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Explorative environmental life cycle assessment for system design of seaweed cultivation and drying

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A R T I C L E I N F O

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A B S T R A C T

Seaweeds are presently explored as an alternative source to meet the future protein demand from a growing world population with an increasing welfare level. Present seaweed research largely focuses on agri-technical and economic aspects. This paper explores directions for optimizing the cultivation, harvesting, transport and drying of seaweed from an environmental point of view. An environmental life cycle assessment (LCA) and detailed sensitivity analysis was made for two different system designs. One system design is featuring one layer of cultivation strips (four longlines side by side) interspaced with access corridors. The other system design is featuring a doubling of cultivation strips by dual layers in the water column. Impact profiles and sensitivity analysis showed that the most important impacts came from drying the harvested seaweed, and from the production of the chromium steel chains and polypropylene rope in the infrastructure. This indicates that caution should be used when designing cultivation systems featuring such materials and processes. Furthermore, the high-density productivity of the dual layer system decreases absolute environmental impacts and so found to be a little more environmentally friendly from a life cycle perspective.

1. Introduction

Seaweeds, similar to terrestrial plants, have been used for centuries as a food source. There is evidence of seaweed food products from the 4th and 6th centuries in Japan and China, respectively [1]. Some archaeological digs have suggested their use in agricultural soil management as well in the 2nd Century BC in Cornwall and perhaps even earlier in Estrucian Malta [2]. The use of ***wild*** harvested seaweed for feed, food and fertilizer is known to have evolved in isolation in various parts of the world from Scotland and Ireland to Japan and Peru [3,4]. The development of seaweed ***cultivation***, however, was until recently mostly restricted to Asian societies for local consumption in coastal areas [5]. In Europe, the majority of seaweed production comes from wild harvesting. However due to concerns over environmental impacts, wild harvests have decreased significantly in the last decade and there is a drive to meet the increasing demand by shifting production toward cultivation [6].

Today, both wild harvest and cultivated seaweeds are exploited around the world for many purposes [4]. They still serve as a fertilizer in agriculture and as food and feed [7]. Seaweed are now also increasingly seen as useful ingredients for products in other sectors, notably the pharmaceutical, cosmetic and food industries. Seaweed extracts can be applied as dyes or hydrocolloids [8], i.e. non-crystalline compounds forming jelly-like substances with water. Seaweed dyes and hydrocolloids have a large variety of applications in the food and cosmetic industry [1]. The main application of seaweeds globally, however, remains for human and animal consumption.

Seaweeds contain significant levels of essential nutrients such as carbohydrates, proteins, minerals, vitamins and trace elements like iodine [9,10] as well as antioxidants [11]. This makes some seaweed species highly suitable for both human and animal consumption [12]. The protein content may vary significantly over the different seasons and amongst different species [5,13] but can be up to 47% of the dry mass in a seaweed specie such as *Porphyria* spp. [14]. Their relatively

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high protein content makes seaweed a relevant alternative for animal proteins [15]. Seaweeds furthermore have extraordinary growth capacities, several times higher than for terrestrial energy or food crops such as rapeseed or sugar beets [16], which makes them suitable alternatives for these crops.

Seaweeds are presently explored as an alternative source to meet the future protein demand [17,18] from a growing world population [19] with an increasing per capita welfare level [20]. The cultivation of seaweed is also seen as an opportunity to reduce agricultural land use and related environmental burdens [21] and to remove elevated levels of nitrogen from estuaries and coastal waters [22]. Studies have furthermore suggested that seaweed growth rates can increase while providing bioremediation services to nearby finfish cultivations by absorbing nitrogen [23–26]. Nevertheless, seaweed cultivation may also have negative consequences for the environment and these are likely to be amplified by increasing the scale of operations. Apart from possible direct consequences for marine ecosystems, other and indirect environmental consequences of seaweed cultivation are limited in their description in literature [16]. Indirect environmental consequences refer to upstream production of the means needed in seaweed cultivation, and downstream transport, drying and processing of harvested seaweed into, for example seaweed meal.

The direct and indirect environmental impacts of seaweed cultivation, i.e. the overall environmental performance of the production system for dried seaweed, can be quantified with life cycle assessment (LCA). LCA is a well-established tool to shed light on the environmental performance of product (and production) systems by quantifying their cradle to grave (or gate) contribution to a range of impact categories [27–29]. Some LCA studies have been conducted with a focus on specific aspects of seaweed supply chains, for instance wild harvests and valorisation strategies [30], photobioreactor cultivation and oil extraction [31], macroalgae biorefinery [32,33], and production of biofuels from cultivated seaweed biomass [34]. This study adds to this body of literature by exploring optimal system design for commercial seaweed cultivation and drying. The drying of seaweed reduces biomass weight for transport, it makes it readily suitable for further processing, and is a reliable way of preserving protein and nutritional values [35]. Such future commercially cultivated seaweed is initially expected to be applied in the agri- and aquaculture sectors, as it is considered a sustainable alternative to soy- and fishmeal and a valuable additive to feeds, but may in the long run serve for human purposes in the food industry [36–38].

The LCA in this paper is of an explorative character since commercialised, large-scale seaweed farms are not yet established in Europe. Some small and medium-scale pilots have been established such as in the Oosterschelde estuary, Netherlands, and the Seafarm near Strömstad, Sweden. These pilots provide insight in agri-technically optimal and economically viable seaweed cultivation. However insight is also needed on how to minimise the environmental impacts of the dried seaweed production systems, i.e. of seaweed cultivation and upstream production of means, as well as of its downstream transport and drying. The design of a potential commercial production system for dried seaweed, particularly the design of the cultivation infrastructure sub-system and associated seaweed yield, has not gained much attention to date.

The design of the cultivation infrastructure sub-system might be of great influence to the overall environmental performance of the dried seaweed production system. Two hypothetical infrastructure sub-systems for future seaweed cultivation have been designed, one with single and the other with dual layer longline configurations. First an LCA has been performed for two reference dried seaweed production system designs, one with a reference design for the single layer and the other with a reference design for the dual layer seaweed cultivation infrastructure sub-system. Next an extensive sensitivity analysis was performed, varying the design of the cultivation infrastructure, transport and drying parameters of the two reference dried seaweed production systems. The aim of the LCA in this paper was to explore potential designs of the future dried seaweed production system in order to identify directions for its optimization from an environmental point of view.

2. Methodology

Life Cycle Assessment (LCA) consists of four methodological phases. The first phase, goal and scope definition, specifies why and how a given LCA is performed. The second phase, life cycle inventory, quantifies all environmental inputs and outputs of the production system under consideration. The environmental inputs and outputs are translated in the third phase, life cycle impact assessment, into their contribution to a range of environmental impacts. The fourth phase, interpretation, evaluates the results of life cycle inventory and impact assessment in relation to the defined goal and scope in order to draw conclusions [27–29].

The goal and scope definition basically sets how the other three phases are performed. The goal or aim of the LCA in this paper, as mentioned already in the Introduction, was to identify directions for optimizing the future commercial dried seaweed production system design from an environmental point of view. The scope of the LCA in this paper, i.e. its methodological approach, is further specified here in terms of the software and databases as well as data processing, the functional unit, description of the dried seaweed production system and life cycle inventory, life cycle impact assessment and finally the sensitivity analysis.

