Advisory Report on opportunities for seaweed in the protein transition

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Executive summary

The urgency to transform food systems is great. Seaweed is seen as a potentially sustainable source of plant-based proteins for the protein transition. The province of Zuid-Holland has asked the European Seaweed Association to investigate whether and how seaweed proteins can contribute to healthier and more sustainable food systems with the central question: **Can seaweed play a significant role in the protein transition for a healthier and more sustainable food system, and if so, how?**

A number of sub-questions have been formulated that are answered in this advisory report. The sub-questions focus on the current use of seaweed proteins and extraction techniques, suitable species, relevant parties, market applications and the possible role of the province of Zuid-Holland in fostering this protein transition.

The main findings from the study are as follows:

- There is little to average interest in seaweed proteins from the market. Seaweed proteins are hardly used in the market. Not as an extract nor as part of a non-extracted seaweed ingredient (fresh or dried). In terms of seaweed extracts, we are now mainly looking at specific sugars or a mix of extracts for specific applications (e.g. biostimulants)
- There is a lot of interest in seaweed derived proteins in research, as they are considered a promising alternative to animal and plant sources. Traditional refining is leading to preferential processes and interesting results have been obtained when paired with marine microorganisms.
- European and national policy objectives on raw material availability, sustainability, healthier food and plant-based proteins offer many opportunities for seaweed proteins. After all, seaweed can be produced locally and on a large scale and there are species that contain sufficient protein.
- To capitalize on this opportunity, this report proposes focusing on the use of seaweed in food to drive the necessary transition to more plant-based proteins. Focusing on the further development and upscaling of hybrid meat products is identified as a readily available and scalable means of achieving this.
- At the same time, it is recommended to do more research into improving extraction (scale, cost price) and into seaweed species with more protein content and better protein composition (breeding).
- The province of Zuid-Holland can play a valuable role in the development of the European seaweed industry by actively linking it to the existing innovation infrastructure and European regional collaborations. In addition, the province can use hybrid meat products with seaweed to help meat producers in the region with the transition to more sustainable business operations.

Based on this advisory report, a roadmap for seaweed proteins has been drawn up with the following ambition:

By 2050, the European seaweed industry will provide one fifth of the extra vegetable proteins needed for Europeans. By then, vegetable proteins will comprise half of all daily protein intake for Europeans.

To achieve this ambition, some 16 million tonnes of fresh seaweed per year will be needed by 2050. Important bottlenecks are identifying (and breeding) the right seaweed species and reducing their production costs (e.g. with a production subsidy). The biggest opportunity lies in the further development and scaling up of hybrid meat products with seaweed.

1 Introduction

In today's world, food systems are increasingly criticized for their harmful effects on both human health and the systems that support all life. The growing world population will only increase pressures. Food systems are often linked to intensive agricultural practices, an abundance of processed foods, and a consumer culture that not only promotes environmental pollution, but also contributes to the increasing prevalence of chronic diseases[1].

Research shows that the consumption of ultra-processed foods, which are often rich in sugar, salt and unhealthy fats, is closely linked to an increased risk of obesity, type 2 diabetes and cardiovascular disease (Monteiro et al., 2018). In Northwest Europe and the United States, obesity has increased rapidly in recent decades, a trend that is strongly influenced by the availability of cheap, unhealthy foods. In addition, our food systems have led to a decrease in dietary diversity. The monoculture practices that are widely adopted result in a limited variety of crops, which not only reduces the nutritional value of our meals, but also leads to a lack of essential nutrients in the human diet[2]. This particularly affects vulnerable populations, such as children and the elderly, who are more at risk of nutritional deficiencies.

The impact of food systems extends beyond human health; they also have far-reaching consequences for environmental sustainability. Current agricultural practices are responsible for a significant amount of greenhouse gas emissions, contributing to global warming. According to the FAO (2019), the agriculture and food production sectors account for about 30% of global greenhouse gas emissions. This is mainly due to deforestation, the use of artificial fertilizers and the intensive use of fossil fuels. In addition, industrial livestock farming has caused significant environmental problems, including biodiversity loss, water pollution, and overexploitation of natural resources. The production of meat and dairy requires much more water and land than plant-based alternatives, leading to unsustainable pressures on our ecosystem services[3] (Gerber et al., 2013).

In short, it is clear that current food systems are not only harmful to our health, but are also the biggest driver for crossing planetary boundaries. A transformation of the global food system is urgently needed. Without adequate action, the world runs the risk of failing to meet the UN Sustainable Development Goals (SDGs) and the Paris Agreement. If we do want to achieve this, we need to focus on 1) promoting healthy diets in which, among other things, vegetable proteins play an equal or preferably greater role (instead of animal proteins; protein transition), 2) supporting sustainable agricultural practices and 3) stimulating local food production[4].

Because seaweed may play an important role in the above-mentioned solution directions, and in particular in the protein transition, the province of South Holland has asked the

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[1] EAT-Lancet_Commission_Summary_Report.pdf
[2] David Tilman, Christian Balzer, Jason Hill, and Belinda L. Befort, "Global Food Demand and the Sustainable Intensification of Agriculture," *Proceedings of the National Academy of Sciences* 108, no. 50 (2011): 20260–20264, https://doi.org/10.1073/pnas.1116437108
[3] Gerber, J., et al., *Global Food Systems and Land Use Efficiency*, Environmental Research Letters, 2013.
[4] EAT-Lancet_Commission_Summary_Report.pdf

European Seaweed Association to come up with an advisory report. The report will try to answer the question of whether and how seaweed can play a significant role in the necessary protein transition for a healthier and more sustainable food system. For the formulation of the theoretical framework, research/projects from the last ten years were analyzed as a basis for further interview questions.

To also get a picture of the actual situation in the seaweed market/chain, interviews were conducted with organizations that may be working on solving this central question. In line with this, attention will be paid to the possible role that the European Seaweed Association can play as a trade association of the European seaweed industry and the province/Netherlands as part of this transition.

2 Central question

2.1 Introduction

Seaweed is increasingly mentioned as a potential source of protein. However, it remains unclear to what extent seaweed can play a role in the protein/food transition. It is true that seaweeds contain proteins, but whether a contribution can be made to the protein transition is often still unclear. There is of course a difference between seaweeds in terms of composition (and therefore protein content), but the application or extraction method is also not yet clear or feasible. For the time being, it seems especially relevant to focus on varieties that can be grown, contain sufficient protein and are scalable at a regional and/or European level.

In recent years, a lot of research has looked at protein extraction in seaweeds. However, this knowledge is not always known to stakeholders or widely accessible. It would be valuable to improve this situation. We need to set clear goals: Are there opportunities for seaweed proteins, what opportunities are there concretely, how can we use them and what ambition fits with this?

North Sea Farmers (NSF) can play an important role in this by identifying the opportunities and making them known to its supporters and relevant stakeholders. In addition, NSF can help to allocate the necessary actions to the relevant stakeholders. In addition, NSF wants to specifically investigate what role the province of South Holland can play in these opportunities.

2.2 Central question

The following question is therefore central to this advisory report:

Can seaweed play a significant role in the necessary protein transition for a healthier and more sustainable food system and if so, how?

2.3 Sub-questions

The central question can be broken down into the following sub-questions:

1. What techniques are there for the extraction of proteins from seaweeds?
2. Which seaweeds are most suitable for the protein transition?
3. Which (seaweed) parties are already able to play a role in the protein transition in terms of technology and upscaling?
4. Are there already examples in the food/feed market in which seaweed is used as a protein source (extracted protein)?
5. What is an achievable ambition for the European seaweed industry within the protein transition towards 2050?
6. What role can the province of Zuid-Holland play in this transition?

3 Research proposal

To answer the questions, literature research and interviews were used.

3.1 Literature review

To gain more insight into the desired ambition for the role of seaweed in the protein transition and to get an overview of the latest state of affairs regarding techniques for protein extraction, a literature review was conducted. As a starting point, the relevant (seaweed) research projects from the past ten years were analysed. From this, an overview has been drawn up of research institutes/groups and their relevant (type of) research to answer the above sub-questions. For each study, a short summary of the research and the (relevant) results was given.

3.2 Interviews

Additional insights were also obtained by conducting interviews with organizations that have knowledge of or are active in the seaweed chain. North Sea Farmers has used its broad network to identify and interview these parties. A lot of attention was paid to which (seaweed) parties can play a role in the protein transition. In this report, the findings of 33 interviews are described. They were semi-structured and based on the following interview questions:

1. What is the level of knowledge/expertise within the organization with respect to seaweed in the protein transition? This was assessed by NSF from the interview and then scaled with a Likert scale:
    - No knowledge
    - Basic knowledge
    - Some knowledge
    - Advanced knowledge
    - Expert knowledge
2. Are techniques already being used for protein extraction from seaweed, and if so, which techniques and with what volumes?
3. Are there already examples of protein extracts from seaweed that are processed in food products?
4. What are the plans for processing seaweed in relation to the protein transition?
5. With regard to proteins, which business model will the organization focus on?
6. Who or what is necessary to move forward with this development?
7. What role can the province of South Holland and the Netherlands play in this?

The results of the interviews provide an overview of the actual state of affairs in the European seaweed chain in the application of seaweed in the protein transition.

4 Literature review: insights from relevant research projects

4.1 Introduction

In recent years, extensive research has been conducted into the possibilities of seaweed. In this study, as many studies as possible were identified that looked at seaweed proteins. Subsequently, the concrete results were examined for each study and whether they offer starting points for the development of seaweed as a source of vegetable proteins for the protein transition.

4.2 Proteins in seaweed

To better understand the opportunities with seaweed proteins, it is important to better understand the properties of these proteins and the difference with land-based vegetable proteins. This has been explained very clearly in an earlier literature study as carried out by Wageningen University[5]. Below is a copy of the relevant passage from this study:

'Seaweeds have a completely different structure than land plants. Seaweeds do not have differentiated cells and cell structures for leaf, stem and root like land plants. Seaweeds have a thallus, possibly with a structure that ensures that the plant does not float away. There are no roots, stems and vessels with which juices are transported, nor any lignocellulose for strength. Just like land plants, seaweeds have cell walls that, among other things, absorb the overpressure in the cell (turgor). Algae have found a different solution for this from an evolutionary point of view than land plants and their cell walls are therefore thicker and heavier. The cell wall of seaweeds consists of several layers of sulfur-containing, branched carbohydrates, polyphenols, alginate (brown algae) and carrageenan (red algae) with protein in between. This different structure of tissue means that protein isolation from seaweed is less efficient with existing methods such as those developed for land plants.

The protein in seaweed is present in different forms, each with a specific function:

- *Enzymes. These are present in the cell and help with chemical conversions. A well-known enzyme involved in photosynthesis and the capture of CO2 by plants, algae and seaweed is RuBisCO. In land plants, soluble protein from leaves can consist of as much as 30-50% RuBisCO. Publications such as by Iñiguez et al. (2019) indicate that many types of seaweed contain lower concentrations of RuBisCo (<10%) compared to the total soluble protein. Only species such as Saccharina spp (37.3% RuBisCO in total soluble protein) and Laminaria spp (24.7-30.1%) were close to wheat leaves (42.3%) in terms of RuBisCO content that had been taken as a control. The researchers could not completely rule out that this conclusion could also be influenced by extraction efficiency, because many secondary metabolites and polysaccharides present in seaweeds will affect protein solubility. Protein isolation protocols such as those developed for e.g. beet leaves will therefore also be less effective.*
- *Glycoproteins. These are present in the cell wall, on the cell surface and outside the cell. They bind to carbohydrates and have the function of sticking cells together. Such protein-carbohydrate complexes disrupt the isolation of protein.*

[5] https://edepot.wur.nl/548874

- *Proteins that are part of the photosystem with which light is captured. Red algae are phycobilliproteins, which are responsible for the red colour. Phycobilliproteins can capture the blue/green light that can penetrate relatively far into the water. The number of photosystems, and thus the amount of these proteins, is adjusted by the seaweed to the amount of light present. This is one of the explanations why protein content varies between seasons, in addition to the fact that younger plant parts can have higher concentrations than older parts and that sink-source fluxes change continuously according to the need for growth and dormancy that are related to climate conditions.*

Seaweeds do not form seeds or pods (reproductive components), which contain relatively little water and many concentrated proteins. Moisture-rich material requires more energy input for processing, for example because of transport, heating and drying of the materials. There may be small differences in protein concentrations between thallus and the leaf-like parts, but it can be said that protein extraction from seaweed will involve processing the entire crop, which requires a relatively large energy input.

In general, the protein content in red algae (7-47% of dry weight) is the highest, followed by green algae (9-26% of dry weight) and brown algae (3-15% of dry weight) (Dumay & Morançais, 2016). In many of the current business cases for the North Sea, the cultivation of Saccharina and Ulva is chosen because these native species can be grown relatively well on cultivation installations. In the TO2 North-Sea-Weed-Chain project (IMARES report C055/16) Saccharina (brown algae) was used with levels between 5-20% protein, and Ulva (green algae) with an average of 9.5% protein by dry weight. The large variation is caused by variation in species (there are more than 10,000 algae), cultivation conditions (availability of nutrients and light) and time of harvest (spring or summer). An important factor that also plays a role is the nitrogen-to-protein factor that is used in the analysis of the protein content. Sometimes 6.25 is used instead of 5 as advised in the literature (Lourenco et al., 2002; Angell et al., 2016; Bjarnadottir et al., 2018; Pliego-cortes et al., 2019). Use of the factor 6.25 leads to overestimation of the protein content.'

