



Environmental impact and nutritional value of food products using the seaweed *Saccharina latissima*

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ARTICLE INFO

Handling editor: M.T. Moreira

Keywords:

Life-cycle assessment
Sustainable food systems
Sustainable diets
Saccharina latissima
Vegetarian burgers

ABSTRACT

Seaweeds are often seen as a healthy, component of future diets with low environmental impacts compared to other food ingredients. This study quantifies the environmental impact of the seaweed *Saccharina latissima* (*S. latissima*) cultivated in the North Sea and applied in food products using Life Cycle Assessment (LCA) The performance under current conditions and in future scenarios is evaluated, drawing on data provided by Dutch companies. The environmental benefits of inclusion of seaweed in diets, taking into account its nutritional value, are evaluated using Optimeal. Under the current cultivation conditions seaweed cultivation has a significant contribution to the environmental impact of the assessed food products, i.e., a burger with *S. latissima* (up to 60%), salt with 10% *S. latissima* (79–94%) and salt replacement based on 100% *S. latissima* (99%). Under current cultivation practices cultivation has an impact between 10 and 52 kg CO₂ equivalent/kg wet weight *S. latissima*. The LCA results of current cultivation practices points towards a hotspot in the transport efforts (responsible for 74–80%) and a different means of installing the seaweed farms can directly reduce environmental impacts. Further reductions can be achieved by increasing yields and increasing the lifespan of materials used in the infrastructure leading to an impact of 0.2 kg CO₂ equivalent/kg wet weight *S. latissima*. In the future cultivation scenario, which is a projection for 5 years from now with estimated yields and more efficient infrastructure design and transport, the impact of *S. latissima* to the total burger and salt product impacts diminished significantly to 1–4% for the burger, 15–40% for the salt, and 63–88% for the salt replacement. The analysis concludes that inclusion of seaweeds in future vegetarian burgers or as salt replacement can have a positive effect on the environmental impacts of diets.

1. Introduction

The world's food system faces a great balancing act (World Resources Institute, 2013). By 2050 it must feed around 10 billion people (United Nations, 2019) in a more sustainable way: without increasing the area of agricultural land, using less natural resources and emitting less greenhouse gases. Diets should be healthier and meet human nutritional needs. Seaweeds are often seen as a promising, sustainable and healthy food source, with potential to increase total global production (SAM High Level Group of Scientific Advisors, 2017; van den Burg et al., 2019).

In 2018 a total of 32.4 million tonnes of seaweeds were produced

globally, 97.1% of which is cultivated seaweed (FAO (Food and Agriculture Organization of the United Nations), 2016). The global production is concentrated in a few countries, predominantly in South-East Asia, where seaweeds are part of the traditional diets (Delaney et al., 2016). In Europe, there is an 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). First studies into consumer acceptance show that Western consumers perceive seaweed food products as natural and healthy (Birch et al., 2019b).

Seaweeds generally have high nutritional value. They have low lipid

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<https://doi.org/10.1016/j.jclepro.2021.128689>

Received 17 March 2021; Received in revised form 4 August 2021; Accepted 16 August 2021

Available online 19 August 2021

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Nomenclature

Abbreviation Explanation

BLV	Buoy-Laying Vessel
eq	equivalent
FEP	Freshwater Eutrophication Potential
FRS	Fossil Resource Scarcity
GWP	Global Warming Potential
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LU	Land Use
LUC	Land Use Change
NSIL	North Sea Innovation Lab
PE	Polyethylene
PUR	Polyurethane
RIB	Rigid Inflatable Boat
<i>S. latissima</i>	<i>Saccharina latissima</i>
SMAC N	Seaweed Macro-Algae Cultivation Net system
SMAC S	Seaweed Macro-Algae Cultivation Sawtooth system
SNB	Sustainability Nutrition Balance
WC	Water Consumption
WW	Wet Weight
WW/m	Seaweed yield in wet weight per meter seeded cultivation line. E.g. 1 kg ww/m yield means that 1 kg of wet seaweed biomass is obtained for each meter of cultivation line.

and carbohydrate content, contain essential amino-acids and have a high fibre content (Rajapakse and Kim, 2011). Seaweeds are rich in carotenes, vitamin C and in vitamin B 12 which generally only occurs in animal-based products. 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. Seaweed salt can aid in reducing sodium consumption and its related diseases. The high mineral content gives seaweed a salty taste (Jónsdóttir, 2015). Nowadays, sodium chloride (table salt) is mainly used for food preservation and flavour enhancement. The consumption of large amounts of sodium is, amongst others, causing cardiovascular disease and hypertension (Cappuccio, 2013).

One major challenge for integrating seaweed into food products is consumer acceptance. Birch et al. gave an overview of why consumers would and would not eat seaweed (Birch et al., 2019a). Sensory characteristics, like taste, appearance and texture, are important driving forces when customers choose their food. Some consumers simply do not like the taste of seaweed or find the greenish colour caused by its pigments not appealing. This is possibly related to the unfamiliarity of seaweed as a food product in western countries (Palmieri and Forleo, 2020). There are however also customers that do not mind the addition of seaweed to food products. Increased availability of seaweed and addressing seaweed characteristics are important drivers that will positively influence consumer attitude towards seaweed consumption (Palmieri and Forleo, 2020).

Saccharina latissima (*S. 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 *S. latissima* under offshore conditions (Azevedo et al., 2019; Peteiro et al., 2016). It is used in food applications and, referring to its lipid profile and nutritional composition, is seen as promising source of functional food ingredients (Neto et al., 2018; Rey et al., 2019). Seaweed can be used for iodine supplementation in case of deficiencies, but excessive intake should be avoided (Grouffh-Jacobsen et al., 2020).

Seaweed cultivation systems are in full technical development across

the globe (García-Poza et al., 2020; Kim et al., 2017; Monagail and Morrison, 2020). The cultivation methods can roughly be distinguished into 'offshore' and 'onshore', meaning cultivation is done in water or on land respectively. One common method for offshore cultivation is the off-bottom monoline method: seeded ropes are tied to stakes that are fixed in the bottom of the sea or lake (Taelman et al., 2015). The systems maintenance and installation are inexpensive and simple, however, this method is only suitable for shallow waters. In deeper waters systems capable of floating are often used, a common example is the floating longline method (Langlois et al., 2012). For this method seeded lines are attached to floating buoys which prevent them from sinking. Cultivation onshore can be done for example in an open raceway system or a bioreactor (Chemodanov et al., 2019; Narala et al., 2016). An advantage of onshore cultivation is that the cultivation conditions can at least partially be controlled. One major downside of onshore cultivation opposed to offshore cultivation is that it is space limited and associated with high cost (Araújo et al., 2021). At this point it is difficult to conclude whether there is one optimal cultivation method since seaweed cultivation techniques are still young and they are known to be affected by variables like seaweed species, location, harvesting regime and system design (Aitken et al., 2014; Barbier et al., 2019).

