Wageningen Economic Research | White paper

The role of seaweed in the future food system

The potential of Dutch parties in this young sector

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Background

1 An introduction to seaweed

2 What seaweed can do for us – Visions for seaweed

3 Limits to the visions, seaweed not always a blessing

4 Reviewing recurrent topics in seaweed: food and feed applications

5 Overview of Dutch expertise on seaweed

6 Conclusion

References

Background

The Dutch Ministry of Agriculture, Nature and Food quality has the ambition to contribute to a transition in the global food system towards circularity. To fulfil this ambition, the Ministry is working on a strategic international agenda for making food systems more sustainable globally. This includes a search for ground-breaking Dutch solutions that can boost nature-positive production.

The Dutch agriculture sector is globally known for its high level of innovation. Dutch solutions are used throughout the world, in various sectors including but not limited to aquaculture, horticulture and breeding.

A particular type of aquaculture that has received a lot of attention in recent years is seaweed farming. Seaweed, or macroalgae, farming is not new and has been practised on a large scale in various countries worldwide, many of which lie in Asia, Africa and South America.[1] European consumers use seaweed extracts in many familiar products such as processed foods, toothpaste and shampoos. Extracts from seaweed are included in products with E-numbers from 400 through to 407a.

What is new are the numerous European research and innovation projects that aim to boost global seaweed production and use in recent years. Growth in seaweed production is targeted in many parts of the world, including a number of countries in Europe (e.g. Norway, Ireland, the Netherlands, France). The potential markets for seaweed based products for Europe include, but are not limited to: food, feed, pharmaceuticals, cosmetics and renewable energy.

For policymakers, agricultural councillors and other stakeholders, it is not always clear what is realistic, given the current state of knowledge and technology. To provide more clarity in this domain, Wageningen UR was asked to assess the present state of seaweed production in the food system in the Netherlands. The objective of this assignment is twofold:

1. Provide policymakers with a realistic vision on the role of seaweeds in the global food system for the future (Chapters 1-4)
2. Provide policymakers with an overview of the Dutch organisations and companies active in the seaweeds sector, their expertise and possible role in the transition for the global food system (Chapter 5).

This report provides both Dutch and foreign policymakers, agricultural councillors and embassies with an overview of the knowledge and expertise present in the Netherlands on the topic of seaweed farming and processing, and how this could be best used. It should be noted that this is not a complete in-depth overview of the existing scientific knowledge. Even though research on seaweed has been done in Asia (e.g. China, Korea and Indonesia) for a long time, other parts of the global seaweed sector are relatively young and the scientific understanding of the potential of seaweed in Europe is also still in development.

This report consist of the following 4 chapters:

Chapter 1 Brief introduction of seaweed to non-experts
Chapter 2 Discussion on some visionary documents on the potential of seaweed
Chapter 3 Formulation of some generic concerns and limitations
Chapter 4 A more detailed analysis of four foreseen seaweed applications
Chapter 5 An overview of Dutch expertise on seaweed
Chapter 6 Some concluding observations and remarks.

1 https://www.fao.org/3/y3550e/Y3550E06.htm

1 An introduction to seaweed

Seaweeds can be seen as plants of the marine system as they use photosynthesis to generate nutrition needed for growth and maintenance. Despite their physical appearance and role in the marine system, they are in fact not plants but algae. Seaweeds are also commonly known as macroalgae, not be confused with microalgae which refers to phytoplankton also found in marine environments. Seaweeds are part of the informal macroalgae group, and belong to the kingdom of Protista. One of the most profound characteristics enforcing this, is the lack of a vascular system (internal transport system). All the internal transport and uptake of essential nutrients are done by transfusion between the environment and the epidermal cells, as well as between cells.

The realm of seaweeds can be divided into multiple groups of which the three main groups are:

1. Brown seaweed (Phaeophyceae), a group containing brown coloured seaweed species which are often rich in alginates. The larger species are often referred to as Kelp. For the Netherlands, species belong to this group are Sea oak (*Fucus* sp.), but also Sugar kelp (*Saccharina latissima*) and Oar weed (*Laminaria digitata*).
2. Green seaweed (Chlorophyta) are mostly found in shallow and intertidal areas. The most well-known species is Sea lettuce (*Ulva* sp.), a genus found all around the globe and known to plague eutrified coastal zones where it can cause 'green tides', a harmful explosive growth affecting water quality, which can be harmful for mankind as well.
3. Red seaweed (Rhodophyta), a group known for containing carrageen and agar, both binding agents used in the food industry. Commonly known species are Irish moss (*Chondrus crispus*) used for the production of carrageen, and Dulse (*Palmaria palmata*) which is sold as a plant-based substitute for bacon. In the Indo-pacific *Kappaphycus*, *Eugeuma* and *Gracilaria* species are cultivated for the production of carageen and agar-agar.

Together these groups represent over 10,000 species. However, only a very small number of species are used for a multitude of purposes and even a smaller number are cultivated. Cultivation of seaweed has been in place in Asia for centuries, and seaweed itself has become a part of the common diet. An example of this is nori, the seaweed that is cultivated, processed and used as wrapping for sushi. Other species such as Kombu (*Saccharina japonica*) have also been used as extensively, as a seasoning for a broad variety of recipes. In Europe, cultivation has only gained substantial interest over the past two decades and is developing rapidly.