2.1. Softwares, databases and data processing

The software SimaPro 7.3 is used for life cycle inventory analysis and impact assessment calculations. EcoInvent v3.0, included in the software SimaPro 7.3, is used where relevant as the source for life cycle inventory data (see Table 1). The impact results for the reference systems are presented in stack-diagrams, produced in excel. Impact results for the sensitivity analysis are processed in excel into graphical representations showing the changes in impact resulting from changes in the amount of inputs.

2.2. Functional unit

The function of the dried seaweed production system in this LCA is the production of dried seaweed with a protein content of one ton, suitable for further processing. In other words, all LCA results are expressed per ton of protein (and thus not, e.g., per ton dried seaweed). Downstream processing of the dried biomass into commercially available products is not included in the present study.

2.3. Dried seaweed production system and inventory analysis

The dried seaweed production system is schematically depicted in Fig. 1. The processes in the grey shaded boxes are included, and the processes in all other boxes are excluded in this LCA. In other words, grey shaded processes are inside and other processes are outside the boundaries of the system. The final product of the system is dried seaweed biomass. Data for sprouting of seeding lines is not available. The materials for production of the service vessel and the diesel used for harvesting are included in seaweed transport. The production of other products used for other harvesting tools, e.g. knives and nets, are excluded in this LCA as they are considered negligible compared to materials used in the boat.

The cultivation of seaweed in a European context still has an experimental character, and only small to medium scale pilots are being implemented to our knowledge. Some pilots are testing different types of cultivation infrastructures, such as those described by Taelman et al. [42]. We have limited information about what large-scale commercial

Table 1
Economic inputs used, input characteristics, source of input information, quantity of inputs used (expressed per single use and in terms of the functional unit), and EcoInvent process applied for calculating environmental outputs of the reference dried seaweed production systems.

Economic inputs used	Life (years)	Input characteristics	Source of input information	Quantity of input used				EcoInvent v3.0 process applied to calculate environmental outputs
				Single layer	Dual layer	Single layer	Dual layer	
Seeding lines	1	Polypropylene, 2 mm ø, 0.0014 kg/m	Author measurement	0.00021 ton/100 m of longline/y	0.00021 ton/100 of longline/y	= 0.016 ton/tonprotein/20 y	= 0.022 ton/tonprotein/20 y	'Fleece, polyethylene terephthalate/RER, at plant/RER', adjusted by: (a) replacing production of polyethylene granulate by polypropylene granulate;
Cultivation & infrastructure rope	5	Polypropylene, 22 mm ø, 0.22 kg/m	Touwfabriek Langman BV [39]	0.030 ton/100 m of longline/5 y	0.028 ton/100 m of longline/5 y	= 0.46 ton/tonprotein/20 y	= 0.58 ton/tonprotein/20 y	and (b) by adding a polypropylene end of life incineration scenario
Chains	20	Chromium steel, 19 mm ø, 8.3 kg/m	Author calculation	0.048 ton/100 m of longline/20 y	0.024 ton/100 m of longline/20 y	= 0.18 ton/tonprotein/20 y	= 0.12 ton/tonprotein/20 y	Chain manufacturing: 'Product manufacturing, average metal working/kg/RER' Steel production: 55.5% recycled 'Steel, electric, chromium steel 18/8, at plant/RER U' and 44.5% virgin 'Steel, converter, chromium steel 18/8, at plant/RER U', based on scrap average in European steel [65]
Anchors	20	Concrete, rectangular block, 1000 kg	Author assumption	2.033 ton/100 m of longline/20 y	1.017 ton/100 m of longline/20 y	= 7.9 ton/tonprotein/20 y	= 5.3 ton/tonprotein/20 y	'Concrete block, at plant/kg/DE'
Small buoys	20	Polyvinyl chloride, 0.31 m ø, 1.2 kg/buoy	Chandelry World Ltd [40]	0.011 ton/100 m of longline/20 y	0.0055 ton/100 m of longline/20 y	= 0.043 ton/tonprotein/20 y	= 0.028 ton/tonprotein/20 y	'Polyvinyl chloride, granulate, at plant/RER' PVC 'Blow moulding/RER' for manufacture of buoys
Large marker buoys	20	Polyvinyl chloride, 0.59 m ø, 4.1 kg/buoy	Chandelry World Ltd [40]					and strip strengtheners 'Disposal, polyvinyl chloride, 0.2% water, to municipal
Strip Strengtheners	20	Polyvinyl chloride, 1.98 kg per rod	Author calculation	0.054 ton/100 m of longline/20 y	0.054 ton/100 m of longline/20 y	= 0.021 ton/tonprotein/20 y	= 0.028 ton/tonprotein/20 y	incineration/CH'
Transport	n/a	5 × 20 km return trips for delivery of seeding lines and monitoring 1 × loaded barge with harvest 10 km	Author calculation. Validated by pilot researchers at Seafarm	246 tkm/100 m of longline/20 y	138 tkm/100 m of longline/20 y	= 955 tkm/ton protein/20 y	= 951 tkm/ton protein/20 y	Barge production, operation & maintenance: 'Transport, barge/RER'
Thermal drying of seaweed biomass	n/a	85% moisture content of *S. latissima* 83% moisture content at start of drying 22% moisture content at end of drying	Schiener et al. [13] Author assumption Scoggan et al. [41]	15 tons/100 m of longline/20 y (of evaporated water)	11 tons/100 m of longline/20 y (of evaporated water)	= 59 tons/tonprotein/20 y (of evaporated water)	= 59 tons/tonprotein/20 y (of evaporated water)	'Maize drying/CH'

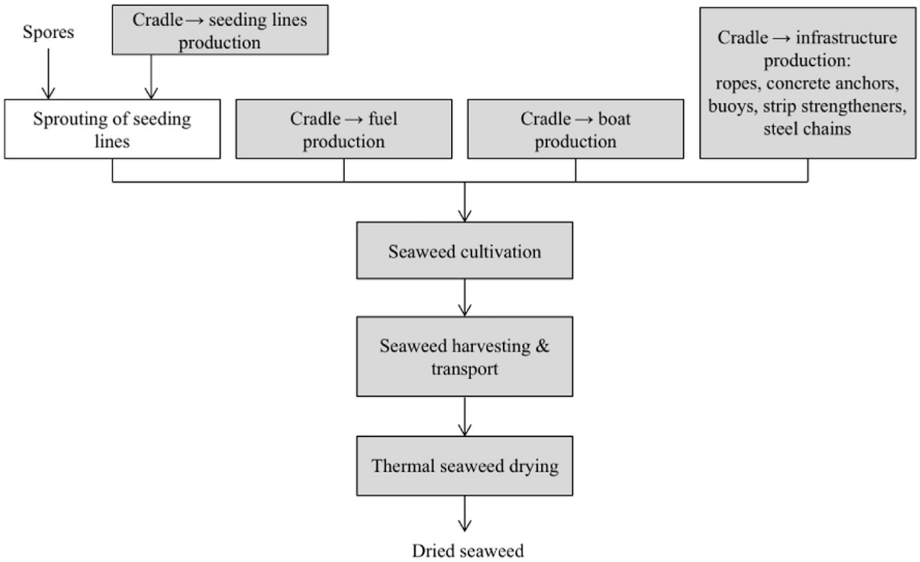

Fig. 1. Dried seaweed production system; the processes in the grey shaded boxes are included in the system boundaries of this LCA.

