Food products from the seaweed *Saccharina latissima*

Assessment of environmental impacts and nutritional value

This research is part of the AF16202 Maatschappelijk Innovatie Programma (MIP) Seaweed for food and feed (BO-59-006-001). The programme is part of the Agri&Food Top Sector, financed by the Dutch Ministry of Agriculture, Nature and Food Quality.

The authors would like to thank Roos Visser, Freija van Holsteijn, Arie Mol, Zinzi Reimert and Eef Brouwers for their support with data collection during the research project, as well as to all the entrepreneurs who wish to remain anonymous.

The scientific publication of this work can be found at: https://doi.org/10.1016/j.jclepro.2021.128689

Summary

Seaweeds are more frequently highlighted as a healthy component of future diets thanks to their low environmental impacts compared to other food ingredients. The Dutch seaweed sector, like its European and US counterparts, is in a nascent stage of development. This report describes the outcomes of the ProSeaweed project focused on "Assessing the environmental impact of food products from Dutch seaweed". Life cycle assessment was used to quantify the environmental impact of both the current state of the art and future *Saccharina l.* cultivation in the North Sea. Next, the environmental impact and Sustainability Nutrition Balance of three food products containing *Saccharina l.* were quantified. The assessed food products are: a burger with *Saccharina l.,* salt with 10% *Saccharina l.* and salt replacement based on 100% *Saccharina l.*

The environmental impact results point to a hotspot in the transport efforts. The results presented in this study are based on experiences with innovative seaweed farming and future scenarios which are a projection for 5 years from now. Under its current conditions, seaweed cultivation makes a significant contribution to the environmental impact of the assessed food products. In the future cultivation scenario, with future estimated yields and more efficient infrastructure design and transport, the impact of *Saccharina latissima* on the total burger and salt product impacts diminishes significantly.

The inclusion of seaweeds in future vegetarian burgers or as salt replacement can have a positive effect on the environmental impacts of certain diets. While this study is based on newly collected data, readers are reminded that the European seaweed cultivation sector is still in an early stage of development. Future innovations in other cultivation technologies and breeding will affect these environmental impacts. The subsequent step is to expand the product portfolio both in product types, as well as the seaweed species included as ingredients.

Key words

Life-Cycle Assessment, Sustainable Food Systems, Sustainable diets, *Saccharina latissima*, vegetarian burgers.

Introduction

In 2018, a total of 32.4 million tonnes of seaweeds were produced globally. Of which 97.1% is cultivated seaweed (FAO (Food and Agriculture Organization of the United Nations), 2016). In Europe, there is increasing interest in using seaweeds for food, feed and other applications as this can contribute to achieving policy objectives related to Blue Growth, climate and food security (Barbier et al., 2019). Various commercial and research-driven initiatives cultivate seaweeds in Europe, with the food market driving commercial seaweed cultivation (van den Burg et al., 2019). Initial studies into consumer acceptance show that Western consumers perceive seaweed food products as natural and healthy (Birch et al., 2019).

Saccharina latissima is a brown seaweed known as sugar kelp or royal kombu in Europe. It is the most cultivated species in terms of volume and number of companies in Europe (Araújo et al., 2021). Various studies have confirmed the feasibility of cultivating *Saccharina l.* under offshore conditions (Azevedo et al., 2019; Peteiro et al., 2016). *Saccharina l.* can be used for food applications and is seen as a promising source of functional food ingredients (Neto et al., 2018; Rey et al., 2019).

This research focuses on 1) quantifying the environmental impact of current, state of the art *Saccharina l.* cultivation in the Dutch Exclusive Economic Zone of the North Sea using Life Cycle Assessment, and 2) identifying the hotspots in current cultivation practice and processing of the grown *Saccharina l.* for use in vegetarian burgers and as salt replacement in terms of environmental impact of diet using the Sustainability Nutrition Balance.