This increase in interest for seaweed cultivation in Europe is driven by multiple factors. We are aware that the world population is growing and we need more climate resilient resources, but we do not have large quantities of land or fresh water available for developing such resources. By using the marine system, occupying about 70% of the world's surface, we gain a vast area which potentially can be used to cultivate such resources. With seaweed being a crop that can grow in the marine environment, with no requirement for fresh water (an increasingly scarce resource), which has a relative low impact on the environment and is versatile in its application and usage, it is clear that it checks all the boxes. For Europe, Sugar kelp (*S. latissima)* and Winged kelp (*Alaria esculenta*) are the most well-known species, but interest is growing for Sea lettuce (*Ulva* sp.), Dulse (*Palmaria palmata*) and Wakame (*Undaria pinnatifida*). In Asia, Wakame (*U. pinnatifida*) and Kombu (*S. japonica*) are the most commonly cultivated brown seaweed, and *Eugeuma*, *Gracilaria* and *Kappaphycus* for red seaweed. In terms of green seaweed, *Ulva* is the dominant species around the world, and the cultivation is mostly land based. However, this species, being cultivated on land, is an exception to the many others of interest for European countries, being cultivated in the sea.

As stated, some of the seaweeds contain binding agents, such as alginates and carrageen, which have dominated seaweed use in Europe. However, more applications are possible:

- **Food**: Seaweed can be consumed whole or in more processed form like agar-agar. This includes the use of seaweed in burgers, wraps, seasoning mixes and the like.
- **Feed**: Seaweed can be fed to animals whole or as a food additive. There has been lot of attention on this form of usage in recent years as it has been shown to improve animal health and in some cases can aid in the reduction of methane excretion by ruminant animals.
- **Pharma**: (i.e. pharmaceuticals and other affiliated products like cosmetics and wellness products) Similar to animal feed, seaweeds are shown to be rich in various bioactive molecules, such as fibres, antioxidants, minerals, and omega-3 fatty acids. As such, seaweeds have been proclaimed to have the potential to promote human health and wellbeing, such as modulating chronic diseases like Alzheimer's disease (Déléris et al., 2016).
- **Fertilisers**: By being an organic matter and containing compounds such as minerals, but also phytohormones, seaweed can be used as fertiliser or biostimulant in agriculture. Studies have found that some applications of seaweed can relieve stress in plants caused by factors like drought and salinisation.
- **Non-food materials**: (e.g. Bio packaging or green

construction material) Due to its carbon capture quality, there are many discussions currently in academia and policy regarding the possibilities of permanent carbon sequestration and storage by seaweed. There has even been research into how to substitute it in cement, with a life expectancy of 150 years. Therefore the carbon would be stored away in the cement for the time being (Widera, 2014). Seaweeds have also proven to be a good green alternative to plastic.
- **Fuel**: If the seaweed of interest (or its residue) is deemed not suitable for any of the applications above, there is also the possibility of converting the biomass resource into fuels. It should, however, be kept in mind that this is one of the uses with the lowest economic value, and studies have shown that with the current state of technology the net GHG emissions of algae fuel are not lower than traditional fossil fuels, due to the high energy demands in biorefinery processes (Alvarado-Morales et al., 2013) namely, biogas production.

2 What seaweed can do for us – Visions for seaweed

In recent years, various visionary documents have been produced and claims have been made that describe how seaweed can be used in a future sustainable food system or sustainable societies at large. The press has also given considerable attention to the potential of seaweed.[2]

> *Box 2 – Seaweed for Europe* is an ambitious organisation giving an overview and summarising what seaweed can do for us in a visionary document '*Hidden champion of the ocean*'.
>
> *https://www.seaweedeurope.com/hidden-champion/*

Food from the sea

Seaweed, being a potential environmentally friendly food source from the sea, has been included in claims to end world hunger and has also gained attention of a smaller but growing movement of plant-based diets. Seaweeds contain not only protein, several vitamins, minerals and antioxidants, but it is also proclaimed as a source of omega-3 and iodine. Yet, the iodine content in seaweeds is often cited as a drawback. Discussions to standardise limits on daily iodine intake from seaweeds have been long-standing in the scientific community. More on seaweeds for human consumption is provided in Chapter 4, 'Recurrent topics'.

> Box 1 – A group of dieticians, calling the wheel of five '*hopelessly old-fashioned*' have come up with the wheel of life, suggesting a plant-based diet. In their vision, a spoonful of seaweed a day can be the daily source of iodine in one's diet.
>
> *https://www.trouw.nl/binnenland/schijf-van-vijf-onder-vuur-dietisten-komen-met-vegan-alternatief~ba6c209d/*

General ecosystem services

Besides being rich in minerals, vitamins and polysaccharides, contributing to a growing range of applications outside the ocean, seaweeds also play a role in providing critical ecosystem services in the marine environment. It forms an integral part of a complex food web (Pereira, 2015) and offers many services such as habitat provisioning, nursery grounds and shelter for various species (Bertocci et al., 2015; Smale et al., 2013). Therefore, the terms 'regenerative' or 'restorative' aquaculture, and sometimes also 'ecosystem approach' aquaculture, are often used in relation to macroalgae farming. In fact, underwater kelp forests are considered one of the planet's most productive habitats (Mann 1973, Smale et al., 2013; Barbier et al. 2019). But it is discussed if farms only have positive effects on biodiversity. On the one hand, studies suggest an increase in biodiversity around farms (Theuerkauf et al., 2021), and farmers report the same, but sound data to quantify this is still missing. On the other hand arguments being voiced are that seaweed farms may serve just as an aggregating devices, much like Fish Aggregating Devices (FADs) used in the fishing industry (Radulovich et al., 2015), which indicated that there is no increase in biodiversity, but solely just an aggregation of it. Yet, even if biodiversity increases, the consequences of harvesting the seaweed have to be considered as well. During harvesting, the created habitat is being abruptly removed as well as all attached marine life. This makes the cultivation of seaweeds a potential sink of biodiversity. Nonetheless, kelp forests can aid in reversing ocean acidification by taking up CO_2 (Krause-Jensen & Duarte 2016; Mongin et al. 2016; Ortega et al., 2019) and mitigating eutrophication by taking up excess inorganic nutrients like nitrogen and phosphorus (World Bank Group 2016; Hasselström et al., 2018; Barbier, 2019). In addition, seaweeds are a natural protector, absorbing the force of the sea by dissipating wave energy and