In the remainder of the research, it is important to take into account that in terms of protein extraction, the greatest opportunity lies with the enzymes and proteins that are part of the photosystem. In addition, the type of seaweed is important, in terms of color, species and growing conditions. From this you could deduce that an optimization of the production chain is needed specifically for the protein application to make it technically and commercially feasible. This is not even the form of that application (extract or whole seaweed).

4.3 Identified seaweed surveys

The table below provides an overview of the identified seaweed studies with a protein component and whether the results may be useful for further study within this study. In other words, projects that have looked at seaweed protein but have not shown positive results in this area have not been looked at further in terms of content.

Name of research	Partners	Objective	Applying input to seaweed in protein transition
FromSea2Society	NIOZ, WUR, Hortimare Westerdijk Institute	Research on alternative production chain of proteins in marine, efficient, sustainable, low trophic aquaculture chain (LTA)	Positive, further analysis of research
Seaseeds	NIOZ, WUR, Hortimare Westerdijk Institute	Research into better adhesion of seed to lines/net structures	Negative, research does not contribute to the question
CircAqua	NIOZ, WUR, Hortimare Westerdijk Institute	Research into improving the upscaling of seaweed production by means of technology and organization	Negative, research does not contribute to the question
ProSeaweed	WUR, NSF	Possibilities of seaweeds grown in the Netherlands as a sustainable source of food. This also includes a protein study	Positive, further analysis of research
SuproSea	UGent, UAntwerp, ILVO, Bio Base Europe Pilot Plant	The development of sustainable proteins from seaweed for food purposes	Positive, research only just started so **no results yet**
Nordic Innovation (CircleFeed, MacroValue)	Nordic Innovation	Promoting a circular economy through innovative data exchange and cooperation between companies (Nordic).	Negative, research does not contribute to the question
Norwegian Seaweed Biorefinery Platform (SBP-N)	Sintef, Norwegian Research Council	Promoting the production and processing of seaweed for the Norwegian bioeconomy, with results for the use of seaweed as a raw material in various industries	Positive, further analysis of research
ALEHOOP	Contactica, ILVO, Horizon Europe, Bio-based industries consortium (BIC)	Developing sustainable alternatives to animal proteins. The project has proven that it is possible to process plant and algae residues into high-quality, low-priced food and feed proteins with biorefineries.	Positive, further analysis of research
CirkAlg	Chalmers, University of Gothenburg	Focused on circular economy and algorithms, explores how algorithms can contribute to optimizing circular business models and sustainable production processes	Negative, research does not contribute to the question
MARIKAT	DTU Food, Lund University	The project focuses on harnessing proteins from marine biomass, with a specific focus on seaweed and other marine resources.	Positive, further analysis of research
North-Sea-Weed-Chain	TNO, WUR, Deltares, MARIN	Focuses on the development of a sustainable seaweed production chain in the North Sea.	Negative, research does not contribute to the question
SeaSolutions	Teagasc	Focuses on exploring sustainable solutions for aquaculture and the conservation of marine ecosystems	Negative, research does not contribute to the question
SeaHealth	Teagasc	Focuses on marine health and the opportunities to harness seafood in the context of nutrition and sustainability.	Negative, research does not contribute to the question
BioAlgae	Teagasc	Focuses on the production of microalgae and its application in various sectors, including food, animal nutrition and biofuels in the context of nutrition and sustainability.	Negative, in this study only macroalgae

Name of research	Partners	Objective	Applying input to seaweed in protein transition
ASTRAL	Norce, Horizon Europe	Focuses on developing innovative technologies and strategies for sustainable energy production and storage	Negative, research does not contribute to the question
ASPIRE	University of Galway, Horizon Europe	Focuses on improving the research infrastructure and promoting collaboration between different research institutions.	Negative, research does not contribute to the question
BLUE IODINE II	Horizon Europe	Focuses on the development and implementation of innovative solutions for the management of iodine in the food chain.	Negative, research does not contribute to the question
FEEDACTIV	Horizon Europe, University of Agronomic Sciences and Veterinary Medicine (USAMV)	Focuses on the development and optimization of diets for livestock to improve the sustainability of livestock farming.	Negative, research does not contribute to the question
CIRCALGAE	Chalmers, Horizon Europe	Focuses on the use of algae in a circular economy, particularly in terms of sustainability and environmental management	Negative, research focuses on environmental impact
PROTEUS	Horizon Europe, Institute of Marine Research (IMR)	Focuses on contributing to the sustainable development of marine ecosystems and the protection of their biodiversity.	Negative, research focuses on environmental impact
MACRO CASCADE	Lund University, TNO, DTU	Focuses on developing an integrated biorefinery technology for processing seaweed, specifically macroalgae, to create sustainable, valuable products for various industries	Positive, further analysis of research
TRANSALGAE	Botnia Atlantica	Focuses on developing algae production in the Nordic region for sustainable energy and environmentally friendly applications.	Negative, research focuses on environmental impact
SeaWheat	Møreforsking	Focuses on exploring seaweed as a sustainable source of food and biomaterials, with a particular focus on its environmental and economic benefits	Positive, further analysis of research
SaferIMTA	Møreforsking	Contains important insights for the sustainable development of aquaculture through the integrated breeding of multiple organisms.	Negative, research focuses on environmental impact
PROMAC	Sintef, Møreforsking, Norwegian Research Council	Aimed at developing sustainable methods for using macroalgae (seaweed) as a raw material	Positive, further analysis of research
SusKelpFood	DTU Food, Møreforsking, Institute of Marine	Focuses on the sustainable and nutritious use of seaweed (kelp) as a source of nutrition.	Positive, further analysis of research

Name of research	Partners	Objective	Applying input to seaweed in protein transition
	Research (IMR), Nofima		
Protein Port	Protein Port	Traditional animal proteins are no longer sustainable for future food production. Research on the use of plant, microbial and insect proteins.	Negative, research focuses on land-based solutions
Sweaweed	Chalmers, University of Gothenburg	Focuses on the potential of seaweed as a sustainable food source and the ecological benefits of seaweed cultivation in Swedish waters	Positive, further analysis of research
Kelp-EU	Oceanium (Company)	Focuses on the opportunities and challenges of kelp as a sustainable food and raw material source within Europe.	Positive, further analysis of research
ValgOrize	ILVO	Focuses on the ecological and economic value of seaweeds and microalgae and the role of marine organisms in ecosystem conservation	Negative, research focuses on environmental impact

Table 1: Overview of identified seaweed studies with a protein question plus an assessment of relevance for this literature review

4.4 Relevant studies with key findings

The relevant studies have been examined in more detail below and assessed for relevance to this research and the associated sub-questions. This forms the input for the theoretical framework and thus the interview questions.

4.4.1 FromSea2Society

4.4.1.1 Description of the research

Research into alternative production chain of proteins in marine, efficient, sustainable, low trophic aquaculture chain (LTA), which is based on biomass from offshore cultivation of seaweed. They will be supported by breakthroughs from the life sciences, such as breeding sterile seaweeds, innovative bio-refinery and insight into the carrying capacity of the natural marine ecosystem.

4.4.1.2 Time frame

2023-2027

4.4.1.3 Key findings in relation to seaweed and the protein transition

- Protein extraction from seaweeds
    - The project has developed methods to efficiently extract proteins from different types of seaweed (such as Ulva, Ascophyllum nodosum, and Laminaria digitata). These proteins are seen as promising alternatives to animal proteins, especially in the context of the circular economy and sustainable food production. The techniques include alkaline and enzymatic

extraction processes, looking at preserving the functional properties of the proteins, such as solubility and emulsification capacity.

- Enzymatic hydrolysis was found to be more effective than conventional chemical methods, especially when marine fungal enzymes were used. Marine fungi enzymes come in a variety of forms, including cellulases, proteases, lipases, and amylases, each of which catalyzes specific biochemical reactions. This points to a synergistic approach to biotechnology, in which marine fungal enzymes promoted the breakdown of cell walls in seaweed and released the proteins more easily.

- The digestibility and solubility of the extracted proteins were also examined, which is crucial for their potential as a dietary source.
- Marine fungi as a source of protein
  - The role of marine fungi, such as Trichoderma and Cladosporium, has been investigated in the context of their ability to produce proteins and other bioactive compounds that can be valuable to both the food industry and the pharmaceutical sector.
  - Enzymatic production of proteins by marine fungi has the potential to generate high-value products, with a particular focus on fermented proteins, which are easier to digest and often exhibit better functional properties in food applications.
  - The use of fungal substrates (such as seaweed) to increase the protein content of the fungi was examined. This could contribute to the efficiency of bio-conversion processes and reduce dependence on traditional protein sources.
- Bioactive peptides and functional properties
  - During protein extraction, a lot of attention was paid to the bioactive peptides released from the seaweed and fungi. These peptides have antioxidant, antibacterial and other health-promoting properties, which makes them valuable not only for the food industry, but also for other sectors such as cosmetics and pharmaceuticals.
  - Seaweed peptides from species such as Ulva showed significant antioxidant activity. This suggests that the proteins from seaweed may also provide health benefits in addition to their role as a nutritional component.

4.4.2 ProSeaweed

4.4.2.1 Description of the research

The ProSeaweed project, led by Wageningen University & Research (WUR) in the Netherlands, has achieved important breakthroughs in the field of functional protein extraction from brown algae, in particular Saccharina latissima and Undaria pinnatifida.

4.4.2.2 Time frame

2017-2022

4.4.2.3 Key findings in relation to seaweed and the protein transition

- Protein Localization and Extraction Challenges:

- In brown algae, proteins are found in various cell compartments, such as glycoproteins in the cell walls, enzymes in the cytoplasm and proteins in photosystems in the cell membranes.
- The complex carbohydrate network of alginate, fucoidan and cellulose in the cell walls poses a challenge for protein extraction, which requires effective methods for cell wall breakdown.

- Effectiveness of mechanical and enzymatic treatments:
  - Mechanical treatments alone resulted in about 35% of the total proteins in the liquid fraction, both for Saccharina and Undaria.
  - Undaria showed a higher protein content (14% of dry weight) compared to Saccharina (10% of dry weight), resulting in higher protein concentrations in the extracts.
  - Combining mechanical and enzymatic treatments with commercial carbohydrases slightly increased the protein yield (up to about 40% in Saccharina); However, many cells remained intact, demonstrating limited effectiveness.
- Limitations of commercial enzymes:
  - Commercial carbohydrases, which are designed for terrestrial plant carbohydrates, were less effective at breaking down specific polysaccharides in seaweed.
  - This limitation highlights the need for specialized enzymes capable of effectively breaking down cell wall components of seaweed, in order to improve protein extraction efficiency.
- Functional properties of the extracted proteins:
  - Despite lower than desired yields, the crude protein extracts exhibited functional properties, such as gelling ability, suggesting potential as functional ingredients in foods.
- Future directions:
  - It was recognized that the current enzymes are inadequate. Therefore, collaboration has been started to identify and develop specific enzymes, derived from marine fungi, that can effectively break down seaweed cell walls. This will improve protein yields and lead to commercially viable extraction processes.

4.4.3 Norwegian Seaweed Biorefinery Platform (SBP-N)

4.4.3.1 Description of the research

The research within the project focuses on the properties of macroalgae biomass, the development of technologies that enable economically and environmentally sustainable biorefinery processes, and the establishment of production chains for high-value products and bulk products.

4.4.3.2 Time frame

2019-2024

4.4.3.3 Key findings in relation to seaweed and the protein transition

Further analysis of the research shows that no specific research has been done into the possibilities of proteins and seaweed.

4.4.4 ALEHOOP

4.4.4.1 Description of the research

The project focuses on the development and validation of innovative bio-based ingredients, in particular bio-functional and technologically advanced proteins. These are produced from green and brown algae as well as legumes. One of the core activities is to design and optimize a bio-refinery process for macroalgae, aimed at extracting proteins from green and brown algae species. The goal is to achieve maximum protein yields on a laboratory scale, both in quantity and quality.
In addition, the project aims to demonstrate the ecological and economic feasibility of the developed bio-refineries. This is done through comprehensive life cycle assessments (LCA) and life cycle cost calculations (LCC). These analyses use advanced modelling tools to achieve an optimised and sustainable design for the biorefineries.

4.4.4.2 Time frame

2020-2024

4.4.4.3 Key findings in relation to seaweed and the protein transition

The project has developed new biochemical and fermentation techniques to extract and concentrate proteins from alternative sources, such as microalgae, macroalgae and by-products from the food industry, more efficiently. The project developed efficient methods to extract proteins from seaweed with high yield and purity. This was achieved by:

- Mild extraction technologies, such as enzymatic hydrolysis, to keep the protein structure intact.
- New biotechnological techniques that increased efficiency through enzymatic pre-treatment and fermentation processes, aimed at higher yields and lower environmental impact.
- Supercritial fluid extraction; Deploy supercritical fluids to extract compounds from various matrices, such as seaweed, to isolate bioactive compounds and proteins from seaweed without loss of quality.