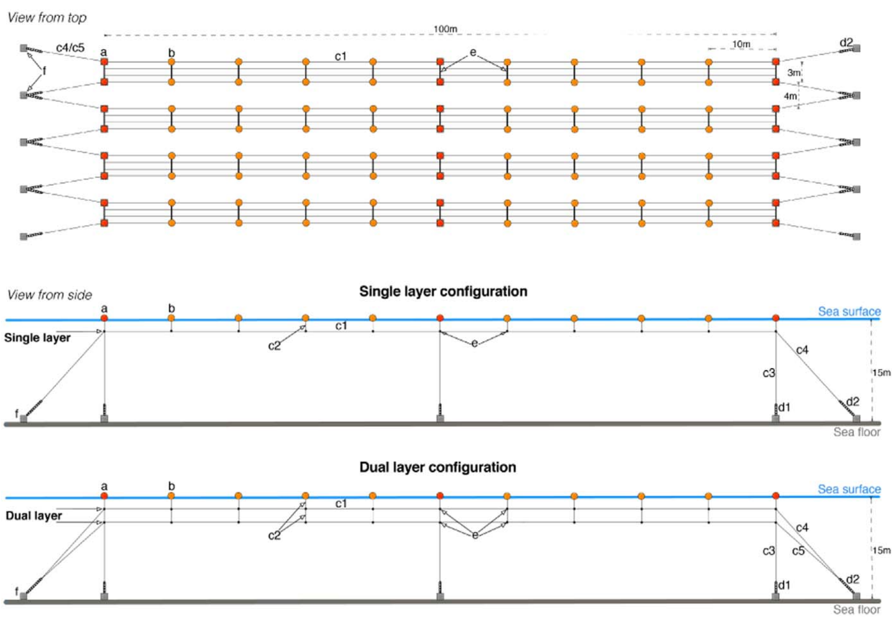

Fig. 2. Schematic representation of the designed strip cultivation infrastructure viewed from above and from the side. The single layer and dual layer seaweed cultivation sub-systems appear identical from the top, however the differences are discernible when viewed from the side. The infrastructural components are (a) marker buoys, (b) small buoys, (c) PP rope (longline), (d) steel chain, (e) strip strengtheners and (f) concrete anchors.

seaweed cultivations in Europe could look like. As a part of the dried seaweed production system, two reference seaweed cultivation infrastructure sub-systems have been designed for high productivity per hectare. The design is after a sketch from Buck [43] included in Wald [44], but adjusted according to suggestions from Brandenburg [45] and Nylund [46]. High productivity in these systems is facilitated by two particular design elements. The first involves the use of an innovative "cultivation strip" configuration consisting of four longlines running parallel to one another 1-meter apart, at a depth of 2 m (single layer configuration). A gap between each strip is maintained throughout the cultivation to facilitate access for service vessels. The second high-productivity element involves the doubling of cultivation strips in the water column, in other words, two strips are held in place one on top of the other, the upper layer at a depth of 2 m and the lower at a depth of 4 m (dual layer configuration). The infrastructure design (Fig. 2) and the amounts of materials used (Table 1), both relevant outcomes of this study, are described in more detail in Section 3.1.

The purpose of the infrastructure is to provide stable longlines at a depth suitable to the cultivation of *S. latissima*. Once seeded with juvenile *S. latissima*, thin polypropylene (PP) string (henceforth referred to as seeded/seeding lines), are unfurled around the far thicker PP longlines that form the cultivation strips. Seeding lines are considered an operational component, to be replaced for every cultivation cycle, as opposed to being considered a permanent infrastructural component. The longlines with seeding lines coiled around them provide a stable anchorage for the growth phase of the seaweed lifecycle. The authors estimate biomass yields for one cultivation cycle per year based on a combination of literature and personal experience gained at pilot sites (see Section 3.2 for more details). The species of seaweed used in this study is *Saccharina latissima* (henceforth *S. latissima*). It is able to thrive in both temperate and polar regions and is commonly found along the European Atlantic coast, from Norway to Portugal. By selecting local specimen adapted to local conditions (e.g. tidal ranges, temperatures, salinities, etc.), populations of *S. latissima* have been successfully cultivated in pilots across Europe, including the test sites in the Oosterschelde estuary, Netherlands, and the Seafarm site near Strömstad, Sweden. From such trials in sheltered/near-shore environments, it is recognised as fast growing and suitable for cultivation on infrastructure systems known as longlines, with negligible levels of accidental loss. The harvested seaweed biomass is assumed to be dried in a thermal air dryer to 22% moisture, a generally recommended moisture level for seaweed biomass storage and subsequent use [41,47]. (see Section 3.3 for more details).

In this study, transport includes the delivery of the seeded lines to the cultivation area, four return trips to account for monitoring during the growth phase, the harvesting of seaweed biomass and returning the harvested seaweed biomass from the cultivation area to the shore. The distance between cultivation area and port is taken to be 10 km. The quantification of the environmental impacts of transport includes construction, maintenance and disposal of a motorised barge and a small port.

2.4. Life cycle impact assessment (LCIA)

Impact assessment was performed with the ten impact categories from the CML 2001 (baseline) method (version 2.5), and supplemented with the cumulative energy demand (CED) from Frischknecht et al. [48]. The CML 2001 (baseline) method quantifies ten impact categories, i.e. ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, climate change, acidification, abiotic depletion and eutrophication [28].

2.5. Sensitivity analysis

Table 1 specifies both reference dried seaweed production systems. It provides characteristics and quantities of all economic inputs and outputs used and the sources for this information. Also given are the EcoInvent v3.0 processes applied for calculating the environmental LCI inputs and outputs. These are provided for all processes in both reference systems for dried seaweed production, i.e. the one with single layer and the other with dual layer seaweed cultivation configurations (harvesting, transport and drying kept similar for both sub-systems). Values for the ‘quantity of input used’ in Table 1 are expressed both per 100 m of longline (per strip divided by the 4 longlines in each strip) and in terms of the functional unit, i.e. per ton of protein. The types of material in the life cycle inventory are based on the pilot cultivation of the Seafarm project in Sweden [46] and adapted to the materials available in the EcoInvent database.

Sensitivity analysis was performed by changing, one by one, selected LCI inputs of the reference seaweed production system while keeping other input values the same. Given the close similarities in design and inputs of both systems, it was considered unnecessary to conduct sensitivity on both the single and the dual layer configurations; sensitivity was only conducted for the single layer strip configuration. LCI inputs for the sensitivity analysis were selected based on two main factors: large impact contributions (i.e. potential to influence results) and data quality/certainty. The selected LCI inputs were transport distance to the shore, the moisture content of the harvested seaweed, relative humidity of air going out of the drying process, biomass production per ha cultivation area, protein content of seaweed biomass, replacement frequency and diameter of sprouted seeding lines, and replacement frequency of infrastructure. The analysis was conducted by changing input values by 10% increments varied from 50% to 150% of the values used in the reference seaweed production systems. For example, the maize drier's specific moisture extraction rate (SMER), a value commonly used as an indicator of a dryer's moisture removal efficiency, is set at 3 MJ/kg_{water} in the base case was re-run at 10% increments to a maximum of 4.5 MJ/kg_{water} (50% added to base case) and a minimum of 1.5 MJ/kg_{water} (− 50% from base case).

3. Results: system description and inventory analysis

Since large-scale commercial seaweed cultivation does not yet take place in Europe, the possible design of the infrastructure and the drying sub-systems are relevant outcomes of this exploratory LCA. The results for the possible design of the seaweed cultivation infrastructure sub-system, more importantly of their permanent infrastructure in the marine environment, are therefore first described in more detail. The results for the biomass and proteins yields are then presented, followed by a description of the drying process.

