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Environmental impacts of protein-production from farmed seaweed: Comparison of possible scenarios in Norway

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As the demand for proteins increases with growing populations, farmed seaweed is a potential option for use directly as an ingredient for food, feed, or other applications, as it does not require agricultural areas. In this study, a life cycle assessment was utilised to calculate the environmental performance and evaluate possible improvements of the entire value chain from production of sugar kelp seedings to extracted protein. The impacts of both technical- and biological factors on the environmental outcomes were examined, and sensitivity and uncertainty analyses were conducted to analyse the impact of the uncertainty of the input variables on the variance of the environmental impact results of seaweed protein production. The current production of seaweed protein was found to have a global warming potential (GWP) that is four times higher than that of soy protein from Brazil. Further, of the 23 scenarios modelled, two resulted in lower GWPs and energy consumption per kg of seaweed protein relative to soy protein. These results present possibilities for improving the environmental impact of seaweed protein production. The most important variables for producing seaweed protein with low environmental impact are the source of drying energy for seaweed, followed by a high protein content in the dry matter, and a high dry matter in the harvested seaweed. In the two best scenarios modelled in this study, the dry matter content was 20% and the protein content 19.2% and 24.3% in dry matter. This resulted in a lower environmental impact for seaweed protein production than that of soy protein from Brazil. These scenarios should be the basis for a more environmental protein production in the future.

1. Introduction

Norway is the second largest exporter of seafood in the world (FAO, 2019a), with key export of Atlantic salmon, whose production is expected to increase six-fold by 2050 (Lundeberg and Grønlund, 2017). In 2015, the Norwegian fishery authorities and the salmon industry emphasised the salmon industry as a “great success story” (Hersoug, 2015, p. 4) in terms of production and economic results. However, consumers have demanded for more sustainable production (Aarset et al., 2020) and fishermen and their organisations, river owners and NGOs, have questioned increases in production without reducing the ecological footprint (Hersoug, 2015). To reduce the use of wild catch fish as feed in salmon aquaculture, aquafeed manufacturers substitute most of the fishmeal with soy protein in order to reduce the marine origin of ingredients from 90% to approximately 30% (Ytrestøyl et al., 2015). The use of plant-based feed ingredients is considered to be more environmentally friendly relative to wild catch fish, as plant-based feed has a lower environmental impact than fishmeal-based feed (Samuel-Fitwi et al., 2013). To achieve a sufficiently high protein content in the feed, soy protein has become an important ingredient, replacing up to half of the fishmeal (Peisker, 2001). In 2017, Norway imported about 201,000 t of soybean-meal for agriculture and 297,000 t for fish farming (Lundeberg, 2018). Following this trend, by 2050, Norway will need to import approximately 1,800,000 t of soybean-meal for fish farming. Although soy protein was considered in the early 2000s to be a suitable ingredient in fish feed, recent life cycle assessment (LCA) studies on Norwegian salmon farming found that soy as a feed ingredient is the main driver of the environmental impact of salmon production (Hognes et al., 2014). Thus, for a more environmental production, alternative protein sources are

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required.

To grow soy necessary for the soy protein concentrate (SPC) imported to Norway, more than 2500 km^2 of agricultural area is used in Brazil (Lundeberg, 2018). While the production and sale of soy for food and feed can provide income to the producers, the expansion of soybean production in Brazil also causes deforestation, globally significant ecosystem losses (Raucci et al., 2015), increases in the degradation of the vulnerable Amazonian habitat (Carvalho et al., 2019), and affects at least 17 SDGs (Mahari et al., 2020). Therefore, to reduce the dependency on soy, it is necessary to investigate an environmentally friendly alternative to SPC in salmon-feed in Norway. Farmed seaweed has been identified as a potential source of protein as it contains many valuable ingredients and does not require the occupation of arable land (Øverland et al., 2019). It can also take up surplus nutrients from fish farms via integrated multi-trophic aquaculture (IMTA) and thus improve the sustainability of the aquaculture industry (Alexander et al., 2016). IMTA is considered to utilize the dissolved inorganic nitrogen from fish farming and creating a valuable resource using farmed algae (e.g. Wang et al., 2012). Both seaweed and aquaculture have both been reported to have the potential to contribute positively to SDGs (Hoegh-Guldberg et al., 2019).

The cultivation of kelp began around 2005 in Norway at an experimental scale based on trials in France, Germany, Ireland, and Scotland (Stévant et al., 2017). Cultivation interest was initially triggered by the potential to produce bioenergy. However, relative to other products, both the production volume and market value of seaweed were too low (Skjermo et al., 2014) to make it cost-efficient. However, cultivation technologies have improved as there is more knowledge regarding the seasonal- and depth-dependent growth of sugar kelp (*Saccharina latissima*) (Handå et al., 2013). In addition, the location of seaweed-farms has been found to have a significant impact on the possible yield. The lowest wet weight (WW) yields are estimated to be 35–74 t ha^{-1} within a territorial zone, 86–126 t ha^{-1} on the continental shelf and 144–219 t ha^{-1} outside the continental shelf with a maximum yield of 230 t WW ha^{-1} (Broch et al., 2019). Furthermore, Sharma et al. (2018) reported a maximum yield of 383 t WW ha^{-1} and an average dry matter (DM) content of 20%, which has a maximum protein content of 24.3% of dry matter depending on the harvest month and deployment depth. However, limited research has been conducted regarding yield variations, DM, protein content, and other factors influencing the environmental performance of seaweed protein production.

However, several studies have evaluated the environmental impact of producing plant-based feed protein using LCAs for both soy (e.g. Raucci et al., 2015) and seaweed protein (e.g. Seghetta and Goglio, 2019). Nevertheless, none of these studies simultaneously addressed the environmental impact of both soy- and seaweed proteins. Moreover, the results of these studies are based on different approaches and use different functional units, resulting in results, difficult to compare. Philis et al. (2018) demonstrated that seaweed protein has environmental advantages with regard to the low usage of mineral phosphorus and marginal use of land. More so, Gilpin and Schipper (2016) conducted an LCA from cradle to harvest for seaweed and emphasised the importance of the yield for the environmental impact. Based on these findings, this study aims to assess the environmental impact of protein production based on farmed sugar kelp in Norway using an LCA. Based on Philis et al. (2018) and van Oirschot et al. (2017) results, the hypothesis of this research is that the environmental impact of current production of Norwegian seaweed protein is higher than that of soy protein from Brazil and that the environmental impact of current seaweed protein production could be reduced. The objectives of this study are twofold: 1) to analyse the environmental performance of today's seaweed protein production and 2) to analyse the impact of different production factors to improve the environmental performance of seaweed protein production.

The paper proceeds as follows. The methodology for the cradle-to-gate LCA employed herein is described in Section 2. Section 3 details the results of current production and future scenarios with a focus on global warming potential. Section 4 discusses the results, including an evaluation of the impact of uncertainty on the results and avenues for further research. Finally, Section 5 presents possible approaches to reduce the environmental impact of seaweed protein production and identifies the best scenarios in terms of environmental impacts.

2. Material and methods

To conduct a life cycle inventory (LCI) for seaweed-based protein and SPC production, an inventory of the current seaweed farming practices in Norway and soy production in Brazil was compiled. The data used were published in the Material Flow Analysis courtesy of Philis et al. (2018), and detailed information can be found in the supplementary files provided with their publication. For soy production in Brazil, the data were based on Escobar et al. (2020). Additional values for the infrastructure of seaweed farming were obtained from van Oirschot et al. (2017). The LCAs of the different scenarios were conducted using ISO 14040 (ISO, 2006). Process-based modelling was conducted in two steps. First, the emissions of climate gases for the two base scenarios were compiled in a spreadsheet using emission values from ecoinvent© (Frischknecht et al., 2005). The modelling was conducted in GaBi© (Kupfer et al., 2018) in combination with the GaBi LCA database©. The results from these two approaches were used to cross-check the results and to exclude errors. GaBi© was then used to model the different scenarios and to calculate the associated environmental impacts. Process-based models were used because of their inherent strength in predicting flows when empirical data are lacking and accounting for underlying processes (Veltman et al., 2017). In addition, process-based models can easily be transferred to other countries because they refer to physical quantities, not price relations for inputs and outputs, which may differ for different countries. The production of seaweed protein from cradle to gate was divided into seven phases, as illustrated in Fig. 1.