Various LCAs have been performed on offshore seaweed cultivation (van Oirschot et al., 2017) and derived products for energy or fuels (Aitken et al., 2014; Assacute et al., 2018; Langlois et al., 2012; Taelman et al., 2015), materials (Helmes et al., 2018) applications or combined production of feed, fuel and fertilizer (Seghetta et al., 2016). Recently, the LCA impact of protein production from seaweeds was evaluated (Koesling et al., 2021). The study by Koesling et al. indicates that it is challenging yet possible to produce feed-protein from seaweed that has a lower environmental impact than soy protein. Various seaweed containing foods are on the market nowadays (Araújo et al., 2021; Roohinejad et al., 2017), for example pasta, burgers, bread, salt and sauces containing seaweed. Yet, current literature does not focus on the environmental impacts of applying cultivated seaweeds in food applications. The goal of this study is to quantify the environmental impact of cultivated *S. latissima* applied in (future) food products and to evaluate if the addition of seaweeds makes diets more sustainable. The following research questions are addressed in this study:

- What is the environmental impact of current *S. latissima* cultivation and how does it change in future scenarios?
- What are the hotspots in current cultivation and processing of *S. latissima* for use in vegetarian burgers and as salt replacement?
- How do these environmental impacts change in a future scenario?
- Can the use of *S. latissima* in vegetarian burgers and as salt replacement reduce the overall environmental impact of diets?
- What are the prospects for including seaweed in sustainable food system/diets?

The analyses focus on current, state-of-the art cultivation of seaweed in the Dutch Exclusive Economic Zone of the North Sea combined with an analysis of the impact of near future cultivation impacts through scenario analysis.

2. Method

Two methods are used to answer the research questions formulated above (1) Life Cycle Assessment was used to systemically quantify the environmental impacts and (2) Optimeal was used to compare the performance of the seaweed-products with conventional products.

2.1. Life Cycle Assessment (LCA)

To quantify the environmental impact of *S. latissima* applied in food products, Life Cycle Assessment methodology was applied 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 (Fig. 1). For current seaweed cultivation, data was provided by North Sea Innovation Lab (NSIL). At the NSIL, multiple pilot-scale cultivation systems are tested to optimise the offshore cultivation of seaweed. North Sea Farmers together with NSIL and seaweed businesses provided data on the envisaged future commercial scale farm. Data on recipes and resources required processing seaweed into selected food products were provided by three companies that remain anonymous. The system descriptions are given in section 2.3.

The three food products evaluated are (1) a *S. latissima* vegetarian burger containing 35.1% *S. latissima*, (2) salt in which part of the sodium chloride is replaced by *S. latissima* (10%) and (3) salt replacement consisting for 100% out of *S. latissima*. In line with the study objective, the study team used the following criteria to select food products for further investigation: 1) product should contain substantial amount of seaweed to have validity of calling it a seaweed product and not a

product with a seaweed additive, 2) seaweed should provide nutritional value to the product which can be compared to current conventional products, 3) the availability of real production data.

All materials, fuel production and processing have been modelled using the ELCD (European Commission et al.), supplemented with Agrifootprint 5.0 data when needed (van Paassen et al., 2019a, b). End of life processes of the materials contributing 93% of the mass of materials used for the functional unit was modelled using the Circular Footprint Formula (Zampori and Pant, 2019). Simapro software version 9.0 (Pré Sustainability) was used for the inventory modelling and impact assessment. The following indicators were determined using ReCiPe Midpoint (H) and selected for further analysis, Global Warming Potential (excluding land use change effects) (GWP), Freshwater Eutrophication Potential (FEP), Land use (LU), Fossil Resource Scarcity (FRS), Water Consumption (WC).

