting and maintenance). Here the use of steel is to be reduced or avoided since this gives the largest environmental impact. Important also is obtaining high biomass yields, since a high yield will directly reduce the cost made per amount of product.

In preservation and storage, ensiling is found to be more attractive in terms of environmental impact, while having similar economics as drying. The suitability of the ensiled seaweed for the downstream biorefinery processes remains an uncertain factor to be addressed experimentally in further R&D. For feed and food, this certainly is not feasible given that this fermentation in ensiling rule out that the feed/food can be again be fermented, but here different production concepts that directly process fresh seaweed could be considered as an alternative. Using fresh seaweed as feedstock will require a steady seaweed supply and long harvesting season, or alternatively a smart integration feed and/or food production with other valorisation methods. A long harvesting season, or multiple harvests throughout the year, was found to be beneficial for preservation and storage costs, particularly for ensiling.

Seaweed drying is challenging in several ways. The environmental impact is significant, and some case studies have been performed on solar-electric drying where the heat is supplied from using electric power with a large share of power generated from solar energy. It was found that such a scheme can significantly reduce the environmental impact, but when the electric mix used in the location of processing still contains a significant amount of fossil energy, the emissions can only be reduced to around one third of the original emissions, thus still higher than ensiling. Reducing the energy use of seaweed drying is limited by thermodynamics. Advanced drying methods such heat pumps could be considered. First, more concrete knowledge about the preferred drying technology and method is required, since knowledge here for upscaled production is limited, and is key to assessing further improvements.

Step-change improvements in the production of functional feed and food are limited because of the relative simplicity of the process. The main challenges here are market development and roll-out. Further evidence from clinical trials such as performed in the Silkeborg Hospital will be very valuable for the food applications.

Despite the fact that the cascading scheme of valorisation makes use of all the main constituents in the seaweed, the economics of the main bulk alginate product is not improved due to the higher CAPEX and OPEX. Several potential improvements have been identified which could lead to improved process performance. The costs of spray drying of the final product streams are very high. Further reduction could be envisaged by further upstream concentration prior to spray drying, or by the selection of an alternative drying method. Membrane separation was found to be capital intensive. Therefore, a review of alternatives for cost reduction is advised. Finally, an overall reconsideration of the process scheme, where some co-production options could be omitted. In that case, not all seaweed constituents would be used, but it could improve overall process economics. In all of these routes, further (experimental) investigation into their feasibility is still key, especially to identify in detail the properties of all intermediate streams, that are required to provide more insight into their application and limitations of the technologies.

For the production of pre-biotic oligosaccharides, the key step is the precipitation of xylans which is induced by addition of IPA as a coagulation agent. This allows for obtaining a pure xylans stream but yields a very large flow of IPA and water which need to be separated at high energy and capital costs. Innovative separations could help to some extent. The main recommendation though is to find an alternative method for isolation of the xylans at sufficient purity for a feasible process. This will help the economics of the concept but at the same time its environmental performance.

Measure to mitigate social risk and risks to local communities were identified and discussed. These include co-use of ocean space, site selection, and for local communities integration programs and consensus building. The proposed mitigation measures can help to lower those risks and have the positive impacts found in economic growth, environment and revival of local communities dominate.

9 Conclusions

The sustainability of seaweed cultivation, preservation and storage and valorisation with different routes was assessed based on cases evaluated in Macro Cascade. After a discussion of the underlying conceptual design results, the sustainability was evaluated using qualitative metrics of economic, environmental and social aspects in a structured discussion.

For the economic feasibility, it was found that the most interesting route on the short term is for fermented feed. Furthermore, very good opportunities are expected for the smaller market of fermented food given the high market price/cost-plus price ratio. For a cascading scheme, aiming at making optimal use of all seaweed constituents, further optimization is still required to find a better balance between increased costs and product revenues. For valorisation towards pre-biotic oligosaccharides, the process economics suffer from high separation costs, thus significant changes in the process are still required to improve feasibility. For all concepts, the interfacing price of cultivated seaweed is a concern. Though being quite uncertain, different approaches lead to different estimated prices for seaweed cultivated at large scale. The price of cultivated seaweed could still be significant and future cost reductions are a key element for further deployment.

In environmental terms, it was found that GHG emissions from the production of fermented feed/food products from seaweed as a protein source are in the low range of other plant-based protein sources. However, comparison of the other seaweed products with existing replaceable products proved difficult. GHG are the main burden in terms of environmental impact of the seaweed products resulting from drying with fossil energy. This can be only partly mitigated with the implementation of renewable energy. Additionally, emissions associated to chemicals used in the cascading scheme can be also significant. The two main benefits of the functional feed and food product as well as for the pre-biotic oligosaccharides are in the indirect effects on human and/or animal health, as well as the negligible impact on land use.

The prospects of the cascading valorisation of seaweed through producing multiple products was evaluated. It is concluded that in all three elements of the value chain there are technical options for significant improvement, which will lead to improvement of all three aspects of sustainability.

The social and regional analysis showed that social impacts on local communities and society in general are expected to be positive, some of them even highly positive, once sustainability criteria for seaweed biorefinery are met and seaweed cultivation is performed based on best practice and sound site selection. However, a few social risks remain even when best practice scenarios are chosen, and sustainability of production chain and product is proven. Mitigation measures can help to lower those risks.

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