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Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy

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ABSTRACT

Blue Economy is seen as an essential contributor to a sustainable development, and it is an important part of the EU Green Deal. Seaweed plays a key role in the Blue Economy as a source of food, feed, and feedstock for biorefineries. Today, the largest part of global seaweed production is based in Asia, but there is also a growing interest in seaweed production in Europe. However, more knowledge on the environmental impacts is needed to ensure sustainable growth of the sector. Seaweed can be used in biorefineries to produce a variety of products for food and non-food applications. The aim of this paper was to perform a life cycle assessment (LCA) of a seaweed value-chain, including seaweed cultivation and production into sodium alginate, biodegradable materials, biogas, and fertilizer in a biorefinery setting. The LCA included 19 environmental impact categories but focused on climate change. The seaweed *Saccharina latissima* was cultivated and processed in Ireland. Sodium alginate was then extracted by means of ultrasound-assisted extraction, a novel extraction technology. Cellulosic residues produced after the extraction were used for the production of films used as a packaging material. Residues that remain after the production of the films were sent to anaerobic digestion to achieve a no-waste concept. For seaweed cultivation, fuel use and drying of seaweed biomass were the main environmental hot spots; and for the alginate extraction process, the yield and purification after extraction were the main hot spots. Overall, the results of this paper showed that the seaweed-based biorefinery has the potential to be sustainable, but several improvements are necessary before it is competitive with land-based systems.

1. Introduction

One of the largest global challenges is to supply a growing population with food and necessary products while limiting the effects of global warming, resource depletion and pressure on ecosystems. As land-based production systems are highly pressured to produce both food, feed and raw materials, it is necessary to explore other sources of protein and macromolecules. Marine resources such as seaweeds can be produced in a resource effective way and have a large potential to supply food and raw material for bio-based products [1].

Blue bioeconomy has been defined by the European Commission [2] as the economic activities and value created from the sustainable and smart use of aquatic resources. Despite the promising potential of the blue bioeconomy, there are several challenges to overcome in order to reach its full potential [2]. These challenges vary from technical, regulatory and market related, but it is also important to acknowledge the sustainability issues on environmental, economic, and social levels [3].

Today, the largest share of the seaweed industry is based in Asia, with China and Indonesia being the largest producers. The majority of the biomass produced is utilized for human consumption [4]. In Europe France, Ireland, Spain, and Norway are the biggest producers of seaweed [3]. The fact that seaweed provides biomass for food, materials, chemicals, biofuels and energy without competition for agricultural land and water has increased the interest in seaweed production also in Europe [5,6]. Hasselström et al. [7] showed that large-scale production of seaweed has the potential to be economically feasible along the Swedish west coast. However, this includes a value for nutrient uptake in coastal waters. Another study by van den Burg et al. [5] showed that seaweed

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production in the North Sea is not yet profitable, but it could be if a biorefinery approach to fully valorize the biomass to high-value products is applied.

Biorefineries are central to the bioeconomy concept, with seaweed having a great potential to be used as a feedstock for it. Nakhate and van der Meer [1] presented an overview of possible seaweed-based biorefinery chains and associated technical and non-technical hurdles to overcome for seaweed-based biorefineries to be successful.

Alginic acid is the dominant polysaccharide in brown seaweed. It has several potential uses, for example, it is used in textile printing with reactive dye, in medical application i.e., for directed release of drugs in the body and in the paper industry [9]. In foods, alginate can provide texture and is an important stabilizer. Alginate can also help to absorb toxins and to mitigate health issues by decreasing the uptake of cholesterol and provide a sense of satiety, which could be efficient for weight loss [10]. In 2001, two thirds of alginate produced globally was used for technical application, and one third for food and pharmaceutical applications [9].

Plastic littering is one of the largest environmental concerns of today. It is estimated that 4.8–12.7 million tons of plastics leak into the oceans every year where it is responsible for severe damage on ecosystems [11]. Technologies can be used to prevent plastic litter from reaching the oceans, but it will not alone solve the issue with plastic pollution [12]. Part of the solution to the problem of plastic pollution can be solved by an increased use of biodegradable, bio-based materials [13]. Seaweed biomass can be used to produce fully biodegradable packaging materials as has been discussed by, among others, Abdul Khalil et al. [14]. However, not all bio-based materials are environmentally favorable. For example, polylactic acid (PLA), which is one of the most used bio-based plastics, is produced from 1st generation raw materials such as sugar cane. PLA is also only degradable in industrial composing facilities, and not in nature [15,16].