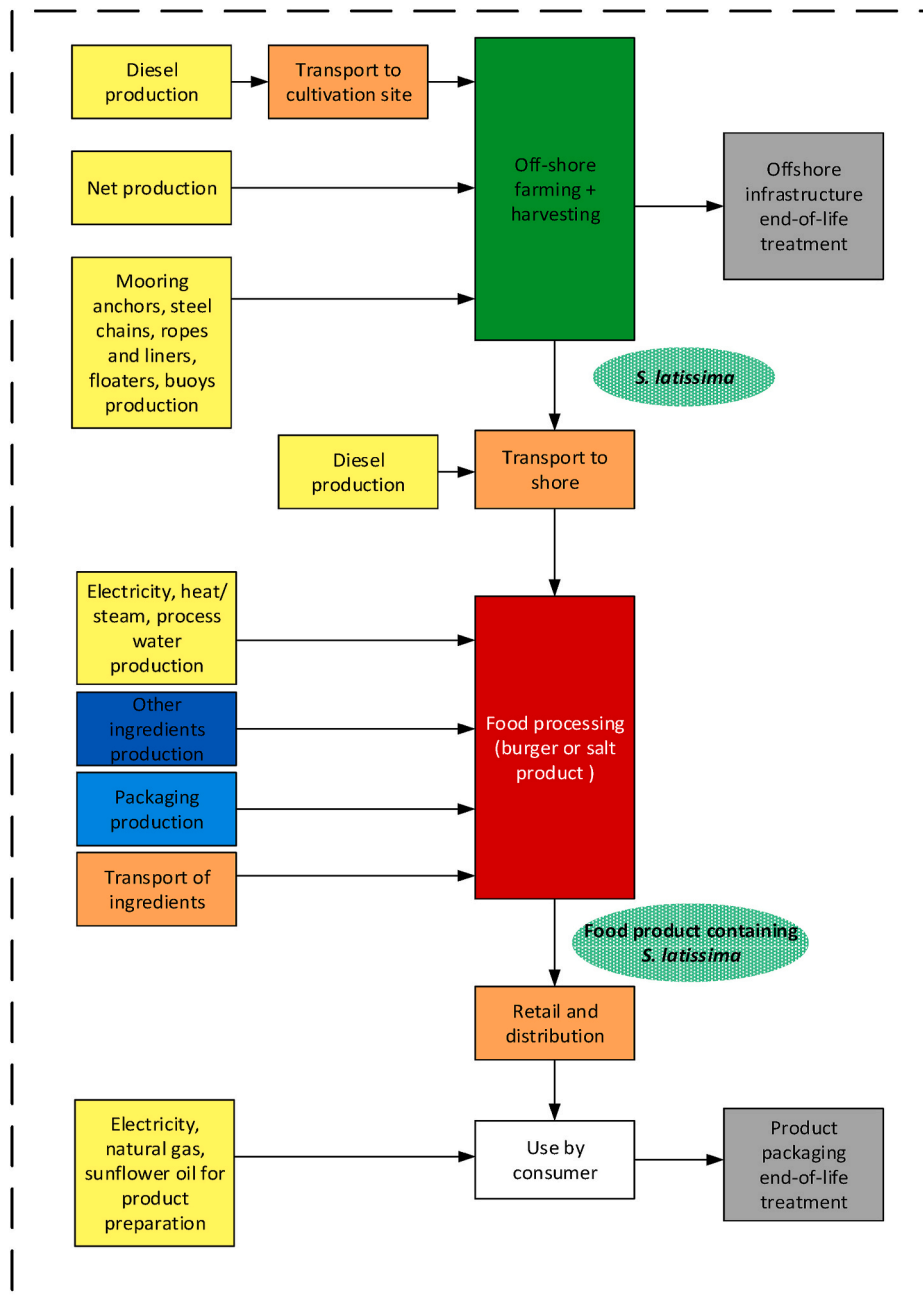


Fig. 1. The foreground activities of this study are off-shore farming and harvesting (green), transport (orange), food processing (red). All background material and energy inputs are indicated in yellow and blue (the production of other food ingredients and food packaging). The end-of-life treatments included in this study are indicated in grey. The products are indicated by green spheres. System boundaries are indicated by the dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2. Sustainability nutrition balance using optimeal

The Sustainability Nutrition Balance (SNB) was used to evaluate the balance of relevant nutrients and environmental impact (Kramer et al., 2018). A product that provides nutrients which 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-score is calculated using stepwise quadratic optimisation. Starting from a current diet in EU, the amounts of a food product of interest were fixed in varying levels. In each step, after fixing the amount of the product of interest, the diet was optimised, allowing changes to the other food products in the diet to correct for nutritional constraints. At each step the environmental impact of the optimised diet is calculated. The SNB-score is the linear relationship between the sustainability indicator (e.g. carbon footprint) of the diet and the product quantity. We investigated the SNB-score of the seaweed food products using optimisation software Optimeal® (Blonk Consultants), using an average EU diet. The Optimeal® software contains all required data on food composition, nutrient requirements, and environmental impacts of food products consumed in the EU. Life Cycle Assessment (LCA) results were used to determine the environmental impact of the products in the diet (Broekema et al., 2020). Data for food consumption, nutritional properties of food products and nutritional requirements of a healthy diet originate from European Food Safety Authority (Blonk Consultants, 2019).

We calculated the SNB-score for the three *S. latissima* food products, using the future scenario for cultivation of *S. latissima* and nutritional data from (Pereira, 2011; Schiener et al., 2015; Sharma et al., 2018). The SNB-scores of the *S. latissima* 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 benchmark product sodium chlorides is made using three technologies according to the market: industry, mining (rock salt) and sea water flooded ponds (sea salt). In the

remainder we refer to this mix of sodium chloride as ‘salt’.

In the stepwise optimisation, the optimal balance between nutritional value and environmental impacts of the diet was assessed. For burgers, each step means adding 50 g of burger to the average daily diets per person (min. 0 g, max. 500 g of burger/p/d). For the burger with *S. latissima* the upper boundary was crossed, therefore for this burger the stepwise optimisation was done with steps of adding 5 g of *S. latissima* burger. The SNB-score for the hamburgers is expressed per 100 g of product. The stepwise optimisation for the salts were carried out between 0 and 16 g per person per day, in steps of 1 g. The SNB-score for the salts is expressed per 1 g of product.

2.3. System descriptions

2.3.1. Seaweed cultivation

The NSIL offshore lab is 6 km², with 6 research plots, located 12 km from the coast of The Hague, The Netherlands. The focus of the LCA analysis will be on the Seaweed Macro-Algae Cultivation Net 3.0 system (referred to as SMAC N3), as this cultivation technique seems most appropriate for large-scale offshore *S. latissima* cultivation. This system measures 30 m in length and 3 m in depth with a mesh size of 0.20 m, using a total line length of 900 m. Two other assessed cultivation systems are SMAC S3.0 and SMAC S2.A systems (S indicating the sawtooth shape of the cultivation line). In the SMAC S3, there are two lines, one with a length of 200 m and one with a length of 100 m, both based on a sawtooth set-up with a depth of 5 m, whereas the SMAC S2 contains 26 lines each with a length of 7 m. A schematic representation of the systems is shown in Fig. 2.

Material use for the offshore cultivation module included ropes, lines, floaters, buoys, steel chains and a concrete anchor. Seedling production is excluded as earlier LCA studies concluded that hatchery has a minor environmental impact (Thomas et al., 2020). Transport activities are related to installation, decommissioning, annually sowing, harvesting and inspection of the modules during the cultivation season. A buoy-laying vessel is used (referred to as BLV) for the former four

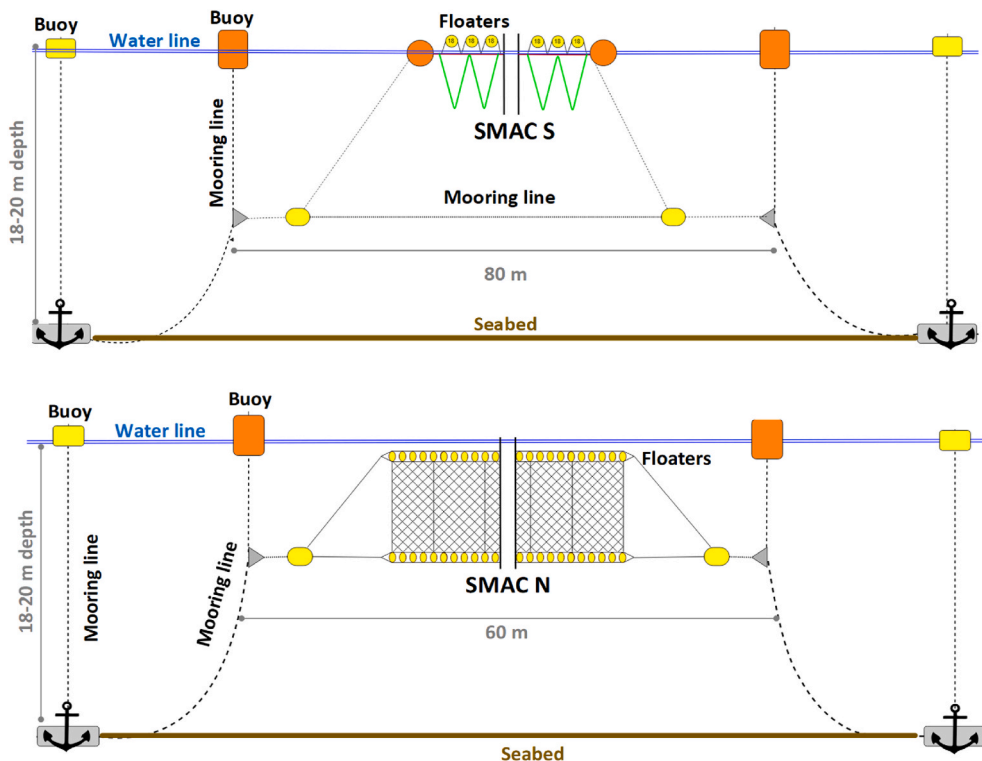


Fig. 2. Schematic representation of off shore infrastructure for *S. latissima* cultivation and attachment of the cultivation modules. Top: SMAC S (sawtooth), bottom: SMAC N (net) system.

activities and a rigid inflatable boat (referred to as RIB) for the inspections as well as harvesting. Primary data on the vessels' fuel use and operating hours was collected and converted to usage per functional unit. Details of the LCI modelling of the cultivation are given in the Supplementary Information.