2 https://www.theguardian.com/environment/2021/aug/26/new-york-seaweed-farming-kelp-producers
https://cen.acs.org/environment/sustainability/Netherlands-building-seaweed-industry/97/i34

preventing coastal erosion (Duarte et al., 2017; Barbier 2019). These services make seaweed farms a potential nature based solution to protect the coasts, reverse anthropogenic ocean acidification and potentially climate change itself. Projects are underway to valorise the ecosystem services offered by seaweed, with the hope that through a monetised value more of these restorative ecosystems are protected or even created.

Carbon sequestration

In the context of global warming, the need for carbon sequestration is growing. The ability of seaweed to capture carbon during its growth phase has gotten it attention on the international scene in recent years. The capacity of seaweeds to draw down anthropogenic CO_2 and fix it into organic matter, has been demonstrated by various studies (N'Yeurt et al., 2012; Chung et al. 2013; Duarte et al., 2017). However, due to the inconsistent range reported in seaweed productivity, it is difficult to estimate the exact carbon capture potential. Based on carbon content measures on wild seaweeds, assumptions of a 30% carbon content on a dry weight basis in cultivated seaweeds were made. This suggests that the carbon capture potential of cultivated seaweeds is at least as high as that of terrestrial farmed crops (Laurens & Nelson, 2020). It has taken a while to recognise (even though not yet officially included in carbon capture schemes) that seaweeds can be considered blue carbon, as it was thought that the vast majority of seaweed production is decomposed in the ocean and therefore not able to lock away the carbon for longer periods. Hill et al. (2015), Trevathan-Tackett et al. (2015) and Moreira and Pires (2016) have challenged that, suggesting part of the of seaweed is buried after being transported to deeper parts of the ocean, and provided evidence that seaweeds are globally relevant contributors to oceanic carbon sinks.

> *Box 3 – Oceans 2050* is one of the organisation with an ambitious vision for seaweed's carbon sequestration potential. Under the lead of Professor Duarte, Oceans 2050 has launched a ground-breaking global study that is aiming to help to restore abundance to the world’s ocean while advancing climate restoration through seaweed aquaculture. The study builds on Professor Duarte’s research on ocean restoration by further assessing what role of seaweed aquaculture can play to world’s oceans and climate’ s recovery, claiming this role to be a key recovery wedge. These efforts will hopefully set a robust scientific foundation to support the development of a new voluntary carbon protocol for seaweed aquaculture, which will be a public good and allow seaweed farmers to monetize the carbon impact of their activities for the first time.
>
> *https://www.oceans2050.com*

Krause-Jensen and Duarte (2016) estimated that seaweed could sequester, that is, capture and bury in the sediment, up to 173 TgC per year (with a range between 61 and 168 TgC yr -1) globally, which is about 11% of seaweed net C-production at the time. The authors further calculated that 90% of carbon sequestered is not close to the production site (i.e. coastal sediments), but that the sequestration occurs through export to the deep sea (Krause-Jensen & Duarte, 2016). Therefore, seaweed should not be neglected as an important source of blue carbon because 73 TgC yr-1 of sequestered carbon is comparable to that from all other (mangroves, seagrass and salt water marshes) blue carbon habitats.

Seaweed's contribution to Sustainable Development

Other organisations have focused on including seaweed in the global debate and linking seaweed's potential to international Sustainable Development Goals.
One seaweed supporter is Ocean Vision, who recently published a road map for seaweed for carbon sequestration. The focus here is on (i) state of technology, (ii) development goals and needs (iii) first order priorities.

> Box 4 – 'Ocean Visions works to catalyse science and engineering to support scalable, equitable, and sustainable ocean solutions. In furtherance of this mission, Ocean Visions has partnered with the Grantham Environment Trust to evaluate and advance ocean-based. Ocean Visions and the Grantham Environmental Trust work together to evaluate the science and engineering of proposed ocean-climate innovations, and Ocean Visions provides third-party advice and assistance on research, development, field testing, impact analysis, and optimisation to Grantham Environmental Trust grantees.'
>
> *https://oceanvisions.org/roadmaps/macroalgae-cultivation-carbon-sequestration/*

> Box 5 - The *Seaweed Manifesto* is a visionary document outlining how seaweed can contribute to delivering on the sustainable development goals. It defines a vision for the industry, explores the opportunities and benefits, as well as outlining the challenges and barriers for a responsible development of the industry. The focus is on the untapped potential, and proposes a set of success factors for all stakeholders and provides the basis for different initiatives that will be required. The collaborative development of the manifesto aims to create increased interest and active contributions to the responsible development of the industry from international donors, intergovernmental organisations, non-governmental organisations, research centres and international companies. The manifesto has been initiated by Lloyd’s Register Foundation, an independent global charity that supports research, innovation and education with a mission to make the world a safer place. The work has been actively supported by the Sustainable Ocean Business Action Platform of the United Nations Global Compact. The Action Platform is taking a comprehensive view on the role of the ocean in achieving the 17 Sustainable Development Goals.
>
> *https://ungc-communications-assets.s3.amazonaws.com/docs/publications/The-Seaweed-Manifesto.pdf*