The seeding production phase (phase 1) included the collection of fertile sugar kelp in coastal zones near the algae farms, the gametophytes and the young sporophytes cultures, to produce the seeding lines, which are twined to longlines. Deployment at sea (phase 2) included all equipment used, such as different ropes, buoys, mooring, and boats, for maintaining seaweed farms. Harvesting (phase 3) comprised the energy and boats required to harvest the yields, which in this case refers to the amount of harvested seaweed, where a loss of 30% was assumed. Phase 4 included transporting the seaweed to storage and later to the refinery. Additional transportation by ship was included in the scenarios in which the storage facility was not located near the drying facility. Only freeze-storage was considered to be a suitable possibility for a simple and effective long-term storage while avoiding quality loss (Choi et al., 2012). During the drying process (phase 5), both equipment used, and energy required to dry the seaweed to a moisture content of 20% were included. In phase 6, the protein was extracted, and finally, in phase 7, the transportation of the protein over 100 km to an aquafeed-producer was considered.

2.1. Functional unit

Soy protein is used as an ingredient in fish feed to increase the protein content. Thus, an important pricing factor is the amount of

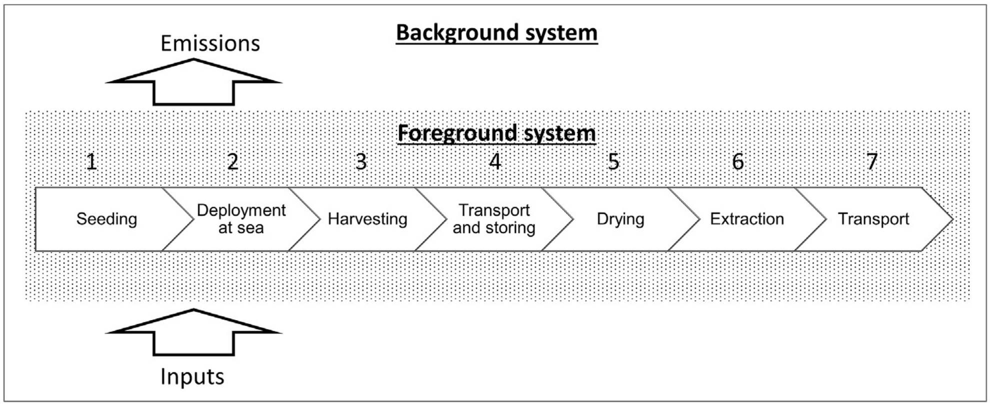

Fig. 1. The foreground- and background systems and different phases for seaweed protein production.

protein, regardless of soy- or seaweed protein use (Emblemsvåg et al., 2020). Because there is a large difference in the protein content of these sources, the products do not have similar competitive advantages. To overcome this problem, the functional unit in this study was 1 kg of crude protein, reflecting the actual function (Sonesson et al., 2019). To distinguish the source, pure protein was mentioned as seaweed and soy protein in this study. Currently, it is possible to produce a seaweed protein product (SPP) on sugar kelp with a crude protein content of 31%, based on weight, which includes 5% moisture (Philis et al., 2018). This protein content does not qualify as a concentrate according to the standard of the Food and Agriculture Organization of the United Nations (FAO, 2019b). The functional unit of 1 kg of pure protein from seaweed amounts to 3.23 kg of SPP. Meanwhile, the functional unit of 1 kg of pure protein from soy amounts to 1.61 kg of SPC, with a protein content of 62% and a moisture content of 10% (Hognes et al., 2014).

2.2. Impact assessment

The impact assessments for different scenarios were calculated using the CML 2016 (Centrum voor Milieukunde Leiden: CML) with GaBi© (Kupfer et al., 2018) and included the GWP (100 years), abiotic depletion energy (ADP fossil), ozone layer depletion potential (ODP, steady state), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and abiotic depletion elements (ADP elements). The data for these categories are provided in Appendix A (Table A.1). The GWP for a 100-year period was selected as this period can reveal long-term effects (Vallero, 2019) and allows the comparison of the potential climate effect from the different greenhouse gases (IPCC, 2013). Using GWP 100, the results from this study are easier to compare with other studies, such as Aitken et al. (2014) and Tallentire et al. (2018), even though a 500-year horizon covers all relevant aspects the best based on a scientific point of view (JRC-IES, 2011). Moreover, the calculation of the GWP for the 100-year horizon was in accordance with IPCC (IPCC, 2013). The advantage of using CML is that it is widely recognised and covers many environmental impact categories at the midpoint level and is well documented and reproducible (Lieberei and Gheewala, 2017). However, in regard to abiotic reserves, CML is considered to be less up to date and have less stakeholder importance, as compared with RECIPE (Goedkoop et al., 2009). Nevertheless, it is a method that follows the recommendations of the International Reference Life Cycle Data System and was determined to perform well at the midpoint level (JRC-IES, 2011).

2.3. Different scenarios to reduce the environmental impact of seaweed protein production

Twenty-three different scenarios were modelled to analyse the impact of different factors on the environmental performance of seaweed protein. In addition to the 1) base scenarios, scenarios were grouped with regard to 2) different energy sources for drying, 3) different sizes of seaweed farms and amount of production, 4) the impact of DM and protein contents, 5) different yields with different protein contents, and 6) different protein extraction rates. The base scenarios also include the production of SPC (1.2). For the different scenarios, the key information is listed in Table 1.

To determine the placement of fish farms, the Yggdrasil map of the Norwegian Directorate of Fisheries (2019) was used. Harvesting was modelled as described by Philis et al. (2018). With the exception of scenario 1.1, the seaweed was transported by ship to one freeze storage facility for each county, which was located near the harbour. For all the seaweed protein scenarios, it was assumed that the algae were freeze stored, with reduced energy demand for increasing volumes (Weilhart, 2010) after harvest to allow for processing over a year. Maps were also used to determine the distance to the intended drying and refining locations in the county of Møre og Romsdal (Tables 1 and 2) and refer to the name of the counties until 2020 (Norwegian Ministry of local Government and Modernisation, 2012). It was assumed that the refinery would process the seaweed for an entire year to achieve the lowest possible costs. As the harvesting was predicted to occur in Norway for two months, the storage period for the frozen seaweed was determined to be maximum of ten months.

Furthermore, to reduce the energy required to dry the algae, data for improved drying by heat circulation technology were used as described by Aziz (2016), except for scenarios with an area of 1 ha. Based on the findings of Emblemsvåg et al. (2020) a seaweed refinery should have an output of at least 65,000 t to achieve an economic break-even scale. Thus, all the seaweed should be processed at one refinery, independent of the number of seaweed farms in the modelled scenarios.

The first scenario group includes the two base scenarios. Base scenario 1.1 describes the production of seaweed protein at an existing seaweed farm, in the west coast of Norway. It was modelled and calculated as described in the material and substance flow analysis by Philis et al. (2018). The base scenario used an area of 1 ha and had a yield of 60 t WW ha^{-1} sugar kelp, with a moisture content of 85% (Philis et al., 2018). Fossil gas, with values specific to the situation in Norway from the GaBi© LCA database, was used as the energy source to dry the seaweed to a moisture content of 20%.

Table 1
Key information for the different scenarios.