Technological innovations: ILVO and Contactica have contributed to the development of an integrated approach to the separation and concentration of functional proteins, with a particular focus on the preservation of bioactive components.

- Impact: Up to 85% of the available protein from biomass could be recovered with a higher degree of purity than with traditional methods.

In addition, the use of enzymes has improved the functionality of proteins, including better solubility (wide PH range), emulsifying properties and increased bioactivity.

In line with this, insights were also gained about protein extraction in a broader bio-refinery process. In addition to proteins, other valuable components, such as polysaccharides and bioactive substances, were also used. This maximized the economic value of the seaweed and minimized waste. Pilot facilities have been set up to scale up and test the extraction processes in industrial conditions.

Circular valorisation of residual flows

The project emphasizes the value of circular biorefinery concepts by combining agro-industrial waste streams, such as potato peels and beet pulp, with micro-algae cultivation. This resulted in proteins that compete with traditional sources, both in terms of cost and quality.

4.4.5 MARIKAT

4.4.5.1 Description of the research

The MARIKAT project focuses on harnessing proteins from marine biomass, with a specific focus on seaweed and other marine resources.

4.4.5.2 Time frame

2020-2023

4.4.5.3 Key findings in relation to seaweed and the protein transition

- Protein extraction efficiency
  - The project has developed innovative methods to extract proteins from seaweed more effectively, with an emphasis on gentle physicochemical techniques.
  - Supercritial fluid extraction; Deploy supercritical fluids to extract compounds from various matrices, such as seaweed, to isolate bioactive compounds and proteins from seaweed without loss of quality.
  - The combination of enzymatic hydrolysis and mild pre-treatment methods (e.g. ultrasonic and microwave-assisted extraction) led to a significant improvement in protein yield, with yields of up to 70% depending on the seaweed species.
- Nutrient composition and quality
  - Extracted proteins showed high nutritional value, with essential amino acids in amounts comparable to conventional animal proteins.
  - Seaweed proteins were found to have bioactive properties, such as anti-oxidative and anti-inflammatory effects, highlighting their potential as a functional food ingredient.
- Marine biomass as a sustainable source
  - The project has identified seaweed species such as Saccharina latissima and Palmaria Palmata as particularly suitable due to their high protein content and relatively simple processing requirements.
  - The seasonal variation in protein content was mapped, which led to recommendations for optimal harvest periods.
- Applications in food
  - Successful formulation of protein-rich prototypes, such as plant-based meat alternatives and fortified snacks. The taste and texture profiles were positively assessed by consumer panels.
  - Admixture of marine proteins into existing food products showed no negative impact on taste, while nutritional value was improved.

4.4.6 MACRO CASCADE

4.4.6.1 Description of the research

The MARCO CASCADE project focused on the development of innovative solutions for the valorisation of biomass, including seaweed, via cascade processing. The project focuses on proving the concept of cascading marine macroalgae bio-refinery.
The project looked at scalable and sustainable extraction/separation methods for the production of multiple products from brown and red seaweeds or seaweed residues by enzyme-supported physicochemical methods. Intended intermediates are alginate, fucoidan, mannitol and protein.

In addition, a variety of efficient and robust carbohydrate-active enzymes were examined, with a range of characteristics relevant to the processing of macroalgae polysaccharides. Intended high-quality products for animal feed, food, pharmaceuticals, cosmetics and chemicals are enzymatic derivatives of alginate, laminarin and fucoidans.

4.4.6.2 Time frame

2017-2020

4.4.6.3 Key findings in relation to seaweed and the protein transition

In the context of protein extraction and seaweed, the main outcomes are as follows:

- Optimization of protein extraction methods
    - Mild extraction technologies: The project emphasized the use of enzymatic hydrolysis and pH-driven methods for efficient extraction of soluble proteins without affecting their functionality.
    - Enzymatic hydrolysis
        - Process description: Specific enzymes were selected to break down seaweed cell walls, which promotes the release of soluble proteins.
        - Innovation: The use of optimized enzyme cocktails reduced the need for harsh chemical agents and increased protein yield.
        - Advantages: Higher functionality of proteins (e.g. solubility and emulsification) and preservation of bioactive properties.
    - Limitation of co-extraction of impurities: By optimizing process parameters, unwanted co-extraction of polysaccharides, phenols, and other components was limited, leading to higher protein purity.
    - pH-controlled extraction
        - Effect: by adjusting the pH, proteins were reversibly dissolved and precipitated.
        - Results: increased purity of the protein fraction and efficient separation of polysaccharides and phenols.
        - Scaling up: this technology turned out to be scalable with a relatively low environmental impact.
    - Supercritial fluid extraction;
        - Deploy supercritical fluids to extract compounds from various matrices, such as seaweed, to isolate bioactive compounds and proteins from seaweed without loss of quality.
- Focus on functionality of seaweed proteins

- Emulsifying and foaming properties: The extracted proteins showed potential as emulsifiers and foam stabilizers in food applications. The functional properties of seaweed proteins (e.g. foaming and emulsifying ability) make them suitable for products such as plant-based milks, sauces, and vegan alternatives.
- Bioactive properties: In addition to nutritional value, some proteins were found to have bioactive properties, such as antioxidant and anti-hypertension effects.

- Scale-up strategies
  - Pathways have been developed for the scale-up of extraction processes, while maintaining high yields and minimal impact on the environmental footprint.
  - Integral use of seaweed: The project emphasized cascading seaweed components, further using residues from protein extraction for bio-based materials or bioenergy.
- Comparison of seaweed species
  - Species-specific characteristics: different seaweed species, such as brown algae (e.g. Saccharina latissima) and red algae (e.g. Palmaria palmata), provided varying protein yields and functionalities.

4.4.7 SeaWheat

4.4.7.1 Description of the research

The SeaWheat project, which focused on the development of new applications for seaweed in the food industry, has yielded several scientific and technological breakthroughs. In collaboration with Møreforsking and other partners, a multidisciplinary study was carried out into both the cultivation techniques and the processing of seaweed. The main results are summarised below:

4.4.7.2 Time frame

2022-2025

4.4.7.3 Key findings in relation to seaweed and the protein transition

- Efficiency in seaweed cultivation and sustainability
  - Improved cultivation methods: the project developed innovative techniques for the cultivation of brown algae, such as sugar algae (Saccharina latissima). These techniques increased productivity per unit area by more than 20%, while minimising the ecological impact (e.g. on local biodiversity).
  - Circular processes: a clear integration of seaweed cultivation in circular aquaculture systems was demonstrated. Residual flows from fisheries and aquaculture were successfully used as nutrients for seaweed growth.
- Functional proteins
  - Protein extraction: the focus on mild extraction processes with enzymatic hydrolysis in combination with membrane filtration resulted in the isolation of high-quality seaweed proteins with a solubility of more than 80%, suitable for application in food. This makes seaweed a potential substitute for soy and pea proteins.
- Consumer Adoption and Product Development

- Consumer research: surveys have shown that there is a growing interest in seaweed-based food products, particularly in European markets. Transparency about sustainability and origin was experienced as essential.
- Product prototypes: The project developed several food prototypes, including protein-rich snacks, vegan spreads, and seaweed-enriched pastas. These were tested for sensory properties and consumer acceptance, with positive results.

- Economic potential
  - Cost-effectiveness: Improved cultivation and extraction methods have significantly increased the economic efficiency of seaweed products. This facilitated the upscaling to industrial applications.

4.4.8 PROMAC

4.4.8.1 Description of the research

The PROMAC (Protein from Marine Aquatic Crops) project is a research initiative aimed at optimising protein extraction from marine sources, such as seaweed and aquatic crops, with the aim of producing sustainable, high-quality proteins for the food and feed industry.

4.4.8.2 Time frame

2015-2018

4.4.8.3 Key findings in relation to seaweed and the protein transition

- Extraction techniques
  - The project has investigated advanced extraction techniques to improve the yield and quality of proteins from marine crops. Both chemical and mechanical processes were evaluated, such as:
    - Enzymatic hydrolysis: This process uses specific enzymes to extract the proteins from the cell walls of seaweed and other aquatic crops. It turned out that enzymatic hydrolysis is a more efficient way to isolate proteins, while retaining their functional properties, such as solubility and gel formation, which is important for applications in the food industry.
    - Ultrasonic extraction: This was used to break the cell structure of the seaweed, leading to higher protein yields and better extraction quality, especially for hard-to-extract proteins.
    - Changing pH conditions: Adjusting the pH during extraction was also found to affect the solubility and quality of the proteins. At lower pH values, a greater yield of soluble proteins was achieved, which facilitated their use in food and feed products.
    - Supercritial fluid extraction; Deploy supercritical fluids to extract compounds from various matrices, such as seaweed, to isolate bioactive compounds and proteins from seaweed without loss of quality.
- Protein quality and functional properties:
  - Another important aspect of the research was the evaluation of the functional properties of the extracted proteins, such as:

    - Solubility: Marine proteins showed different solubility patterns depending on the extraction method used. This has direct implications for their application in liquid food products.
    - Emulsifying and foaming properties: The proteins from seaweed and aquatic crops showed potential for use as emulsifiers in food. This makes them attractive for the production of plant-based alternatives to dairy and meat.
    - Amino acid profile: The proteins of seaweed contain a complete amino acid profile, which makes them suitable as a high-quality protein source for human consumption. The amino acids such as glutamic acid and aspartic acid are present in abundance, which contributes to the nutritional value of the proteins.
- Applications in animal nutrition and human nutrition:
    - The functional properties, such as digestibility and amino acid profile, make these proteins suitable for use in both the human and animal food chains.

4.4.9 SusKelpFood

4.4.9.1 Description of the research

The SusKelpFood research project focused on the sustainable use of brown algae, such as sugar algae (Saccharina latissima), in food products. The project has gained insights into seaweed production, nutritional value, food safety and consumer acceptance.

4.4.9.2 Time frame

2018-2022

4.4.9.3 Key findings in relation to seaweed and the protein transition

- Protein Composition and Extraction Efficiency
    - Protein content: The crude protein content of Saccharina latissima varied between 6% and 12% of the dry weight, depending on the growing location, seasonality and processing technique. This is lower than in other protein sources such as legumes, but still valuable due to its functional properties.
    - Extraction efficiency: Innovative extraction methods, such as enzymatic hydrolysis combined with membrane filtration, have been shown to be effective in isolating proteins with high bioavailability. A combination of milder enzymatic processes (tested by Nofima and DTU Food) led to higher yields without structural damage to the proteins.
- Nutritional value of seaweed proteins
    - Amino acid profile: The proteins contain all the essential amino acids, especially methionine, lysine and leucine, which makes them suitable as a complete protein source. Its amino acid profile was found to be competitive with other plant sources such as soy and peas.
    - Bioactivity: Enzymatically hydrolyzed seaweed proteins showed bioactive properties, including anti-oxidative and anti-inflammatory effects. This offers opportunities for functional foods.
- Applications in food production
    - Functional properties: Seaweed proteins showed good emulsifying and foaming properties, which increases their potential for applications in plant-based dairy and meat alternatives.

    - Salt reduction: The use of seaweed proteins as flavor enhancers (umami effect) showed that they can support salt reduction in processed foods. Research from IMR pointed to synergy with other seaweed components such as glutamate and fucose.
- Consumer Acceptance and Food Safety
    - Sensory properties: Consumer panels from Nofima and DTU Food gave positive feedback on products that incorporated purified seaweed proteins, but a "seaweed-like" aftertaste remains a challenge with less refined fractions.
    - Food safety: Tests by IMR confirmed that toxic metals (such as cadmium and arsenic) remained below safe levels when strict harvesting and processing guidelines were followed.

4.4.10 Sweaweed

4.4.10.1 Description of the research

The Sweaweed project focused on developing sustainable solutions for the valorization of seaweed, with a particular focus on protein extraction and application. Together with Chalmers and the University of Gothenburg, important steps were taken in understanding the potential of Swedish-grown seaweed as a source of high-quality protein.

4.4.10.2 Time frame

2017-2020

4.4.10.3 Key findings in relation to seaweed and the protein transition

- Protein composition and bioactivity
    - Analysis of seaweed biomass: The protein composition of different seaweed species, such as Saccharina latissima and Ulva lactuca, was extensively investigated. Ulva lactuca was found to have a higher protein content (up to 20-25% of the dry matter), while Saccharina latissima was found to be higher in carbohydrates.
    - Functional properties: The extracted proteins showed interesting bioactive properties, such as antioxidant and anti-inflammatory effects, which enhances their potency for use in functional foods and nutraceuticals.
- Optimization of extraction technologies
    - Mild extraction methods: The study emphasized the importance of mild, environmentally friendly extraction techniques, such as enzymatic hydrolysis and membrane filtration. These techniques not only ensured a higher protein yield, but also preserved the bioactivity of the proteins.
    - Comparison of technologies: Mechanical techniques combined with enzymatic processes proved to be more effective than chemical methods, contributing to a more sustainable production process.
- Potential for human nutrition
    - Nutritional value: The amino acid profiles of the extracted proteins were compared with conventional protein sources, such as soy and whey protein. Although seaweed proteins contain some amino acids to a limited extent (such as lysine and methionine), they can play a complementary role in protein-rich products.