Approach

Life Cycle Assessment (LCA)
To quantify the environmental impact of *Saccharina l.* applied in food products, Life Cycle Assessment methodology was employed following the guidelines formulated in ISO14041. A cradle-to-grave analysis was performed, starting with offshore seaweed cultivation until end of life treatment of materials used (Figure 1). This included offshore seaweed cultivation including material use for the infrastructure, installation, harvesting, processing of the seaweed into food products, distribution, retail and consumption by consumers. The following indicators were determined using ReCiPe Midpoint (H) and selected for further analysis, Global Warming Potential (excluding land use change effects), Freshwater Eutrophication Potential, Land use, Fossil Resource Scarcity and Water Consumption.

Sustainability Nutrition Balance using Optimeal
The Sustainability Nutrition Balance (SNB) was used to

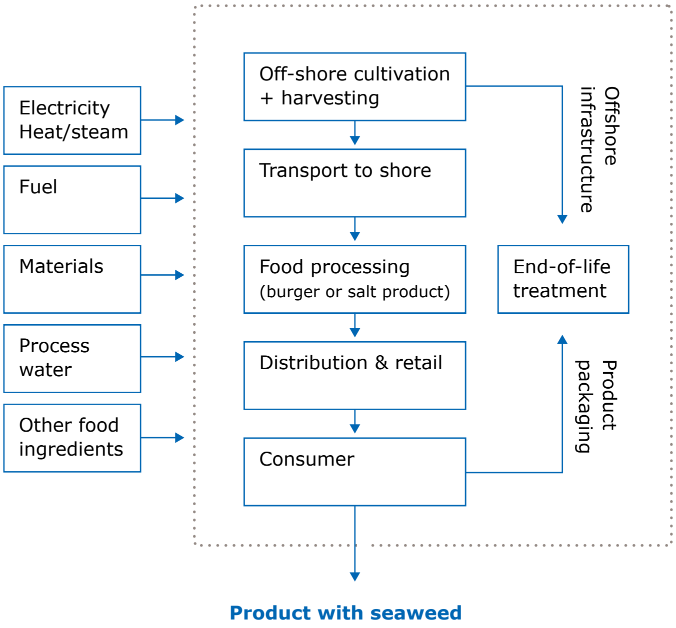

Figure 1 System boundaries for the LCA.

evaluate the balance of relevant nutrients and environmental impact (Kramer et al., 2018). A product that provides nutrients that improve the quality of the current diet with a low sustainability impact will have a better SNB-score than a product that contains nutrients that we tend to consume in excess (like salt or saturated fat) and/or with a high sustainability impact (Tyszler et al., 2016).

The SNB-scores of the *Saccharina l.* products were compared to a benchmark product. The benchmark products for the vegetarian burgers were a soy and wheat protein-based vegetarian burger and a mycoprotein-based vegetarian minced meat burger. The sodium chloride benchmark product is made using three technologies in line with market standards in industry, mining (rock salt) and sea-water flooded ponds (sea salt). Hereinafter, we refer to this mix of sodium chloride as 'salt'.

Seaweed cultivation
Data was provided by North Sea Farmers for the current seaweed production. At the test site of North Sea Farmers, multiple pilot-scale cultivation systems are tested to optimise the offshore cultivation of seaweed. The focus of the LCA analysis is on 3 cultivation systems: the Seaweed Macro-Algae Cultivation Net 3.0 system (referred to as SMAC N3), and the sawtooth systems SMAC S3.0 and SMAC S2.A. A schematic representation of the systems is shown in Figure 2.

North Sea Farmers together with seaweed businesses provided data on the envisaged future commercial scale farm, which represents a future projection for 5 years from now. This projection entails: 1) the cultivation system is expected to be 10 times larger, while using the