Scenario group and Scenario name	Scenarionumber	Phase 1	Phase 2				Phase 3		Phase 4				Phase 5		Phase 6
		Transport to dock	Yield	Area per location	Ropes service-life	Anchoring service-life	Seaweed DM-content harvested	Protein content	Distance truck to drying	Average distance ship to storing	Average distance ship to refinery	Energy needed to freeze 1m[c]	Drying energy	Energy demand drying	Protein extraction rate
		[km]	[t WW ha^{-1}]	[ha]	[years]	[years]	[% of WW]	[% of DW]	[km]	[km]	[km]	[kWh yr^{-1}]		[%]	[%]
1 Base scenarios															
Seaweed protein	1.1	24	60	1,0	5	20	15	10	300	0	0	200	Fossil gas	100	80
Brazilian soy prot.	1.2														
2 Drying energy															
Fossil gas	2.1 (1.1)[a]	24	60	1,0	5	20	15	10	300	0	0	200	**Fossil gas**[b]	100	80
Surplus energy	2.2	24	60	1,0	5	20	15	10	300	0	0	200	**Surplus energy**	100	80
Incineration energy	2.3	24	60	1,0	5	20	15	10	300	0	0	200	**Incineration**	100	80
Norwegian electricity	2.4	24	60	1,0	5	20	15	10	300	0	0	200	**NO electricity**	100	80
EU electricity	2.5	24	60	1,0	5	20	15	10	300	0	0	200	**EU electricity**	100	80
3 Size of the seafarms															
60 t - XS[c]	3.1 (2.4) [a]	**24**	60	**1.0**	5	20	15	10	**300**	0	0	200	NO electricity	**100**	80
170 kt - S	3.2	**12**	60	**2.5**	5	20	15	10	**0**	**178**	**543**	**120**	NO electricity	**50**	80
170 kt - M	3.3	**6**	60	**32**	5	20	15	10	**0**	**98**	**74**	**65**	NO electricity	**50**	80
6 mt - L	3.4	**5**	60	**100**	**4.5**	**18**	15	10	**0**	**100**	**534**	**40**	NO electricity	**11**	80
6 mt - XL	3.5	**4**	**75**	**13,300**	**4**	**15**	15	10	**0**	**83**	**256**	**40**	NO electricity	**11**	80
4 Valuable content of harvested seaweed															
Dry matter 20%	4.1	6	60	32	5	20	**20**	10	0	98	74	65	NO electricity	50	80
Dry matter 10%	4.2	6	60	32	5	20	**10**	10	0	98	74	65	NO electricity	50	80
Dry matter 15%	4.3	6	60	32	5	20	**15**	10	0	98	74	65	NO electricity	50	80
Protein 20% in DM	4.4 (3.3) [a]	6	60	32	5	20	15	**20**	0	98	74	65	NO electricity	50	80
Protein 32% in DM	4.5	6	60	32	5	20	15	**32**	0	98	74	65	NO electricity	50	80
5 Harvesting month and deployment depth															
May, 3 m	5.1	6	**60**	32	5	20	20	**14.0**	0	98	74	65	NO electricity	50	80
May, 8 m	5.2	6	**30**	32	5	20	20	**14.7**	0	98	74	65	NO electricity	50	80
June, 3 m	5.3	6	**383**	32	5	20	20	**11.7**	0	98	74	65	NO electricity	50	80
June, 8 m	5.4	6	**190**	32	5	20	20	**12.6**	0	98	74	65	NO electricity	50	80
August, 3 m	5.5	6	**290**	32	5	20	20	**19.2**	0	98	74	65	NO electricity	50	80
August, 8 m	5.6	6	**170**	32	5	20	20	**24.3**	0	98	74	65		50	80

												NO electricity		
6 Protein extraction rate and service-life of seafarm infrastructure														
Prot. extr. rate 60%	6.1	6	60	32	5	20	15	20	0	98	74	65	NO electricity	50	**80**
Prot. extr. rate 70%	6.2	6	60	32	5	20	15	20	0	98	74	65	NO electricity	50	**70**
Prot. extr. rate 80%	6.3 (4.4) [a]	6	60	32	5	20	15	20	0	98	74	65	NO electricity	50	**60**
Service life 50%	6.4	6	60	32	**2.5**	**10**	15	20	0	98	74	65	NO electricity	50	80
Service life 125%	6.5	6	60	32	**6.25**	**25**	15	20	0	98	74	65	NO electricity	50	80

[a] Scenario numbers in parentheses indicate identical scenarios.
[b] Numbers or energy sources in bold are specific for that scenario.
[c] The first part in short-name indicates the annual production volume and the second indicates the sea farm-size (Table 2).

The final SPP had a water content of 20% and a protein content of 31%.

Soy protein production (Philis et al., 2018) started with soil preparation, seeding, and growth and included purchased inputs such as fertilisers, chemicals, machinery, and tractors (Maciel et al., 2016). Of the soy imported to Norway, 70% is farmed in central west Brazil and 30% in southern Brazil (Philis et al., 2018). The varied rainforest and other natural vegetation losses in the regions are reflected by the different values for land use change (Flysjö et al., 2012) which is included in the GWP (Escobar et al., 2020). Harvest and drying included the energy and machinery used. Further, truck and railway use differed for the different regions in which soy was cultivated. The extraction was based on the Agri-footprint© database and the results of Hognes et al. (2014). The soy was transported to Norway by ship.

In scenario group 2, the effects of different energy sources for drying were considered. Four energy sources were compared: fossil gas, surplus heat, incineration and electricity. Using incineration to dry the seaweeds, all the emissions from incineration were allocated to the drying process. In addition, the use of electricity from the Norwegian and the European Union electricity mixes as energy sources for drying were modelled.

In scenario group 3, three production levels for the entire country were defined and combined with different sizes and numbers of seaweed farms (Table 2). In scenario 3.1, the annual production of sugar kelp was 60 t WW at one seaweed farm. The remaining two production levels were hypothetical. Specifically, in scenarios 3.2 and 3.4, the seaweed farms were considered to be IMTA in combination with existing fish farms.

For scenarios 3.2 and 3.3, an annual national seaweed production of 170,000 t WW was adopted, which corresponds to approximately one-tenth of the estimated upper potential seaweed biomass production for IMTA determined by Wang et al. (2012). In scenario 3.2, it was assumed that every existing fish farm also produces seaweed on 2.5 ha as an IMTA. Thus, each farm would produce 150 t WW of seaweed per year, and the total Norwegian seaweed production would be nearly 170,000 t WW per year. In scenario 3.3, the number of locations was reduced to 90, while the size of each seaweed farm was increased to 32 ha, as calculated by Wang et al. (2012). In this scenario, the harvested seaweed would be transported by ship to two different freeze storages sites, one located beside the refinery in Møre og Romsdal and the other in the county of Sogn og Fjordane.

For scenarios 3.4 and 3.5, an annual national production of 6,000,000 t WW seaweed was assumed, which replaced one-third of the SPC used in Norwegian fish farming in 2017 (Lundeberg, 2018). In scenario 3.4, the number of possible locations for seaweed farming is 1000, and the farms are dispersed in nine counties, with a freeze storage site in each county. Meanwhile, the sea farms in scenario 3.5 are placed offshore with a yield of 75 t ha^{-1} (Broch and Tiller, 2017), but a shorter service life for infrastructure (Lagerveld et al., 2014) can be expected. Each farm had an area as modelled by Broch and Tiller (2017). The farms were located in four counties near to Møre og Romsdal, to keep the transport distance from the freeze storage sites to the refinery short.

In scenario group 4, the effect of different DM (10%, 15% and 20%) in harvested seaweed as well as different protein contents (10%, 20% and 32%) in DM were analysed based on reported values. The sugar kelp harvested on the coast of Hitra in Norway had a water content of 89.5% (Stévant et al., 2018), while that in Nordtvedt (2018) had a water content of 80%.

In scenario group 5, the effects of yield and protein content differences caused by harvesting month and cultivation depth were analysed, as reported by Sharma et al. (2018). In the scenarios 5.1 to

Table 2
Different key-data for scenarios with different farm-sizes.

Scenario	Scenarionumber	Annual production in Norway	Number of locations in Norway	Area per location	Yield per year	Production per location	Placed in counties
		[t WW]	[n]	[ha]	[t WW ha^{-1}]	[t WW]	[n]
60 t - XS	3.1	60	1	1	60	60	1
170 kt - S	3.2	170,000	1132	2.5	60	150	10
170 kt - M	3.3	170,000	90	32	60	1900	2
6 mt - L	3.4	6,000,000	1000	100	60	6000	6
6 mt - XL	3.5	6,000,000	6	13,333	75	1,000,000	4

5.6, the environmental impacts based on three harvesting months and two cultivation depths were calculated.