To this point, little is known about the environmental aspects related to extraction of phytocolloids from seaweed. There are many studies examining the environmental impacts concerned with seaweed-based biorefineries [17–19]. To the best of our knowledge, no previous environmental assessments of a seaweed based biorefinery for production of alginate and materials have been published. However, due to the large potential and growing interest in this area more research is needed to increase the knowledge about blue bioeconomy and seaweed biorefineries. Thus, the aim with the study is to shed light on the most promising environmentally routes for production of a spectrum of products from seaweed biomass. This study will also identify and discuss key issues in the seaweed value chain.

2. Materials and methods

2.1. Goal and scope

This study presents a life cycle assessment (LCA) performed based on the ISO standards 14040 and 14044 [20,21]. The goal is to assess the environmental performance of a biorefinery concept utilizing *Saccharina latissima* (*S. latissima*) as feedstock for production of alginate, cellulose-based packaging film, electricity and fertilizer. Two functional units (FU) are used in the study, 1 kg sodium alginate and 1000 kg dry weight (DW) biomass from the seaweed *S. latissima*. The system studied includes the production of *S. latissima*, and the processing to final products. However, the use phase and end-of-life of biorefinery products are not included. A schematic drawing of the biorefinery concept is depicted in Fig. 1.

The seaweed cultivation system did not produce any other products than biomass, and thus no allocation was necessary in this step. For the biorefinery a system expansion approach was applied.

2.2. Life cycle inventory

2.2.1. Seaweed cultivation

Brown algae (Phaeophyceae) of the species *S. latissima* was cultivated in Blacksod Bay off the coast of Ireland. Fig. 2 shows a simplified drawing of the farm site. The farm had been running for two years at the time of this study, and was constructed by eleven 440 m long lines held up by buoys and attached to the shore and the seafloor by concrete anchors. The farm had one growth cycle per year that consisted on five steps: 1) collection of fertile algae, 2) spore preparation and seeding, 3) deploying and on-growth, 4) harvesting, and finally 5) post-harvest preservation (drying). Fertile algae for seeding of a new generation of algae were collected by boat during the harvest. Fertile algae were transported to a hatchery where their spores were released and seeded on thin line, to be attached to the main line of the deployed farming site. The farm had two boats that were used for different farm operations. The

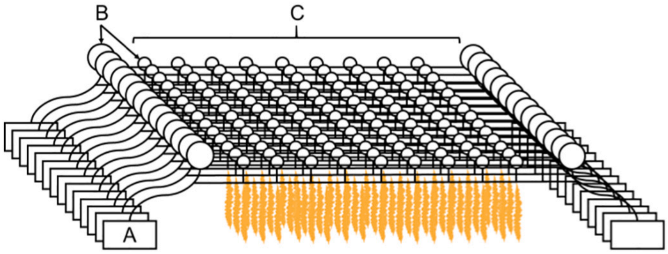


Fig. 2. Simplified schematic drawing of the seaweed cultivation site with A) concrete anchors, B) large and small buoys, C) 220 m long nylon longlines.

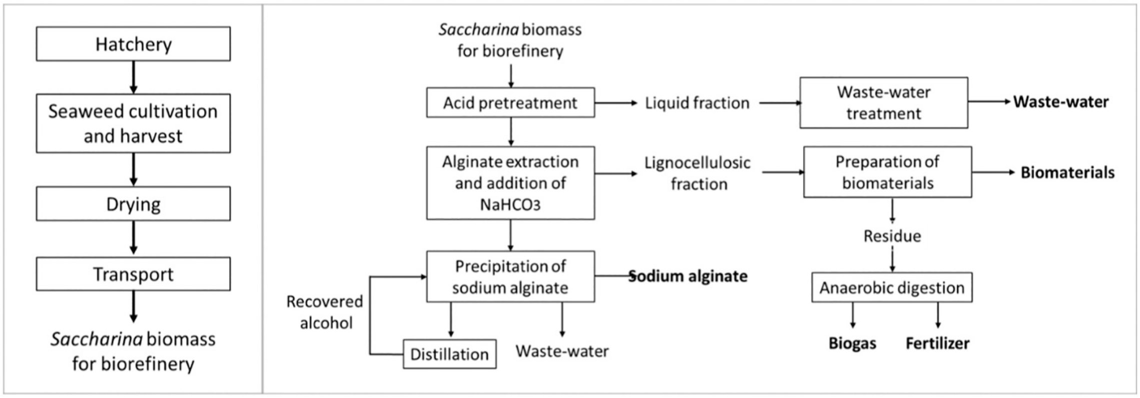


Fig. 1. The seaweed biorefinery concept.

seaweed was harvested manually in March from a boat approximately six months after deployment of seedlings and subsequently transported to a drying facility for post-harvest preservation.