2.3.2. Future scenarios

In the future scenarios we assume that only the foreground system technologies related to seaweed cultivation improve, while everything else remains unchanged. A future projection for 5 years from now has been made for the cultivation system design and operation, as well as for the seaweed yields.

In the design projection, it is estimated that a net cultivation system with the dimensions of 3m depth and 300 m length will be used. Commercial scale farms will likely reach the size of 1 km² in the near future with 40 modules placed in it. It is expected that yield will increase in the future due to improvement in cultivation techniques. These improvements will occur in multiple areas that influence the yield such as seeding techniques, seaweed seeds and improvements in net system to better suit the cultivation environment and seaweed species. A net system with the dimensions of 300 m length, 3 m depth, and a mesh size of 0.20 m uses 9000 m of line. In the design projection installation and harvesting are done more efficiently. The BLV has enough space on deck and carrying capacity to transport and install the full infrastructure of 3 complete modules at the same time, and to carry, place and harvest the nets of 8 modules per trip (annual net placement and harvesting). For inspection and assisting with harvesting, the same RIB boat as currently is used. These inspections will take place 4 times a year for a commercial farm of 100 ha. These inspections can be executed much faster than in the baseline scenario, as cultivation techniques are optimised and more remote sensing equipment will be used. All 40 modules in a 100 ha farm can be inspected in one day. The projected design is referred to as 'SMAC N3 projection'.

The cultivation design influences seaweed yield, together with various environmental factors like water temperature, pH, salinity and water movement. It is expected that future obtainable seaweed yields of 5 kg wet weight (WW)/m are realistic (van Oirschot et al., 2017). An overview of the evaluated cultivation scenarios is given in Table 1.

For comparing future food products it is assumed that the foreground system technologies related to seaweed improve, but that the other background data such as egg production will have the same current environmental impact.

Table 1

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

Scenario	Seed line yield (kg ww/m)	Annual productivity (kg/module/yr)
SMAC N3 [-25% kg/m]	0.656	590.6
SMAC N3	0.875	787.5
SMAC N3 [+25% kg/m]	1.094	984.4
SMAC S2	0.875	159.3
SMAC S3	0.875	262.5
SMAC N3 projected module	0.875	7875
SMAC N3 [future yield]	5.00	4500
SMAC S2 [future yield]	5.00	910
SMAC S3 [future yield]	5.00	1500
SMAC N3 projected module [future yield]	5.00	45,000

2.3.3. Sensitivity analysis

For the current SMAC N3 system the effect of transport effort, lifespan of the materials and yields were studied in the sensitivity analysis, each with a 75% and 125% variation of the standard value. Table 1 The transport effort was selected since it is known upfront that (a) there are more inspections in the pilot system than one might do at large scale cultivation and (b) the carrying capacity of the BLV is not fully used at the moment. The sensitivity to the lifespan of the materials was evaluated because of uncertainty about the exact lifespan of all the materials when part of the infrastructure remains on-site in the sea for the full lifespan while other materials are taken onshore after harvesting. The currently achieved yields in the SMAC N3 system are promising, yet variations in yield can be expected in any cropping system and at the same time further yield improvements are likely. For the current SMAC N3 system the yields were varied with 75% (low) and 125% (high) yields in kg/m seeding line, and the yield of the future projection was evaluated as 'SMAC N3 [future]' (linearly downscaled to a 30 m net module). For the SMAC N3 projection the linearly upscaled baseline yield of SMAC N3 was included to enable comparison of the system design impacts.

2.3.4. Food processing and consumer phase

2.3.4.1. Burger. The functional unit is 1 kg of edible product, which was translated to 100 g of edible product for the calculation of the SNB-score (as all nutritional properties are given per 100 g). The recipe of the vegetarian burger with *S. latissima* was provided by a food producing company. The scenario SMAC N3 projection was used for the calculation of the SNB-score. The recipes of the alternative benchmark vegetarian products was based on previous studies performed by Blonk Consultants (Broekema and Blonk, 2009; Broekema and van Paassen, 2017). The data for processing of the burgers and packaging were also based on these previous studies, from which an average production process and an average packaging of vegetarian products is derived. For distribution and retail default data were used based on the Product Environmental Footprint guidance (European Commission, 2017). The consumer phase was modelled considering energy consumption for cooling and preparation and added fats during preparation. Municipal incineration was selected for waste treatment of the packaging. Losses were accounted for at several stages of the life cycle: (a) at retail, (b) a raw-to-cooked ratio, accounting for the loss of mass during preparation and (c) Edible losses. Details of the LCI modelling are given in the Supplementary Information.

2.3.4.2. Salt. The functional unit is 1 kg of edible product, which was translated to 1 g of edible product for the calculation of the SNB-score (as all nutritional properties are given per 1 g). The salts with 10% *S. latissima* added and the salt replacement (100% *S. latissima*) are assumed to be made according to the cultivation system SMAC N3 projection. For both salt and salt replacement *S. latissima* needs to be dried, for which primary data were supplied by a seaweed salt producing company that remains anonymous. 16.351 MJ electricity is used per kg of dried *S. latissima* for salt with 10% and 6.019 MJ is used for *S. latissima* salt replacement. An inbound transport of 500 km was assumed for the salt, as reported by the same primary source. ELCD process for sodium chloride was selected as the salt component and was also used as the benchmark product. Packaging was modelled by linking the reported amounts of packaging from our primary source to ELCD processes. In calculating the SNB-score, packaging of the salts with *S. latissima*, salt replacement and the benchmark rock salt were assumed to be the same, as differences in packaging should not influence the comparison. No energy is needed for storage and use of the salt by the consumer. It is assumed that packaging goes to municipal incineration. Losses were considered at similar life cycle stages to the hamburgers.