The effect of the protein extraction rate and service life of the sea farm-infrastructure was analysed in scenario group 6. The protein extraction rate for Norwegian sugar kelp ranges from 70% (Sandbakken et al., 2017) to 80% (Philis et al., 2018). To analyse the effect of different protein extraction rates, the results based on the conditions from scenario 4.5 with extraction rates of 80%, 70%, and 60% were calculated. The impacts of the service life in scenarios 6.4 and 6.5 were analysed based on Gilpin and Schipper (2016). Finally, in scenario 6.4, the service life was reduced by 50%, and in 6.5, it was increased by 25%, as compared with scenario 6.1.

2.4. Regression models, and uncertainty and sensitivity analyses

To analyse the impact of the 14 different variables in the LCA model for seaweed protein production on the GWP, multi-linear regressions were conducted based on Di Lullo et al. (2020). Further, the software package R (Fox and Leanage, 2016) and stepwise regression were used to determine whether a reduced number of indicators describe the environmental performance with sufficient accuracy (Pascual-González et al., 2015). This approach was first conducted for the 23 different scenarios and subsequently performed for those that only used electricity as an energy source for drying. The continuous variables are listed in Table 1. Note that the amount of kg CO_2 emissions per MJ was used as a continuous variable instead of the name of the source for the drying energy used.

The final model determining the emissions of kg CO_2 per kg seaweed protein based on the 23 seaweed scenarios using the different drying energy sources is expressed as:

$$\text{kg } CO_2 = \beta_0 + \beta_1\,(\text{DM}) + \beta_2\,(\text{protein content}) + \beta_3\,(\text{drying energy}) + \varepsilon \quad (1)$$

The final model determining the emissions of kg CO_2 per kg seaweed protein based on 19 seaweed scenarios, in which electricity is used as the source for drying, is:

$$\text{kg } CO_2 = \beta_0 + \beta_1\,(\text{DM}) + \beta_2\,(\text{protein content}) + \varepsilon \quad (2)$$

To analyse the impact of uncertainty (e.g. Igos et al., 2019) and to improve the reliability of the results (Guo and Murphy, 2012), Monte Carlo simulations were conducted (Emblemsvåg, 2003). To analyse the impact of input variables on the results, 1000 Monte Carlo trials were run for each scenario, wherein the LCA-software randomly selects values for inputs variables, according to the given distribution for each variable. Further, sensitivity analyses were conducted to quantify how the uncertainty in the results could be allocated to different sources of uncertainty in the input variables. For both analyses, the same model and LCA software package were used.

For different variables, the minimum and maximum values and standard deviations were based on data from the analysed sea farms (Philis et al., 2018), expert estimates, and for the scenarios concerning harvesting month and deployment depth derived from Sharma et al. (2018). The included variables and their minima and maxima used in the different scenarios are summarised in Table A2 in order to describe the distributions of the input variables, as performed by Heijungs (2020). In addition to the variables listed in Table 1, transport utilisation, the re-use of culture-ropes, and harvesting losses were also considered. Harvesting losses were estimated to be, on average 30% of the harvestable yield based on previous sea farms data (Philis et al., 2018). Based on the input variables and their distributions, the LCA model was used to calculate the environmental impact for each of the 1000 input variations per scenario. Thus, in addition to calculating one value for each environmental impact category in the deterministic model, the results were calculated for each run (Heijungs, 2020), and the resultant distributions are presented in Fig. 2.

3. Results

The median values of the different scenarios varied from 2 kg to 142 kg carbon dioxide equivalent (CO_2 eq.) for the GWP, and from 25 MJ to 520 MJ for abiotic depletion, as shown in Fig. 2.

Figs. 3–8 show the results for the deterministic calculation of the GWP as a total for the different scenarios and different phases of seaweed protein production (referred to in Fig. 1). In addition, the corresponding ADP fossil depletion results are shown in Appendix A (Fig. A.1-A.5), wherein the advantages of some scenarios differ, depending on the impact category. The results indicate that it is necessary to consider different impact categories. As the values for the seeding phase and transportation to seafood producers were relatively low, they were summarised as “Rest”.

3.1. Base scenarios

In scenario 1.1, the production of 1 kg of protein of seaweed resulted in 32 kg CO_2 eq. emissions and required 455 MJ of energy (Table A.1 and Fig. 2). Owing to the use of fossil gas for drying, the drying process contributed more than 60% of the GWP and 66% of the energy consumption (scenario 2.1 in Fig. 3). Meanwhile, for the production, processing, and transportation of 1 kg of soy protein to Norway (scenario 1.2), was found to result in 3.3 kg CO_2 eq. emissions and 35 MJ of energy consumption. Thus, compared with soy protein, the GWP of seaweed protein dried with fossil gas was approximately ten times higher.

3.2. Different energy-sources for drying

For the entire process, from collecting spores for gametophyte culture to the final processed protein, the different energy sources used for drying contributed to large differences in environmental performance (Fig. 3). The highest GWP was obtained for the scenario in which the drying energy was derived from a waste incineration (139 kg CO_2 eq.; scenario 2.3). Meanwhile, using electricity from the Norwegian grid (scenario 2.4) resulted in 18 kg CO_2 eq. while that using fossil gas (scenario 2.1) resulted in 32 kg CO_2 eq.. Conversely, using the EU-electricity mix (scenario 2.5) for drying resulted in 44 kg CO_2 eq. to produce 1 kg of protein. When surplus energy from incineration was used for the drying process (scenario 2.2), the production of 1 kg of protein resulted in the lowest value of 12.9 kg CO_2 eq. per kg of protein. Because the other processes were not affected by the drying source, their values were the same for the different scenarios in this group.

Moreover, the use of surplus energy was found to be better than that of fossil gas or electricity from the EU grid (scenario 2.5). In particular, using electricity from the Norwegian grid (scenario 2.4) required 202 MJ to produce 1 kg of protein, which was slightly higher than that when using surplus energy from incineration (186 MJ).

3.3. Different sizes of seaweed-farms and total production

The size of the seaweed farms influenced several factors (Table 1) and had a strong influence on the impact of drying, transportation, and storage (Fig. 4). Differences in the deployment phases of scenarios 3.4 and 3.5 were caused by a shorter infrastructure expected lifetime. However, the higher yield in scenario 3.5, which produced 7.5 kg WW m^{-1} longline instead of 6.0 kg, overcame this issue. Further, improved drying technologies for larger amounts of seaweed reduced the energy requirement in the drying phase.

The environmental impact from transportation was lower for scenarios 3.3 and 3.5, as production increased, and the farms were placed closer to the drying facility. Thus, positioning the farms closer to the refinery and making use of the possibility of transporting the yield via boat instead of truck in scenario 3.1 were favourable. An additional effect was the possibility of improving the freeze storage sites to hold larger volumes, thereby reducing the energy demand.

3.4. Impact of DM and protein content

The environmental impacts of different DM and protein contents are shown in Fig. 5. Both a higher DM content in the harvested seaweed and a higher protein content in the DM reduced the environmental impact for all phases.

3.5. Different yields with different protein content

Yield and protein content were influenced by the harvest month and cultivation depth. When harvesting in May and June, the higher protein content was not sufficient to compensate for the reduced yield, as shown in Fig. 6. However, in August, the increased protein content at 8 m deep (scenario 5.6) resulted in a lower total GWP than all the other scenarios. For deployment and growth at sea, the GWP was higher at a depth of 8 m than at 3 m because of the relatively higher yield per meter of the longline and the relatively high protein content. Note that scenarios 5.5. and 5.6 that achieved lower environmental impacts concerning both GWP and energy consumption than that of soy protein production.

3.6. Different protein extraction rates

Scenarios 6.1 and 6.2 exhibited reduced protein extraction rates. In particular, extraction rate reductions of 10 and 20% resulted in an increase in the total GWP by approximately 15% and 30%, respectively, as compared with scenario 6.3 (Fig. 7). Meanwhile, scenarios 6.4 and 6.5 analysed the effect of reduced (−50%) and increased (+25%) service-life, respectively, of the infrastructure at the sea farms, as compared with that of scenario 6.3. The results show that the increased service-life reduced the environmental impact and vice versa.

