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Potential of the Chilean seaweed sector

Sustainable large scale production opportunities and beneficial effects of local seaweed varieties

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Summary

Worldwide over 10.000 species of seaweed (macroalgae) exist which are often divided into three groups; green seaweeds (Chlorophyta), red seaweeds (Rhodophyta) and brown seaweeds (Phaeophyta). High abundance of seaweeds can be found along coast lines with a hard substrate (i.e. rocky shores) to which they can attach, while some free floating species exist. In 2015 the global seaweed production was 30.4 million with an estimated worth of more than 6 billion USD, of which 29.4 million tonnes derived from aquaculture production and 1.1. million tonnes from wild harvest. Seaweeds are rich in all kinds of bioactive compounds, minerals and specific carbohydrates and are commonly used in the nutraceutical, pharmaceutical and biorefinery industries Apart from being consumed as a food product, the largest application of seaweeds in the food industry is the extraction of specific carbohydrates to be used in a wide range of food products. The most important carbohydrates extracted from More recently the use of seaweeds as feed supplements for livestock has (re-)emerged as a research interest due to recent results, and markets are being developed. In addition, the use of seaweeds and extracts there off as a biostimulant for crop production under both stressed and normal condition are promising.

Using seaweeds for all kinds of purposes, from food and feed to materials, is a long standing tradition in Chile. The current market revolves mainly around the harvest of large amounts of seaweed biomass from natural seaweed beds, which are exported directly after drying or after undergoing initial processing steps. Chile ranks as the 6th largest seaweed producing country worldwide and largest when only considering wild harvest from natural beds, about 97% of the total production is wild harvested seaweed while the other 3% originates from aquaculture activities. While in recent years a lot of research has been performed on the aquaculture of different seaweed species, this practice is not yet commonly established. Multiple stakeholders of local fisherman communities, indigenous communities, research institutes and national authorities expressed a clear positive interest in collaboration with Dutch counterparts.

For Dutch companies there are two main opportunities to collaborate with Chile in the seaweed sector. Dutch seaweed producing companies can bring activities, technology and knowhow to Chile and combine with the local knowhow to start up seaweed aquaculture. Secondly, Dutch companies active in processing and livestock feed can assist on how to best apply local seaweed products in for example animal diets for the South and or North American market. Key infrastructure components for scaling up are already in place due to other aquaculture activities. The seaweed sector could be complimentary and can be an interesting partner for both the salmon and dairy sector which are searching for innovations.

Current aquaculture related legislation in Chile can be a challenge for starting new seaweed related activities. These legislations are focused on protecting the environment and new activities should not have negative effects compared to the reference level. A potential opportunity is to collaborate with indigenous communities in Chile, which have more sovereignty in the exploitation of certain areas of land and sea that they can claim. This can serve as a spin-off point for further development. The embassy of the Netherlands in Chile has a central role and can offer assistance to connect the Chilean and Dutch ambitions. Seaweeds with its many different applications fits within the vision on the protein shift of the Dutch Ministry of Agriculture, Nature and Food Quality as an alternative marine resource. Simultaneously, the embassy can connect and facilitate in conversations with the Chilean authorities, local markets and knowledge institutes. This helps the Dutch companies in developing long term relationships and understand the regulations and requirements from a Chilean perspective.