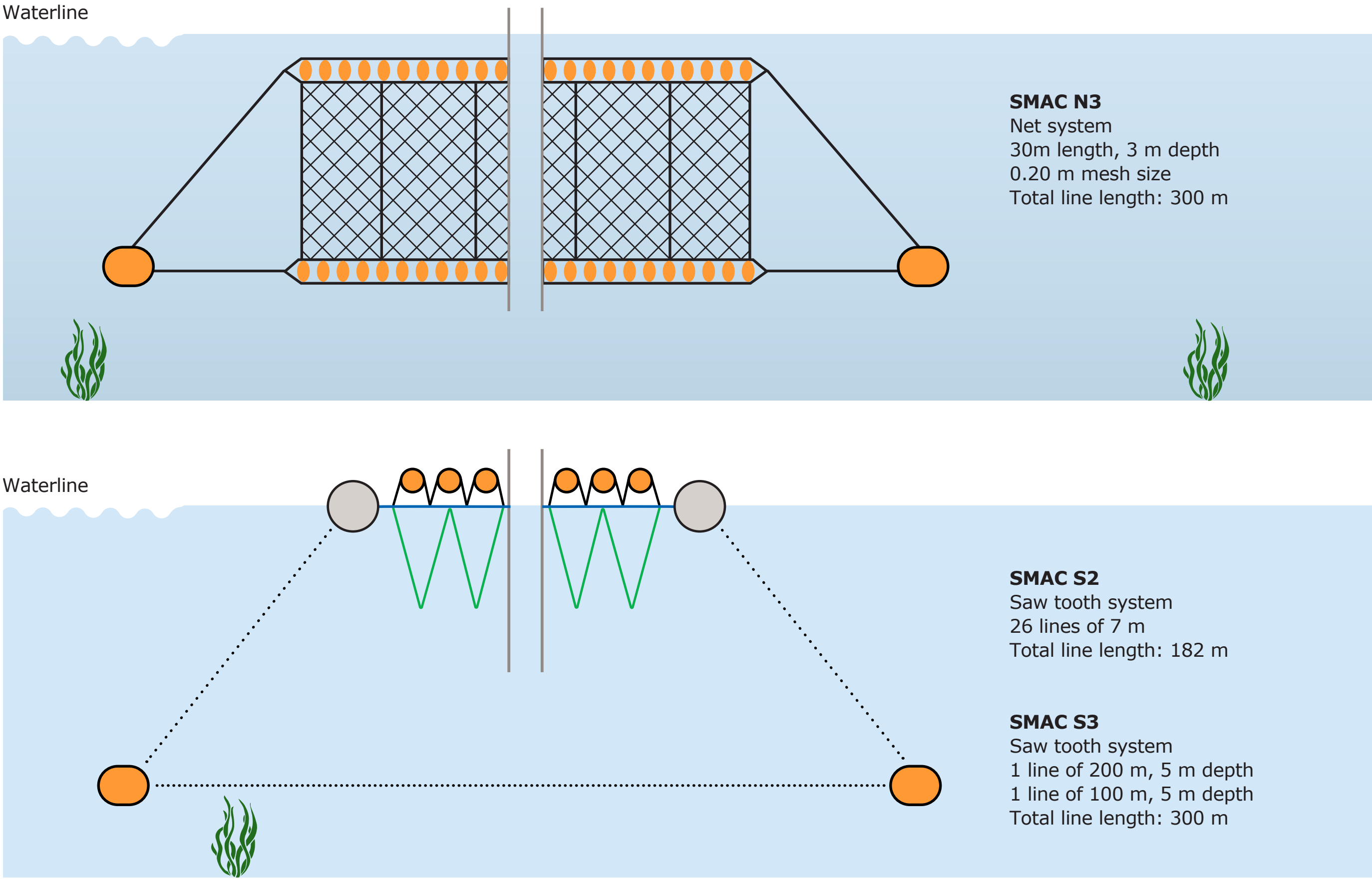

Figure 2 Schematic representation of offshore infrastructure for *Saccharina l.* cultivation and attachment of the cultivation modules. as ued in the Impaqt project by North Sea Farmers. Top: SMAC N (net) system, bottom: SMAC S (sawtooth)

same key infrastructure as an anchor, 2) increased yield to 5 kg w/w seaweed /m line, 3) more efficient installation and harvesting. The projected design is referred to as 'SMAC N3 future'. An overview of the evaluated cultivation scenarios is provided in Table 1.

Food products

The following criteria were used to select food products for further investigation: 1) the product should contain a substantial amount of seaweed to validly be called a seaweed product and not a product with seaweed as an additive; 2) within the product, the seaweed should provide nutritional value, comparable to a conventional reference product; and 3) real production data should be available.