3.7. Regression models, and uncertainty and sensitivity analyses

The final regression models show that in the first model (Equation (1)), three variables were sufficient to describe the emission of kg CO_2 per kg seaweed protein produced (Table 3). These variables are the DM-content of the harvested seaweed, the protein content in the DM, and the GWP of the drying energy used. Because the GWP of the drying energy alone had an *R*-squared-value (R^2) of 0.76 (Table A.3), it dominated the model. Testing the other two variables, resulted in R^2-values of 0.31 and 0.17 for the protein and DM contents, respectively. Another model was tested in which the drying energy used was excluded (Equation (2)). In this model, the R^2-values were 0.80 for the model and 0.43 and 0.39 for the protein and DM contents, respectively, when each variable was tested separately.

The Monte Carlo simulations revealed that while the emissions of CO_2 eq. and the required energy vary among scenarios (Table A.3 and Fig. 2), they are positively skewed. The standard deviations of the results were lower for soy protein than for seaweed protein. In addition, the standard deviations were higher for the seaweed protein scenarios with higher emissions of CO_2 eq. and required energy (approximately 20%) than for those with the lowest emissions and energy demand (approximately 12%; scenarios 5.5 and 5.6).

For each scenario, a separate sensitivity analysis was conducted. The results are shown in Figs. 8 and 9 and summarised in detail in Table B.1 for the different seaweed scenarios and in Table B.2 for soy protein. The results show that only some of the variables had important impacts on the results. In particular, results of scenario groups two to six were primarily affected by five variables, influencing the results for seaweed protein production, on average, by more than one percent. The amount of protein content in the dry weight of the seaweed and the DM content in the harvested seaweed had the highest impacts on the LCA results. Higher values for these parameters improved the results by reducing the GWP by −8.1% and −9.4% (Fig. 9), respectively, when the variables were improved by one standard deviation (increase of the GWP by 12.6% and 11.2%, respectively for lower protein and DM contents, Figs. 8 and 9).

4. Discussion

Sonesson et al. (2017) and Sonesson et al. (2019) used protein as the basis for the functional unit to reflect the actual function of two feed ingredients. If one kg of SPC and SPP were used as functional units, the results for the base scenarios would have been 62% and 31%, respectively. Meanwhile, for climate gas emissions in the base scenarios, one kg SPC (scenario 2.1) and SPP (scenario 1.1) produce 5.0 kg CO_2 eq. and 9.9 kg CO_2 eq., respectively, which suggests that soy protein production has a much lower impact on the environment than seaweed protein production according to the uniform functional unit. However, this effect would be lower for the scenarios in which the harvested seaweed had a higher protein content (scenarios 4.4 and 4.5) and higher for scenarios with a lower protein extraction rate (scenarios 6.1 and 6.2). Nevertheless, the selected chosen functional unit of one kg of crude protein allows for the simple comparison between the results herein with other proteins.

The production of seaweed protein with a low environmental impact requires improving several factors. Specifically, the drying process is energy demanding, and the environmental impact

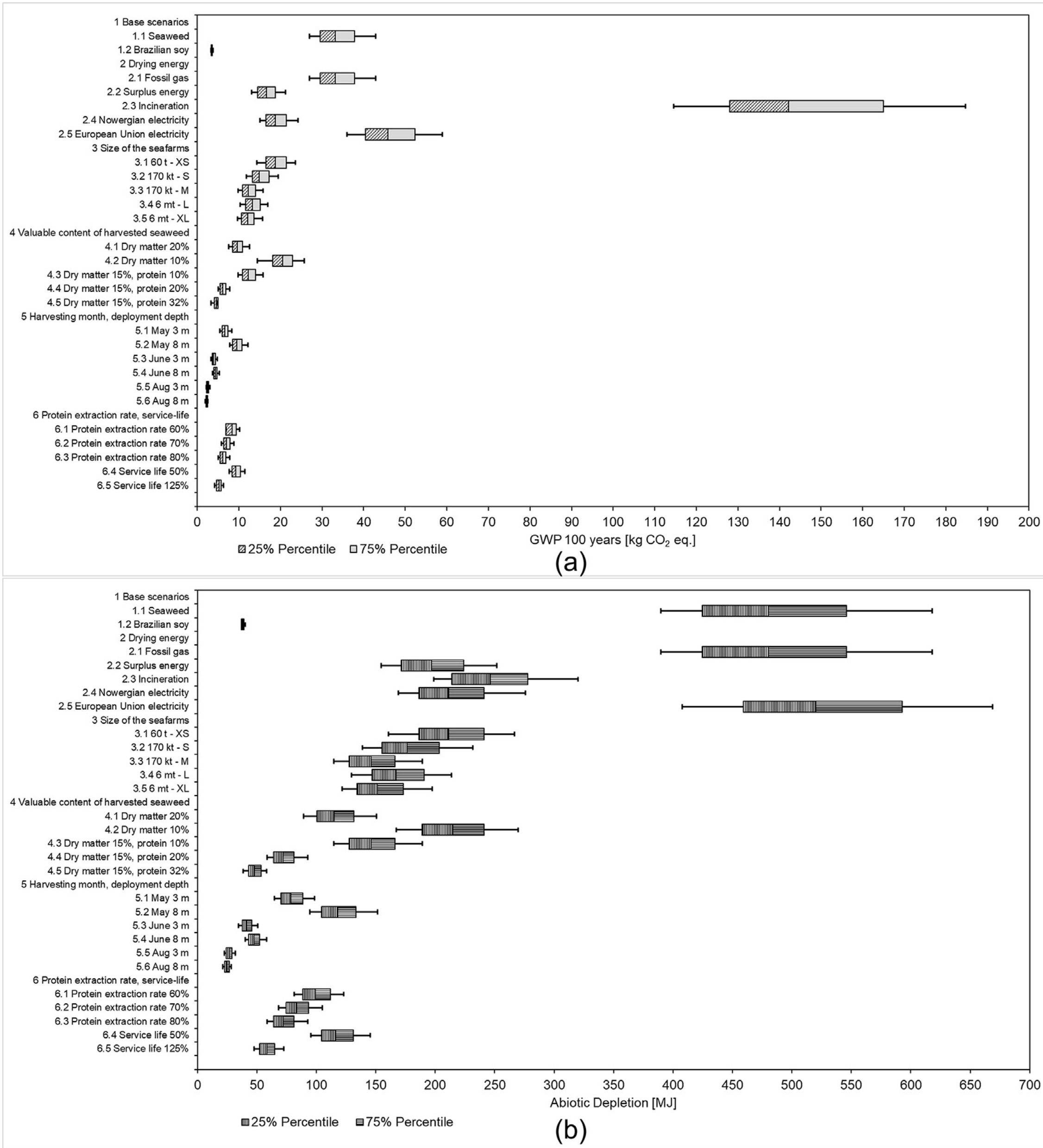

Fig. 2. Results from 1000 Monte Carlo trials for (a) global warming potential and (b) abiotic depletion for each scenario. Boxes denote median, 25th and 75th percentiles and whiskers represent 10th and 90th percentiles.

depends on the energy sources available in each country. This is consistent with the findings of Seghetta et al. (2017), who conducted an LCA for biogas production and the production of feed protein based on sugar kelp and oarweed (*Laminaria digitata*), in which they calculated a cumulative energy demand of 340 MJ kg^{-1} seaweed protein. In this study, higher values were found for the scenarios using fossil gas or EU electricity for the drying process. By comparing the results of the scenarios using fossil gas as an energy source for drying with surplus energy, it was demonstrated that both the GWP and energy demand were reduced by more than 60%. Meanwhile, using electricity from the Norwegian grid had a low environmental impact as more than 96% of Norway's electricity is produced using hydropower. In particular, when fossil gas or EU electricity was used, the utilisation of conventional heat recovery (Aziz et al., 2013) had a significant effect on improving the environmental performance. Therefore, future studies should compare the environmental impact of seaweed protein with that of algae from photobioreactors, as conducted by Hulatt et al. (2017) and Pavlik et al. (2017). Draaisma et al. (2013) found that protein production based on microalgae in flat panels has a comparable GWP (3.83 kg CO_2-eq./kg of protein) to soy protein (land use change included), while that of macroalgae in open ponds was higher (7.03 kg CO_2-eq./kg of protein). Other alternative protein sources, such as insects, could also be potential solutions (Cadillo-Benalcazar et al., 2020).