4.4.11 KELP-EU

4.4.11.1 Description of the research

The KELP-EU project, led by Oceanium Ltd in Scotland, focused on advancing seaweed cultivation and developing a seaweed bio-refinery process in Europe. This project, funded by the European Maritime and Fisheries Fund, aims to contribute to both food security and the reduction of carbon emissions through a circular economy.
The project has several goals, including scaling up the processing of European seaweed, to 150 tonnes per year, and the development of new products such as kelp protein, fibre, fucoidan and beta-glucans. The short-term ambition was to build a bio-refinery plant (pilot) with a capacity of 5000 tons per year. In addition, the project focused on improving cultivation and processing methods.

4.4.11.2 Time frame

2021-2023

4.4.11.3 Key findings in relation to seaweed and the protein transition

The project has focused on the use of sugarweed (*Saccharina latissima*) and wingweed (*Alaria esculenta*), which represent half of European seaweed cultivation. The proteins and other bioactive compounds from these species are processed through a biorefinery process that makes full use of the biomass.

4.5 Analysis of relevant studies

4.5.1 Introduction

In order to gather the relevant insights regarding the feasibility of seaweed proteins from the above identified studies, analyses were carried out on the following subtopics:

- Summary and assessment of the different extraction techniques
- Identification of the types of seaweed used for protein extraction
- Examples and/or food products in which protein extraction (based on seaweed) is processed
- The possibility of adding value to other (nutrient) substances in addition to protein extraction (bio-refinery)

4.5.2 Summary of the different extraction techniques used in projects

4.5.2.1 Alkaline extraction

Alkaline extraction is a chemical process that is widely used for extracting biomolecules such as proteins, polysaccharides, and other components from biomass.

- Chemical base: Alkaline extraction involves treating materials with a high pH solution, often based on sodium hydroxide (NaOH) or potassium hydroxide (KOH).
- Mechanism: High pH leads to swelling of cell walls, hydrolysis of bonds (such as ester bonds), and solubility of specific components such as proteins and polysaccharides.
- Optimal conditions: The exact parameters (such as pH, temperature, and duration) vary depending on the source and the desired end product.

Applications

- Protein extraction:
    - Alkaline conditions dissolve proteins by avoiding their isoelectric point.
    - Often used with vegetable proteins (soy, peas) and seaweed proteins.
    - Useful for obtaining functional proteins with improved solubility.
- Polysaccharides:
    - Extraction of sulfate polysaccharides such as fucoidan from brown seaweed.
    - High pH helps loosen cell walls and release complex polysaccharides.
- Bioactive substances:
    - Release of phenolic compounds or other bioactive components.
    - Efficient in treating by-products (e.g. peels, stems) for value addition.

Advantages

- Efficiency: Quick and easy method to release desired components.
- High yield: Often higher yields than other methods, especially with solid biomass such as seaweed.
- Scalable capable: Easy to implement on an industrial scale.

Disadvantages

- Denaturation:
    - Proteins and other biomolecules can be degraded or denatured at extremely high pH.
    - Limited usability for applications where natural structures are required.
- By-products:
    - Production of unwanted by-products through hydrolysis or oxidation.
    - May cause discoloration or change in taste and texture.
- Environmental impact:
    - Alkaline solutions require neutralization or careful disposal to avoid environmental damage.
- Specific equipment needed:
    - High pH requires the use of corrosion-resistant equipment.

4.5.2.2 Supercritical fluid extraction (sfe)

This is an innovative separation technique that uses supercritical fluids to extract compounds from various matrices, such as seaweed. A supercritical fluid is in a physical state between liquid and gaseous, which occurs above the critical temperature and pressure of a substance. The most commonly used medium for SFE is supercritical carbon dioxide (CO_2) due to its mild critical conditions (31.1°C and 73.8 bar), low toxicity and environmental friendliness.

Pre-treatment of the seaweed
The seaweed is typically dried and finely ground to increase the surface area and increase the efficiency of extraction. Enzymatic hydrolysis can be applied to break down the cell walls and improve the accessibility of proteins.

Selection of supercritical fluid
CO_2 is often chosen for its stability, but the polarity of CO_2 is low. Therefore, co-solvents such as ethanol can be added to increase the solubility of polar compounds, such as proteins and amino acids.

Extraction process

- The ground seaweed is placed in an extraction chamber.
- Supercritical CO_2, possibly mixed with a co-solvent, is passed through the matrix under controlled temperature and pressure conditions.
- The supercritical fluid penetrates deep into the matrix and disburses the target substances, such as proteins.

Separation of extracted compounds

When the mixture of supercritical fluid and dissolved compounds is passed out of the extraction chamber, the pressure and temperature are reduced. This returns the CO_2 to gaseous form, so that the dissolved substances precipitate and can be collected.

Purification of proteins

The extracted proteins can be further purified by additional processes such as filtration, chromatography or drying techniques.

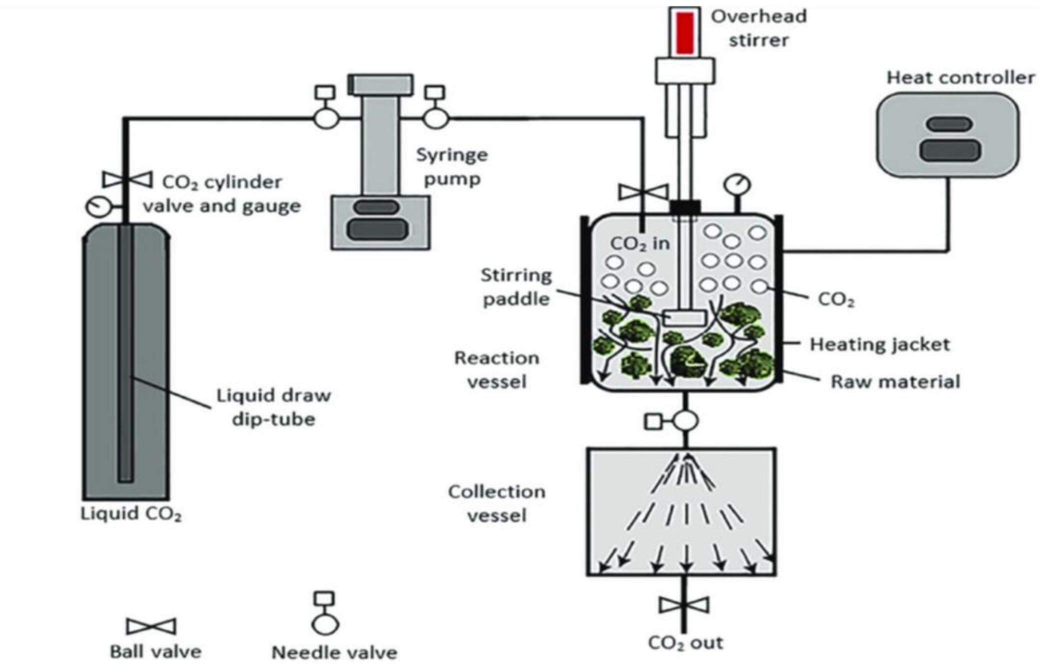


Figure 1: Overview of the SFE set-up[6]

Benefits of SFE for Seaweed Protein

- Environmentally friendly: The use of CO_2 is sustainable and leaves no harmful solvent residues.
- Precision: By adjusting pressure and temperature, selectivity for specific compounds can be improved.

[6] Alzaidi, Mohammed & Kumar, Pavan & Ismail-Fitry, M.R. & Jusoh, Shokri & Faris, Muhamad & Ab Aziz, Muhamad Faris & Sazili, Awis Qurni. (2021). Green Extraction of Bioactive Compounds from Plant Biomass and Their Application in Meat as Natural Antioxidant. Antioxidants. 10. 1465. 10.3390/antiox10091465.

- Quality: SFE is a gentle technique that ensures minimal denaturation of proteins.

Challenges of Protein Extraction from Seaweed with SFE

- Cell wall resistance: Seaweed has sturdy cell walls that make extraction difficult. Pre-treatment is often necessary.
- Polar nature of proteins: CO_2 alone is less effective at dissolving polar compounds, making co-solvents essential.
- Cost: The equipment required and energy intensity make SFE a relatively expensive technique.

4.5.2.3 Enzymatic extraction

Enzymatic extraction is a method of isolating specific substances from biomass by using enzymes that specifically break down certain bonds in cell walls or cell structures.

- Enzymes such as cellulases, hemicellulases, pectinases, and proteases are used depending on the target component. For example:
    - Proteases for protein extraction.
    - Cellulases for the breakdown of cellulose and release of sugars.
    - Alginate lyases for isolating alginates from seaweed.
- Pre treatment
    - Mechanical or thermal pre-treatments (such as grinding or heating - Microwave-Assisted Extraction) improve enzymes' access to intracellular components.
    - Ultrasound breaks open cell walls, allowing enzymes to gain easier access to their substrates during hydrolysis.
- Reactor conditions
    - Optimal pH and temperature are chosen based on the type of enzyme.
    - Batch, semi-continuous or continuous processes can be applied.

Advantages

- Mild conditions: No need for high temperatures or harsh chemicals.
- Specific targeting: Enzymes break down specific binding sites, leading to higher purity.
- Durability: Reduces the use of solvents and minimizes waste streams.

Disadvantages

- High cost of enzymes: Enzymes that can specifically degrade seaweed polysaccharides are often expensive and have limited commercial availability, making the process costly.
- Low efficiency in brown algae: The complex and firm cell wall structure of brown algae, which is high in alginate and fucoidan, makes it difficult for enzymes to work effectively, leading to low yields.
- Longer processing time: Enzymatic processes are relatively slow, as enzymes take time to break down the cell walls. This hinders large-scale and efficient production.

Applications

1. Protein extraction from seaweed

   - Enzymatic hydrolysis can release proteins that are tightly bound to the cell walls of macroalgae.
2. Polysaccharide insulation
   - Alginate, carrageenan, and fucoidan are efficiently extracted by enzymes without chemical degradation.
3. Bioactive substances
   - Polyphenols, lipids, and other bioactive compounds can be isolated with minimal degradation.
4. Food ingredients and biofuels
   - Seaweed and other biomass are processed into high-quality ingredients or biobased chemicals.

4.5.3 Assessment of the above extraction techniques in relevant projects

4.5.3.1 Sea2Society

It shows that enzymatic hydrolysis is more effective than conventional chemical methods (alkaline), especially when marine fungal enzymes were used.

4.5.3.2 Proseaweed

From ProSeaweed, it is particularly striking that the returns are very low. This seems to be due to the use of enzymes that are not suitable for the brown algae Saccharina and Undaria. It is also striking that Undaria has been used in this project in contrast to all other projects.

4.5.3.3 ALEHOOP

The ALEHOOP project also looked at enzymatic hydrolysis, to keep the protein structure intact. In addition, new biotechnological techniques were used that increased efficiency through enzymatic pretreatment and fermentation processes. In short, an innovative and integrated approach with the aim of optimizing downstream processing processes for separating and concentrating (membrane separation methods) functional proteins from alternative sources.
Impact: up to 85% of the available protein from biomass could be recovered with a higher degree of purity than with traditional methods.

4.5.3.4 MARIKAT

The MARIKAT project has also focused on a combination of enzymatic hydrolysis and mild pre-treatment methods (ultrasonic and microwave-assisted extraction). This has led to a significant improvement in protein yield, with yields of up to 70% depending on the seaweed species.

4.5.3.5 Macro Cascade

In the Macro Cascade project, research has also been done on enzymatic hydrolysis. Specific enzymes were selected to break down seaweed cell walls, which promotes the release of soluble proteins. By using optimized enzyme cocktails, the need for aggressive chemicals was reduced and the protein yield increased. By optimizing process parameters, unwanted co-extraction of polysaccharides, phenols, and other components was limited, leading to higher protein purity. In line with this, experiments were also carried out with alkaline (pH-controlled) extraction.

4.5.3.6 SeaWheat

The SeaWheat project also focused on mild extraction processes with enzymatic hydrolysis in combination with membrane filtration. This resulted in the isolation of high-quality seaweed proteins with a solubility of more than 80%, suitable for application in food.

4.5.3.7 PROMAC

The PROMAC project also investigated enzymatic hydrolysis and mild pretreatment methods (e.g. ultrasonic extraction). In this project, results were also achieved in which up to 70% of the available proteins could be recovered from certain types of seaweed.

4.5.3.8 SusKelpFood

The SusKelpFood project also looked at innovative extraction methods, such as enzymatic hydrolysis combined with membrane filtration. Once again, it was found that these techniques are effective in isolating proteins with high bioavailability.

4.5.3.9 Sweaweed

Here too, enzymatic hydrolysis and membrane filtration were examined in the Sweaweed project. These techniques not only ensured a higher protein yield, but also preserved the bioactivity of the proteins. It has also been shown that mechanical techniques in combination with enzymatic processes proved to be more effective than chemical methods, which also contributed to a more sustainable production process.