3 Limits to the visions, seaweed not always a blessing

Carrying Capacity

Like with other forms of agri- or aquaculture, the sustainability of seaweed production depends on the intensity and size of the farm as well as the carrying capacity of the system. Alterations to the physical and biochemical environment can occur when the sector upscales production levels (Campbell et al., 2019). If the farm is too big and/or the cultivation too intense, nutrient uptake can affect primary production (phytoplankton). By affecting the primary resources of the food chain, a tipping point could be reached, after which the ecosystem is affected beyond acceptable levels. In extrema this could mean that nutrients are depleted and not enough food is made available to sustain the marine system. It is strongly debated by Van der Meer (2020) that the orders of magnitude on increasing marine food production proposed by The Food and Land Use Coalition (Pharo et al., 2019) can be met due to the high efficiency of the marine system. Data on when exactly such tipping points are reached has not yet been documented, but it is a topic of interest for further research. The biggest inhibiting factor is the lack of field data, although some initial work has been done on this involving mainly modelling studies (e.g. (Vilmin & van Duren, 2021). The vision of having seaweed cultivation in between wind turbines, in so-called multi-use areas, is very promising and provides efficient use of the marine space. However, there are still a number of safety and technological issues that remain (Van den Burg et al., 2020). With further development in seaweed research and the industry itself, these will no doubt be addressed.

Reality of carbon sequestration

It is often claimed that seaweed can end climate change due to its capacity to take up carbon. However, it should be kept in mind that the carbon taken up isn't equal to sequestered carbon – i.e. the long-term storage of carbon. If seaweed is used by organisms, marine or terrestrial (humans included), the carbon taken up will eventually be released again and cannot be calculated as sequestered. If it is used for products that are an alternative to carbon heavy products (plastic, fuel, meat, etc.), then carbon emissions can indeed be avoided, but a life cycle analysis will be needed to calculate the exact net carbon emission of the particular seaweed application. As noted before, carbon sequestration happens mostly when seaweed drifts to the deep sea, where it could remain in the sediment for centuries.

When seaweed poses a problem

Sargassum is a brown seaweed that is beneficial when used in moderate quantities. Out in the open ocean, it provides floating habitat for animals like fish, shrimp, eels, turtles and birds, and is often called the golden forest. Since 2011, due to multiple factors including climate change and the growing human nitrogen footprint, an increasing amount of *Sargassum* is flooding the Caribbean coasts causing all kinds of problems. Apart from the smell, *Sargassum* piles can also prevent sea turtles from laying their eggs, keep sunlight from reaching the coral reefs, and its decay can harm marine life. Knowing about the positive effect of seaweeds (e.g. capturing carbon), researchers and the private sector have tried to come up with solutions like using the excess *Sargassum* for further purposes, but there many challenges that remain to be solved (López-Contreras et al., 2021).

Green tides is a phenomenon whereby a type of green seaweed, most of the time Sea lettuce (*Ulva spp.*), blooms due to anthropogenic eutrophication (Fort et al., 2020) and takes over large areas of marine environment. This causes problems for the local ecosystems and its inhabitants, similar to *Sargassum*. In a particular case, the green seaweed *Ulva* washed ashore in France, Brittany, and produced deadly fumes[3], but this seems to be an exception so far (Schreyers et al., 2021).

3 https://news.sky.com/story/deadly-algae-on-french-beaches-releasing-toxic-fumes-that-can-kill-in-seconds-11805466#:~:text=Fears%20over%20toxic%20algae%20%2D%20which,lose%20consciousness%20and%20stop%20breathing.

4 Reviewing recurrent topics in seaweed: food and feed applications

Looking over visionary documents (see blue reading boxes 1-5 in the previous chapter), a number of recurrent ambitions for seaweed use come to the forefront. Table 1 summarises recurrent ambitions for use in food systems.

Upon reviewing by the study team, four food related ambitions were selected for further scrutiny: seaweed as source of proteins (I), biostimulant (II), feed (III) and feed additive to reduce methane emissions (IV).

I. Protein for human consumption

Seaweeds are presented as a sustainable source of protein from the sea, decreasing the pressure on wild-capture fisheries and being an eco-friendly alternative to meat protein. Seaweed mariculture seems like a perfectly fitting solution to secure food and feed demand, all the while avoid placing additional pressure on arable/available land and freshwater resources (leaving aside possible land-based cultivation of certain seaweed species). Kazir (2019) called seaweed 'a new and renewable source for extracted nutrients', referring to its additional benefits like antioxidant activity, for example in *Ulva* sp. and *Gracilaria sp*., compared to other proteins we are commonly used to (Kazir, 2019).

Looking at the protein content, studies show ranges from 5% up to 47% of dry matter (Cerna, 2011). Brown seaweeds generally have the lowest protein content (up to 24% of dry matter), green seaweeds contain higher levels (10-26%), but red seaweeds have the highest protein content (35-47%) (Garcia-Vaquero & Hayes, 2016). The protein level of red seaweeds can actually be compared to other conventional protein sources (Garcia-Vaquero & Hayes, 2016) for example the protein content of meat is 71–76% DM and soybeans around ~40% DM (Boukid et al., 2021; Lupatini et al., 2017).

Studies generally agree that seaweeds contain high quality proteins with essential amino acids, (lysine, methionine, to name a couple, depending on the strain) and are a rich source of other bioactives, including taurine, lipids, carotenoids, and pigments (Boukid et al., 2021; Černá, 2011; Garcia-Vaquero & Hayes, 2016; Harnedy & FitzGerald, 2013; Lupatini et al., 2017; van der Heide et al., 2021). Krogdahl (2021) further describes the high nutritional value of microalgae and seaweed stating that 'the algal biomass is enriched with polysaccharides, protein, polyunsaturated fatty acids, carotenoids, vitamins and minerals' (Krogdahl, et al., 2021).