1 General Introduction

Worldwide over 10.000 species of seaweed (macroalgae) exist which are often divided into three groups; green seaweeds (Chlorophyta), red seaweeds (Rhodophyta) and brown seaweeds (Phaeophyta). High abundance of seaweeds can be found along coast lines with a hard substrate (i.e. rocky shores) to which they can attach, while some free floating species exist (i.e. *Sargussum* spp.). It is generally thought that human communities close to the shore have used seaweeds for various purposes for thousands of years (Buschmann et al., 2017). In 2015 the global seaweed production was 30.4 million with an estimated worth of more than 6 billion USD, of which 29.4 million tonnes derived from aquaculture production and 1.1. million tonnes from wild harvest (FAO, 2018). Seaweeds are rich in all kinds of bioactive compounds, minerals and specific carbohydrates and are commonly used in the nutraceutical, pharmaceutical and biorefinery industries (Holdt and Kraan, 2011). Apart from being consumed as a food product, the largest application of seaweeds in the food industry is the extraction of specific carbohydrates to be used in a wide range of food products. The most important carbohydrates extracted from seaweeds are carrageenan, agar and alginate and are used in the food industry as hydrocolloids. Hydrocolloids are ingredients that are used as thickening, stabilising, gelling, (anti)foaming or emulsifying agents (Phillips and Williams, 2009). For example, in Indonesia the seaweed species *Euchema* spp. and *Gracilaria* spp. are specifically cultivated for the production of carrageenan and agar, resulting in 11.3 million tonnes of seaweed in 2015 (FAO, 2018). More recently the use of seaweeds as feed supplements for livestock has (re-)emerged as a research interest due to recent results, and markets are being developed. In addition, the use of seaweeds and extracts there off as a biostimulant for crop production under both stressed and normal condition are promising (Deolu-Ajayi et al., 2022).

In the past in areas close to the coast seaweeds could have been regular part of the diets of livestock due to natural grazing or harvesting and substitution of other ingredients by washed-off and natural growth of seaweeds (Evans and Critchley, 2014). Due to their diverse chemical content, seaweeds have been broadly researched for the use in animal diets, for example as a novel nutrient source, dietary fibre or bio-stimulant to improve animal health (Makkar et al., 2016). Due to the large diversity of seaweed species and composition, very seaweed species has its own potential specific use. In dairy cattle the brown seaweed *Saccharina latissima* increased the milk and lactose production (Muizelaar et al., in preparation[1]), which are intriguing results and need further understanding. Also in other livestock species, seaweeds have potential beneficial effects for animal health and productivity (Øverland et al., 2019). In addition, the livestock sector and in particular ruminants face large challenges to reduce their greenhouse gasses emissions. The red seaweed species *Asparagopsis taxiformis* and *Asparagopsis armata* are rich in bromoform and similar components and can reduce enteric methane production by 0-98% (Roque et al., 2019; Kinley et al., 2020; Stefenoni et al., 2021). However, the use of these seaweeds may result in reduced feed intake (Roque et al., 2019; Stefenoni et al., 2021), damages to the rumen wall (Li et al., 2018; Muizelaar et al., 2021) and transfer of bromoform and other compounds to the milk and urine of dairy cattle (Muizelaar et al., 2021; Stefenoni et al., 2021). Other seaweeds such as *Ulva* spp, *Macrocystis pyrifera* and *Pterocladia capillacea* produce bromoform but do not have the high concentrations as *A. taxiformis* (Carpenter et al., 2000; Abbott et al., 2020). The brown seaweeds *Ascophyllum nodosum* and *Laminaria digitata* have also been researched as a mineral source, especially iodine, for dairy cattle and transfer of these minerals to milk (Antaya et al., 2015, 2019; Newton et al., 2021).

From north to south the mainland of Chile has a shoreline of over 4200 km resulting in a claimed exclusive economic zone (EEZ) of 1.9 million km^2, excluding the island territories, additional to the territorial sea which stretches 22.2 km from the mainland into the sea. The territorial sea is the area in which a country has full sovereignty of the area from the sea floor to the airspace above it, while in the EEZ a country has sovereign rights to exploit the marine resources (including wind and water energy) but does not control the movement of ships or airplanes in the surface water or airspace.