3. Results

3.1. Environmental impact of cultivation

3.1.1. Global Warming impact

The Global Warming Potential (GWP) impacts of cultivating and harvesting 1 kg WW *S. latissima* are shown in Fig. 3 for four different cultivation designs, using yields as specified in Table 1. The results are given for the currently used SMAC N3, SMAC S2, SMAC S3 and for the future SMAC N3 projected scenario. In each of these scenarios most of the impact is caused by transportation of the cultivation structure (Transport BLV). This is caused by the diesel consumption, as the Buoy Laying Vessel has to operate the engine during the 8 h that it remains on site. The PE/PUR buoys are causing most of the material impacts. The difference between the currently used cultivation designs is significant. The impact varies between 10.15 and 52.16 kg CO_{2eq.} when comparing the 3 systems (SMAC N3, S2, S3 in Fig. 3) with the same yield per meter seeded line. The total meters of seeded line differ greatly between the systems and as a result the total productivity per cultivation module varies as well. Yields have a large effect on the impact per kg harvested *S. latissima*, which is further illustrated with the low, baseline, and high yields of the SMAC N3 system in Fig. 3 (first 3 bars).

The sensitivity analysis (See Table 2) confirmed that varying the yield has the largest effect on the GWP of cultivation, followed by the transport effort. The effect of varying the lifespan of the materials is marginal. More efficient transportation and infrastructure design for coupled cultivation modules (with baseline yields) will decrease the impact to 1.14 kg CO_{2eq.}/kg WW *S. latissima* (SMAC N3 projection). These changes in infrastructure and transportation have a significant effect on the contribution of each material and transport effort to the total impact. The BLV transport is reduced to 18.8% of the total impact. In the projection the floaters have the largest contribution (29.8%), followed by the buoys (15.9%) and the ropes (12.8%). All other materials and transport are below 10%.

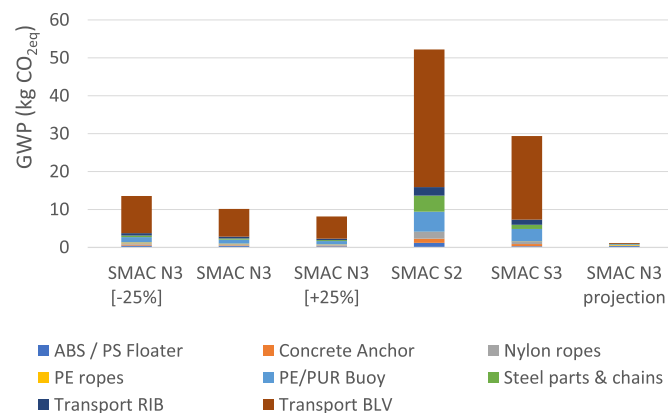


Fig. 3. Impact of cultivation for various cultivation systems based on current yields, expressed in Global Warming Potential GWP (kg CO_{2eq.}) per kg harvested wet seaweed *S. latissima*. Cultivation designs are indicated by SMAC N3 (net), SMAC S2, SMAC S3 (saw tooth) and SMAC N3, projected module.

Table 2
Sensitivity analysis results for SMAC N3. Global Warming potential (kg CO_{2eq.}/kg harvested wet seaweed).

Factor	Change	Influence on GWP
Yield	+25%	-20
	-25%	+33%
Lifespan materials	+25%	-4
	-25%	+7%
Transport effort	+25%	+19%
	-25%	-19%

The results presented in Fig. 4 show the effect of future yields on the GWP. The impacts of cultivation in the SMAC N3 system are expected to decrease to 1.78 kg CO_{2eq.}/kg WW *S. latissima* if future yields of 4500 kg/module are achieved. 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 the GWP of the SMAC S systems. Combining the optimisation of the cultivation system (SMAC N3 projection) and increasing yields will result in an impact of 0.20 kg CO_{2eq.}/kg WW *S. latissima*.

3.1.2. Other impact categories

Freshwater Eutrophication Potential (FEP), Fossil Resource Scarcity (FRS) and Water Consumption (WC) show similar trends in total impact between the scenarios for both current and future scenarios. The results for FEP, FRS and WC are given in the Supplementary Information. For the future scenarios the hotspots differ for FEP and WC, being buoys and buoys with floaters respectively.

3.2. Environmental impact of food products

The absolute environmental impact of the evaluated food products is given in Table 3 for both the baseline and future cultivation scenarios. The impact of the products in the future scenarios is reduced by at least

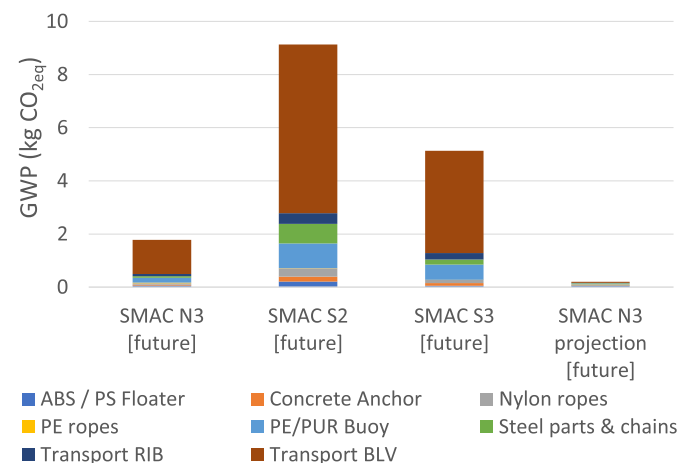


Fig. 4. Impact of cultivation with estimated future yields. Global Warming potential (kg CO_{2eq.}/kg harvested wet seaweed). Cultivation designs are indicated by SMAC N3 (net), SMAC S2, SMAC S3 (saw tooth) and SMAC N3, projected module.

Table 3
Absolute environmental impacts of the evaluated food products.

Food product	Burger		Salt		Salt replacement	
	Reference flow	1 kg burger, processed and packaged at supermarket	1 kg salt, processed and packed at supermarket	1 kg salt replacement, processed and packed at supermarket	100%	100%
<i>S. latissima</i> content	35.1%	10%	6.31	0.72	57.61	1.76
Scenario	Baseline	Future	Baseline	Future	Baseline	Future
GWP (kg CO_{2eq.})	7.20	3.47	6.31	0.72	57.61	1.76
FEP (g P_{eq.})	510.09	430.74	131.61	12.99	1245.37	59.11
FRS (kg oil_{eq.})	2.03	0.84	2.05	0.28	18.46	0.71
WC (m³)	0.124	0.114	0.022	0.006	0.180	0.020

50%, due to the reduced environmental impact of cultivation as was illustrated above. The impacts differ between the products, as the *S. latissima* content varies, in addition to differences in processing and packaging. Each of the products is analysed in detail in terms of impact hotspots and sustainable nutrition balance in the next sections.