Concerns about the feasibility of using seaweeds as a protein source have been raised by several scientists. For instance the variation in the protein content, which depends on species, geographical location and seasonal growth (Fleurence, 1999), (Galland-Irmouli, 1999), or the possible traces of heavy metal, radioactive isotopes,

Table 1: Topics on seaweed use in food systems[1]

Topics	Explanation	Examples
Protein source	Replacing meat proteins and soy proteins and being more climate friendly. Less pressure on land and resources	An area roughly 4 times as big as Portugal could produce enough protein from the sea to feed the entire global population.
Methane reduction	Making meat more climate friendly	Field trials with live sheep cut emissions as much as 80%, while the UC Davis experiment, the first on live cattle, showed a 58% reduction on average when a related seaweed made up 1% of their diet.
Pharmaceutical & nutraceuticals (dietary supplements)	Source of bioactive and nutrient-rich ingredients, vitamins	Gastrointestinal protectors, biodegradable wound care products / nutrient health supplements. Source of iodine, contains vit K and Bs, Zinc, Iron, Antioxidants., that help protect your cells from damage
Additives (Hydrocolloids)	Provision of thickening, stabilising and emulsifying properties	Gelatine substitutes (carrageenan, agar-agar, alginic acid) for processed meat and dairy, also going for the vegan, Halal and kosher markets
Biostimulants	Seed treatments, fertilizer (rich in potassium, nitrogen and phosphorus)	Stimulation of plant growth, protection against abiotic stress, Betaines, Sterols, soil structure and moisture retention, effect on rhizosphere microbes, root development and mineral absorption
Animal Feed, indirectly for food industry	Livestock feed supplements, aquafeed supplements, pet food additives	Promotion of positive immune response and gut health; improvement of digestive processes

1 Based on the opportunities for seaweed from the Seaweed for Europe, hidden champion of the ocean: https://www.seaweedeurope.com/wp-content/uploads/2020/10/Seaweed_for_Europe-Hidden_Champion_of_the_ocean-Report.pdf

dioxins, pesticides, kainic acid, and antinutritional factors within seaweed (Garcia-Vaquero & Hayes, 2016). Arsenic, cadmium, iodine, and *Salmonella* have been identified as major hazards, according to Banach et al. (2020). Therefore, careful testing of seaweed uses for food, feed and pharma is necessary.

Another challenge is that algal proteins can be found as a part of the cell membrane or even entrapped in the cell walls, which might make it more difficult to extract them, potentially leading to lower protein yields (Kazir, 2019). The extraction technology is still in its infancy and the technical cost of extracting and purifying algal proteins is hindering production in Europe at the present time. In addition, there is the difficulty of wanting to get a maximum yield without damaging the nutritional and functional properties (Boukid et al., 2021). Bead millings, ultrasound technology, pulsed electric field and freezing are a few of the processes that have been developed for cell wall disruption and advancing the technology to reach the proteins trapped in the cell walls (Lupitani, et al., 2017) (Bleakly & Hayes, 2017).

When it comes to vegetable protein, not only is the nutritional value important, but also the protein's digestibility (Galland-Irmouli, 1999). Laboratory tests have shown that the proteins were hydrolyzed to a limited extent, which confirmed a rather low digestibility. For example, the digestibility of Dulse (*P. palmata*) proteins seems to be limited by the seaweed's non-proteic fraction. A possible reason for this may be the presence of polysaccharides (Galland-Irmouli, 1999). Kazir (2019) came to other results with his newly developed protein extraction protocol and showed in his study that extracted proteins were ~90% digestible under simulated gastro-intestinal conditions, stating that 'this procedure is scalable and suitable for obtaining a 'food-grade' product'. Harnedy and FitzGerald (2011) have argued however, that the ability of protein hydrolysates (or purified peptides to exhibit a specific biological activity) in vitro is only an indicator of how it is actually digested in vivo (saying that 'the bioavailability of the active peptide after oral ingestion is an important factor associated with the action of the bioactive agent in vivo').

Even though seaweeds have been consumed by humans for centuries, especially in Asian countries, and have been tested for their nutritional values in vitro, scientific information on the digestibility in vivo isn't widely available. Initial tests using minks (monogastric animals) show a low biological value of seaweed proteins (Krogdahl et al., 2021). The study names only Dulse (*P. palmata*) protein concentrate as a considerable protein source, but their results showed 'no clear beneficial or detrimental effects of the seaweed products observed on gut health and function'. Additionally, recommendations were made about the necessity for further investigations to exclude animal health issues relating to results for kidney structure and function, as well as the high iodine in the urine referring as well to the possible impact on human health (Krogdahl et al., 2021).

The aspect of allergenic reactions needs to be kept in mind, as they are not yet approved as 'novel foods' or algal deriving ingredients such protein isolates (Boukid et al., 2021). Regarding novel foods, which includes protein from macro- and microalgae, EU legislation requires that all characteristics that could pose a risk to human health be investigated and effects determined (European Parliament Council of the European Union, 2015). Seaweed farming is being conducted in the open waters, therefore certain naturally occurring phenomena need to be monitored closely as they can be hazardous for human consumption. For example, heavy metals or chemical elements (iodine, arsenic) can accumulate to a certain extent, crustaceans (that can cause allergic reactions) might find habitat within the farm and get caught up during cultivation, or microplastic that shred of the ropes or are already present in the surrounding waters might find their way into the storage containers. Yet, these hazards are known to the industry and already heavily regulated (arsenic levels for example) and monitored with measures taken to minimize risk to humans.