3.1. Design of seaweed cultivation infrastructure sub-systems

Two reference seaweed cultivation infrastructure sub-systems have been designed, one featuring a single layer longline strip design and the other a dual layer longline strip design. The designs for both reference infrastructure sub-systems follow a sketch from Buck [43] included in Wald [44], but are adjusted according to suggestions from Brandenburg [45] and Nylund [46]. Seeding lines covered in juvenile *S. latissima* (replaced once a year) are coiled around longlines (replaced every 5 years), in turn held in place by the rest of a permanent infrastructure with a lifetime estimated at 20 years. See Fig. 2 for a schematic presentation and below for further description of the single layer seaweed cultivation infrastructure sub-system.

Seeded PP string (2 mm ø) is coiled around PP longlines (22 mm ø). The seeding lines are 1.5 times the length of the longlines. Four longlines next to each other, with 1 m in between, together form a cultivation strip with a width of 3 m. A cultivation strip, i.e. each of its four longlines, is 100 m long. To avoid tangling of the lines, they are held in place by rigid polyvinyl chloride (PVC) rods (henceforth “strip strengtheners”) every 10 m. Between each strip, a 4 m gap acts as a corridor providing access for service vessels (e.g. for harvesting), reducing shadowing in the water column (to avoid negative consequences for the marine ecology) and may also provide passages for migrating wild life.

The cultivation strips are held in place by rope (22 mm ø) and steel chains (19 mm ø) at both ends and at their centre, connected to 1ton concrete anchors on the seafloor. To further secure the cultivation strips and add tension to the longlines, additional lateral concrete anchors sit at each end of, and in between, each cultivation strip. Even buoyancy is maintained by buoys (31 cm ø, PVC, 1.2 kg each) located either side of each strip every 10 m, i.e. directly above the ends of the PVC rods, while marker buoys (59 cm ø, PVC, 4.1 kg each) located at each end and in the middle of the strips, i.e. directly above the 1 ton concrete anchors, serve both for buoyancy and to make the cultivation more visible at Sea. Together, the elements represented in Fig. 2 form the permanent infrastructure in the marine environment, and were selected based on their ability to carry a significant burden in dynamic marine conditions over their expected lifetimes. The material end of life scenarios for the PP seeding lines, PP longlines, PVC buoys and PVC strip strengtheners are incineration in municipal incinerators with energy recovery. The end of life of the chromium chains and of the concrete anchors are recovered for recycling and left on the seafloor, respectively.

The design of the reference single layer and dual layer seaweed cultivation infrastructure sub-systems are similar. The main difference is a doubling of the strips (longlines, strip strengtheners and seeding line) and associated tethering lines (to lateral anchors and to buoys). The number of buoys, anchors and the amount of chain used are the same in the single and dual layer systems.

3.2. Seaweed biomass and protein yield

Seaweed biomass production is estimated based on adequate conditions for seaweed cultivation in the Oosterschelde estuary, on the growth rates of seaweed farms in the Netherlands [45], in Sweden [46], and in Ireland and France [42]. The estimated seaweed biomass production for a single layer cultivation is 1.2 ton fresh weight (FW) 100 m^{-1}. For the lower cultivation strip in the dual layer system, the authors assume that seaweed yields are 50% (0.6 ton FW 100 m^{-1}) of the single layer yields as a result of shading from the upper cultivation

Table 2
Assumptions for quantifying annual biomass and protein yield.

	Symbol	Formula	Single layer	Dual layer
			ton/ha-year	ton/ha-year
Fresh weight[a]	m_{wet}		72	108
Dry matter[b]	m_{dry}	$m_{wet} * (1–0.85)$	11	16
Dried mass[c]	m_{dried}	$(m_{dry}/(100 - 22)) * 100$	14	21
Total protein[d]	$m_{protein}$	$7.1 * m_{dry}$	0 0.77	1 0.16

[a] The fresh weight of the harvested biomass is estimated by the authors as being 12 kg/m of longline on the cultivation strip of the single layer configuration. For the dual layer configuration, the upper strip is assumed to be the same, while the lower strip is estimated as half of the upper layer, at 6 kg/m.

[b] The water content of the *Saccharina latissima* is approximately 85%, giving a dry matter content of 15% [13].

[c] 22% moisture content is a commonly acceptable level of moisture for the preservation and storage of seaweed biomass [41,47].

[d] The yearly average protein content of *Saccharina latissima* [13].

strip. Colleagues at both the Seafarm pilot near Strömstad report that only a single harvest per year is manageable at the moment for this species. This is partly due to fouling by bryozoans which attach to the biomass in early summer when sea surface temperatures increase, but also because the fastest growth period for *S. latissima* is winter/spring. Thus the aforementioned estimated yields are also representative over one year. These yield estimates include consideration of biomass detaching from the infrastructure as they are based on yield measurements at the time of the harvest; specific quantification of biomass losses from the infrastructure before the harvest are not included in the present study as they are considered negligible given the location of the site is sheltered, protected from storms and strong currents.

Seaweed protein content was based on the average for *S. latissima* (7.1 ± 1.7% of dry matter) provided by Schiener et al. [13]. These values translate to 0.77 tons protein per hectare per year for the single layer and 1.16 tons protein per hectare per year for the dual layer (see Table 2 for a further specification of the seaweed biomass composition). The biomass yield (and subsequent protein yield) from a dual layer seaweed cultivation is thus 50% higher per ha than from the single layer cultivation. All environmental impact results in the following sections relate to per ton protein in dried seaweed (the functional unit) based on a 20-year life expectancy of the infrastructure.

3.3. Drying sub-system

The water fraction adhered to the seaweed contains part of the available proteins. Mechanical drying would result in loss of the protein contained in this water fraction through drippage and thus is supposed not to be suitable as drying method. The harvested seaweed biomass is assumed to be dried in a thermal air dryer to 22% moisture, a generally recommended moisture level for seaweed biomass storage and subsequent use [41,47]. Due to an increased risk of denaturalisation and loss of proteins at temperatures above 35 °C and a need to preserve these proteins in the dried seaweed, the heated ingoing air is limited to 35 °C. The energy requirements for the drying are calculated in two steps: the first by means of a simplified mass balance, to determine the amount of water in the seaweed following the harvest, transport to shore and overnight storage. During transport and temporary storage prior to drying, the seaweed will be compressed under its own weight and partly dewatered [49]. It is assumed that 20% of the harvested biomass water content is lost during this time, while preserving the protein containing water adhered to the seaweed. The second step calculates the impacts resulting from the removal of the rest of the water, reaching 22% moisture, using the process in SimaPro called “maize drying”.

The maize drying process was used as a proxy due to a lack of literature regarding energy requirements to dry seaweed and the lack of a marine biomass drying process in SimaPro. The process was deemed adequate when adapted to the drying of seaweed biomass by changing the amount of water to be evaporated. Drying related parameters such as moisture content in the ingoing biomass and the specific moisture extraction rate (SMER) of the drier, were considered key sources of uncertainty and were included in the sensitivity analysis. The drying process also includes the production of the drying infrastructure machinery, as well as a share of impacts from the premises to house the drying equipment and undertake the drying process. The EcoInvent v3.0 process “light fuel oil burnt in an industrial furnace” is used as a fuel source for the drying. This gives the advantage over an electrical drying process by decoupling the electrical input impacts from varying national energy mixes, as discussed in Raghavan et al. [50].