[1] https://www.wur.nl/nl/Onderzoek-Resultaten/Onderzoeksinstituten/livestock-research/show-wlr/Voorlopig-beeld-uit-project-Zeewier-in-een-gezonde-melkveehouderij.htm

The Humboldt current extends from southern Chile to northern Peru and is one of the most productive currents (Montecino and Lange, 2009). Cold, nutrient rich waters from deeper seawater are upwelled and collide with warmer surface waters due to the eastern winds which create the Humboldt current. This results in a large biodiversity and abundance of all kinds of fish, molluscs, crustaceans and seaweeds. Local (indigenous) communities close to the coast have for centuries exploited these rich areas and have an strong history with harvesting and using seaweeds in all kinds of daily practices. Livestock are left to roam and graze among the beached seaweed, green seaweeds are used as soil fertilizer on arable land, certain species are harvested and sold for their specific carbohydrates and sea urchins are hunted and harvested in between the seaweed fields. Across Chile the local indigenous communities control large protected concessions of coastal areas which are often rich in all kinds of seaweed species, in the region of Los Lagos the total protected concessions by indigenous communities total up to more than 150.000 hectare.

This report gives an overview of the developments and research in the Chilean seaweed sector and gives insights in the application of local seaweed species in ruminant feed and opportunities for cooperation between local and indigenous communities with Dutch SME's for large scale seaweed production.

2 Seaweeds and Chile

2.1 Historical production

With a total of 358.000 tonnes of seaweed produced in 2015, Chile ranks as the 6th largest seaweed producing country worldwide (FAO, 2018), see also table 1. About 97% of the total production is wild harvested seaweed while the other 3% originates from aquaculture activities (Figure 1), making Chile the largest country in the wild harvest of seaweeds. In contrast Japan, the 5th largest seaweed producer in 2015, produced a total of 493.000 tonnes in 2015 of which 19% was from wild harvest and 81% from aquaculture (FAO, 2018). These seaweed production numbers are minimal compared to the two largest seaweed producers, China and Indonesia. In 2015, China produced 14 million tonnes and Indonesia 11 million tonnes of seaweed of which 98% and 99% originated from aquaculture activities (FAO, 2018). Approximately 90% of the seaweeds harvested in Chile are directly exported, while the other 10% are processed within the country and mostly exported afterwards (Camus and Buschmann, 2017). Aquaculture of seaweeds in Chile is mainly limited to the red seaweed "pelillo" or *Gracilaria chilensis*, a seaweed species which is used for the production of agar (Buschmann et al., 2017). While wild harvest is mostly limited to brown seaweeds, mainly *Lessonia nigrescens*, *Lessonia trabeculata* and *Macrocystis pyrifera* or "huiro", which are mainly processed for the extraction of alginates or used as feed for abalone production (Buschmann et al., 2014; Camus et al., 2018).