Furthermore, our results revealed the high impact of the harvested yield on the environmental performance and the optimal results for high DM yields with a high protein content. In particular, higher DM yields and increased share of valuable ingredients contributed to a more efficient material and energy utilisation, which is consistent with the findings by Seghetta and Goglio (2019). Currently, green and red seaweeds are not farmed in

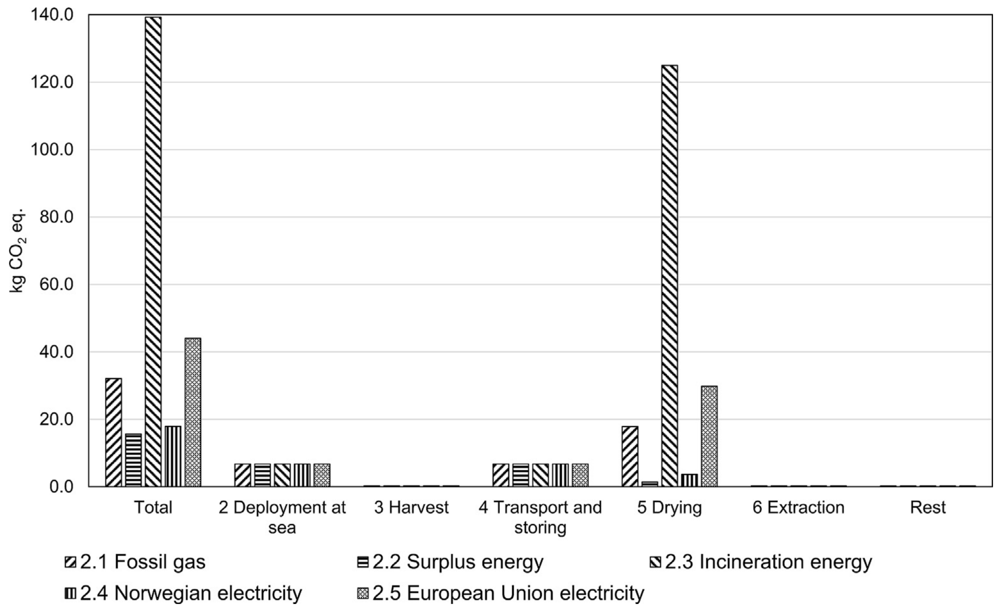

Fig. 3. Global warming potential (GWP) in relation to using different source of energy to produce 1 kg of protein under current conditions and a dry matter content of 15% in harvested seaweed.

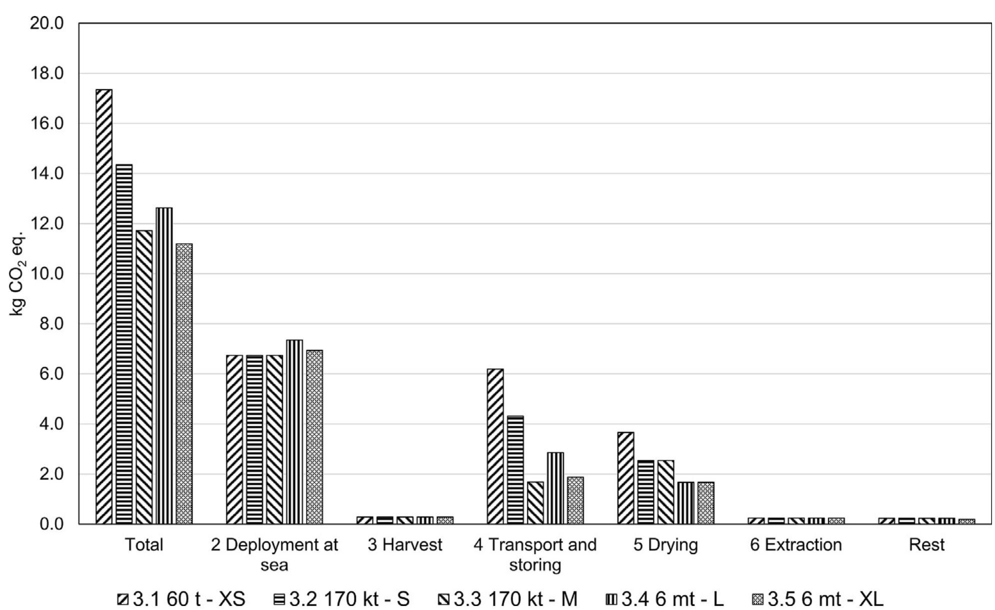

Fig. 4. Influence of the size of the seaweed-farms and total production on the global warming potential (GWP) for producing 1 kg of protein, using Norwegian electricity for drying and 15% dry matter harvested.

Norway, but because of their higher protein content (Angell et al., 2016) they are another potential option to investigate. To achieve high yields, it is crucial to obtain a more comprehensive understanding of seasonal variation (Schiener et al., 2014), the effect of cultivation depth (Sharma et al., 2018), and local conditions and variations within the farm (Broch et al., 2019). Herein, for all scenarios, a harvesting loss of 30% was assumed. However, lower losses would have positive effects on our findings by increasing harvested yields. It would also be important to evaluate the possibility of increasing yields and valuable ingredients by selective breeding (Aitken et al., 2014). Nonetheless, Goecke et al. (2020) underlined that such a breeding must be conducted in a way to prevent negative impacts on wild populations, and cultivars should not be transported too far from their natural habitats, as recommended by the Norwegian Environment Agency (Fredriksen and Sjøtun, 2015). Consequently, species domestication to optimise the cultivation with focus on the market supply must be addressed with precaution (Barbier et al., 2019). Further, before starting the breeding programme, it is necessary to evaluate the potential environmental risks of breeding and the irreversible environmental impacts of seaweed aquaculture, as mentioned by Campbell et al. (2019) and Préat et al. (2018).

In addition, the life span of the sea farm infrastructure has, in combination with yield, an important impact (Gilpin and Schipper, 2016) on the GWP. This effect was observable in scenarios 6.4 and 6.5 as a result of the production of the plastic parts used. Thus, it

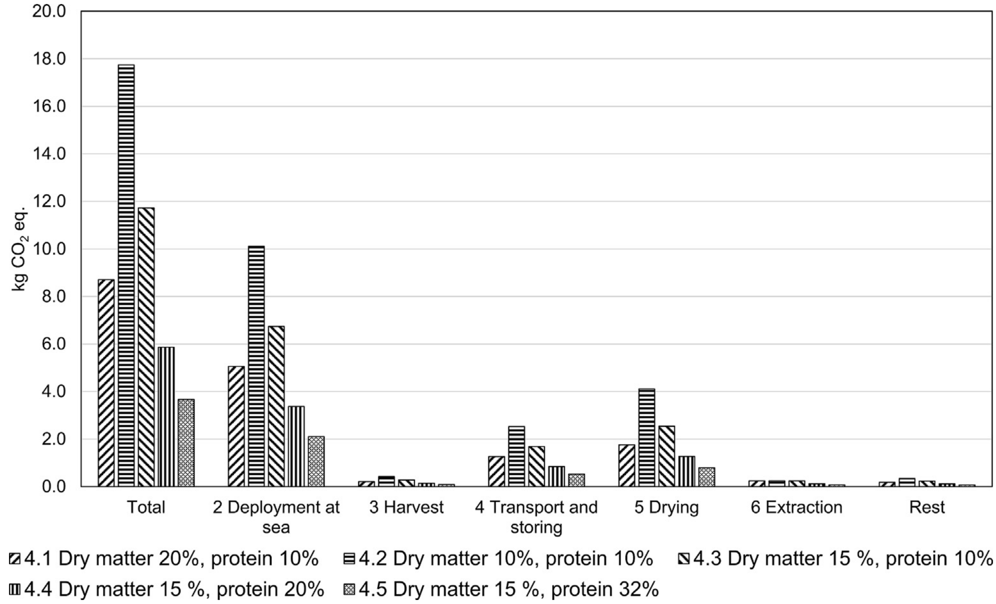

Fig. 5. Global warming potential (GWP) based on different dry matter and protein content for producing 1 kg of protein.