2.2.2. Biorefinery system

The biorefinery system is modelled based on results from experiments and literature data. Extraction of alginate is performed as described below. The extraction generates a solid residue that is turned into a film that can be used as a packaging material as described by Cebrián-Lloret et al. [22]. Residues that are left after the production of packaging film are digestate in an anaerobic digester and turned into biogas. The biogas can be used in electricity production and the digestate as a fertilizer in agriculture.

Sodium alginate was extracted from dried flakes of *S. latissima* by employing conventional methods, and ultrasound-assisted methods. Briefly, the conventional method involved soaking the *S. latissima* flakes in 0.2 M HCl (1:25 ratio), and leaving the mixture stirring overnight at room temperature. The mixture was then filtered by using a muslin cloth, and the residue obtained was washed several times with distilled water until the pH was neutralized. Then, the wet residue was mixed with 0.1 M $NaHCO^3$, and left stirring overnight at room temperature. The permeate was collected, and separated from the retentate with a double layer muslin cloth, and NaCl (0.2% w/v) was added to the permeate. An equal volume of propan-2-ol (99%) was added to the permeate extracted for the precipitation of alginate and dried in an air convection oven at 30 °C.

For ultrasound-assisted extraction, the first step involved the use of ultrasonic probes (1000 UHdt Hielscher Ultrasound Technology, Teltow, Germany) at 100% power for 30 min while the use of HCl extraction followed by method described above whereas, for the ultrasound step three the ultrasound treatment was introduced while mixing the wet residue with 0.1 M $NaHCO^3$ at room temperature.

The environmental performance of the described technologies was assessed in a gate-to-gate LCA with the aim to find the most promising extraction method and thus excluding the impacts of the seaweed biomass.

2.3. Life cycle impact assessment

We assessed the 19 impact categories included in the Life Cycle Impact Assessment method EF 3.0 (adapted) which reflects the recommended impact categories of the EU initiative Product Environmental Footprint as described by the European Platform on Life Cycle Assessment [23].

All LCI modelling and characterization was performed using the SimaPro 9.1 software using the impact assessment method EF 3.0 (adapted), with background data from the Ecoinvent 3.6 database (cut-off by classification) and Agribalyse 3. The background data from Agribalyse e.g. on farming equipment was in turn based on Ecoinvent cut-off by classification processes.

Data on seaweed cultivation and post-harvest processing reflects the production year 2021 and was retrieved from the farm except for the spore preparation and seeding step which is based on inventory data from Thomas et al. [24].

2.3.1. Sensitivity analysis and evaluation of production improvement potential

The alginate extraction was performed in a small pilot scale but is still not fully representative for an industrial scale production. The following alternative scenarios were tested both to identify weaknesses in the modelling as well as production improvement potential:

1) Avoid drying of algae biomass.
2) Substitute isopropanol for ethanol in precipitation and increase the recovery rate.
3) Reduce process inputs by a factor 3 to simulate an optimized industrial scale process.
4) Substitute precipitation with alcohol for a process based on addition of $CaCl_2$ as described by McHugh [9].
5) Apply all improvements 1–4.

3. Results

3.1. Life cycle inventory results

A total harvest of 3520 kg dried seaweed was obtained per year, equalling 35,200 kg wet weight and 8 kg wet seaweed per meter line. Inputs of equipment and energy for the cultivation steps are presented in Table 1. All material inputs are divided by their life expectancy, also presented in Table 1. The permanent farm materials such as concrete anchors and main ropes stood for the largest input of material and drying of seaweed for a considerable electricity input. The yearly maintenance using boats stood for the main part of boat fuel use. The fuel for setting up the permanent farm frame was divided by the expected life length of 15 years.