II. Biostimulant

To meet future global food demand, we need a higher food production while dealing with less favourable environmental conditions. Drought, extreme temperatures, water logging and salinity may negatively affect productivity and quality of agricultural crops. This challenge forms the basis for a new era in food production where a stable and sustainable increase of crop yield across different environments and under different conditions is key. Apart from the traditional approaches to increase food production under adverse environmental conditions (e.g. breeding programmes and new agricultural practices), recent approaches using seaweed have been tested to increase stress resistance of major food crops on land.

One is the application of seaweed-derived biostimulants. Biostimulants are 'materials other than fertilizers and pesticides' that can stimulate nutritional processes in plants independent of the crop's nutrient content with the specific aim of enhancing nutrient use efficiency, resilience to abiotic stress, quality traits, or availability of confined nutrients in the soil or rhizosphere (European Parliament and the Council 2019). Biostimulants can be obtained from microorganisms, plant- or animal-based by-products recycled from the food industry, or seaweed extracts. This latter is one of the most promising classes of biostimulants, representing the fastest growing biostimulant industry (Carmody et al., 2020; Markets & Markets, 2019).

The extracts derived from seaweeds contain a plethora of bioactive compounds, including polysaccharides, pigments, phenolic compounds, proteins and (bioactive) peptides, phytohormones and micro- and macronutrients (Craigie, 2011; El Boukhari et al., 2020; Khan et al., 2009; Stirk & Van Staden, 2014). This complex chemical composition could explain the wide range of bio-functionality of these extracts. The processing of seaweed into biostimulant extracts that are of constant quality depends on many factors, for example: algal species, composition, season, growth conditions, process technology, etc. This is an area that is in its infancy and needs more research.

Several papers have shown the potential advantages of using seaweed extracts as biostimulants in both normal (unstressed) and stress conditions (Khan et al., 2009; Shukla et al., 2019). In general, a significant increase in crop productivity and final yield have been observed under both stress and non-stress conditions for glasshouse and field production systems. For example, in the presence of drought stress, cherry tomato seeds treated with an Ascophyllum nodosum-based biostimulant resulted in an increased fruit quality and fruit yield (Murtic et al., 2018).

To summarise, seaweed-derived biostimulants have great potential because:

- a Only very low concentrations of seaweed extract are needed, and in relatively low volumes (up to a few litres per ha per application). This offers opportunities to use the harvested seaweed biomass for a diverse range of products (e.g. food, feed and biostimulants) and makes it very cost effective for farmers
- b Off-shore seaweed cultivation does not compete with land use for producing food
- c Seaweed extracts are able to increase abiotic stress resilience in many crops;
- d the application of seaweed biostimulants can enhance protein production in protein-rich crops;
- e The underlying mechanisms of seaweed biostimulants in target crops is still poorly understood, and so further research is needed as to optimise chemical composition of the seaweed extracts

III. Feed

The demand to produce animal protein more sustainably has driven the search for more sustainable resources to feed livestock. As seaweeds are seen as a sustainable resource with a low environmental impact, interest in using seaweeds as animal feed has been increasing over the past decade (Bikker et al., 2020). Utilisation of seaweed as feed dates back to ancient Greece. In Iceland, seaweed is used supplementary or as substitute in periods when fodder production is limited (Evans & Critchley, 2014), which is not odd as digestibility of some seaweed species is comparable to that of good quality fodder (Makkar et al., 2016). Sheep in the Northern part of Scotland are also known to eat seaweed and use it as their main food source (Hansen et al., 2003; Makkar et al., 2016). The shortage of terrestrial resources has facilitated the usage of seaweed as animal feed in both countries due to natural shortages. Nonetheless, anthropogenic activities can result in the usage of seaweed as substitute or replacement for feed and this be seen by the increased interest in seaweed use in animal feed during the WW-I (Makkar et al. 2016 and references therein).

As mentioned in the first recurrent topic, protein levels of seaweed range between 5% and 47%, with red seaweeds being on the upper range, brown seaweeds on the lower end and green seaweed in-between at 10 and 26% (Fleurence, 1999; Makkar et al., 2016).[4] Where brown seaweed (e.g. kelp) often contain large quantities of mineral (up to 35%), their protein content is relatively low (around 3-15% with outliner reaching up to 24% in *U. pinnatifida*). The high mineral content makes brown seaweed a suitable source for minerals and other compounds.

Composition varies between groups and species, but is also affected by the time of harvest and environmental factors such as light, temperature and sea currents. Variances in composition strongly affect digestibility, supporting the need for proper analysis per batch to ensure stability in the feed. Amino acid composition, the 'building blocks' of the protein, also differ, making some seaweed species more suitable for different livestock. The influences of environmental factors and time can alter the suitability for different seaweed for different applications, making it possible for farmers to align their farm set up and the time of harvest to meet customer preferences. Nonetheless, the amino acid composition is close to the standard protein based on their EAAI (Essential Amino Acid Index) exemplary are Dulse (*P. palmata*) with an EAAI of 103.7% and Wakame (*U. pinnatifida*) with an EAAI of 95.9% (Dawczynski et al., 2007).

Research for application in ruminant diets show a broad variety of effects, including correcting mineral deficiencies (important for milk production), enhance immunity, reduce pathogenic microorganisms and provide overall health for animals. Implementation of seaweeds in animal

4 Percentages are given as % Dry matter

diet in some cases can also depress food intake, potentially affecting the animal's health on the longer term (Makkar et al., 2016). When fed to pigs, seaweed (*A. nodosum*) supplements have been shown to even have a negative effect, like weight loss after several weeks. Similarly, other studies have shown limited to no positive effects on animal health (reviewed by Makkar et al. 2016). When fed to chickens, seaweeds do not seem to have any major impacts. One type of seaweed does however make an exception to the case: calcified seaweeds like *Phymatolithon* and *Lithothamnion* species, also known as Mearl. These seaweeds are a proper calcium source for broilers due to the fact that it is an organic calcium which is taken up much better by chickens than inorganic (mineral) calcium. Also inorganic calcium decreases the digestibility of phosphor improving the bone heath and reduce leg problems (Bradbury et al., 2012).