The three selected food products are:
- a vegetarian burger containing 35.1% *Saccharina l.*
- salt in which part of the sodium chloride is replaced by *Saccharina l.* (10% on weight basis)
- salt replacement consisting of 100% *Saccharina l.*

Data on recipes and resources required for processing seaweed into selected food products were provided by three companies that wished to remain anonymous.

Table 1: Evaluated scenarios and data on yields, annual productivity per module, and low/high lifespan of offshore materials and low/high effort of transport efforts for offshore cultivation. SMAC N3 has 900 m seeded line, SMAC S2 182 m and SMAC S3 300 m. The SMAC N3 future projection is 10x larger than the SMAC N3 current system.

SMAC	Seed line yield (kg/ww/m)	Annual productivity (kg/module/yr)	Cultivation infrastructure design
SMAC N3	0.875	787.5	SMAC N3 current design
SMAC N3 [improved yield]	5.000	4,500.0	SMAC N3 current design
SMAC N3 future	0.875	7,875.0	SMAC N3 future design
SMAC N3 future [improved yield]	5.000	45,000.0	SMAC N3 future design
SMAC S2	0.875	159.3	SMAC S2 current design
SMAC S2 [improved yield]	5.000	910.0	SMAC S2 current design
SMAC S3	0.875	262.5	SMAC S3 current design
SMAC S3 [improved yield]	5.000	1,500.0	SMAC S3 current design

What is the environmental impact of current *Saccharina l.* cultivation and how does it change in future scenarios?

Cultivation of *Saccharina l.* at the test site of North Sea Farmers has been used as a proxy for estimating the environmental impact of current offshore seaweed cultivation in the North Sea (Figuur 3). The impact results show that transportation of the cultivation modules to the off-shore location and transport used for harvesting are the major contributors to the environmental impact.
Currently, these two transport activities are responsible for 73-80% of the impact of cultivation. Inspections take place relatively frequently at the experimental cultivation site to monitor seaweed growth and the various installations. The impact results indicate that one should optimise the transport setup for placing the cultivation modules, harvesting the biomass and inspecting seaweed growth to reduce the overall impact of cultivation. This can be achieved by combining several cultivation modules and by placing and harvesting several modules at the same time. Based on the results of this study, the North Sea Farmers are now using smaller boats for these activities and are considering to use electric powered boats in the future.

The current design of the seaweed cultivation modules can be further optimised by reducing the relatively large number of buoys, anchors and chains needed. The PE/PUR buoys are causing most of the material impacts Improvements here are expected to be implemented in the next 5 years. By combining decreased transport efforts with a more optimised cultivation structure, the Global Warming Potential is expected to decrease from 10.15 to 1.14 kg $CO_{2\ eq.}$/kg ww.

Besides transportation and system design, the seaweed yield was found to be an important factor. The cultivation system used at the test site is experimental in nature, and has not yet been tested in other offshore environments nor used on a commercial scale, and thus reflects current pilot scale cultivation. Experts expect that the currently achieved yields can be further improved. In the future projection, the effect of increased seaweed yields of 5 kg ww/metre cultivation line have been explored. This would reduce the Global Warming Potential of cultivation with about a factor 6 from 10.15 to 1.78 kg $CO_{2\ eq.}$/kg ww.

This does not affect the hotspots; transport with the BLV is still responsible for most of the impact. Yield improvements have similar order of magnitude effects on