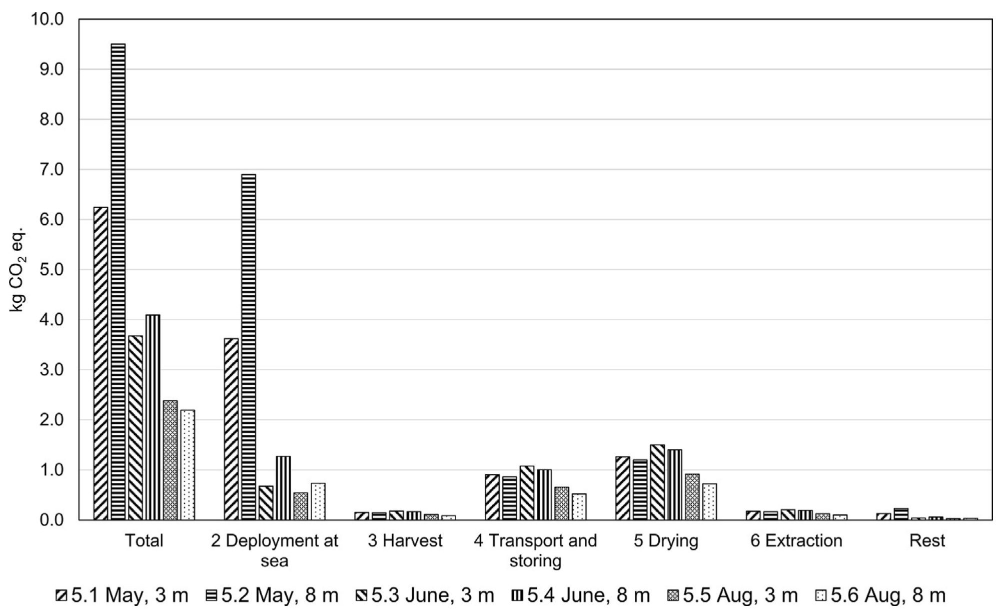

Fig. 6. Global warming potential (GWP) based on different harvest months and deployment depths for producing 1 kg of protein.

would be favourable to utilise infrastructure with a longer service life produced with a lower environmental impact, or to use more environmentally friendly materials. Moreover, both seeding lines and other plastic parts can emit microplastics, and parts of the infrastructure can be lost. These emissions should be included in future studies to consider increasing plastic pollution in the oceans (Haward, 2018).

Furthermore, carbon is sequestered by seaweed (e.g. Froehlich et al., 2019), and if it is not transferred to the pool of dissolved inorganic carbon, it will return to the atmosphere. Thus, carbon sequestration was not considered, in accordance with the IPCC (Houghton et al., 2001), as it was determined that there is no basis to account for a long-term sequestration by seaweed (Gilpin and Schipper, 2016).

In our model, losses from harvesting were estimated to be 30%, and other expected losses were not included. However, it can also be expected that storms will result in yield or infrastructure losses, especially at offshore sea farms. It is worth noting that all losses increase the environmental impact of the final product. In addition, loading and unloading the biomass will increase economic (Suurs, 2002) and environmental costs and provide the opportunity for additional losses. These were also not considered herein and should thus be addressed in future studies. Moreover, based on our research, the combination of large-scale seaweed farms with wind farms should be studied, as presented conceptually by Lagerveld et al. (2014). Finally, drying at a stage between harvest and storing would reduce both the volume and weight of transported and stored seaweed and would allow for transport and storage without

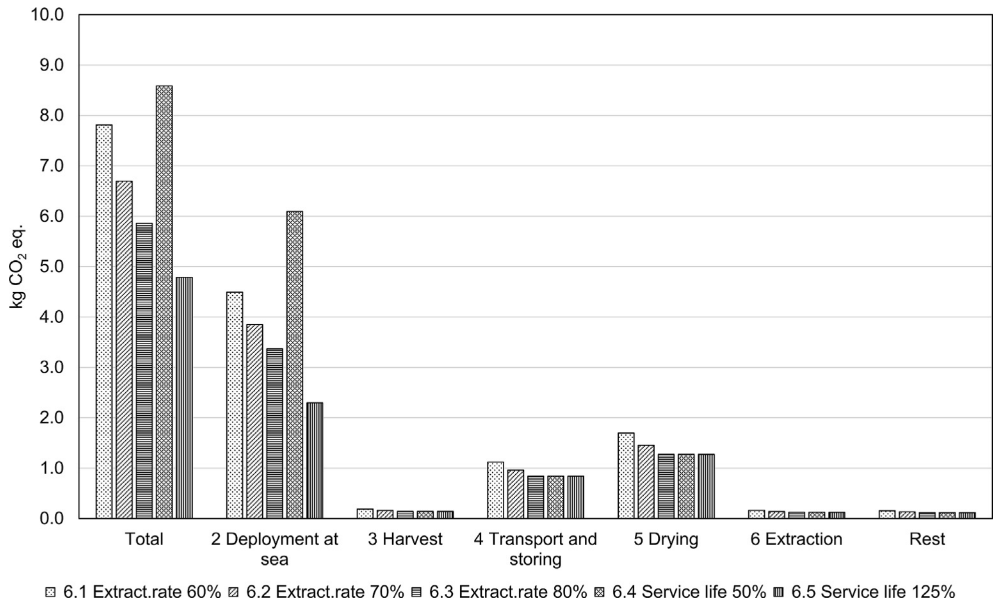

Fig. 7. Global warming potential (GWP) based on different protein extraction rates to produce 1 kg of protein.

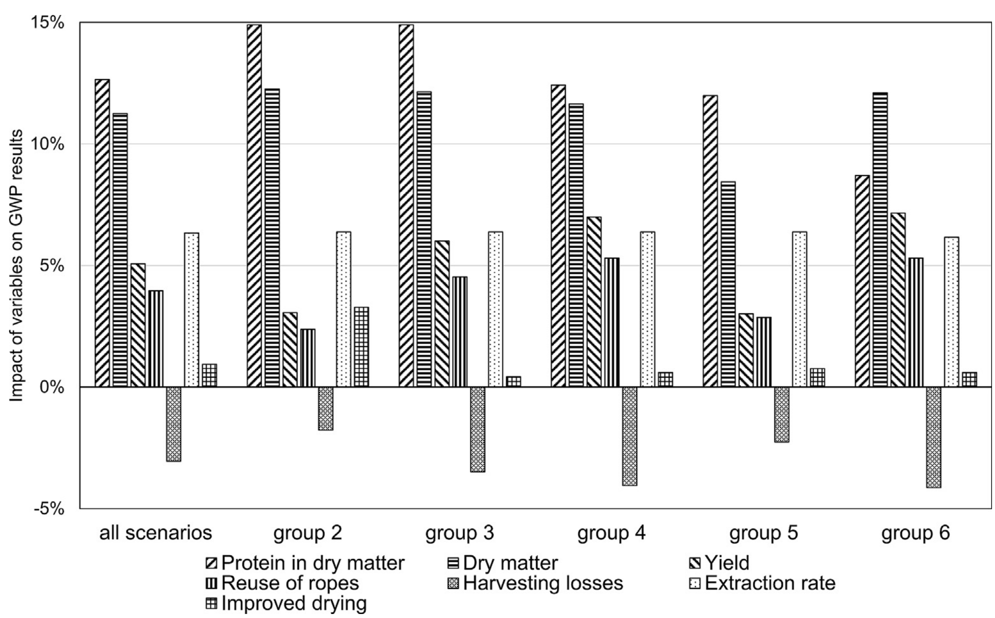

Fig. 8. Impact of increasing input variables by one standard deviation of the global warming potential (GWP) results based on sensitivity analyses.