Constraints for using seaweed as feed have also been found. Heavy metal content and other contaminants pose a potential threat on animal health. Feeding animals large quantities of seaweed can exceed acceptable feed safety levels and also result in a mineral overload due to the high mineral content in some seaweed species.

All in all, it can be concluded that seaweed can be a valuable asset to animal feed, but it is doubtful whether seaweed will become a major component in animal feed. The strong variations in composition make it crucial to analyse batches separately to ensure product stability. Improving seaweed cultivation and standardising processes (e.g., harvesting, timing, processing) can contribute to quality stability, supporting the safe use of seaweed as animal feed and reducing the need for frequent quality checks. Even so, applications such as feed supplement or extracted proteins can replace a part of the now used ingredients and enhance animal health, quality and productivity.

IV. Methane emission reduction in ruminants

Over the past years, considerable attention has been given to the use of seaweed to reduce methane (CH_4, a powerful greenhouse gas) emissions. Livestock production is a major contributor to Greenhouse gas (GHG) emissions (Johnson & Johnson, 1995) among others, because the enteric fermentation of ruminants causes methane gas emissions. Ruminant livestock can produce between 250 to 500 L of methane gas per day (Johnson & Johnson, 1995). Enteric methane emissions are the single largest source of direct GHG emissions in beef and dairy value chains and are a substantial contributor to anthropogenic methane emissions globally. Dietary manipulation is one of the proposed strategies to reduce methane emissions (Haque, 2018). Substantial resources have been allocated in recent years to further the research on the effects of adding seaweed to ruminants diets – among others USD 5m in the US and USD 13m in Australia.

In 2016, Maia et al. claimed to publish the first study evaluating the effects of adding seaweeds on gas and methane production in ruminal fermentation in an in vitro study (Maia et al., 2016). Five types of seaweeds were evaluated: *Ulva sp*., *Laminaria ochroleuca*, *S. latissima*, *Gigartina sp*. and *Gracilaria vermiculophylla*. While results were mixed, with eventual reductions being dependent on the feed use and the type of seaweed used, the study spurred further investigations.

A meta-review conducted by Lean et al. (2021) observed that the dominant species used in experiments are *Asparagopsis taxiformis* and *A. nodosom*, although there are multiple publications that describe the use of different species present in Northern and Southern hemisphere. Lean et al. (2021) concluded that the data available, if limited, points to a significant and substantial reduction in methane emissions, while there is no evidence that the addition of seaweeds benefitted growth.
Reduction percentages are at times impressive. It is claimed that adding *A. taxiformis* at an addition rate of just 2% of organic matter, a reduction of methane production of 99% can be realized (Machado et al., 2016). The mechanism by which methane emission are reduced is described by various authors. In short, the halogenated compounds, of which bromoform is the most important one, inhibit methane formation in the rumen.

A recent study by Muizelaar et al. (2021) points towards potential negative impacts of adding seaweed to the diet of cattle. Three effects were observed after feeding *A. taxiformes* (1) reduced feed intake by lactating dairy cows, (2) the extraction of Bromoform ($CHBr_3$) in the urine and milk and (3) abnormalities in the rumen wall. Concerns about the long-term effects on productivity, animal health, product quality, digestibility of nutrients, compound residues in manure and manure GHG emissions are also voiced (Vijn et al., 2020). A 2021 study on beef cattle concludes that the use of *A. taxiformis* reduced enteric methane emissions for a duration of 21 weeks without any loss in efficacy and concluded that the addition of this seaweed had no measurable bromoform residues, no detrimental iodine residual effects in the product, and did not alter meat quality or sensory properties (Roque et al., 2021).

Overlooking the evidence base, the following conclusions are drawn:
- Various studies confirm that adding seaweed to the diets of ruminants reduces CH_4 emissions.
- Various seaweed species can be used to achieve this effect, although most studies have focussed on *Asparagopsis taxiformis* and *Ascophyllum nodosom*.

- Initial studies into the negative effect of adding seaweeds point towards animal health concerns but other studies have shown no negative effects.
- A complicating factor is that these studies focus on different production systems (e.g. dairy vs beef) and with different feed compositions.
- Both short- and long-term animal trials are needed to comprehensively evaluate the use of seaweed in cattle production (Vijn et al., 2020).

In vivo, experiments are required to strengthen the evidence base for claims on methane reduction and to better understand possible negative effects (Muizelaar et al. 2021; Lean et al. 2021).

5 Overview of Dutch expertise on seaweed

The last question addressed in this study is how the Dutch expertise fits in with the broader, international perspective. To do so, a better understanding is needed of the present state of the parties, being entrepreneurs, scientists and/or policymakers active in Dutch seaweed industry. To get this overview and the present expertise and possible role in the transition for the global food system, a survey and a literature research was conducted.

Methodology

The survey contains four parts, letting respondents choose if they would like to answer questions directed towards (i) private companies, (ii) research institutions, (iii) governmental institutions and ministries or (iv) 'Other' parties working with seaweed or the Netherlands in some way. In each part, similar questions were presented to the respondents, but reformulated to fit to their working context. For instance, private companies were asked what they see an investment worthy ambition for seaweed, whereas scientific institutions were asked in which ambition for seaweed they have or would like to have extensive expertise in. All respondents were provided lists of applications for seaweed, four of which we have discussed in the previous chapter, which are either to be evaluated for the relevance to their business or their expertise in such applications etc. This way we built a common ground of seaweed applications which were then analysed in the Dutch context. To complete the overview for knowledge institutions, a Scopus search was done to gather information on which topics Dutch institutions publish.