3.3. Seaweed burger

3.3.1. Environmental impact

In Fig. 5 the contribution of different aspects of the production chain to the environmental impacts of burgers with *S. latissima* are shown for both current seaweed cultivation and the future scenario. Under current cultivation conditions the cultivation of *S. latissima* has a significant contribution to GWP and FRS. The production of the other burger ingredients dominate the impacts of FEP, and WC. Packaging contributes also to each of the impact categories and processing of the ingredients into the burger product is relevant for the GWP and FRS. The dominance

analysis changes for the future cultivation system, with future estimated yields and more efficient infrastructure design and transport (Fig. 5B). In the future scenario the impact of *S. latissima* cultivation to the total burger impacts would significantly diminish. As a result, the other ingredients play a larger role in the impact, especially egg for GWP, FEP, FRS and walnuts for WC.

3.3.2. Sustainability nutrition balance

The Sustainability Nutrition Balance (SNB) scores for the *S. latissima* burgers (based on future scenario) in comparison to a vegetarian and minced meat burger are given in Fig. 6. Negative SNB scores are most preferred. The results show that for GWP and LU the *S. latissima* burger has favourable SNB scores compared to the vegetarian hamburgers and vegetarian mincemeat burgers. The burger with 35.1% *S. latissima* scores has an upper boundary for average daily consumption of at most 14 g per day due to the high iodine levels in the seaweed. This implies that the diet should contain on average at most one *S. latissima* burger every

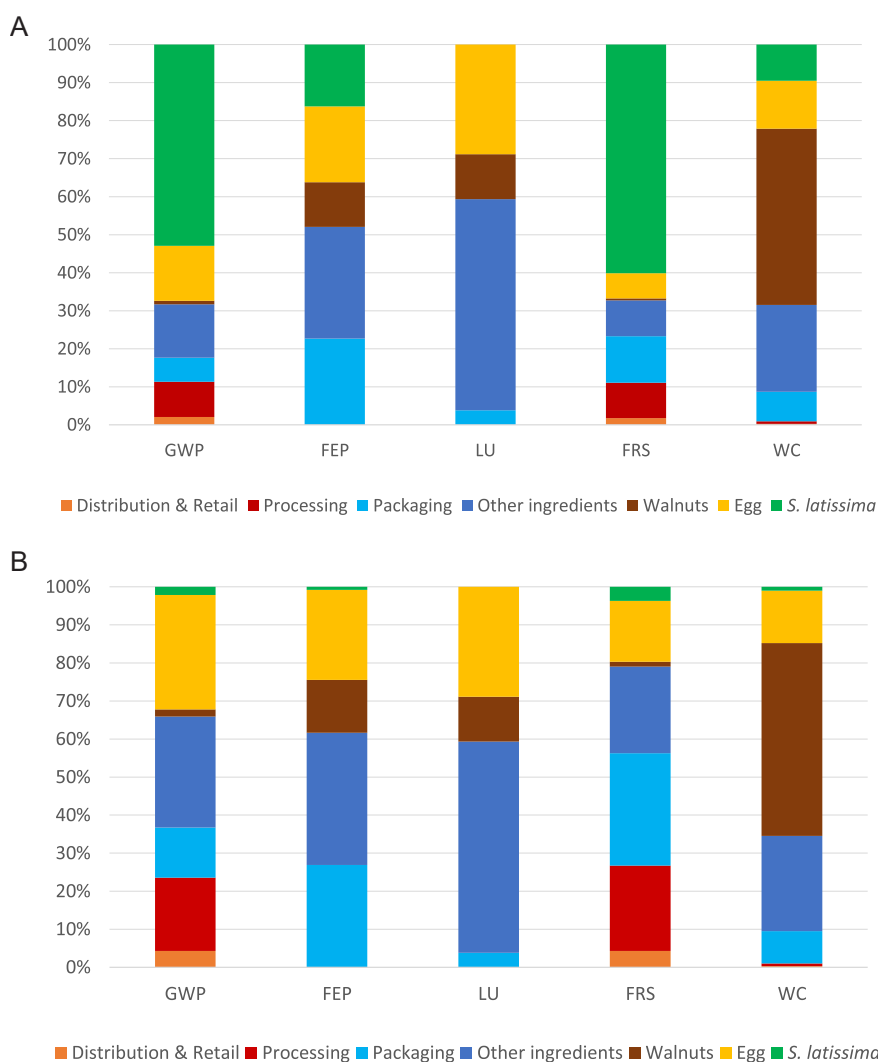


Fig. 5. Dominance analysis of the environmental impacts A) *S. latissima* burger based on current baseline yields in the SMAC N3 net3.0 cultivation system. B) *S. latissima* burger based on future system SMAC N3 projection with future yields. GWP = Global Warming Potential, FEP = Freshwater Eutrophication Potential, LU = Land Use, FRS = Fossil Resource Scarcity, WC = Water Consumption.

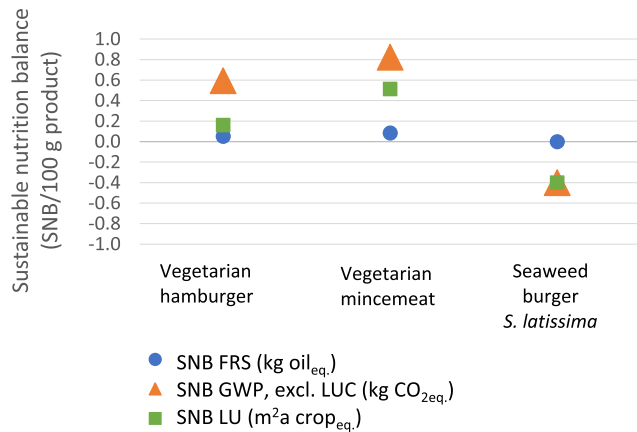


Fig. 6. Optimeal results burger (based on 100 g burger). Note: upper bound for *S. latissima* burger of 10 g a day, due to iodine. FRS = Fossil Resource Scarcity, GWP = Global Warming Potential, LUC = land use change, LU = Land Use.

7–8 days. For the impact FRS the SNB score of *S. latissima* burgers is quite similar to that of vegetarian hamburgers.

3.4. Seaweed salt

3.4.1. Environmental impact

The contribution of different aspects of the production chain to the total impacts are shown in Fig. 7 for the different *S. latissima* salt products. In the left graphs the impacts based on current baseline yields in the SMAC N3 cultivation system are given. For both salt products the majority of impacts are from *S. latissima* cultivation under current conditions, but for the salt replacement the contribution of processing, transport and packaging is negligible compared to the impact of *S. latissima* cultivation. In the right graphs the dominance analysis is shown for future cultivation conditions, based on SMAC N3 projection with future yields. For salt containing 10% *S. latissima* the impact of seaweed cultivation is reduced from 80–90% to 15–40% of the total impact. For the future scenario the impact of packaging becomes significant for all four impact categories. For GWP processing and transport becomes more prominent, while for WC the salt production is dominant. For the salt replacement with 100% *S. latissima* even for the future project the majority of impact is caused by the cultivation of seaweed s (60–90%),.