4. Results: LCIA

In this section the environmental impact results are presented, first for the overall dried seaweed production system and then for the infrastructure alone. This section concludes with the results from the sensitivity analysis.

4.1. Dried seaweed production

Fig. 3 shows that, on the whole, the contribution of the seeding lines as well as the harvesting and transport to the overall impacts is insignificant. Both the infrastructure and the drying process share the majority of all impacts, but not equally. The drying dominates ozone depletion, abiotic depletion, acidification, climate change and photochemical oxidation, whereas the infrastructure dominates human toxicity, freshwater ecotoxicity and marine ecotoxicity. Eutrophication and terrestrial ecotoxicity are shared more or less evenly by both drying and infrastructure. All of the main system components, except infrastructure (see Section 4.2), are described in more detail here.

The drying process makes a large contribution to all impact categories, with the exception of human toxicity and fresh water ecotoxicity. It particularly dominates ozone layer depletion due to emissions of methane and ethane compounds (methane, bromotrifluoro-, halon 1301) from the burning and refining of light fuel oil for production of heat. Other dominated impact categories (by over 70% contribution) include abiotic depletion, climate change, photochemical oxidation and acidification. The majority of non-renewable CED also is a result of the drying process. In terms of the drying process, it is worth noting that the

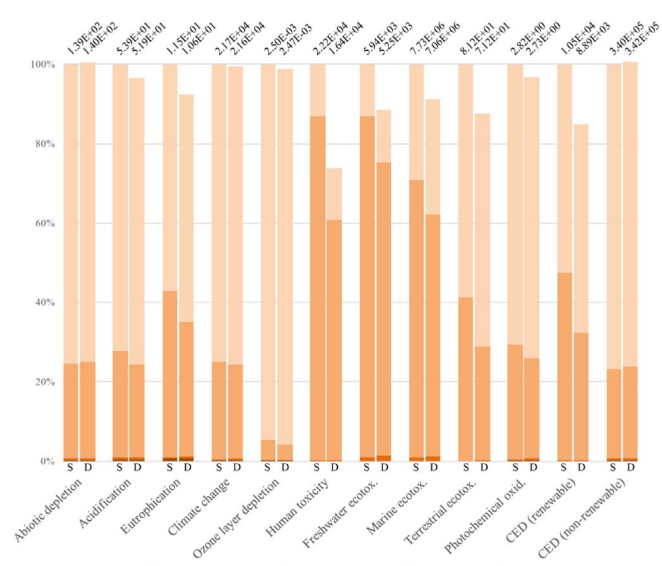

Fig. 3. Impacts per ton of dried protein for the dried seaweed production systems with the single layer (S) and dual layer (D) configurations.

relative contribution toward impacts remains exactly the same, regardless of the single or dual layer configuration. This is because the drying process is the same in both systems: the production of 1 kg of dried seaweed, or more specifically per ton of protein, requires the same amount of energy and material investment, regardless of total volumes of each scenario. As such the contribution of the drying process does not change per ton of protein between the single and dual layer systems, however it remains the single most dominant impact contributor in the overall dried seaweed production system.

The seeding lines, which are considered an operational component and thus separate from the infrastructure, make a very small contribution to overall impacts and make no visible contribution to any impact category in the stack diagrams. Their impacts can be considered negligible, in spite of their yearly replacement. Harvesting and transport also make a very small contribution to the overall environmental impact of both reference systems with the distance from the cultivation area to the shore set to 10 km. As a precaution and to shed light on the contribution of transport to overall environmental impacts over much larger distances, the authors recalculated using a distance of 100 km (from cultivation to shore). Contributions across almost all of the impact profiles remained below 5%, except for the acidification and eutrophication categories, for which the contributions rose to 6 and 7% respectively. To summarise, the overall contribution of harvesting and transport is considered almost negligible in our model over the 10 km distance and remains small over 100 km.

Finally, from Fig. 3 it is also clear that, per ton of protein in the dried seaweed, the dual layer system performs slightly better than the single layer system in almost all impact categories. This is principally due to the 50% higher yields of the dual layer system (see Section 3.2). The only impact categories where the dual system performs worse, but only marginally (less than 1%) are the abiotic depletion and non-renewable CED categories. The explanation for this lies in the greater infrastructural requirements of the dual layer configuration compared to that of the single layer configuration. The impacts of the infrastructure are further explored in the next section.

4.2. Infrastructure

The stack diagram in Fig. 4 shows the relative contributions of each infrastructural component, both for the single layer and dual layer configurations. The chains have the highest contribution followed by the ropes, then the anchors, the buoys and finally the strip strengtheners. Ropes and chains dominate the environmental contribution of the infrastructure of most categories. Particular dominance comes from the chains in human toxicity due to the emissions of chromium VI and arsenic from the production of chromium steel and terrestrial ecotoxicity due to the emission of mercury and chromium VI from the production of chromium steel. The main relative contributions of the ropes are in abiotic depletion where it represents a majority of the infrastructure contributions due to the use of crude oil for the production of PP. The ropes also have a large contribution to climate change as a result of the CO2 emissions from the production of PP granulate and incineration of the PP ropes at the end life. The ropes also contribute an important share of impacts in the photochemical oxidation, marine and freshwater ecotoxicity categories. The anchors contribute little to all impact categories, but are notable in the ozone depletion and climate change categories. Both PVC components, the buoys and strip strengtheners, have small contributions overall.

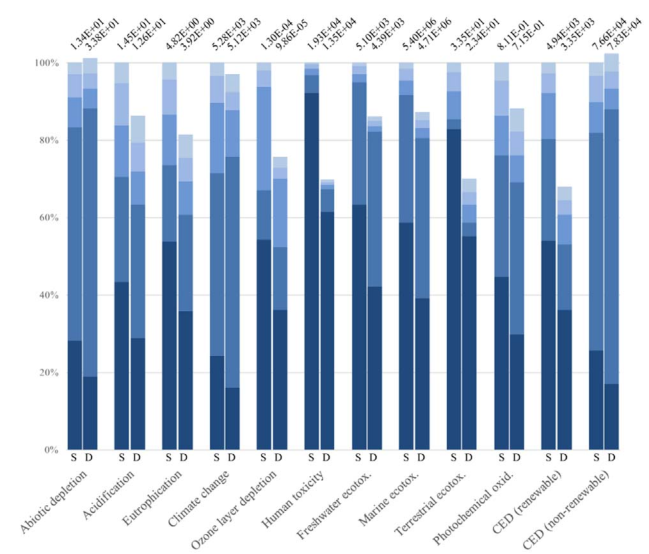

Fig. 4. Impacts per ton of dried protein for the cultivation infrastructure components for the single layer (S) and dual layer (D) configurations.