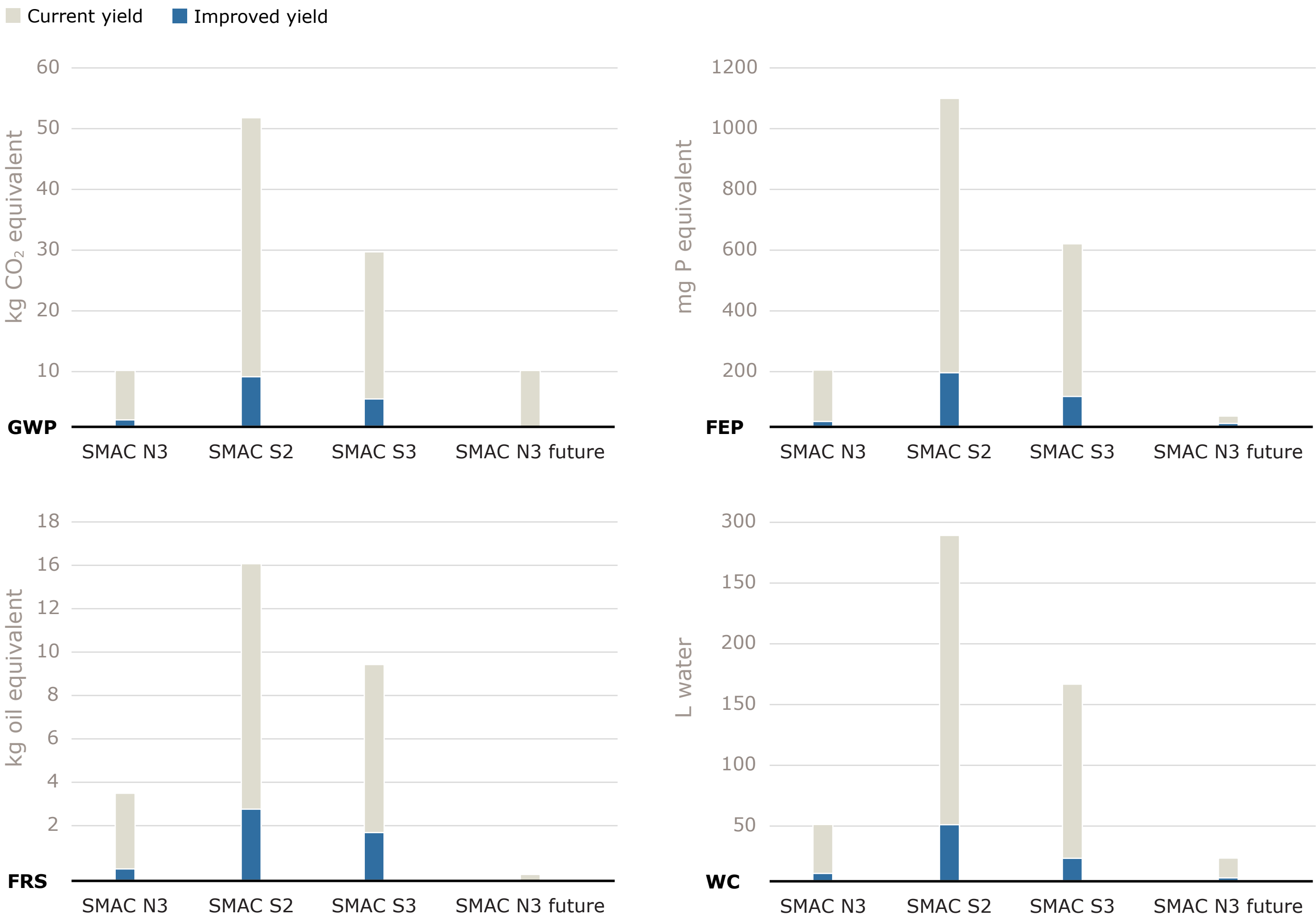

Figure 3 Impact of cultivation for various cultivation systems per kg harvested wet seaweed *Saccharina l.* Cultivation designs are indicated by SMAC N3 (net), SMAC S2, SMAC S3 (saw tooth) and SMAC N3, future. **GWP** = Global, Warming Potential, **FRS** = Fossil Resource Scarcity, **FEP** = Freshwater Eutrophication Potential, **WC** = Water Consumption

the Global Warming Potential of the SMAC S systems. By increasing the yields in combination with the improved cultivation design and transportation, the impact can be reduced to 0.20 kg $CO_{2\ eq.}$/kg ww.

Freshwater Eutrophication Potential, Fossil Resource Scarcity and Water Consumption show similar trends in total impact between the scenarios for both current and future scenarios. In terms of the future scenarios, the hotspots differ for Freshwater Eutrophication Potential and Water Consumption, namely being buoys and buoys with floaters respectively.

The difference between the currently used cultivation designs is significant. The total metres of seeded line differ greatly between the systems and, as a result, the total productivity per cultivation module varies as well.
A net-type system will have lower environmental impacts than a saw-tooth system.