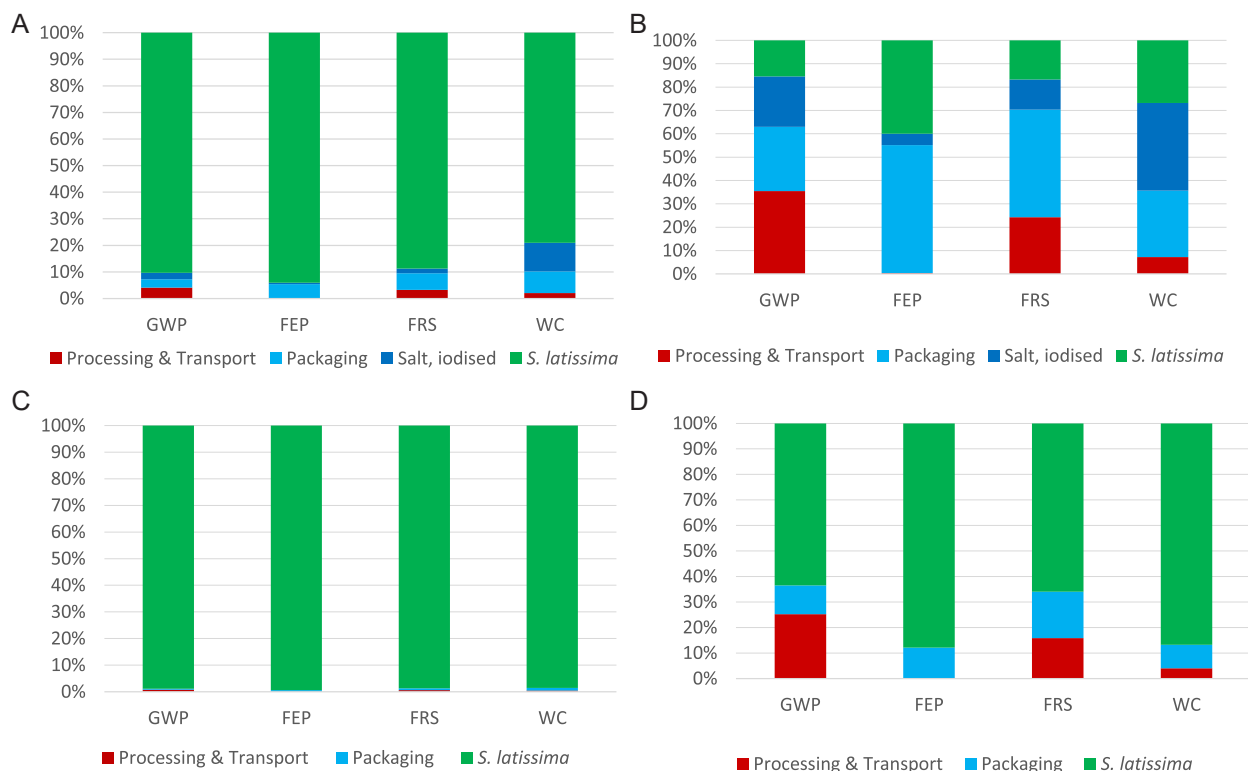


Fig. 7. Dominance analysis of the environmental impacts for (A,B) salt containing 10% *S. latissima* and (C,D) salt replacement with 100% *S. latissima*. The graphs on the left (A,C) are based on current yields in the SMAC N3 cultivation system, the graphs on the right (B,D) are based on SMAC N3 projected module with future yields. GWP = Global warming potential, FEP = Freshwater eutrophication potential, FRS = Fossil resource scarcity, WC = Water consumption.

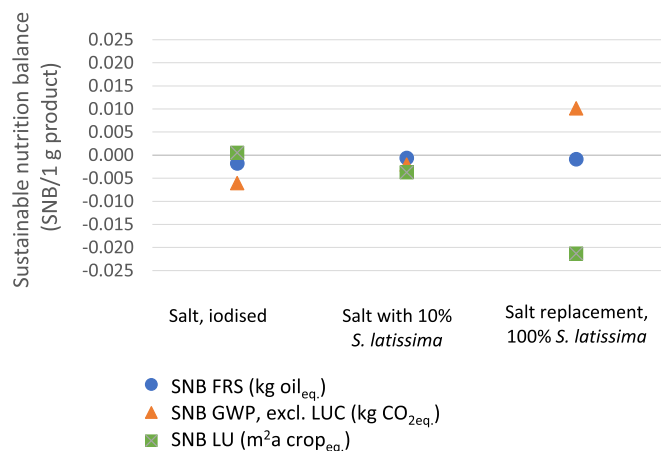


Fig. 8. Optimeal results salt (per 1 g of salt product). FRS = Fossil Resource Scarcity, GWP = Global Warming Potential, LUC = land use change, LU = Land Use.

3.4.2. Sustainability nutrition balance

The Sustainability Nutrition Balance (SNB) scores for the *S. latissima* salts (based on future scenario) in comparison to a regular iodised salt are given in Fig. 8.

The results show that particularly for LU the *S. latissima* salts have a favourable SNB score compared to the benchmark. For GWP and FRS the results are not that unambiguous. The seaweed salts are made with *S. latissima* which contains relatively high amount of iodine. This means the upper boundary for consumption is 5 g/d for the 100% *S. latissima* salt replacement. It also means that the calculation of the SNB score of these salts is based on less datapoints than the 10% *S. latissima* salt and the benchmark, adding to uncertainty.

4. Discussion

4.1. Hotspots in seaweed cultivation

Cultivation of *S. latissima* at the North Sea Innovation Lab (NSIL) has been used as a proxy for offshore seaweed cultivation on the North Sea. The impact results show that an important hotspot for the cultivation is transportation of the cultivation modules to the off-shore location and transport used for harvesting. Currently, these two transport activities by two types of ship are responsible for 73–80% of the impact of cultivation. At the experimental cultivation site at NSIL inspections are taking place relatively frequently to check the seaweed growth. Our results indicate that one should optimise the transport set-up 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 NSIL is now using smaller boats for these activities and is considering to use electrified boats in the future.