The main differences in terms of impacts between the single and dual layer are also clarified from the infrastructural component fragmentation in Fig. 4. One can see that the impact contributions per ton of protein of the ropes are clearly higher in the dual layer system, while the chains are lower in the dual layer system. Less easy to see, because their impact contributions are relatively small, is that the strip strengtheners and seeding lines have slightly greater impacts in the dual layer system, while the contributions of the buoys and anchors are lower in the dual layer system. This is a reflection of a 50% higher biomass yields per hectare in the dual layer system relative to the single layer system, in parallel with a 100% increased use of ropes, strip strengtheners and seeding lines to double the number of strips in the dual layer. This is opposed in most impact categories, however, by a reduced share of total material inputs for the buoys, chains and anchors, which are the same in both the single or dual layer configurations. These patterns are clearly visible in the impact categories where those materials have the largest impacts. For instance, as mentioned in above, the ropes have a large contribution to abiotic depletion as well as several other categories. The increased contributions of the ropes in the dual layer system are thus evident in this impact category in Fig. 4. Similarly, the chains are noted to have a particular dominance of the human toxicity category. Their decreased contribution to the dual layer system is thus evident in this impact category in Fig. 4.

4.3. Sensitivity of LCIA

The sensitivity analysis exposed the specific moisture extraction rate (SMER) of the biomass drying process, protein content and biomass yield as the most sensitive parameters (see Fig. 5). The SMER value is the most sensitive parameter in the all impact categories except the toxicity and eutrophication categories, showing a linear change whereby higher SMER values resulted in higher impacts, and lower SMER values resulted in lower impacts. As to be expected, across every impact category, higher protein content was found to decrease absolute impacts while lower protein content increased absolute impacts. Overall, protein content was found to be the second most sensitive parameter, closely followed by biomass yield. These two parameters are central to this LCA model, both having a direct influence on the functional unit. Hereafter, the highlights of the parametric sensitivity analysis are presented.

The replacement frequency of the total infrastructure is assumed to be 20 years, with the exception of the longline ropes, whose life expectancy is assumed at 5 years. Since replacement frequency values remain uncertain factors, these were included in the sensitivity analysis. Replacement frequency of the infrastructure was found to be very sensitive, particularly in the toxicity, acidification and eutrophication categories, but only slight in the acidification and eutrophication categories.

A preliminary analysis of the sensitivity of infrastructural components showed negligible sensitivity for all of them with the exception of

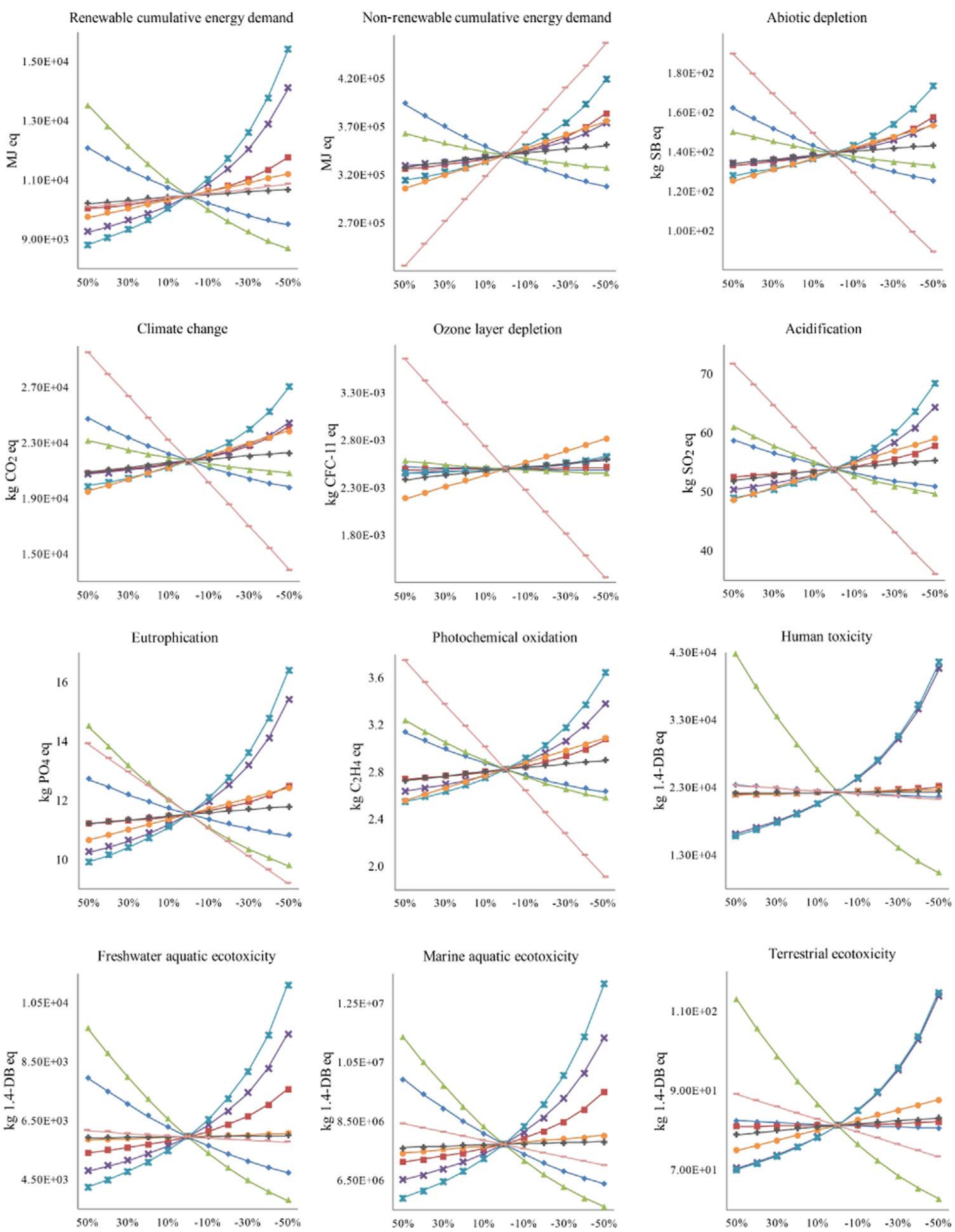

Fig. 5. Sensitivity analysis of the total environmental impacts of dried seaweed production systems for the single layer cultivation configuration. The impacts of both reference systems are represented by the "0" on the x-axis, the other % show the influence of changing input values compared to the reference system for ropes diameter (—◆—), ropes replacement frequency (—■—), chains diameter (—▲—), infrastructure replacement frequency (—✕—), biomass yield (—✳—), water loss during harvest (—●—), water content of outgoing biomass (—+—) and the specific moisture extraction rate (SMER) of the biomass dryer (——).

the chains (diameter) and ropes (diameter), so only these components were included in the final sensitivity. Both were found to be highly sensitive: increasing their diameter rapidly increases their mass, which in turn increases the magnitude of impacts. The chains are particularly sensitive for the impacts in the toxicity categories, eutrophication and acidification. The impact categories most affected by the ropes are the freshwater and marine aquatic ecotoxicity categories, as well as climate change and abiotic depletion. Beyond these aforementioned categories, both diameters of the ropes and chains demonstrated moderate sensitivity.

Sensitivity analysis was also conducted for the key variables in the drying process, including assumed water lost during harvest, moisture content in outgoing product and the SMER of the biomass dryer. As mentioned above, the SMER was exposed as the most sensitive parameter in the model. The water loss during harvest and the moisture content in the dried seaweed have only minor sensitivities relative to the other parameters, with the exception of ozone layer depletion, where water loss during harvest is the most sensitive parameter second only to the SMER.