The biorefinery was modelled based on literature data. Data for alginate extraction was based on the ultrasound 3rd step extraction method as described above. Production of film was based on Cebrián-Lloret et al. [22]. The methane and NH_3 yields were estimated using Buswells' equation and assuming 50% digestibility according to Tedesco and Daniels [25]. Data for production of the substituted products comes from Ecoinvent database.

The yields of the biorefinery products per 1000 kg DW *S. latissima* biomass are shown in Table 2.

The inputs for the biorefinery processing are shown in Table 3. The production of film and anaerobic digestion are not affected by the assumed process optimizations. The reductions in energy use in the optimized production are due to smaller volumes being processed in the system, no energy efficiency is assumed in the optimized system.

3.2. Life cycle impact assessment results

In the following sections of this paper results for alginate extraction and potential environmental impacts are shown. For the seaweed cultivation, results for the environmental impact categories except climate are given in the supporting information. For the biorefinery system, only results for climate impacts are shown. This choice was motivated by the acute global challenge that climate change represents.

3.2.1. Alginate extraction yield

The alginate yields obtained using the three methods are given below in Fig. 3. Using ultrasound in the 3rd extraction step increased the yield significantly but applying ultrasound at the 1st processing step lowered the yield of alginate. Yields are given as a mass percentage of dry *S. latissima* biomass.

3.2.2. Production of *S. latissima* biomass

The dried seaweed as raw material for alginate production had a climate impact of 6.12 kg CO_2 equivalents (CO_2 eq.) per kg dry seaweed at post-harvest drying. The high electricity consumption to dry the seaweed explains why the drying stood for 75% of the climate impact (Figs. 4, and 5). Algae in its wet form just after harvest had a considerably lower climate impact of 0.16 kg CO_2 eq. per kg wet weight. Only negligible climate change was caused by the two initial seaweed cultivation steps collection of algae and spore preparation (Fig. 3).However, it should be noted that fuel used for collection of fertile algae could not be distinguished from the harvesting operation and is thus included there. Followed by drying, the boat fuel for farm maintenance was the second largest climate hot spot in the seaweed cultivation (Figs. 4, and 5). Fuel use dominated not only the climate impact of the deploying, on-growth, and maintenance step, but also the harvest step (Fig. 5).

Table 1
Inventory data per 1 t dry seaweed.

Activities and inputs	Input type	Amount	Life expectancy (years)
Collection of fertile algae			
Plastic bags	Polypropylene (kg)	0.1	5
Fabric cloths	Woven cotton (kg)	0.1	5
Transportation to hatchery	Lorry transport (tkm)	0.1	N/A
Spore preparation and seeding			
Energy for aeration, lights, seawater sourcing and filtering[a]	Electricity, Irish market mix (MJ)	656[a]	N/A
Bucket for cultivation[a]	Polyethylene (kg)[a]	0.17[a]	1
Seawater filters, plastic part[a]	Polyethylene (kg)[a]	0.45[a]	[a]
Seawater filters, metal part[a]	Chromium steel (kg)[a]	0.32[a]	[a]
Nutrients[a]	Phosphate (25%) and ammonium nitrate (75%) (kg)[b]	0.19[b]	N/A
Aquaria[a]	Polymethyl methacrylate (kg)[a]	2.91[a]	[a]
Collectors[a]	Polyvinylchloride (kg)[a]	2.75[a]	[a]
Thin cultivation line	Nylon (kg)	3.8	1
Transportation to farm site	Lorry transport (tkm)	1.6	N/A
Plastic container for storage at farm prior deployment	Polyethylene (kg)	0.03	5
Cold storage at farm prior to deployment	Storage in refrigerator (day)	25	N/A
Deploying, on-growth and maintenance			
Anchors and mooring block[c]	Concrete blocks (kg)	547.0	20
Base shackles and hooks[c]	Chromium steel (kg)	4.9	15
Metal chains[c]	Unalloyed steel (kg)	0.6	15
Riser ropes and straps[c]	Nylon (kg)	1.4	10
Buoys[c]	Polypropylene (kg)	8.1	15
Main long line[c]	Nylon (kg)	3.3	25
Boat operation for setting permanent frame up	Diesel (kg)	26.0	N/A
Boat operation for seeding	Petrol (kg)	66.0	N/A
Boat operation for maintenance	Diesel (kg)	244.0	N/A
Maintenance of equipment	Permanent farm equipment[c] (% of total)	1.5	N/A
Harvesting			
Boat operation for harvesting incl. collection of fertile algae	Petrol (l)	99	N/A
Big bags for harvest	Polypropylene (kg)	3.1	10
Post-harvest preservation (drying)			
Energy for drying	Electricity, Irish market mix (kWh)	8800	N/A
Transportation to drying facility	Lorry transport (tkm)	1000	N/A

[a] From Thomas et al. [24], Tables 1 and 2A.
[b] From Agribalyse database v. 3.
[c] Permanent farming equipment.