4.5.3.10 Kelp-EU

Within this project, enzymatic hydrolysis was also applied, followed by ultrafiltration. This was used to make a concentrate that contained a reasonable concentration of proteins.

4.5.3.11 Final observations

Looking at all projects/studies, it can be concluded that one method is more successful for protein extraction from seaweed, namely **enzymatic hydrolysis with mechanical cell disruption** as a pre-treatment. The main features of this method were:

- Pre-treatment: Drying and grinding seaweed was crucial to open the cell structure. This process improved enzyme access to intracellular proteins.
- Enzymatic hydrolysis: The use of specific enzymes, such as proteases, resulted in a higher protein yield. Enzymes such as Alcalase and Papain were found to be effective in breaking down the cell wall and releasing the proteins.
- Mechanical cell disruption: Methods such as high-pressure homogenization or ultrasonication were used to increase the efficiency of the enzymatic hydrolysis. This allowed for better access to the intracellular fractions.
- Selective extraction with mild solvent: Use of aqueous solutions with a mild pH adjustment (pH 8–9) was shown to be effective for protein dissolution without leaving harmful residues.
- Drying techniques: After extraction, proteins were concentrated and dried using techniques such as spray drying, to preserve the functional properties.

Results and efficiency:

- Protein yield: Up to **80%** of the available protein could be recovered from certain types of seaweed.
- Protein quality: The amino acid profiles of the extracted proteins were suitable for human consumption and showed a good balance of essential amino acids.
- Sustainability: The method reduced the use of chemicals and energy compared to traditional extraction methods such as acid hydrolysis.

4.5.4 Identification of the types of seaweed used for protein extraction

In the **FromSea2Society project**, the following seaweeds were investigated, namely: Ulva (sea lettuce/green algae), Ascophyllum nodosum (club wrack/brown algae) and Laminaria digitata (finger algae/brown algae). Saccharina l. and Undaria p. are used in ProSeaweed. In the **MARIKAT** project, seaweed species such as Saccharina latissima (sugar algae/brown algae) and Palmaria palmata (palm algae/red algae) have been identified as particularly suitable due to their high protein content and relatively simple processing requirements. The **MARCO CASCADE** project looked at the same seaweeds as the MARIKAT project. SeaWheat and **Sweaweed** looked at the protein composition of the seaweed species Saccharina latissima (sugar algae/brown algae) and Ulva lactuca (sea lettuce/green algae). Ulva lactuca was found to have a higher protein content (up to 20-25% of dry matter), while Saccharina latissima was found to be higher in carbohydrates. The **PROMAC** project also looked at Saccharina latissima (sugar algae/brown algae). In addition, Alaria esculenta (Wing algae/brown algae) has also been studied. The **SusKelpFood** research project focused on the sustainable use of brown algae, such as Saccharina latissima (sugar algae), in food products. The **KELP-EU** project focused on Saccharina latissima (sugar algae/brown algae) and Alaria esculenta (Wing algae/brown algae), as these seaweeds represent half of European seaweed cultivation. The above is also clearly shown in the table below.

4.5.5 Tabulated overview

Below are all the studies that actually show results from extraction tests.

Research project	Extraction method used	Used seaweed	Results	Time Frame
FromSea2Society	Enzymatic hydrolysis, mechanical cell disruption	Ulva (sea lettuce), Ascophyllum nodosum, Laminaria digitata	70% protein yield, functional properties retained	2023-2027
ProSeaweed	Enzymatic hydrolysis, mechanical cell disruption	Saccharina latissima (sugar algae), Undaria pinnatifida	40% protein yield, functional properties (partially) intact	2017-2022
SusKelpFood	Enzymatic hydrolysis, membrane filtration	Saccharina latissima (sugar algae)	High bioavailability, higher yields	2018-2022
SeaWheat	Enzymatic hydrolysis, membrane filtration	Saccharina latissima (sugar algae), Ulva lactuca (sea lettuce)	Solubility >80%, food-grade	2022-2025

Research project	Extraction method used	Used seaweed	Results	Time Frame
KELP-EU	Enzymatic hydrolysis, membrane filtration	Saccharina latissima (sugar algae), Alaria esculenta (wing algae)	New products such as kelp protein, fiber developed	2021-2023
PROMAC	Enzymatic Hydrolysis, Ultrasonic Extraction, Changing pH	Saccharina latissima (sugar algae), Ulva lactuca (sea lettuce), Palmaria palmata	High protein yield, functional properties retained	2015-2018

Table 2: Overview of research projects and their results from extraction tests

4.5.6 Examples and/or food products that incorporate protein extraction

4.5.6.1 MARIKAT

The MARIKAT project developed protein-rich prototypes, such as plant-based meat alternatives and fortified snacks. The taste and texture profiles were deemed desirable by consumer panels. Admixture of marine proteins into existing food products showed no negative impact on taste, while nutritional value was improved.

4.5.6.2 Macro Cascade

In the Macro Cascade project, it was mainly demonstrated that the extracted proteins have the potential to be used as emulsifiers and foam stabilizers in food applications. The functional properties of seaweed proteins (e.g. foaming and emulsifying ability) make them suitable for products such as plant-based milks, sauces, and vegan alternatives. As far as could be judged, no actual product (prototypes) was made during this project.

4.5.6.3 SeaWheat

Product prototypes have also been developed at SeaWheat. Think of protein-rich snacks, vegan spreads and seaweed-enriched pastas. These were tested for sensory properties and consumer acceptance, with positive results.

4.5.6.4 PROMAC

The PROMAC project mainly looked at the functional properties, such as digestibility and amino acid profile. Research has shown that these proteins are suitable for use in both the human and animal food chains. As far as could be judged, no actual product (prototypes) was made during this project.

4.5.6.5 SusKelpFood

The SusKelpFood project has also shown that seaweed proteins have good emulsifying and foam-forming properties, which increases their potential for applications in plant-based dairy and meat alternatives. In addition, it emerged that the use of seaweed proteins as flavor enhancers (umami effect) can also result in a salt reduction in processed foods. As far as could be judged, no actual product (prototypes) was made during this project.

4.5.6.6 Sweaweed

Finally, the **Sweaweed** project looked specifically at nutritional value. The amino acid profiles of the extracted proteins were compared with conventional protein sources, such as soy and whey protein. Although seaweed proteins contain some limiting amino acids (such as lysine and methionine), they can play a complementary role in protein-rich products. As far as could be judged, no actual product (prototypes) were made in this project.

4.5.6.7 Observations

From all the projects, it can be concluded that protein extraction from seaweed is very minimally processed in food products. Apart from a number of product prototypes, there are currently **no food products** on the market that use this protein extraction. However, the potential of seaweed proteins has been demonstrated by the functional properties of foaming, emulsifying effect and flavour enhancement (umami), which makes salt reduction possible. In the long term, this would make application in food products (technically) possible.

4.5.7 The possibility of adding value to other substances in addition to protein extraction

4.5.7.1 ALEHOOP

The ALEHOOP project also looked at the value of circular biorefinery concepts by combining agro-industrial waste streams, such as potato peels and beet pulp, with micro-algae cultivation. This resulted in proteins that compete with traditional sources, both in terms of cost and quality.

4.5.7.2 Macro Cascade

The Macro Cascade project focuses on cascading seaweed components, where residues from protein extraction were further used for bio-based materials or bio-energy.

4.5.7.3 Kelp-EU

The most concrete project on bio-refinery is the KELP-EU project. The ambition has been expressed to process 150 tonnes of European seaweed per year in products such as kelp protein, fibre, fucoidan and beta-glucans. The short-term ambition is to build bio-refinery (pilot) with a capacity of 5000 tons per year.

4.5.7.4 Observations

After analyzing all the projects/studies, the conclusion is that nowhere in Europe is there a bio-refinery (not even a pilot) that commercially uses side streams in addition to the production of seaweed proteins. Extracting proteins from seaweed is not yet done in a commercial biorefinery environment.

5 Interviews

5.1 Introduction

In order to get a better picture of the practical uses for seaweed protein, in addition to the theory/research, a wide range of people (organizations) were interviewed who are (in)directly part of the seaweed chain.

5.2 Interviewees (organisations)

Below is a comprehensive list of the organizations and people within who took part in interviews (online and physical).

No.	Organization	Name	Core activity	Position
1	GOA ventures	Arnaud Backbier	Development of biorefinery techniques	Processor
2	IlVO Flanders	Johan Robbens	Research organisation	Research
3	Sintef	Jorunn Skjermo	Research organisation	Research
4	TNO	Jaap van Hal	Research organisation	Research
5	Teagasc	Maria Hayes	Research Organisation (National Ireland)	Research
6	Green Cell Technologies	Roy Henderson	Development of biorefinery techniques	Processor
7	Origin by Ocean	Marc Desmarais	Development of biorefinery techniques	Processor
8	Nestlé	Christophe Fuerer	Food producer	Application s
9	Sea & Believe	Jennifer O Brien	Ingredient producer	Processor
10	RVO	Saske Hoving	Government of the Netherlands	Facilitator
11	Bodec	Frank de Boeff	Development and production of biorefinery	Processor
12	NIOZ	Klaas Timmermans	Research organisation	Research
13	Westerdijk Institute	Ronald de Vries	Research organisation	Research
14	The Blue Cluster	Sofie van den Hende	Network organization	Facilitator
15	Westerdijk Institute	Raquel Ledo Doval	Network organization	Facilitator
16	The Blue Cluster	Jurgen Adriaen	Network organization	Facilitator
17	Contactica	Sara Lago	Project management	Facilitator
18	Ghent University	Floriele Gonzaga	Research organisation	Research
19	Ghent University	Jessica Knot	Research organisation	Research
20	Møreforsking	Celine Rebours	Research organisation	Research
21	Chalmers	Ingrid Undeland	Research organisation	Research
22	Protein Port	Bram Kerssemakers	Network organization	Facilitator
24	Eco Cascade	Alison Baker & Jemima Cooper	Ingredient producer	Processor
26	Tekkoo	Alexander Ebbing	Project management	Facilitator
27	Wageningen UR	Antoinette Kazbar	Research organisation	Research
28	Oceanium	Charlie Bavington	Ingredient producer	Processor
29	Seaweed Food Solutions	Foppe Wiersma	Ingredient producer	Processor

30	Ocean Rainforest	Urd Grandorf Bake	Seaweed and ingredients producer	Farmer/ Processor
31	Murre Technologies	Jan Murre	Seaweed processing machinery	Facilitator
32	Rovensa Next	Camila Levy	Ingredient producer	Processor
33	North Seaweed	Hessel Altenburg	Ingredient producer	Processor
34	Algaia	Franck Hennequart	Ingredient producer	Processor
35	EABA conference	Not applicable	Network organization	Facilitator

Table 3: Overview of the 35 people interviewed to gain more insight into the development, production and use of seaweed proteins in practice

This report describes the findings from 35 interviews. As described in chapter 3 The following questions were asked. The most important findings and conclusions will be shared for each question.

5.2.1 Level

What is the level of knowledge/expertise within the organization with respect to seaweed in the protein transition? (Likert scale: 1. No knowledge – 2. Basic knowledge – 3. Some knowledge – 4. Advanced knowledge – 5. Expert knowledge)

In the interviewed group, there is quite a lot of knowledge about seaweed in relation to the protein transition. With an average grade of 3.9, it is almost advanced knowledge. The interviewees also include many research organizations that are connected to the previously described projects/studies (chapter 4).

5.2.2 Use of extraction techniques

Are techniques already being used for protein extraction from seaweed, and if so, which techniques and with what volumes?

Yes, techniques are used for protein extraction, but these are all still in the pilot phase as carried out for projects/research (the largest has <500L production capacity per year). There is **no** production capacity yet in operation for protein extraction from seaweed. The techniques with the corresponding volumes mentioned by the interviewees are numbers that they think they can realize (capacity) if there is demand. Then it immediately goes to large numbers where the highest production capacity is 1 million liters per year that they can increase tenfold in 10 years. Of the latter group, they already have production capacity for processing biomass, but not specifically for seaweed (protein). In addition, there is also sufficient capacity available in Europe for enzymatic hydrolysis in combination with mechanical pre-processing as this is a standard technique. But this is also not currently used for seaweed (protein) as far as could be assessed in this study. This means that the interviewed parties do not have it, but that they also do not know anyone who already does.

5.2.3 Examples with protein extracts

Are there already examples of protein extracts from seaweed that are processed in food products?

Apart from product prototypes as mentioned in the studies/projects, no food products have been mentioned/known in which a protein extract of seaweed is processed.

To date, the commercial application of isolated seaweed proteins has been limited, as the development of efficient and cost-effective extraction methods is still under investigation. For products in which such extracted proteins can play an important role, the possibilities are being investigated in:

- Functional foods, such as protein supplements and shakes.
- High-quality food products that require specific nutritional claims, such as hypoallergenic products.

The barriers often lie in the cost of extraction, the taste of the pure protein and the (missing) functionality.

There are many food products known in which seaweed proteins play an important role, but these proteins end up in these products through the direct addition of unprocessed seaweed.

5.2.4 Seaweed and the protein transition

What are the plans for processing seaweed in relation to the protein transition?