5. Discussion

The LCA in this paper used EcoInvent v3.0 for calculating the environmental LCI inputs and outputs, and the CML 2001 (baseline) method (version 2.5) and CED [48] for converting these environmental inputs and outputs into their environmental impact contributions. EcoInvent v3.0, the CML 2001 (baseline method) and CED are considered robust and authoritative. The uncertainty in the present study comes largely from the design of the dried seaweed production system, in particular from the seaweed biomass and thus protein yield, the cultivation infrastructure sub-system design, and the drying process. These sources of uncertainty are discussed in the following section and the results of the study are also discussed in relation to broader literature to provide environmentally friendly recommendations for dried seaweed production system designs.

5.1. Robustness of dried seaweed production system design and inventory analysis

Life Cycle Analyses of macroalgae, or seaweed, cultivation systems are fairly scarce in literature [51]. Some have emerged in the last few years relating to cultivated macroalgae as a feedstock for biofuels [34,42,52] and other sustainability related modelling tools have also been applied [47,53]. To the authors' knowledge, a gap in the literature remains in regards of LCAs of seaweed products that require biomass drying, e.g. seaweed food products, which are broadly recognised for their potential health benefits to both humans and in animal husbandry [54,55]. As such there are few studies to conduct full comparisons with, thus the following sections discuss the robustness of the dried seaweed production system and provide comparative insights with literature, where possible.

5.1.1. Seaweed biomass and protein yield

It was assumed that the biomass yields per hectare were approximately 50% higher in the dual layer system relative to the single layer system. This assumption has a high influence on the comparison of the dual and single layer configurations. It was also found that the material and energy inputs of the dual layer system (per ton protein) were greater, resulting from the additional material components in the dual layer system. These two sets of factors - higher yields and more system inputs - almost balance each other out. One may have expected 50% lower impacts in the dual layer resulting from the 50% higher yields per hectare, however the increased material and energy inputs per ton protein offset the savings to an average below 10% (see Fig. 4) across all impact categories. In other words, it was found that the dual layer system, on average, reduced impacts per ton of protein compared to the single layer system, but only to a small extent.

Some limitations and uncertainties about seaweed biomass and protein yield in our LCA should be highlighted. Rather than being obtained from measurements at a pilot or commercial cultivation site, the seaweed biomass yield and protein content were conservatively estimated from literature and from personal communications with seaweed cultivation researchers [45,46]. As knowledge of seaweed cultivation develops in Europe, it is expected that yields will increase and it may even be plausible to anticipate multiple harvests every year by, for instance, coppicing the biomass rather than removing it entirely from the infrastructure at Sea at the first harvest. In addition, annual variability to yields and protein content are also inherent sources of uncertainty, thus impacts are likely to be affected from year to year. The absolute impacts per ton of protein produced in this study should thus be considered with caution (see next paragraph), both given the uncertainties surrounding biomass yields and protein content, and the high sensitivity of these parameters. However, neither biomass yield nor protein content affects the relative shares of impacts from different infrastructural components as the functional unit is per ton of protein. The results thus remain robust in their provision of recommendations for dried seaweed production system designs, and cultivation infrastructure sub-system designs in particular.

A recent study by Angell et al. [56] concluded that the commonly used conversion factor of 6.5 from nitrogen to protein may be over optimistic and that a conversion factor of 5 may be more accurate. This suggests that the protein levels used in this study, from Schiener et al. [13], may also be overoptimistic and thus the absolute impacts should be considered with care. Digestibility of seaweed and seaweed proteins is also not considered in the present study [57,58]. *S. latissima* may therefore not be the best-suited seaweed for further processing as a protein source but it was selected nonetheless since it is a well-documented, cultivable species, well adapted to the marine conditions (e.g. tidal ranges, temperatures, salinities, etc.) of European latitudes, and because of the additional health benefits from the nutritional value of using seaweed as food supplements both for humans and in animal husbandry [10]. However, there are also species of seaweed such as such as *P. palmata* (also known as dulce) with higher protein content and digestibility than *S. latissima* [36]. These species could also be cultivated using longlines [59], i.e. with the same cultivation infrastructure sub-system as designed in this study. This illustrates that there is much room for further optimisation of protein production in systems in addition to the design of the cultivations system evaluated in the present study. Once again, however, varying protein yields only affects absolute impacts, not the relative contributions of processes in dried seaweed production.

5.1.2. Seeding process

Another important decision taken by the authors was the exclusion of the seeding process also commonly known as the indoor cultivation: controlled seaweed reproduction, seeding of spools and juvenile maturation. There are several reasons for this, the first being that alternative technologies are still being developed and tested, each with important differences in energy, material, process, temporal and labour requirements, and the selection of any one of these methods in this explorative LCA would have been inherently arbitrary. Second, the different indoor cultivation methods are significantly affected by the scale of operations [60], i.e. economies of scale are achieved in a system producing 10 km of seeded line compared to a system producing 100 m of seeded line. The setting of a specific scale of seeding operations for this explorative study would have also been arbitrary and a source of uncertainty. There is indeed a need for elucidation of seeding methods, across a range of time and production scales and from a life cycle perspective, however it was not in the scope of this study to conduct such an investigation.

5.1.3. Drying process

A lack of studies in literature documenting the drying of seaweed biomass lead the authors of the present study to use a simple model for the dewatering and drying processes. The amount of water lost during the harvest, transport and overnight storage of the biomass is particularly uncertain, as it was based on literature and personal communications, not practical measurements. Furthermore, the use of a dryer designed for a different form of biomass (maize) provides only a vague idea of energy use. Both of these uncertainties affect the absolute impacts and the relative shares of impacts of the system. The result from the drying calculation was nevertheless found to be a little higher than other calculations in literature. Where our calculations estimated that 9.9 MJ were required to produce 1 kg of dried biomass, Philippsen et al. [47] estimated 4 MJ were required, both to reach 22% moisture content. Another potential proxy, the drying of cotton textile in a tumble dryer was found in a study by Uitdenbogerd and Vringer [61] to require 6.3 MJ/kg of dry cotton, a result which is higher than Philippsen et al. [47], though lower than those estimated in our model. Both of these comparisons illustrate the conservative approach applied to the present study. Practical studies are needed to ascertain energy requirements of seaweed drying with greater certainty, and to gain a better understanding of the trade-offs between the SMER of driers, different heat energy sources and potential life-cycle environmental impacts. The effect of alternative drying methods such as the use of wind or solar dryers on direct and indirect environmental impacts, as well as the biomass itself, should also be subject of further research. Finally, the drying of biomass was selected as a post-harvest preservation strategy in the present study as drying is a suitable process to preserve seaweed for further use, e.g. as a food. Other preservation methods can be applied to seaweed for other uses and lifecycle analyses of such methods should also be compared.

5.1.4. Seaweed cultivation infrastructure sub-system

A main source of uncertainty in the present LCA is the design of the seaweed cultivation system, or in other words, the infrastructural design. Existing small-scale pilots have been established in Europe to gain an insight in agri-technically optimal and economic viability of seaweed cultivation, for example those described in the study by Langlois et al. [34]. However, seaweed cultivation infrastructure designs are described only vaguely and in a limited number of publications in literature. Due to a lack of specific data and definitions of conventional seaweed cultivation systems, two hypothetical reference systems were designed, one with single and the other with dual layer longlines. Though these designs have not been tested at sea, they are considered advantageous, structurally sound and similar systems are being developed in the Netherlands.

The greatest impacts from a single source in the infrastructure come from the use of marine grade stainless steel chains made of chromium alloys. This represents that, although it may be essential for certain aspects of a seaweed cultivation design, the use of marine grade stainless steel should be minimised whenever possible, and as portrayed in this model, attempts should be made to recycle as much of it as possible.