The drying process dominated impacts also when looking beyond climate impact. For all other 18 environmental impacts assessed, the drying contributed to 38–95% of total impacts (Supporting information, Fig. S1). Only for three impacts was the contribution from drying lower than half of the total impact.

Table 2
Product yields in biorefinery from processing 1000 kg DW *S. latissima* biomass.

Product	Amount	Comment
Alginate	338 kg	
Liquid residue from alginate extraction	352 kg	Not further processed in the modelled biorefinery
Cellulosic film	116 kg	Substitutes PLA on a 1:1 basis
Electricity	277 kWh	Substitutes Irish average electricity
Fertilizer (NH_3)	73 kg	Substitutes chemical fertilizer based on N-content

Table 3
Inputs used in biorefinery processing per 1000 kg DW *S. latissima* biomass.

Input	Amount (optimization 1)	Amount (optimization 5)	Comment
Alginate extraction			
Hydrochloric acid (HCl), concentrated (pre-treatment)	411 kg	137 kg	
Sodium bicarbonate ($NaHCO_3$)	420 kg	140 kg	
Sodium chloride (NaCl)	86 kg	23 kg	
Ethanol	1769 kg		Lost ethanol when 95% recovery is assumed
Hydrochloric acid (HCl), concentrated (purification)		137 kg	
Calcium chloride ($CaCl_2$)		68 kg	
Electricity	1254 kWh	446 kWh	
Electricity (ultrasound treatment)	2878 kWh	959 kWh	
Heat	30,282 MJ	63 MJ	Ethanol recovery and drying of alginate
Film production			
Potassium hydroxide (KOH)	78 kg	78 kg	
Electricity	16 kWh	16 kWh	
Heat	450 MJ	450 MJ	
Anaerobic digestion			
Electricity	100 kWh	100 kWh	
Heat	350 MJ	350 MJ	

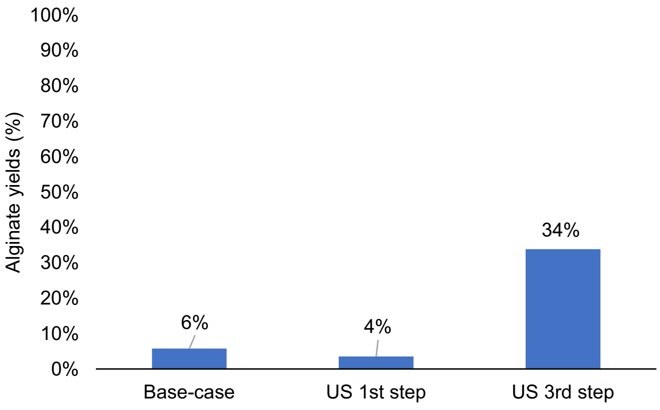
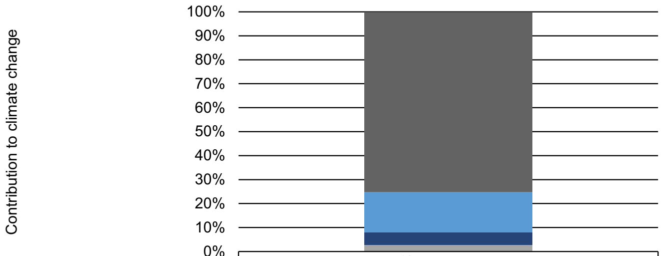
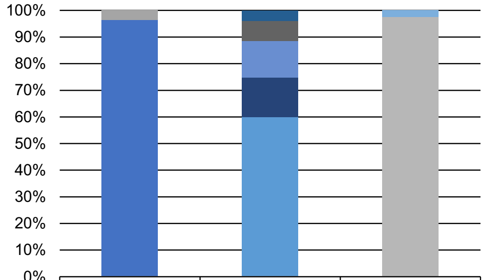


Fig. 3. Alginate yields obtained using different methods (US: ultrasound).