What are the hotspots in current cultivation and processing of *Saccharina l.* for use in vegetarian burgers and as salt replacement?

In Figure 4, the contribution of different aspects in the production chain to the environmental impacts of burgers with *Saccharina l.* are shown for both current seaweed cultivation and the envisioned future scenario. Under current cultivation conditions, the cultivation of *Saccharina l.* makes a significant contribution to Global Warming Potential and Fossil Resource Scarcity. The production of the other burger ingredients dominate the Freshwater Eutrophication Potential and Water Consumption impacts. Packaging also contributes to each of the impact categories and processing the ingredients into the burger product is relevant for the Global Warming Potential and Fossil Resource Scarcity. The dominance analysis changes when looking at the future cultivation system, with future estimated yields and more efficient infrastructure design and transport. In the future scenario, the impact of *Saccharina l.* cultivation on the total burger impacts would significantly decline. As a result, the other ingredients play a larger role in the impact, especially egg and walnuts.

For both salt products, the majority of impacts are from *Saccharina l.* cultivation under current conditions, however, in the case of the salt replacement, the contribution of processing, transport and packaging is negligible compared to the impact of *Saccharina l.* cultivation. For salt containing 10% *Saccharina l.*, the impact of seaweed cultivation is reduced from 80-90% to 15-40% of the total impact in the future scenario. The impact of packaging looms large in all four impact categories. For Global Warming Potential, processing and transport becomes more prominent, while for Water Consumption salt production is dominant. For the salt replacement with 100% *Saccharina l.*, the majority of impact is caused by the cultivation of seaweed (60-90%), even for the future project.

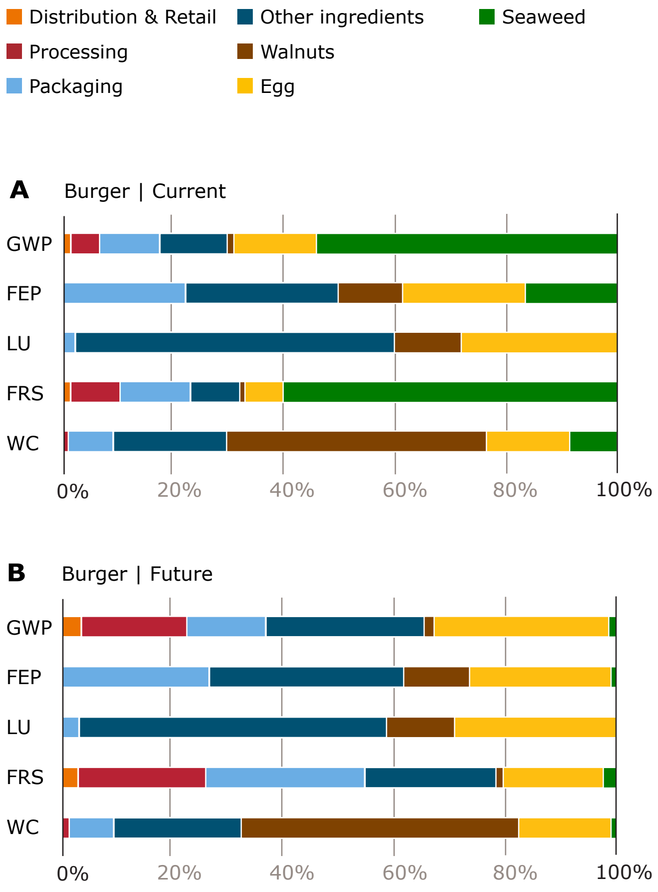

Figure 4 Dominance analysis of the environmental impacts **A)** *Saccharina l.* burger based on current baseline yields in the SMAC N3 net3.0 cultivation system. **B)** *Saccharina l.* burger based on future system SMAC N3 projection with future yields. **GWP** = Global Warming Potential, **FEP** = Freshwater Eutrophication Potential, **LU** = Land Use, **FRS** = Fossil Resource Scarcity, **WC** = Water Consumption.