In relation to protein extraction from seaweed, the focus is mainly on the development of techniques for extraction (see also all projects in chapter 4). There are few plans for the development of products that have market value/potential. The developments are therefore mainly technically driven (pioneering phase) instead of market-driven. So far, no organizations have been found that have succeeded in developing a sustainable business model with seaweed proteins from the technique (extraction).
For the direct application of unprocessed (not extracted) seaweed for vegetable proteins in food products, it is a different story. The functional foods and hybrid meat/fish markets offer many opportunities. Especially because the other functional benefits of seaweed can also be used optimally. See further chapter 6.

5.2.5 Feasible business models with seaweed protein

Which business model will the organization focus on?

In this pioneering phase, no organizations were found with a clear business model with extracted proteins from seaweed. If one looks at seaweed protein at all (i.e. companies and not research projects), the focus is on improving extraction techniques and (feasibility of) certification (in the context of food market regulation). Despite the fact that this is not directly indicated in interviews, the observation is also made that after this, or in parallel, possible protein products and opportunities in the market should be examined. Sustainable business models already exist for the direct application of unprocessed (non-extracted) seaweed.

5.2.6 Who or what is needed to move forward

Who or what is necessary to move forward with this development?

In terms of extraction, it seems wise to see which proteins can be efficiently extracted from which proteins and with which techniques. From these, you can then select the most promising combinations, in terms of technical and commercial feasibility, for further optimization. More targeted research and innovation projects can support this.
Shorter strokes are possible by supporting organizations that process seaweed directly into food products and thereby increase its protein content. Think of applications such as those mentioned in chapter 6.

5.2.7 Role of the Province of South Holland

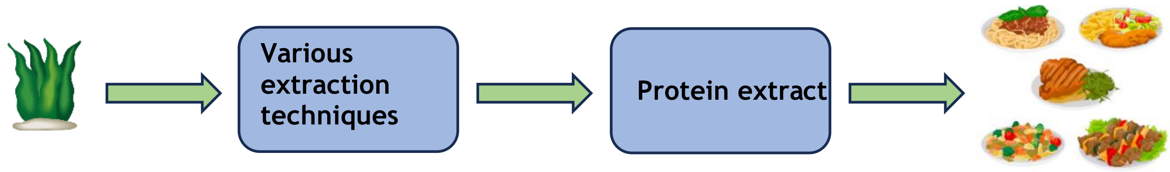
What role can the province of South Holland and the Netherlands play in this?

The province of Zuid-Holland and the Netherlands can play a pioneering role in stimulating the European seaweed sector. This can be achieved by creating an attractive investment climate, in particular through subsidies, public-private partnerships and investments in research and development (R&D). Consider, for example, the financing of innovative projects such as seaweed farms, a processing plant and bio-refinery facilities, in collaboration with top universities and research institutes such as Wageningen University & Research, TNO and NIOZ. The Netherlands can focus on the development of knowledge through innovation and the processing, valorisation and European distribution of biomass flows.

6 Insight from studies and interviews

6.1 Proteins via extraction or directly in food products

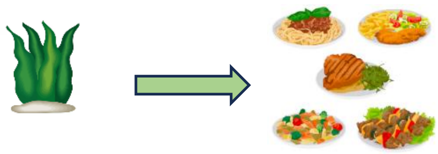
The studies analysed only looked at the extraction of proteins from seaweed. The extract can then be processed as an ingredient in food products.



The advantages of working with extraction are:

1. Some food products very specifically ask for an increase in the protein percentage. This should cause as little disruption as possible to other properties in terms of taste, texture and nutritional values. An extract can meet these requirements better than seaweed as a whole.
2. The possibility of adding value to side streams in addition to the proteins used. This can have additional social value (circularity) and can contribute to the economic feasibility of seaweed proteins.

As previously concluded (chapter 4.5), there are no known (large-scale) examples of the use of protein extracts from seaweed in food products. However, there are many products in which seaweed (wet & dry) is processed directly (without extraction).



The direct processing of seaweed (often via blends) in food products brings the following advantages due to the unique properties of seaweed:

1. Taste: seaweeds have a strong profile as a flavor provider. They contain natural flavor components such as glutamate, inosinate, and guanylate. These substances work synergistically to enhance the umami taste, similar to the action of monosodium glutamate (MSG). In addition, seaweed contains minerals and bioactive compounds that add a complex flavor dimension, often described as savory, salty, or even slightly sweet.
2. Binding and texture: Seaweed has hydrocolloidal properties and contains polysaccharides such as alginates, carrageenan, and agar. These substances have excellent and often precise gelling, thickening and stabilizing properties, which makes them suitable as a binder in various food products.
3. Nutritional values: in addition to high-quality proteins with essential amino acids, seaweed is a source of:
    a. Fiber: Insoluble fiber and unique polysaccharides such as alginates, fucoidans, and carrageenan have prebiotic properties and support gut health.

  b. Vitamins and minerals: Rich in vitamins A, C, E, and K, and minerals such as iodine, iron, calcium, and magnesium. This makes seaweed suitable for supplementing nutritional deficiencies.
  c. Omega-3 fatty acids: Some species like *Saccharina latissima* contain eicosapentaenoic acid (EPA), which is beneficial for cardiovascular health.
4. Increasing shelf life: Bioactive compounds such as polyphenols act as antioxidants and antimicrobials, which reduces food waste.

It is important to note that if only the proteins from seaweed are used (isolate), most of the above benefits will be lost and perhaps only the taste benefits will still be present. If a protein concentrate is used (other molecules in addition to protein), several of the above benefits may be present.

6.2 Applications of (protein rich) seaweed directly in food products

At the moment, we can distinguish the following categories in which seaweed is processed directly (without extraction):

6.2.1 Hybrid meat

The unique properties of seaweed in terms of taste, binding and moisture regulation make it possible to develop meat products in which up to 50% of the meat can be replaced by plant-based ingredients. Within the vegetable part, about half can consist of seaweeds (i.e. 25% of the total) without compromising taste and food safety. This concerns meat products based on minced meat where it can be applied to beef, pork and chicken.

6.2.2 Hybrid cultured meat

Developments in cultured meat follow each other in rapid succession, both in terms of technology and market opportunities. The production cost is now much lower due to improved techniques and more efficient media for cell growth. However, a significant decrease could still be achieved by also working with hybrid variants for cultured meat. Projects are currently being started to see if it is possible to develop products.

6.2.3 Hybrid fish

In addition to health and sustainability, another aspect plays an important role in the development of hybrid fish variants, namely availability. Especially with species such as salmon and tuna, supply is under pressure. An additional advantage of the scarcity is that the average kilo prices of the fish species in question are also high, especially compared to meat prices. This makes the processing of seaweed blends with a relatively high cost price promising and also offers opportunities to look at the retail market (supermarkets).

6.2.4 Meat and fish substitutes

Seaweed can play an important role in fully plant-based variants. Due to the unique properties of seaweed (including moisture-regulating), a wide range of ingredients can be used, allowing unique plant-based flavors to be developed. In addition, seaweed has advantages in terms of health (nutritional values) and the environment (no agricultural land, freshwater and fertilizer) compared to other land-based ingredients.

6.2.5 Bakery products

Seaweed offers interesting opportunities for the bakery sector because of its nutritional and functional properties. It can be used as an ingredient in bread, crackers, wraps, cookies, brownies, and other baked goods.

6.2.6 Dairy products

Dairy products include ice cream, yogurt, milk drinks and cheese again for both nutritional benefits and functional properties.

6.2.7 Snacks

Seaweed is also increasingly used in snacks. Think of seaweed snacks, seaweed crackers, seaweed popcorn, seaweed snack strips, seaweed protein bars, seaweed cookies and seaweed wraps.

6.2.8 Salads

The most common seaweed salads are Wakame, Green Sea Lettuce, and Kelp Noodle Salad. With these products, a clear choice is made in the communication to put seaweed forward.

7 Ambition

7.1 Policy context

7.1.1 Netherlands

For the Netherlands, the policy context seems to be best described in The National Protein Strategy (NES). Below is a brief summary of the purpose and context of this strategy.

7.1.1.1 The National Protein Strategy[7] (NES)

In 2018, the European Commission called on the member states to shape a national protein strategy for strategic food sovereignty. In December 2020, the then Ministry of Agriculture, Nature and Food Quality published The National Protein Strategy. Its aim was to increase the self-sufficiency of new and plant-based proteins over the next 5 to 10 years, in a sustainable way that contributes to the health of humans, animals and the natural environment.

The most impact on increasing the EU degree of self-sufficiency lies at the European decision-making level, such as EU import policy and EU regulations on residual flows, insects, new breeding techniques, novel food and the Common Agricultural Policy (CAP). The National Protein Strategy focuses on what can be contributed to the EU's self-sufficiency rate at the national level in the Netherlands. Moreover, the National Protein Strategy is an integrated approach that also aims to contribute to circular agriculture, Dutch soil quality and biodiversity, sustainable livestock farming and to a strong agro-food economy, to less emissions and less food waste, and to a more sustainable, healthier and more plant-based diet for Dutch consumers.
Finally, the NES establishes the relationship with other Dutch policy documents, including the 2019 climate agreement.

7.1.2 Europe

The European Green Deal and the resulting Farm to Fork strategy aims to promote the transition to more sustainable (plant-based) protein sources. In a broad sense, this strategy boils down to the following points:

- Making protein sources more sustainable: production of sustainable, locally grown vegetable proteins such as legumes (e.g. peas, beans, lentils) and other protein-rich crops in order to reduce the share of less sustainably produced imported crops/proteins (and of course also reducing the share of animal protein).
- Food safety and autonomy.
- Healthy and sustainable diets with more plant-based proteins.
- Research and innovation to improve the production of plant-based proteins.
- Reducing CO2 footprint through less livestock farming and more plant-based alternatives.

The relevant policy documents are therefore

[7] Paraphrased from The National Protein Strategy: https://open.overheid.nl/documenten/ronl-6ea7577b-85a6-425a-9dad-b9b9cf695495/pdf

- The European Green Deal[8]: this is the European Commission's overarching policy strategy aimed at sustainability and climate neutrality.
- Farm to Fork Strategy[9]: this is part of the Green Deal and therefore focuses specifically on food production, sustainability and health, including the focus on more plant-based proteins as explained above.
- European Protein Plan (2018):[10] This plan aims to reduce the EU's dependence on imported proteins and increase local production of protein-rich crops.
- EU Circular Bioeconomy Strategy[11]: This strategy supports the sustainability of agriculture and food production, including the use of plant-based proteins.

Finally, the EU Commission has set up the EU Algae initiative as shown in Figure 2 hereunder. This is not a specific plan, but rather a collection of policy documents with which the committee can contribute to the development of a European algae industry (of which seaweeds are a part). This does not have anything to do with proteins specifically, but through the farm to fork strategy there is a clear connection between the two policy documents. In other words, with the help of the farm to fork strategy, the EU Commission can contribute to the development of the algae industry through applications in food.

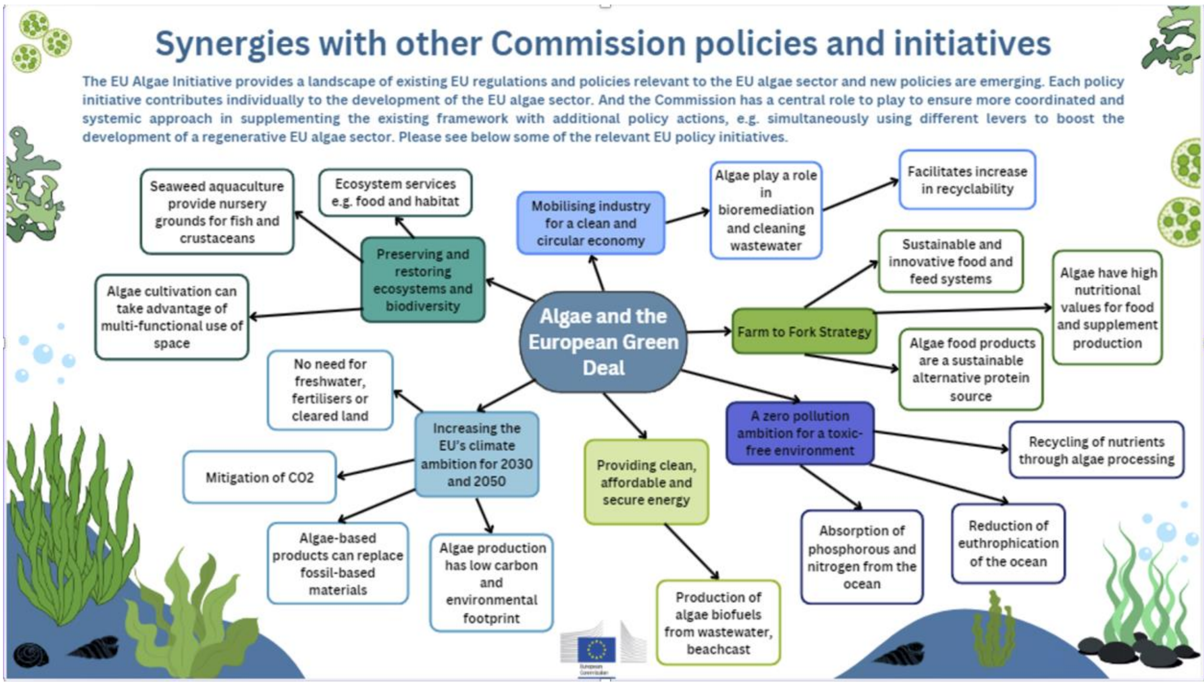


Figure 2: Overview of coherence between EU policy and European seaweed (algae) ambitions (credits DG Mare)

[8] https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691
[9] https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en
[10] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0757
[11] https://ec.europa.eu/info/research-and-innovation/research-area/environment/bioeconomy/bioeconomy-strategy_en

7.2 Dutch ambitions and European ambitions regarding plant-based proteins

7.2.1 Netherlands

The Dutch ambitions seem to be best reflected in The Dutch Protein Strategy (NES) as published in December 2020, updated in June 2022 (in the form of a letter to parliament with further specification of a number of goals) and with the latest state of affairs communicated to the House in March 2024.