	% contribution
■ Post-harvest preservation (drying)	75%
■ Deploying, on-growth and maintenance	17%
■ Harvesting	5%
■ Spore preparation and seeding	3%
■ Collection of fertile algae	0%

Fig. 4. Contribution to climate change of dried seaweed (*S. latissima*) from five cultivations steps.

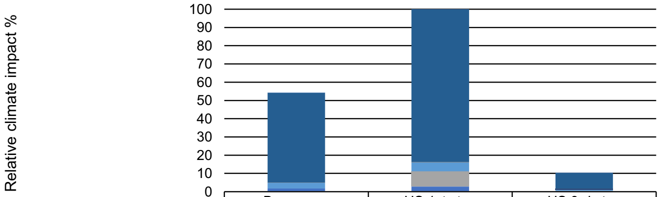


	Post-harvest preservation (drying)	Deploying, on-growth and maintenance	Harvesting
■ Containers for harvesting			3%
■ Fuel for harvesting			97%
■ Ropes		4%	
■ Concrete anchors		8%	
■ Remaining materials		14%	
■ Fuel for deploying seeding line		15%	
■ Fuel for maintenance		60%	
■ Transportation	4%		
■ Electricity	96%		

Fig. 5. Activity contribution to climate change of three main seaweed cultivation steps.

3.2.3. Alginate extraction processes

The first step in the assessment of the *S. latissima*-based biorefinery is to decide which extraction process to study in more depth. The results for the climate impacts of the initial gate-to-gate LCA of alginate extraction are shown in Fig. 6. As is clearly seen, the extraction process that includes ultrasound at the third extraction step has the best environmental performance. The most important explanation for this is the higher alginate yield that is obtained by this method. The higher yield makes less inputs necessary to produce the same amount of product. The energy consumption in the ultrasound process is justified by the higher yields obtained. The step in the extraction process that contributed most to climate change is the precipitation with isopropanol. Thus, alternatives for this are further examined in this study.



	Base-case	US 1st step	US 3rd step
■ Drying of alginate	0	0	0
■ Precipitation	49	84	9
■ Na-alginate formation (NaCl+el)	0	0	0
■ Extraction (US)	0	0	1
■ Extraction (NaHCO3+water+el)	3	5	1
■ Pretreatment (US+water)	0	8	0
■ Pretreatment (HCl+water+el)	2	3	0

Fig. 6. Relative contribution to climate impact by the different processing options for alginate, results shown for 1 kg Na-alginate. US = ultrasound.

3.2.4. Sensitivity analysis and evaluation of production improvement potential

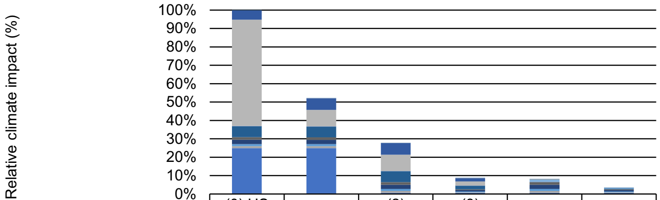
To resemble an industrial production, assumed process improvements as are described above were applied. As shown in Fig. 7, process optimization has a huge impact on the environmental performance. The single biggest impact was to avoid drying of seaweed, and to avoid precipitation as a method to purify alginate. Further reductions of inputs would have positive effects even though these have not been studied and may not be feasible. In the following sections of this paper however, they are assumed to be feasible.

3.2.5. Biorefinery results

The climate impacts of a seaweed-based biorefinery concept are shown in Fig. 8. The process needed for extracting alginate gives the single largest contribution to the overall environmental impact. However, the impact of producing film is significantly lower than the impact from PLA which is the offset product. The seaweed-based film also has the benefit of being fully biodegradable while still having good barrier properties [22]. A 1st generation PLA is chosen as the alternative product since it has more similar properties to the seaweed-based film than fossil-based plastics i.e. polyethylene. Anaerobic digestion shows to be an efficient way to use the residues that remain after extraction of alginate and production of film, the benefit of anaerobic digestion is that two useful products, energy and fertilizer, are produced.