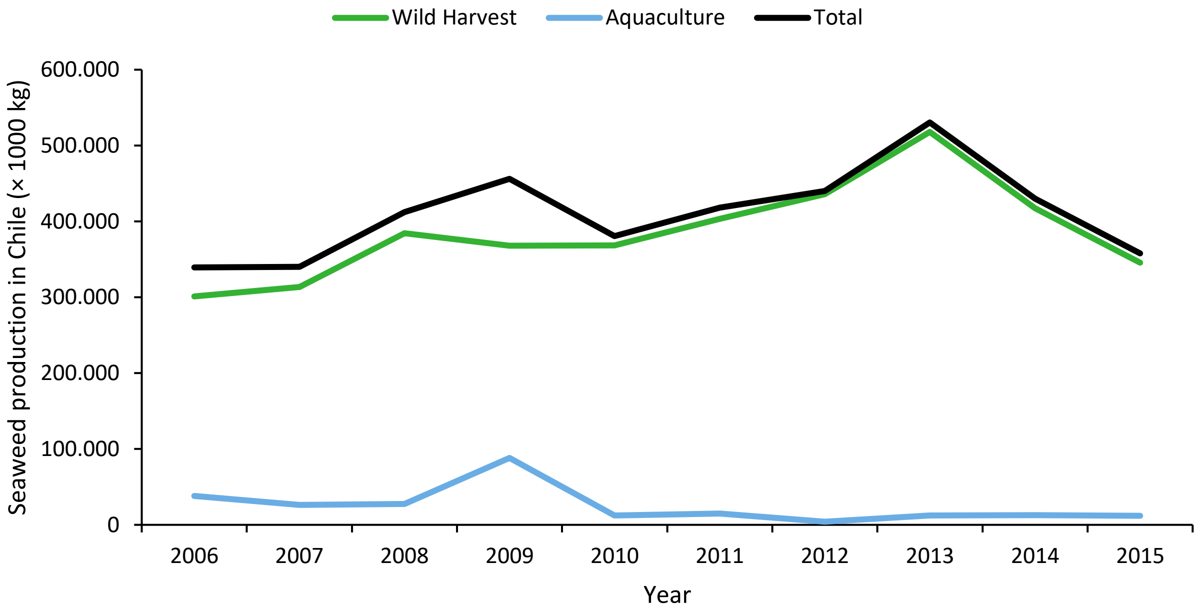

Figure 1 *Seaweed production in Chile from 2006 to 2015 (Source FAO, 2018).*

2.2 Seaweed aquaculture development

In Chile the aquaculture production of seaweeds has a long history and has already been researched since the 1990's, with the main focus on how to combine seaweed farming with the salmon aquaculture (Buschmann et al., 1994; Troell et al., 1997). More recently the research focused on the production of the brown seaweed *M. pyrifera* (huiro). Several experiments showed the feasibility of offshore and near shore production of *M. pyrifera* (Gutierrez et al., 2006; Macchiavello et al., 2010; Westermeier et al., 2011; Correa et al., 2016). While these experiments were on an experimental or pilot scale, recent experiments upscaled to precommercial size. Three different pilot farms of precommercial scale (up to 21 Ha) at three different areas in Chile were developed and evaluated (Camus et al., 2018). The pilot farms were located at Caldera in the North and Quenad and Ancud in the South of Chile. A land based hatchery produced starting materials (sporophytes) of the seaweed and attached them in different densities to the ropes, which were subsequently deployed at the pilot farms at different times of the year. These results show that depending on the location, which influences the biological as the physiochemical factors, offshore aquaculture of *M. pyrifera* is possible with production levels up to 124 wet MT Ha^{-1} $month^{-1}$ (Camus et al., 2018).

Multiple experiments show that cultivation of *M. pyrifera* is technically possible, knowledge exists on the production of starting material as well as on how to scale up. Still, industrial aquaculture of brown seaweeds has not taken off yet in Chile. Several factors such as regulations and lack of financial incentives are restricting this development (Buschmann et al., 2014), and no clear market exists yet that can use large amounts of brown seaweeds. Developing industrial seaweed aquaculture has a direct conflict with current regulations in place in Chile (Buschmann et al., 2013). These regulations are focused on protecting the marine environment and new activities must show that they will not negatively affect the production of the marine system. For example, seaweeds take up nutrients from the surrounding water potentially limiting other organisms to grow, while simultaneously providing other ecosystem services that stimulates other forms of life. Additionally, offshore seaweed cultivation takes place on installations in the water, and what material is used for these installations is crucial from a regulatory perspective.