7.2.1.1 Observations from The National Protein Strategy (NES)

From 2012 to 2016, the Dutch consumed an average of 79 grams of protein per day per person, about 15% of their total energy intake. According to the RIVM, 61% of this protein is of animal origin, or around 48 grams (this leaves 31 grams to vegetables[12]). If you then want to improve self-sufficiency and the health of humans, animals and the environment, you can 1) use/consume less protein and/or 2 continue to use/consume the same amount of protein but become less dependent on non-EU raw materials (which motivates the open question of whether this provides an improvement for human health, animal and/or environment). Within these two categories, there are several possibilities:

- Using/consuming less protein
  - For/by consumers:
    - Consuming less protein in the total daily diet.
    - Consuming more vegetable protein (since the conversion to animal protein is less efficient, this ultimately leads to lower protein consumption because less protein needs to be sent to livestock farming).
    - Less food waste.
  - For/by the livestock sector:
    - Innovations to convert current protein crops (e.g. grass) into animal proteins more efficiently.
    - Regulations that lead to a reduction in livestock in the Netherlands, which automatically reduces protein consumption.
- Continue to use/consume the same amount of protein while becoming less dependent on non-EU raw materials
  - For/by consumers:
    - Shifting consumption patterns to products that contain less or no imported soy ingredients and/or to animal products that are less or not made with imported soy raw materials.
  - For/by the livestock sector:
    - Produce more proteins locally (European) from sources such as grass, aquaculture and other (innovative) protein-rich crops and/or additives.

The conclusions from NES indicate that:

- For livestock farming, the choice is made to maintain the amount of protein while reducing dependence on imported soy.

[12] If you were to extrapolate this to annual plant-based protein consumption in the Netherlands, you end up with about 200t of protein per year

- For consumers, the focus is on using/consuming less protein by reducing animal protein consumption and shifting towards 50-50% animal-vegetable protein. It should be noted that the role of the Dutch consumer is modest, with only 11% of imported vegetable proteins making it to domestic consumption.

7.2.1.2 A scenario for animal husbandry and vegetable proteins: 50-50% distribution of animal vegetable protein without adjusting total daily protein consumption

For livestock farming, you could say that there will initially be no change in the total amount of protein required. In the long term, due to a shifting consumption pattern (50-50% plant-based), less protein would be needed annually. As noted above, the influence of Dutch consumers is limited in this, but perhaps European guidelines could offers more support.
The Netherlands imports 6.6 million tons of soy from outside Europe and 93% of this is used for animal feed, or 6.1 million tons. For the sake of convenience, let's assume that Europe's inhabitants need 6.0 million tons of soy per year to produce the meat and dairy they eat annually in animal protein.
With an equally gross simplification, we can deduct from EFSA that the average European consumes about 86 grams of protein and weighs about 78 kg (this would be 65 grams of protein when following the EFSA's recommendation to consume 0.83 grams of protein per kg of body weight daily). The current distribution of proteins is 61-39 animal-vegetable, or 52.5 grams-33.5 grams (RIVM). If you decide to adjust the distribution to 50-50 (and not reduce the total intake to, for example, 65 grams per day), then with 43 grams, you need 9.5 grams of animal protein less, or a reduction of animal protein by 18%. If we project this percentage on the total non-EU soy use in Europe, it means a reduction of around 1.1milion tons of soy imports.
On a total Dutch import of 15.6 million tonnes of protein-rich crops (8.3 million non-EU, 7.3 million tonnes from Europe), this means that the distribution of EU versus non-EU imports for the Netherlands can reach almost 50-50 (7.2 million non-EU and 7.3 from Europe[13]). In short, this scenario shows that if we 1) maintain the target of maintaining our current protein consumption, 2) get 50% of the proteins from vegetable sources and 3) manage to implement this for the whole of Europe, that 1.1 million tons less soy imports will ultimately be needed.

Total average protein consumption per person in Europe [grams p.p.]			
86 grams			
	Vegetable protein		**Animal protein**
Current distribution of plant - animal protein [%]	39%	50%	61%
Current distribution of vegetable - animal protein [grams p.p.]	33.54	43	52.46
Change needed for distribution 50-50 [grams p.p.]	9.46		-9.46
Vegetable-animal protein distribution 50-50 [gram p.p.]	43		43

[13] All these numbers are derived from the numbers from the NES, chapter 1.2

Change needed in percentage of current usage [%]	28%		-18%

Table 4: Calculation of change in protein consumption

The above scenario also shows that about 1.6 million tons (9.5 grams per day x 450 million Europeans) of extra vegetable protein must be added annually for consumption by Europeans to achieve the 50-50 split for animal and plant. These numbers are generalized for the whole of Europe and therefore deviate from the numbers you would end up with if you based this scenario on the NES. That doesn't affect much our conclusion. Current total protein consumption by Europeans is about 14 million tons of protein per year, averaging out at 86 grams per day.

Finally, it should be noted that the NES mentions advice from the 2019 climate agreement to consume 10-15% less protein, but this is not directly reflected in the conclusions of the report.

7.2.2 European ambitions

There are no direct quantitative targets in the European ambitions. It only states that we should consume more vegetable and less animal protein. That is why in this study we look at the report of the EAT-Lancet Commission on Food, Planet, Health. They specifically looked at how we can achieve a healthy diet, sustainable food production within planetary boundaries for 10 billion people by 2050. All this is based exclusively on the latest scientific insights. An important aspect is that this report is also subject to a peer-review process. Something that EAT says is often missing from reports from knowledge institutes.

7.2.2.1 Insights from the EAT Lancet Commission Summary Report

Their publication puts forward a number of concrete goals for a healthy diet for people and the planet[14]. As far as protein is concerned, it follows that this diet contains more than 209 grams of protein-rich food per day.

[14] Summary Report of the EAT-Lancet Commission, see link

	Macronutrient intake grams per day (possible range)	Caloric intake kcal per day
Whole grains Rice, wheat, corn and other	232	811
Tubers or starchy vegetables Potatoes and cassava	50 (0–100)	39
Vegetables All vegetables	300 (200–600)	78
Fruits All fruits	200 (100–300)	126
Dairy foods Whole milk or equivalents	250 (0–500)	153
Protein sources		
Beef, lamb and pork	14 (0–28)	30
Chicken and other poultry	29 (0–58)	62
Eggs	13 (0–25)	19
Fish	28 (0–100)	40
Legumes	75 (0–100)	284
Nuts	50 (0–75)	291
Added fats		
Unsaturated oils	40 (20–80)	354
Saturated oils	11.8 (0-11.8)	96
Added sugars All sugars	31 (0–31)	120

Figure 3: Table from EAT Lancet report showing how many grams of food we need per day for a healthy diet and a healthy environment

The 209 grams mentioned in the EAT-Lancet report actually refers to the total daily intake of protein-rich foods by weight—not the total protein content. This is a common source of confusion. 209 grams of protein rich food provides about 50 grams of actual protein in accordance with the recommended protein intake according to the EAT-Lancet diet. This means that:

- 209 grams of total weight of all protein-rich foods per day.
- 50 grams of actual protein from these foods, which meets the daily protein requirement.

The following percentages are used for the various food sources:

- Meat & fish: 34%.
- Vegetable: 36%.
- Other sources (eggs & nuts): 30%.

The same figures are shown below compared to the current consumption of protein-rich foods

Food Source	EAT-Lancet Recommended Intake (grams/day)	Protein Content from Recommended Intake (grams/day)	Current Average European Intake (grams/day)	Protein Content from Current Intake (grams/day)
Red Meat	14	3	50-100	10-20
Poultry	29	6	30-50	7-12

Food Source	EAT-Lancet Recommended Intake (grams/day)	Protein Content from Recommended Intake (grams/day)	Current Average European Intake (grams/day)	Protein Content from Current Intake (grams/day)
Fish	28	6	20-30	4-6
Eggs	13	2	13	2
Dairy	250	8	250-400	30-40
Legumes (Beans, Lentils, etc.)	50	10	10-15	2-3
Nuts and Seeds	25	5	3-5	0.5-1
Whole Grains	232	10	100-150	6-10
	641	**50**	**~ 620**	**~78**

Table 5: Composite table based on EAT Lancet dietary recommendations for protein-rich foods versus the current diet in Europe

The results suggest we need to eat less protein. This is in line with the conclusions from the Dutch NES (see above), although it should be noted that with 50 grams of protein per day, the EAT Lancet advice is much more conservative than NES's and EFSA's advice of 63 grams of protein per day (based on an "average" European of 76 kilos with 0.83 grams of protein per kg of body weight).

7.2.3 Conclusions regarding the Dutch and European ambitions

The Dutch and European ambitions seem to be fairly similar. This in itself is logical since the NES arose from the European Commission's request to member states to set up a national protein strategy. There does seem to be a difference in motivation. The original request from the European Commission was to shape a national protein strategy for strategic food sovereignty. The European Green Deal also focuses much more clearly on 1) making protein sources more sustainable, 2) health and sustainable diets and 3) reducing linked CO2 footprints (e.g. by reducing livestock). In any case, what both ambitions do agree on is that

- Europeans should eat more plant-based proteins and less animal proteins.
- We need to become (slightly) less dependent on protein-rich raw materials imports (mainly soy) from outside the EU. In the Netherlands, there is now 53-47% for non-EU versus EU.

What has remained unclear in this study is whether there is an ambition to consume less protein at all. Given the principles in the EAT Lancet Summary report, this seems a logical step, but for the European seaweed ambitions we consider it to be outside the scope. It is not up to the European seaweed industry to implement a food agenda. The seaweed industry should rather focus on offering solutions to current policies.

7.3 Protein ambitions for the European seaweed sector

7.3.1 Principles

Based on the above, we can formulate an ambition based on the following principles:

- By 2050, we want to be able to provide Europeans with a healthy diet.
- We want to ensure that the food for this diet is produced sustainably (sustainably within the boundaries/boundary conditions of our planet's ecosystem).

- For the time being, we take the current daily protein intake in Europe of 86 grams as a starting point. At least 50% of this should consist of vegetable proteins instead of 60-40%. This means that an order of magnitude of 2.1 million tons of extra vegetable protein is needed per year in Europe (see also chapter 7.2.1.2).
- The European seaweed sector wants to contribute to this transition by focusing on solutions for food for people.

7.4 Roadmap Proteins of the European Seaweed Industry for 2050

7.4.1 Ambition

Based on the above, we assume that about 1.6 million tons of vegetable protein are indeed needed annually for a European diet with 50-50 distribution of animal and vegetable protein (9.5 grams of protein x 450 million Europeans). You can try to fill this in by getting people to eat more protein-rich vegetables such as seaweed. Most well known seaweeds in Europe contain between 1-3% protein (based on wet weight). If we assume 2% for the sake of convenience, then to provide the 0.3 million tons of vegetable protein (about a fifth of the 1.6 million tons of vegetable protein expected to be needed in Europe) you need about 16 million tons of fresh seaweed per year.

By 2050, the European seaweed industry will provide a fifth of the extra vegetable proteins needed for the protein diet of Europeans, half of which should consist of vegetable proteins

For now, we take this number as a starting point for the protein ambitions of the European seaweed industry. Then there is still an important question to be answered, namely how do you get the European inhabitants to consume 16 million tons of seaweed annually for protein. Below are the 3 options calculated in extreme scenarios:

- In a scenario where everything is consumed fresh, Europeans have to eat about 97 grams of fresh seaweed per day.
- In a scenario where everything is consumed dried, Europeans would have to eat about 10 grams of dry seaweed per day (based on the simplistic factor of 10 from wet to dry).
- In a scenario in which the proteins are first extracted from the seaweeds, the amount of protein consumed daily could go to 0 (zero) grams.

If we succeed in achieving the above ambition, a combination of our scenarios will probably arise.

7.4.2 Bottlenecks within the European seaweed industry

These are bottlenecks that lie within the industry and that the seaweed industry itself can also influence. External bottlenecks such as policy etc. can be found in the SWOT below:

- There is no clearly identified seaweed species, production method and chain with which the broader protein ambitions can be fulfilled (e.g. will it be Ulva from land or Sugarweed from sea?).
- No clear product-market combinations have been identified for protein extracts from seaweed, without further direction in which further development of protein extractions from seaweed is difficult.