Since the seaweed sector is still developing, it is too early to pass definitive judgement on the environmental impacts of seaweed products compared to food products produced in mature sectors such as soy or maize. The two food products of this study show the potential of incorporating seaweed into future diets. *Saccharina l.* is a versatile species, which could be incorporated in more food products, provided that a solution is found to deal with the iodine content. The next step is to expand the product portfolio both in terms of product types as well as the seaweed species included as ingredients.

Can the use of *Saccharina l.* in vegetarian burgers and as salt replacement reduce the overall environmental impact of diets?

The Sustainability Nutrition Balance (SNB) has been used to compare the nutritional value and environmental impact of the seaweed food products with conventional food products that have a similar function. The results show that for Global Warming Potential and Land Use, the *Saccharina l.*

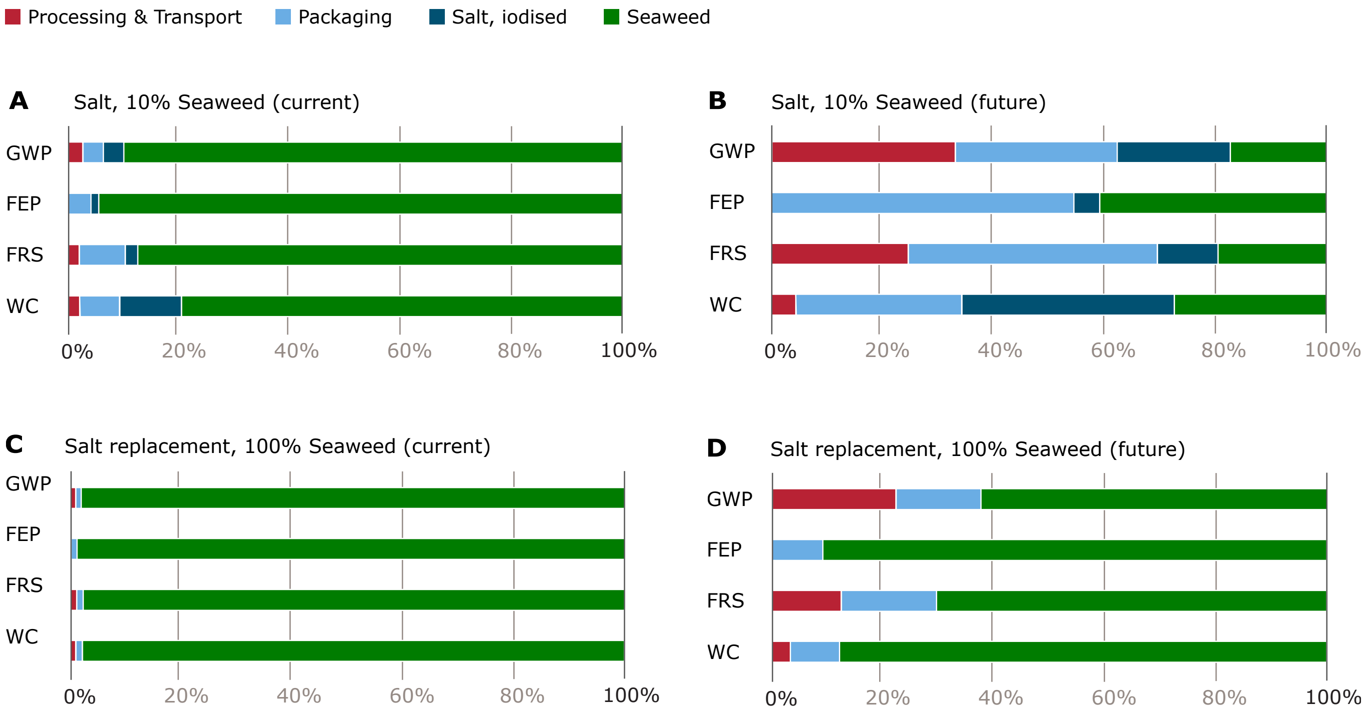

Figure 5 Dominance analysis of the environmental impacts for **(A,B)** salt containing 10% *Saccharina l.* and **(C,D)** salt replacement with 100% *Saccharina l*. The graphs on the left **(A,C)** are based on current yields in the SMAC N3 cultivation system, the graphs on the right **(B,D)** are based om SMAC N3 projected module with future yields. **GWP** = Global Warming Potential, **FEP** = Freshwater Eutrophication Potential, **FRS** = Fossil Resource Scarcity, **WC** = Water Consumption.