Table 1 *Seaweed production per country in 2015 (Source FAO, 2018).*

Country	Total × 1000 kg	Wild Harvest × 1000 kg	Aquaculture × 1000 kg	Wild harvest %	Aquaculture %
China	14,186,305	261,770	13,924,535	2	98
Indonesia	11,347,571	78,230	11,269,341	1	99
Philippines	1,566,361	0	1,566,361	0	100
Korea, Republic of	1,204,955	7,826	1,197,129	1	99
Japan	492,600	93,300	399,300	19	81
Chile	357,656	345,704	11,952	97	3
Malaysia	260,760	0	260,760	0	100
Zanzibar	172,490	0	172,490	0	100
Norway	147,391	147,391	0	100	0
Korea, Dem. People Rep.	48,900	0	48,900	0	100
Ireland	29,500	29,500	0	100	0
India	21,652	18,650	3,002	86	14
France	19,110	19,110	0	100	0
Iceland	16,830	16,830	0	100	0
Madagascar	15,377	0	15,377	0	100
Peru	14,824	14,824	0	100	0
Solomon Islands	12,200	0	12,200	0	100
Viet Nam	11,822	0	11,822	0	100
Canada	11,573	11,573	0	100	0
Mexico	11,331	11,331	0	100	0
South Africa	9,131	7,131	2,000	78	22
Russian Federation	8,698	6,662	2,036	77	23
Tanzania, United Rep. of	6,750	0	6,750	0	100
United States of America	6,469	6,469	0	100	0
Morocco	5,284	5,284	0	100	0
Sri Lanka	4,760	0	4,760	0	100
Papua New Guinea	4,000	0	4,000	0	100
Kiribati	3,600	0	3,600	0	100
Spain	2,386	2,386	0	100	0
Myanmar	2,324	0	2,324	0	100
Australia	1,923	1,923	0	100	0
Portugal	1,574	1,574	0	100	0
Total	30,006,107	1,087,468	28,918,639	4	96

Financial incentives or market perspectives for seaweed aquaculture are lacking. Current wild harvested seaweeds are mainly exported and are a tough market to compete with. Additionally, multiple Chilean contacts indicated illegal wild harvesting is prominent, and can potentially cause overharvesting of the natural beds in an unsustainable manner. The advantage of aquaculture produced seaweeds are that they can be of a more consistent and higher quality than wild harvested seaweeds. Two markets have been identified for the use of aquacultured seaweeds in Chile namely, feed production for abalones and as feedstock for the production of biofuels. Production for abalone feed could be economically possible (Correa et al., 2016), but the abalone market is limited. The biofuel market is limited due to the large quantities needed for a low price, and with the global transition to more renewable resources biofuels have to compete while staying cost and environment efficient. New applications that are in development might offer more opportunities for aquaculture seaweed production. Several seaweed species, including *M. pyrifera*, are under research for the use in livestock feed for several purposes. Also, extracts made of seaweeds for the use as crop fertilizer is a highly promising opportunity.

2.3 Current research in livestock application

Several research projects on feeding seaweeds to dairy cattle are ongoing at the moment. At the Universidad Santo Tomás (Santiago de Chile) a 4 year research project started in 2022 which investigates native Chilean seaweeds for the potential to reduce enteric methane produced by dairy cattle. The project starts with a questionnaire, followed by *in vitro* trials and then *in vivo* trials. Main species of interest are for red seaweeds *A. taxiformis* and *A. armata*, brown seaweeds *Macrocystis* and green seaweeds *Ulva*. The Universidad Santo Tomás collaborates in this project with the University of Texas in the United States of America, and plans to perform the trial with the dairy cattle in the south of Chile using Greenfeed systems to measure enteric methane production. The National Institute of Agricultural Research (Instituto de Investigaciones Agropecuarias; INIA) started a 4 year research project in 2022 at their regional research institute Remehue in the Los Lagos region focusing on three specific seaweed species. A combination of *in vitro*, *in vivo* and modelling research will be used to study the effects of *Gracilaria chilensis*, *Lessonia* sp. and *M. pyrifera* on ammonia and enteric methane emission. The first *in vitro* trials have been carried out and the results are being evaluated.

3 Opportunities for Dutch SME's

Using seaweeds for all kinds of purposes, from food and feed to materials, is a long standing tradition in Chile. The current market revolves mainly around the harvest of large amounts of seaweed biomass from natural seaweed beds, which are exported directly after drying or after undergoing initial processing steps. Aquaculture of seaweeds does exist in smaller amounts, consisting mainly of the red seaweed species *Gracilaria chilensis* and several (pilot scale) experiments on the aquaculture of *M. pyrifera* have been performed. Aquaculture of seaweeds might be interesting if it has an offset market. However, both wild harvest and aquaculture production of seaweeds can have strong negative impacts on the environment if not managed properly (Mac Monagail et al., 2017; van den Burg et al., 2020) In Chile there is knowledge on local seaweed species and how they can be potentially cultured on industrial scale. The challenge lays in overcoming the limitations in the legislation and creating a market opportunity for the produced seaweeds.