Results

Private companies

From the 11 companies that replied to the survey, the most important seaweed application for their business was by far seaweed for human consumption, ranking a 4.2 out of 5 (most important). Only one company mentioned having local and national scope, while the rest had international reach and even global scope. They clearly mentioned ambitions for several other seaweed application to include in their portfolio in the near future. Some are about refining their products within the human consumption applications, others have ambitions to get involved in bio-packaging, cosmetics, biostimulants etc. When asked what support from the government the private companies would like to receive, they express the wish for financial support, support in the Novel food procedures and approvals, regulations for land-based production, certification of product and clear regulations on sea vegetables (similar to those that exist for land vegetables).

Those replied are only a part of the existing private companies, but their unique responses added value or presented illustrative selling points for potential uses of seaweeds within the Netherlands. Aspects of circularity, combining seaweed processing with the processing of fish waste to achieve sustainable food and feed products, having the right exposure, owning technology to cultivate at large scale offshore, or being ready for every demand in the market by having their own hatchery, farm and food safety process facility were also mentioned.

Within the network of the North Sea Farmers, there are most seaweed related Dutch companies. An overview of the members can be found on: Northseafarmers.org/community/farmers.

Knowledge institutes

In the past 10 years, the Dutch knowledge institutes' publication on seaweed and/or macroalgae augmented steadily. Our explorative literature research, using Scopus, reveals that Agricultural- and Biological Sciences is by far the biggest subject of interest, making up 34.4 % of publications over that time frame. This was followed by Environmental Sciences (18.5 %), Biochemistry, Genetics and Molecular Biology (7.5 %), Earth and Planetary Sciences (7.3 %) and a number of smaller subject areas. Looking at the four knowledge institutes with the highest number of publications on seaweed and/or macroalgae, a few trends can be observed.

For Wageningen University and Research, interestingly Environmental Sciences only started gaining interest in 2017 but quickly gaining in interest. Energy and Engineering, two other subject areas outside the four main topics, reduced in publications, but still playing a role in 2021. Even though the Royal Netherlands Institute of Sea Research is strong in Agriculture, and the total amount of publications on seaweed are in this subject area, one can see a trend of Environmental Sciences replacing the research focus for the institute. In 2021, for the first time the publications with a focus on Environmental Sciences outranked the ones on Agricultural sciences. For the Rijksuniversiteit Groningen, in 2011 the subject area Agriculture Sciences made up 67% of their 8 publications, which then dropped in the following years and only regained interest in 2017. It is important not to forget that the number of publications and duration it takes until a paper is published can bias the results. Looking at seaweed from an Environmental Sciences perspective, the focus was already early established, while it gained interest at other institutes only after 2016. At Universiteit Utrecht, a clear trend favouring environmental sciences and less on agricultural publications is visible.

Discussion

The global seaweed industry accounts for about 6 billion euros annually, with China being the largest producer accounting for 65% of the total global production.

While Asian countries are known for their expertise in seaweed cultivation, application and utilisation, the Netherlands' extensive agricultural knowledge is what it is internationally recognised for. The Dutch expertise on use of seaweed in food, feed and agricultural applications is globally recognised, like the knowledge on water management and coastal defence. Opportunities for collaboration and knowledge exchange, where the Netherlands can apply their knowledge to other markets, like the Japanese market, can be fruitful for both sides.

In general, the Netherlands is on the lower end of a list of countries producing raw seaweed material. In Europe, Norway is the country with the highest number of seaweed aquaculture companies. The unique selling point, and recognised expertise, of the Netherlands is in agricultural knowledge in particular, the breeding of seaweed species. Norway, for instance, lacks on this point and could therefore benefit from Dutch expertise.

6 Conclusion

Our review of state-of-the-art scientific knowledge summarises potentials of seaweeds: Its positive effects on the ecosystem often name it regenerative or restorative aquaculture, it provides a number of ecosystem services and to dietary benefits as well as providing an alternative for plastic or fossil fuels on the long term. The list of benefits is long and can easily lead to promising visions with enthusiastic supporters to claim to have a new solution in mitigating climate change and feeding the world.

While we endorse the fact that seaweed is an interesting resource for the future, we ask attention for some drawbacks and potential negative effects that might occur when using seaweed in food products. It is necessary not to get carried away and skip steps by oversimplifying the 'seaweed wonder'. For example, just because seaweed captures a great deal of CO_2, this doesn't mean this amount is the same as that sequestered from the atmosphere and stored away.

If the potential of seaweed is to be supported, a sector should be built in a sustainable and inclusive way. To safely call something positive, one should also cover the bases and study its potential negative effects. Seaweed farms can be a hazard in the open waters, just as any other aquaculture practice and this should not be overlooked. A potential for seaweed is there, even if it is on other levels, other foci and other scales. Research and new business opportunities should still be supported to allow the Dutch seaweed industry to grow on the global scale.

The Dutch seaweed industry is in its infancy but growing. The close cooperation between government, knowledge institutes and the private sector can benefit sector development within the Netherlands. Implementation of present knowledge derived from more or less affiliated industries (e.g. fisheries and agriculture) in which the Netherlands has a strong presence. Both technological knowledge as well as lessons learnt, combined with the strong entrepreneurship of the Dutch, can help build greater experience and expertise in seaweed cultivation. The expertise on the production of cultivars is unique in Europe. The Dutch seaweed sector is well organised, grounded in solid scientific research and has strong ties to the food and feed sectors. Cooperation with global producers, processors and research institutes can further benefit the development of a sustainable seaweed sector in the Netherlands, and be a means to further strengthen the global role of the Dutch seaweed sector.

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2021-152

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