- The associated seaweed ingredients, protein concentrates or isolated proteins are therefore also not yet available for the market to assess feasibility.
- The price of European cultivated seaweed is too high compared to other plant-based protein raw materials such as soy, legumes, non-European cultivated seaweed etc.
- Lack of (cost) effective extraction methods and/or facilities of seaweed proteins.

7.4.3 Opportunities within the European seaweed industry

These are opportunities that lie within the industry and that the seaweed industry itself can also influence. External bottlenecks such as policy etc. can be found in the SWOT below:

- Development of hybrid meat and fish products with high inclusion of (fresh) seaweed.
- Development of scalable and mainstream food products with a higher percentage of seaweed.
- Exploration of possible protein concentrations from seaweed that have valuable functional properties (health, amino acid profiles, etc.).
- The valorisation of other ingredients in the seaweed in addition to the extraction of proteins (sugars, fibers, minerals, vitamins, fats).
- Taking advantage of the opportunities that the seaweed proposition offers to the market and policymakers to achieve their own objectives on food, circularity, sustainability, health and local for more resources for development of the chain.

7.4.4 Actions to be taken by the European seaweed industry by 2030

What are the most important actions that will benefit seaweed protein ambitions for 2030:

- Scaling up production of fresh seaweed in Europe with the (provisional) target of 16 million tonnes of fresh seaweed per year by 2050 on the horizon)
    - Scaling up production capacity (more farms).
    - Improving production yield (more seaweed per unit of production, e.g. ha).
    - Inventory of the most promising seaweed (species) production chains for vegetable proteins.
    - Developing seaweed species with more (protein) yield.
    - Developing production methods that increase protein yield in produced seaweeds.
- Improving the investment climate for seaweed production in Europe, for example through a production subsidy
- Filling in preconditions for scaling up seaweed production in Europe and the Netherlands within ecological limits
- To develop food products and ingredients that enable the corresponding increase in seaweed protein consumption.
- Identification of suitable markets for protein extracts from seaweed and then development/improvement of the extraction processes needed for these ingredients at market prices.
- Setting up pilots with the most promising combinations of seaweed production and processing.
- Market exploration with the (prototype) food ingredients or food products made in these pilots.
- Drawing up a market development plan based on insights from the above steps.

7.4.5 Current relevant policy programmes

7.4.5.1 Programme Integrated approach to methane and ammonia in livestock farming

The **Integrated Approach programme**, funded by the Ministry of Agriculture, Nature and Food Quality, was launched in 2020 and is being implemented by Wageningen Livestock Research, LTO Noord, ZLTO, LLTB and Schuttelaar & Partners. It focuses on identifying and implementing practice-oriented measures to reduce methane and ammonia emissions in livestock farming, with an eye for animal welfare, animal health and biodiversity. The Ministry of Agriculture, Nature and Food Quality supports this process financially, among other things, with a methodical 10-year approach.
Useful action for the seaweed sector: making contact for the inclusion of promising solutions with seaweed within this context.

7.4.5.2 Agrofood Groningen programme

The Groningen Agro Programme supports farmers in the earthquake zone who are inconvenienced by gas extraction. The aim is to help these farmers with claims handling, reinforcement and future planning of their farms. The associated subsidy and customised schemes can be relevant in realising future-proof plans for farmers.
Useful action for the seaweed sector: making contact for the inclusion of promising solutions with seaweed within this context.

7.4.5.3 Climate agreement

The Climate Agreement focuses on achieving national climate targets, including a 49% reduction in greenhouse gas emissions by 2030 (compared to 1990). Within this framework, seaweed plays a promising role for the following reasons, namely: CO_2 storage and mitigation, alternative to fossil raw materials, food transition and circular agriculture.
Useful action for the seaweed sector: contact the respective top sectors that implement the climate agreement to discuss how seaweed plays a valuable role in this context.

7.4.5.4 North Sea Agreement

The North Sea Agreement is an important cooperation agreement in the Netherlands between governments, nature and environmental organisations, the fisheries sector and other stakeholders, aimed at the sustainable use of the North Sea. The agreement contains agreements on how different interests, such as nature conservation, energy generation, fisheries and shipping, can be balanced. Agreements have been reached on: expansion of offshore wind farms, protection of nature and biodiversity and transition for the fisheries sector.
Useful action for the seaweed sector: making contact because seaweed can play an interesting and increasingly important role within the context of the North Sea Agreement, especially because of its focus on sustainability, climate goals and biodiversity.

7.4.6 SWOT Roadmap Proteins

For the purpose of tightening the roadmap, a SWOT analysis has been given below as a basis for further discussion within the sector:

7.4.6.1 Strengths (S)

I. General benefits of seaweed: no need for fresh water or farmland.
II. A circular raw material that can be produced locally and that can help close cycles.

III. Less dependence on imported protein-rich crops from outside the EU.

7.4.6.2 Weaknesses (W)

i. Seaweed cannot (yet) be produced on a large scale at a market price.
ii. No type of seaweed has yet been specifically bred for protein for humans and/or animals.
iii. Extraction of protein from seaweed (insofar as necessary for the application) is not yet efficient or large-scale enough.

7.4.6.3 Odds (O)

I. Selection and breeding of fast-growing local seaweed species that can be developed as a fully-fledged alternative to soy.
II. Use of (unrefined) seaweed as a basic ingredient in hybrid meat products to replace animal protein in human food.
III. Development of seaweeds with a specific amino acid profile that can be used as a supplement for European protein crops so that they become as valuable as soy protein.

7.4.6.4 Threats

I. Development of grass as a source of protein for animal feed.
II. Policy to reduce the amount of protein in human consumption via less meat. Then in fact, no more vegetable sources are needed to get enough (vegetable) protein.
III. Innovation and sustainability in the soy value chain. There is more scale and market power there than with innovative alternatives.
IV. If the approach is to get people to eat more plant-based proteins, this can be done with seaweed, but there may be alternatives that are more promising because of scale, awareness, cost price and availability in the short(er) term.

8 Conclusions

8.1 Introduction

In this chapter, the most important findings and conclusions of this research are summarized and placed in the broader context of the central research question. The answers to the sub-questions not only provide more insight but also form a basis for concrete recommendations aimed at future developments, applications and/or policymaking. The recommendations are based on the analysed data/reports, insights from projects/studies and interviews. In this way, this advisory report aims to bridge the gap between theory and practice.

8.2 Conclusions on the sub-questions

This report looked at the following sub-questions. The most important conclusions will be formulated for each question.

8.2.1 What techniques are there for the extraction of proteins from seaweeds?

The most described and tested techniques are:

- Alkaline (chemical) extraction.
- Supercritical Fluid extraction (SFE).
- Enzymatic extraction.

Enzymatic hydrolysis in combination (beforehand) of mechanical cell disruption seems to be the best method for protein extraction from seaweeds so far. Various studies have shown that up to **80%** of the available proteins could be recovered from the seaweed biomass present. The amino acid profiles of the extracted proteins were suitable for human consumption and showed a good balance of essential amino acids. In addition, good results are expected when extracted using (yet to be identified) marine microorganisms.

8.2.2 Which seaweeds are most suitable for the protein transition?

There is no single answer to this question. To this end, much more research needs to be done into the different types of seaweeds and respective protein extraction. Now the focus of the research is much more on the techniques of extraction and only at a later stage can more attention be paid to the suitability of species. However, it can be said that the following types of seaweeds have been used most often in studies, namely: Ulva lactuca (sea lettuce/green algae), Saccharina latissima (sugar algae/brown algae) and Alaria esculenta (Wing algae/brown algae). These last two seaweeds represent half of European seaweed cultivation.

Other species that are also mentioned in studies are Ascophyllum nodosum (club wrack/brown algae, not cultivable), Laminaria digitata (finger wrack/brown algae), Undaria P. and Palmaria palmata (palm algae/red algae). Almost all of these seaweeds are easy to cultivate in Europe.

8.2.3 Which (seaweed) parties are already able to play a role in the protein transition in terms of technology and upscaling?

In terms of technology, the following parties have actually gained experience with protein extraction from seaweed, namely: GOA Ventures, ILVO Vlaanderen, TEAGASC, Ghent

University, Møreforsking, Eco Cascade, Westerdijk Institute, WUR and Oceanium. However, none of these parties has taken the step to scale up their tested extraction techniques. So, there is no significant production capacity for extracting proteins from seaweed, only pilot plants. By extension, there is also no commercially operating bio-refinery that can add value to other streams in addition to seaweed proteins.

8.2.4 Are there already examples in the food/feed market in which seaweed is already used in the protein application (extracted protein)?

After research, we do not come across any food products or animal feed products on the market that contain protein extracts from seaweed. However, prototype products have been developed for research purposes. In short, technically it is quite possible, but the chain is still in a premature phase where there are no market impulses yet to process protein extracts from seaweed as an ingredient in food products.
On the other hand, there are many food products (see chapter 6.2) with direct processing (without extraction) of seaweed with proteins. The functional properties of seaweed with all their advantages offer enormous opportunities for hybrid meat and fish, for example.

8.2.5 What is an achievable ambition for the European seaweed industry within the protein transition towards 2050?

In chapter 7 a first version of the roadmap for the seaweed industry for seaweed proteins has been drawn up (Roadmap Proteins). This results in the following ambition:

By 2050, the European seaweed industry will provide a fifth of the extra vegetable proteins needed for the protein diet of Europeans, half of which should consist of vegetable proteins

As a result, the European seaweed industry would generate about 16 million tonnes of fresh seaweed for this application/market. For the time being, this is a guideline number for which the feasibility cannot yet be properly estimated. This has to do with 1) how much seaweed can eventually be produced in Europe within ecological limits and 2) how much fresh seaweed the other potential seaweed markets (e.g. cosmetics, packaging, etc.) need. It can already be said that a lot of time is needed to realize this ambition. Currently, the European seaweed industry produces a very limited amount of cultivated seaweed (less than 3000 tons of fresh seaweed per year). Scaling up to millions of tons of seaweed per year will take at least 10 years and probably longer. For further information, please refer to the Roadmap Seaweed Production of North Sea Farmers. In doing so, one must take into account the bottlenecks, opportunities and actions as described in the Roadmap Proteins.

8.2.6 What role can the province of Zuid-Holland play in this transition?

As mentioned in chapter 5.2.7 already described, the province of South Holland and the Netherlands can play a pioneering role in stimulating the European seaweed sector. This can be achieved by creating an attractive investment climate, in particular through subsidies, public-private partnerships and investments in research and development (R&D). Moreover, the province of Zuid-Holland can make use of existing innovation infrastructures such as a Biotech Campus Delft to develop a central ecosystem that can drive this innovation and thus quickly fulfil the European pioneering role. In the long term, there may also be opportunities with the port of Rotterdam as a logistics hub and/or large-scale bio-refinery. Zuid-Holland can also support the involvement of adjacent provinces and regions (e.g. Flanders, Northern Germany) in order to join forces financially and policy-wise. Finally, support for the case with hybrid meat offers a great opportunity to help make the meat industry in the region more sustainable and thus also to help develop the seaweed industry at the same time.

8.3 Answering the central question

Can seaweed play a significant role in the necessary protein transition for a healthier and more sustainable food system and if so, how?

The answer to this is twofold:

- Seaweed is in an excellent position to play an important role in the protein transition if it is used in its entirety as a food ingredient in hybrid meat and fish products. The latter is important because for the first time a very good natural "fit" seems to occur with these traditional, less sustainable products. Consumers confirm that meat products become better by the addition of seaweed. The European market for minced meat products has a size of about 11 million tons of product per year (around 15% protein, about 1.7 million tons of protein). If you manage to fill that in with hybrid products (up to 50% vegetables and up to 25% seaweed), you could replace almost 0.9 million tons of animal protein with vegetable protein. Mainly with the seaweed ingredient. This is a hugely attractive proposition from the perspective of sustainability (less emissions from livestock farming), protein transition (more plant-based proteins, possibly slightly less protein consumed), health (more nutrients, better Nutriscore), animal welfare (fewer animals needed with the same (hybrid) meat and fish consumption) and biodiversity (less intensive livestock farming is possible, seaweed cultivation can contribute to strengthening the marine ecosystem). Actually, there are no disadvantages to this proposition for any stakeholder, which in fact makes it a "no-regret" option. Moreover, this directly helps both the protein transition and the development of the European seaweed sector. Therefore, the advice is to concentrate as much of the available resources as possible on developing this proposition.
- Protein extracts from seaweed still have a long way to go to technical and commercial feasibility. Results are encouraging, but a clear proposition for the application and the market still lacks. If a more strategic selection can be made on where the better opportunities lie, further research will be of great added value. The advice is to make this strategic assessment in the context of the Roadmap European Seaweed Industry and to provide this as a guideline for setting up new research (anywhere in Europe) in the field of protein extraction. An additional reason to continue in this direction is to eventually have an alternative to European protein security if global conditions deteriorate with a negative effect on global supply chains. An important point of attention here is the regulation and possible novel food dossiers of future promising protein extractions. These aspects could mean a major delay in the roll-out of possible solutions.