Current aquaculture related legislation in Chile is focused on protecting the environment and new activities should not have negative effects compared to the reference level (Buschmann et al., 2013). These legislations make it difficult for new seaweed related aquaculture to develop and establish. Currently, two main groups are active in the wild seaweed harvest in Chile. Artisanal fisherman, mainly active in the north of Chile, harvest mostly from natural seaweed beds and indigenous communities, mainly in the south, have both aquaculture activities and harvest from natural seaweed beds. Officially there are licenses for how much seaweed can be harvested, however in conversations with multiple stakeholders concerns were raised if these limits were not exceeded. While some organisations exist that are focused on reforestation of the natural seaweed beds, multiple stakeholders mentioned a general trend in decline of natural seaweed beds reflecting a potential negative effect. Reshaping this sector offers the opportunity to transform the unsustainable wild harvesting sector into an innovative productive regenerative sector.

Indigenous communities can claim a certain area of land and sea from a cultural and historical perspective, have more authority in the management of these areas and are possibly less restricted by governmental legislation. These communities often have a long history with the use of local seaweed species. At the island of Chiloé the locals allow livestock to graze on the available seaweed at low tide (cows mainly graze on brown seaweeds), pigs are fed cochayuyo (*Durvilaea antarctica*) when there are suspicions of a parasite infection which causes them to have short term diarrhoea, certain species (mainly green seaweeds) are harvested and used on the acres as a sort of fertilizer and many families have one or multiple lines for the production of *Gracilaria* spp. and help in the yearly harvest of natural seaweed beds which are sold to outside companies. Collaboration with indigenous communities might be a first step opportunity for collaboration, however good relationship management is crucial. Several NGO's, like Costa Humboldt, have a good relationship with these communities and can help bridge the gap.

In conversations with multiple stakeholders of local fisherman communities, indigenous communities, research institutes and national authorities a clear positive interest was expressed in collaboration with Dutch counterparts. For Dutch companies there are two main opportunities to collaborate with Chile in the seaweed sector. Dutch seaweed producing companies can bring activities, technology and knowhow to Chile and combine with the local knowhow to start up seaweed aquaculture. Secondly, Dutch companies active in processing and livestock feed can assist on how to best apply local seaweed products in for example animal diets for the South and or North American market, e.g. cows, pigs, poultry, pets, salmon, shrimp or abalone. For scaling up the infrastructure of the already available large-scale ecosystem for the aquaculture sector (salmon and seafoods) can be used. The seaweed sector could be complimentary to this sector and can be an interesting partner for both the salmon and dairy sector which are searching for innovations.

The embassy of the Netherlands in Chile and the Netherlands Agricultural Network has a central role and can offer assistance to connect the Chilean potential to the Dutch ambitions. Seaweeds with its many different applications fits within the vision on the protein shift of the Dutch Ministry of Agriculture, Nature and Food Quality as an alternative marine resource.

The embassy has a broad overview of different financial instruments and can link the Dutch private sector to possible finance institutions like Invest International and RVO instruments and more. These instruments can help Dutch companies to acquire the needed investments to start the collaboration in Chile. Simultaneously, the embassy can connect and facilitate in conversations with the Chilean authorities, local markets and knowledge institutes. This helps the Dutch companies in developing long term relationships and understand the regulations and requirements from a Chilean perspective. The embassy aims to setup a innovation mission from the Netherlands to Chile for 2023 on novel ingredients for animal feed in which seaweeds will play an important role.

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To explore the potential of nature to improve the quality of life

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