Table 3
Variables, influencing the global warming potential (GWP) per kg seaweed protein produced.

Coefficients	Results for equation (1)			Results for equation (2)		
	Estimate	Standard error	*P*-value	Estimate	Standard error	*P*-value
β_0 (Intercept)	32.185	3.511	<0.001	28.334	3.068	<0.001
β_1 (For seaweed dry matter content harvested)	−1.048	0.200	<0.001	−0.924	0.153	<0.001
β_2 (For protein content)	−0.566	0.089	<0.001	−0.434	0.073	<0.001
β_3 (For drying energy)	325.271	22.719	<0.001			
	R^2: 0.945.			R^2: 0.799.		

freezing. These additional improvements were not included in our study and should be addressed in future research.

Overall, this study focused on the production of a protein product. In addition to protein, seaweed contains a range of different valuable ingredients (e.g. Øverland et al., 2019). Therefore, a refinery concept with the approach of the complete exploitation

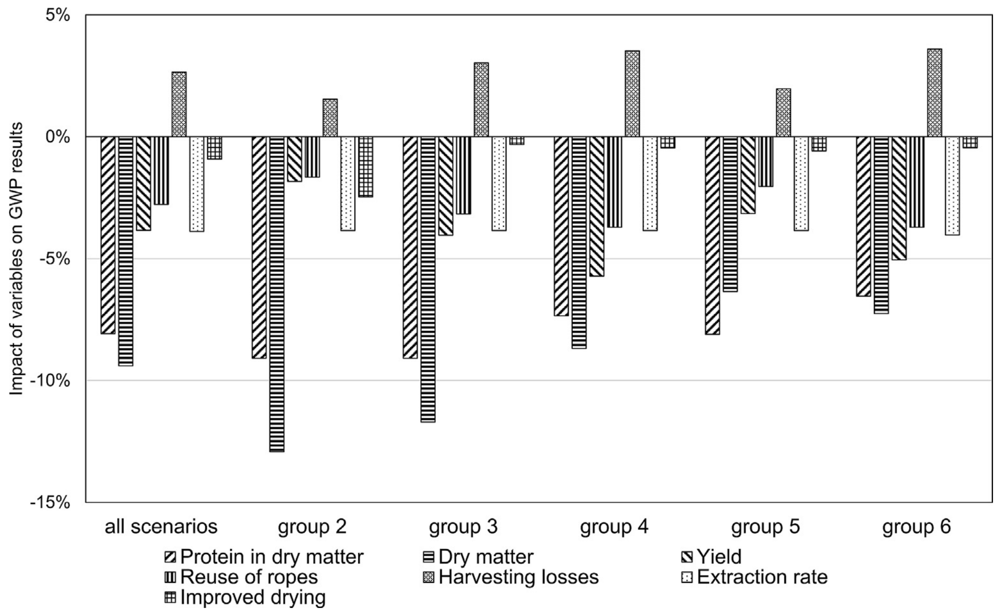

Fig. 9. Impact of reducing input variables by one standard deviation of the global warming potential (GWP) results based on sensitivity analyses.

of all components to marketable products (Zollmann et al., 2019) has the opportunity to lessen the environmental impact, as well as the economic output (Greene et al., 2020). For example, bio-refineries that produce both protein, energy sources, and other products, as proposed by Seghetta et al. (2016) and Lehahn et al. (2016), could result in the additional production of energy based on macroalgae (Aziz, 2016). Further, coupled production would distribute the environmental impact between the protein and the other products ingredients, thereby reducing the sole protein impact. The result herein showed that seaweed protein can be produced more sustainably than soy protein. However, its potential as an ingredient in food or fish feed depends on its quality and price. While our approach focused on the production of protein measured in the final product, the nutritional value of protein from sugar kelp in mink was found to be low in a recent study (Krogdahl et al., 2021). Therefore, further research is required to test the nutritional value of seaweed protein. A more sustainable protein source used as an ingredient in fish feed than soy, could however contribute to more environmentally fish-farming. as discussed in Hersoug (2015). Therefore, to accomplish a more sustainable fish farming, several improvements are necessary (Bailey and Eggereide, 2020) to solve both the social and environmental issues (Aarset et al., 2020). Thus, future studies should include the environment, economy, and society, which are the three pillars of sustainability (Abualtaher and Bar, 2020).

5. Conclusions

The objectives of this study were to assess the environmental performance of seaweed protein based of the nascent Norwegian seaweed production and evaluate the impact of different factors in improving the environmental sustainability of the feed production. For the seaweed production in our base scenario for today's production, the GWP for seaweed protein, measured for one kg of protein, was approximately four times higher than that of soy protein from Brazil. The GWP of the drying energy used, the DM content of the harvested seaweed, and the protein content in the dry weight had significant impacts on the environmental performance of the protein product. By focusing on these variables to improve the environmental performance of the production, it is possible to produce seaweed protein with a better environmental performance than soy protein from Brazil. In this study, two scenarios (scenarios 5.5 and 5.6) resulted in a lower GWP and energy demand for seaweed protein than for soy protein. And therefor, only these scenarios are recommended for the development of seaweed protein production. The research emphasises that producing feed-protein from seaweed while achieving a lower environmental impact than from soy protein production, is not simple, but possible. While the findings herein are based on a Norwegian case, many improvement pathways were found that are applicable to other countries.

Future work should explore for the complete exploitation of all components in the seaweed biomass into marketable products. Finally, as plastic pollution in the oceans continues to increase, future work should also consider the impact of microplastics emitted by the infrastructure of seaweed farms, as well as the loss of infrastructure parts to be covered by impact categories used in LCAs. Further, future research should also investigate more environmentally friendly materials and the effects of a longer infrastructure lifetime, which may in return increase the risk of losses and the emission of microplastics. The exploration of these different approaches would then contribute to science-based proposals for developing more environmentally farmed seaweed production.

CRediT authorship contribution statement

Matthias Koesling: Conceptualization, Writing – original draft, Investigation, Formal analysis, Visualization. **Nina P. Kvadsheim:** Conceptualization, Writing – review & editing, Validation. **Jon Halfdanarson:** Conceptualization, Writing – review & editing, Investigation, Validation. **Jan Emblemsvåg:** Conceptualization, Writing – review & editing, Validation. **Céline Rebours:** Conceptualization, Writing – review & editing, Funding acquisition, Project administration, Investigation, Validation, Formal analysis.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127301.

Nomenclature

ADP	Abiotic Depletion Elements
ADP fossil	Abiotic Depletion Energy
AP	Acidification Potential
Aug	August
CML	Collection of Impact categories by the Institute of Environmental Sciences Faculty of Science University of Leiden, Netherlands
CO_2 eq.	Carbon Dioxide equivalent; measured in kg
DM	Dry matter
DW	Dry weight
EP	Eutrophication Potential
EU	European Union
Extract	Extraction
GWP	Global Warming Potential(s)
GWP 100	Global Warming Potential(s) (GWP) calculated on a 100-year time horizon
ha	Hectare (1 ha = 10,000 m2)
IMTA	Integrated Multi-Trophic Aquaculture
m	Meter
M	Medium
MJ	Megajoule; 1 MJ = 1,000,000 J
mt	Megaton; 1 mt = 1,000,000 metric t
kg	Kilogram
km	1 km = 1000 m
km^2	Square kilometre
kt	Kilo ton; 1 kt = 1000 metric t
kWh	Kilowatt-hour; 1 kWh = 3600 kJ
L	Large
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MFA	Material Flow Analysis
NO	Norway
ODP	Ozone Layer Depletion Potential
Prot	Protein
POCP	Photochemical Ozone Creation Potential
S	Small
SDG	Sustainable Development Goal
SPC	Soy Protein Concentrate
SPP	Seaweed Protein Product
t	Metric ton
WW	Wet-weight
XL	Extra large
XS	Extra small

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