Finally, it is worth noting that the particular strip configuration of both single and dual layer cultivation systems provide significant advantages in terms of impacts, when compared to a conventional longline cultivation. In a conventional system, each 100 m longline is held in place by its own set of buoys, anchors, chains and ropes; in comparison, a strip requires twice the number of components but for four longlines rather than just one. The strip configuration requirements per 100 m of longline are thus approximately half that of the conventional longline, with the exception of the additional strip strengtheners, which add only a minor contribution of impacts. In other words, it would seem that the cultivation of seaweed using a strip configuration would be more environmentally friendly than seaweed cultivated on a conventional longline.

5.2. Other environmental issues

Although practised for centuries, the impacts of seaweed cultivations on benthic environments for instance, are still largely undetermined. Oceans, seas, estuaries and coastal zones are amongst the most complex, dynamic and unrevealed environments on our planet. The cultivation of seaweed in near- and offshore areas is likely to have impacts, environmental or other, that have not been covered by this study and that LCA methods are not designed to address [62], for instance the degradation of plastic materials at sea that contribute to plastic soup.

Seaweed cultivation infrastructure represents a three-dimensional, man-made structure consisting of a mixture of metals, concrete and plastics, usually stretching from surface to seabed. Its physical presence can act as an agent of opportunity for some species or of liability for others. The partial shading of the benthic environment could, for instance, favour the establishment of some species that may eventually outcompete the original flora. Similarly, a set of longlines at one-meter intervals may block access or even entangle larger fauna, such as whales. Unintended consequences of human interference in marine environments are a real challenge to determine with certainty. More research is needed to further our understanding of a broad spectrum of potential interferences and mitigation measures when introducing structures into marine spaces.

It has been suggested that seaweed cultivations could act as agents for nitrogen and phosphorus bioremediation in estuaries or along coastlines of particularly agricultural regions [22], or in integrated multi trophic aquaculture (IMTA) to mitigate impacts of fish aquaculture [23–26]. This kind of so-called ecosystem service presents significant potential for contributions to long-term human well-being. Technologies have also been proposed to enhance ecosystem services, for instance by using mooring anchors designed with tunnels and holes that act as shelter and provide habitat, e.g. for lobsters [63], or to use even larger structures known for their ability to foster the development of coral reefs. Other ecosystem service opportunities resulting from the cultivation of seaweed, for instance carbon uptake and mitigation of ocean acidification [64], are critically unexplored and should be subject of further research.

The complexity of marine ecosystems is such that the ecosystem services rendered by a cultivation have the potential to be both positive and negative; for instance, habitat provision services may serve an invasive species which could thrive, affect the local environment and result in a chain of unintended consequences. While the LCA method is limited to providing insights into life-cycle impacts, a thorough appreciation of environmental impacts can be achieved by complementing LCA with an understanding of the ecological interactions in and around a cultivation system, and the linkages between ecological and socioeconomic systems resulting therefrom. Ecological interactions of seaweed farms with their environment are not yet thoroughly understood, nor are the risks or impacts of certain inevitable consequences of seaweed farming such as those resulting from the detachment of biomass during storm events. Further transdisciplinary research is needed to develop reliable methods that can help determine the extent and nature of ecosystem service provision and broader ecological interactions.

5.3. Lessons learnt

The present study provides the life cycle environmental impacts of two dried seaweed production system designs, one with a single layer strip cultivation configuration, the other with a dual layer strip cultivation configuration. Some key highlights of the study are highlighted hereafter.

Intensification of seaweed cultivation by the use of a dual layer configuration does not significantly reduce environmental impacts per ton protein compared to a single layer configuration. Much depends on the specific materials and design differences between the conventional or intensified cultivation designs. In the cultivation systems of the present study, the use of some components remains the same (chains, anchors and buoys) in the two systems, however other materials are used to a greater extent in the intensified cultivation design (ropes, seeding lines and strip strengtheners). Those that remain constant have smaller net shares of impacts resulting from the larger yields (50% higher yields in this case) of the intensified cultivation (dual configuration), whereas those that were increased in their use show slight increases in their relative contributions. Overall, the dual layer system was found to be only a little more environmentally friendly than the single layer system in the production of 1 ton of protein in dried seaweed. It should also be noted that an intensification such as that presented in this study could offer significant productivity advantages for seaweed cultivations limited by permits/licenses of small areas. In such cases, a similar intensification of cultivation systems could enhance productivity in their small designated space, without significantly affecting life cycle environmental impacts.

The drying of the seaweed was the process with the highest contribution to environmental impacts. Any seaweed production system requiring the drying of biomass should approach dewatering strategically, look for innovative uses of the energy available at sea (e.g. wind, waves or currents) that could initiate the drying process during harvest and transportation, and adopt low energy alternatives, for instance using solar dryers. Alternative biomass preservation methods, such as ensilage, should also be considered when possible. Chromium steel chains and PP ropes were the material components of the infrastructure with the highest contributions to environmental impacts. When designing cultivation systems, one should minimise their use or look for alternative materials with lower life cycle impacts. Finally, the direct environmental impacts of seaweed cultivation are not within the scope of this study, for instance the degradation of plastic ropes at sea contributing to "plastic soup", or the potential ecosystem services delivered by the cultivation of seaweed.

6. Conclusions

An explorative environmental life cycle assessment was performed of two dried seaweed production systems, using one ton of protein in the dried seaweed as a functional unit. The difference between the two systems was limited to alterations in the configuration of the seaweed cultivation infrastructures (Fig. 2). Harvesting, transport and drying were kept the same. Both were designed featuring access corridors for the cultivation longlines using a strip configuration. One of them was designed for increased productivity per hectare relative to the other, by doubling the number of strips in the vertical water column.

An analysis of the life cycle environmental impacts of the system (Figs. 3 and 4) showed that the highest impacts came from the biomass drying process followed by key elements of the infrastructure, notably the chromium steel chains connecting the infrastructure to the concrete anchors on the sea floor, and to a lesser extent the PP ropes that constitute the majority material (by mass) of the infrastructure (excepting concrete). Comparing the two cultivation systems, the dual layer system delivers 50% higher yields per hectare but has slightly lower impacts relative to the single layer system per ton of protein in the final dried seaweed product. This is due to the larger biomass yields offsetting the higher environmental impacts from the higher material inputs in the dual system. In other words, the dual layer configuration produced more biomass per hectare but was only slightly more environmentally friendly in the production of 1 ton of protein in dried seaweed, relative to the single layer system.

A sensitivity analysis (Fig. 5) revealed that the most sensitive aspects of the model were the protein content in the biomass, the specific moisture extraction rate of the biomass dryer, the biomass yield from the cultivation and the diameter (and therefore mass) of the chains. As a result of the sensitivity of certain parameters, the absolute impacts of the present study should be considered with caution, however the recommendations in this study are based on relative contributions which are considered robust.

This paper set out to shed light on the life cycle environmental impacts of commercial scale cultivation designs, and in so doing, to highlight some recommendations for cultivation infrastructure designers. Further research is recommended to validate these results as commercial scale cultivation infrastructures emerge, but also to further explore the direct and indirect environmental impacts of alternative cultivation systems (such as the degradation of plastic ropes at sea and ecosystem services, which were beyond the scope of this study) and seaweed biomass processing at industrial scales.

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