burger has favourable SNB scores compared to the vegetarian hamburgers and vegetarian mincemeat burgers. The burger with 35.1% *Saccharina l.* scores has an upper boundary for average daily consumption of at most 14 gram per day due to the high iodine levels in the seaweed. This implies that the diet should contain on average no more than one *Saccharina l.* burger every 7 to 8 days. For the Fossil Resource Scarcity impact, the SNB score of *Saccharina l.* burgers is quite similar to that of vegetarian hamburgers.

The results show that, particularly for Land Use, the *Saccharina l.* salts have a favourable SNB score compared to regular iodised salt. For Global Warming Potential and Fossil Resource Scarcity, the results are not wholly unambiguous. The seaweed salts are made with *Saccharina l.* which contains relatively high amounts of iodine. This means the upper boundary for consumption is 5 g/d for the 100% *Saccharina l.* salt replacement. It also means that the calculation of the SNB score of these salts is based on fewer data points than the 10% *Saccharina l.* salt and the benchmark, adding to the uncertainty.

What are the prospects for including seaweed in sustainable food systems and diets?

Seaweeds are seen as sustainable food ingredients for the future. Cultivation of seaweeds does not require land nor fertilisers, and is expected to cater to the needs of a growing world population. Seaweeds generally have high nutritional value and are rich in carotenes, vitamin C and in vitamin B 12. The mineral content can reach up to 36% of the dry mass. Eating seaweed can therefore help in consuming the recommended daily intake of minerals, including iodine. As a consequence, seaweed salt can aid in reducing sodium consumption and its related diseases.

However, seaweed can also have a relatively high iodine content, which in turn may negatively impact the reception of seaweed based products. Nutritional aspects of seaweed are therefore important to consider when assessing the potential and impact of food products. In this study, the impact of a seaweed burger, salt with seaweed added and salt replacement were compared to alternatives while including the nutritional profile using SNB. The inclusion of *Saccharina latissima* in vegetarian burgers or as salt replacement has multiple positive effects, reducing impact on Global Warming Potential and Land Use of the overall diet. Thus, in this respect, seaweeds like Sac*charina l.* can play a role in future sustainable diets. Our Sustainability Nutrition Balance analysis showed an upper boundary for consumption of 1 burger per 7 to 8 days due to the high iodine levels in the *Saccharina l*. The iodine content in seaweed is a recognised concern in other studies as well (Banach et al., 2020). A better understanding of the iodine concentration in seaweeds over time, per production location, and the right time for harvesting can minimise food safety risks. Furthermore, it has been recently shown that blanching can be applied to reduce the iodine content (Nielsen et al., 2020). The results of this study should be regarded as an initial starting point. To assess the full potential of seaweed foods, more food products should be evaluated, as well as other seaweed species.

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Figure 6

Sustainability Nutrition Balance Scores for the burger (left) and salt (right). Good means that the product provides nutrients which improve the quality of the current diet with a low sustainability impact, little means that the product contains nutrients that we tend to consume in excess and/or has a high sustainability impact.

For Fossil Resource Scarcity **(FRS)**, the seaweed burger scores similar as the vegetarian hamburger and vegetarian mince meat. For Global Warming Potential **(GWP)**, the seaweed burger scores better (more beneficial SNB score) than the vegetarian hamburger. The vegetarian mincemeat scores worse than the veg. Burger. For Land Use **(LU)**, similar trend as for GWP, but a bit less extreme. For Fossil Resource Scarcity **(FRS)** the salt with 10% seaweed and salt replacement both score similarly than the iodised salt. For Global Warming Potential **(GWP)** the salt with 10% seaweed scores similar to the iodised salt. The salt replacement scores slightly worse. For Land Use **(LU)** the salt with 10% seaweed scores similar to the iodised salt. The salt replacement scorses favourable compared to iodised salt.

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