Seaweed cultivation systems are in full technical development across the globe (García-Poza et al., 2020; Kim et al., 2017; Monagail and Morrison, 2020). It is therefore important to note that data that has been used for the baseline scenario represent the current situation of experimental offshore seaweed cultivation techniques. Previous studies have also identified improvements for cultivation practice, for example exchanging the metals used as ballast with stone to reduce the human toxicity potential (van Oirschot et al., 2017) (Seghetta et al., 2017). In the current cultivation system evaluated in this work, concrete blocks are used as ballast instead of metal blocks. The current cultivation modules can still be further optimised, by reducing the relatively large number of buoys, anchors and chains needed. These improvements are

expected to be implemented in the next 5 years. By combining decreased transport efforts with a more optimised cultivation structure the GWP decreased 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 hotspot in the cultivation phase, illustrated by the sensitivity analysis. The cultivation system used at NSIL is experimental in nature, it is not yet been tested in other offshore environments nor used on a commercial scale, and thus reflects current pilot scale cultivation. The currently achieved cultivation yields at NSIL are lower than experts expect for future large-scale commercial seaweed cultivation. In the future projection for cultivation we have explored the effect of increased seaweed yields to 5 kg ww/meter cultivation line, reducing the GWP of cultivation with about a factor 6 from 10.15 to 1.78 kg CO_{2eq.}/kg ww. Increasing the yields in combination with the improved cultivation design and transportation the impact reduced to 0.20 kg CO_{2 eq.}/kg ww.

A recent study found that to a smaller extent the life span of the cultivation infrastructure are a focus point to reduce the impact of seaweed cultivation (Koesling et al., 2021). In the current study similar assumptions for the life time of the infrastructure were made as by Koesling et al., i.e. a lower lifetime of 5 years for ropes, a lifetime of 10 years for buoys and the longest lifetime of 20 years for steel elements. Our results indicated that the cultivation design has a larger impact on the GWP than the lifetime of the materials, the effect of the latter in the +-25% sensitivity analysis was marginal.

While this study is based on newly collected data, it must be kept in mind that the European seaweed cultivation sector is still in an early stage of development. Future innovations in among others cultivation technologies and breeding will affect the environmental impacts. The sensitivity analyses conducted above captures some of the expected innovation. Nevertheless, the data should be considered as best available data at the moment and needs to be updated as more experiences with seaweed cultivation are gained.

4.2. Environmental hotspots of seaweed food products

For the burger and salt products currently most of the impacts are caused by *S. latissima* cultivation, except for FEP and WC where the impact share related to seaweed is less than 15% of the total. In the scenario “SMAC N3 project with future yield”, the production of other ingredients is responsible for most of the environmental footprint of the burger. Compared to other vegetarian burgers the seaweed burger has an advantageous SNB in terms of GWP and LU. For salt with 10% *S. latissima* and a salt replacement of 100% *S. latissima*, seaweed cultivation is expected to keep having significant contribution to the environmental footprint of the product, partly due to the limited processing efforts needed for sodium chloride and the absence of other ingredients in the product. The seaweed salt and salt replacement have a slightly advantageous SNB compared to iodised salt. In the SNB analysis, an upper boundary for consumption of 1 burger per 7–8 days (equalling an average of 4.4 g *S. latissima*/d) was reached due to the high iodine levels in the seaweed. The iodine content in seaweed is a recognized concern in other studies as well (Banach et al., 2020). Concerns about high iodine levels in seaweed can negatively impact the reception of seaweed based products. A better understanding of the iodine concentration in seaweeds over time, per production location, and the right time of harvesting can reduce food safety risks. Furthermore, recently it has been shown that blanching can be applied to reduce the iodine content (Nielsen et al., 2020). Specifically labelling iodine on seaweed containing food products would also be an option (Bouga and Combet, 2015).

In this work we have focused on a variety of environmental impacts. An obvious difference between producing offshore seaweed and crops is the use of sea area versus land area for cultivation. Therefore, the SNB results with regard to LU should be treated with caution, as for *S. latissima* no land-use nor sea area-use was accounted for.

Quantification of the sea surface occupation and how to compare it to terrestrial land occupation is a new field of research (Taelman et al., 2015). Additionally, monitoring and evaluating the environmental effects of seaweed cultivation such as nutrient dynamics, effects on marine life and impact on the physical sea environment are in early stages of development (Wood et al., 2017).

The hotspots of the seaweed based food products can shift over the course of technical development of the seaweed cultivation techniques. Since there are no known other LCA studies published on the environmental impact of seaweed food products, the results cannot be compared directly to literature. However, recently 23 scenarios for protein production from seaweeds were evaluated in terms of environmental impacts (Koesling et al., 2021). That study concluded it is challenging yet possible to produce feed-protein from seaweed that has a lower environmental impact than soy protein, provided that the protein content and dry matter content after harvesting are increased and that drying is done efficiently. Nutritional aspects of seaweed are important to consider when assessing the potential and impact of food products. In this study the impact of a seaweed burger, salt with seaweed and salt replacement were compared to alternatives while including the nutritional profile using SNB. These results should be regarded as a starting point. To assess the full potential of seaweed foods more food products should be evaluated, as well as other seaweed species.

5. Conclusions

Seaweeds are seen as sustainable food ingredient for the future. Cultivation of seaweeds does not require land, nor fertilizers, and is expected to cater to the needs of a growing world population. This study confirms that seaweeds like *S. latissima* can play a role in future sustainable diets. The inclusion of *S. 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.

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. The Dutch seaweed sector, like its European and US counterparts, is in an early stage of development. Since the seaweed sector is in development, it is too early to have a definitive judgement on the environmental impacts of seaweed products compared to food products produced in mature sectors such as soy or maize. Instead, the main contribution of this work lies in pinpointing environmental hotspots and directing future investigations.

A reduction of the environmental impact can be achieved by increasing yields, increasing the lifespan of materials and increasing transport efficiency. In particular, the study points towards a hotspot in the cultivation of seaweeds: the vessel used for transport of the modules and harvested seaweed contributes significantly to the Global Warming Potential. Research into different means of installing the seaweed farms can directly contribute to a reduction of environmental impacts. The two food products of this study show the potential of incorporating seaweed in the future diet. *S. latissima* is a versatile species, which could be incorporated in more food products, provided that a solution is found to deal with the iodine content. A next step is to expand the product portfolio both in product types as the seaweed species included as ingredient.

CRedit authorship contribution statement

Petronella Margaretha Slegers: Conceptualization, Methodology, Supervision, Formal analysis, Writing – original draft. **Roel Johannes Karel Helmes:** Conceptualization, Investigation, Formal analysis, Writing – original draft. **Marlies Draisma:** Conceptualization, Validation, Writing – review & editing. **Roline Broekema:** Conceptualization, Investigation, Writing – original draft. **Mila Vlottes:** Resources, Investigation, Writing – original draft. **Sander Willem Kors van den Burg:** Conceptualization, Funding acquisition, Project administration, Writing

– original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is part of the AF16202 Maatschappelijk Innovatie Programma Seaweed for food and feed (BO-59-006-001). The programme is part of the top sector Agri&Food, financed by the Dutch Ministerie van Landbouw, Natuur en Voedselkwaliteit.

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.128689>.

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