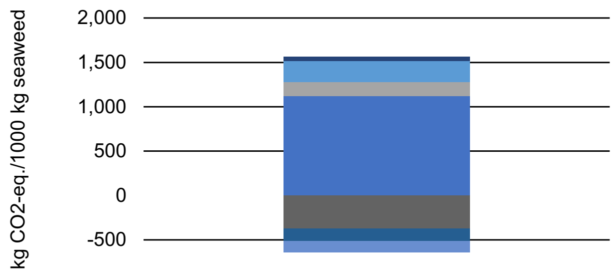
Since alginate does not substitute any other product, the biorefinery will generate a net emission of greenhouse gases. However, an increasing global population will need additional products, and producing alginate in a biorefinery setting is more beneficial than producing alginate as a single product and to send residues to waste treatment.

The net emissions of CO_2-eq from the modelled biorefinery are 921 kg CO_2-eq/ton DM seaweed or 2.73 kg CO_2-eq/kg Na-alginate when all assumed process optimizations are applied.



	(0) US 3rd step as in experiments	(1) EtOH instead of IPA	(2) Avoid drying of seaweed	(3) Reduce inputs by a factor 3	(4) Avoid precipitation	(5) All improvements applied
■ Drying of Na-alginate	0%	0%	0%	0%	0%	0%
■ Electricity, separation	0%	0%	0%	0%	0%	0%
■ Energy, alcohol recovery	5%	6%	6%	2%	0%	0%
■ CaCl2 and HCl, separation	0%	0%	0%	0%	1%	0%
■ Alcohol, precipitation	58%	9%	9%	2%	0%	0%
■ NaCl	0%	0%	0%	0%	0%	0%
■ Electricity, US	6%	6%	6%	2%	0%	0%
■ Electricity, extraction	1%	1%	1%	0%	1%	0%
■ NaHCO3, extraction	2%	2%	2%	1%	2%	1%
■ Electricity, pretreatment	1%	1%	1%	0%	1%	0%
■ HCl, pretreatment	1%	1%	1%	0%	1%	0%
■ Seaweed	25%	25%	1%	1%	1%	1%

Fig. 7. Climate impacts from different processing options, results shown for 1 kg Na-alginate. US = ultrasound.



	1
■ Fertilizer	-125
■ Electricity	-141
■ PLA	-372
■ AD	45
■ Production of film	237
■ Seaweed	155
■ Alginate extraction	1123

Fig. 8. Climate impacts for a seaweed-based biorefinery. Substitutions are shown as negative contributions (AD: anaerobic digestion).

4. Discussion

This study points out some environmental hot-spots and necessary process improvements that will make it possible for a seaweed-based biorefinery system to be environmentally sustainable. However, using seaweed for applications as described here is a new field and more research is needed to overcome the technical, economic, and environmental hurdles that this sector still faces. Among others, Gao et al. [6] have studied the feasibility of using algae in a variety of fuel production pathways with promising results. Gao et al. [6] showed that there are both advantages and disadvantages with the different types of fuel. In the present study anaerobic digestion was assumed to be used to turn the residues after extraction into energy and fertilizer. However, it may be necessary to co-digest the seaweed with other substrates to achieve a good C:N ratio that makes it possible to reach the full potential [26,27].

Previous studies have shown the importance of utilizing the entire biomass to produce useful products in order to be sustainable [19]. Similar to the present study, previous studies have also pointed out the need for resource efficient processing and clean energy input [19,28]. Nevertheless, it is not always relevant to compare seaweed-based products with conventional ones or produces based on terrestrial biomasses since the chemical composition of seaweed makes it possible to produce products with new unique properties and functions. The utilization of these new properties and functionalities in products should also be further studied [8].

While Europe produced less than 1% of global production volume of aquatic algae in 2018, China, Indonesia and Republic of Korea produced over 90% [29]. Asia has long been leading seaweed cultivation and large parts of local populations rely on seaweed cultivation as their main source of income [30]. Despite that, most of the sustainability assessments of seaweed have focused on small-scale European production [24,31–33]. An LCA of seaweed cultivation in Southeastern China identified that the environmental hotspot of the cultivation was fuel use [30], which agrees with the findings of this study. Previous studies on European production reported 20–30% higher yield per meter for *S. latissima* than this study [24,33]. The large environmental impact from preservation of seaweed by drying and freezing [24,33] is well known and testing and evaluating less impactful alternatives has therefore been a focus in research [24]. In addition to changing to more resource efficient preservation methods, e.g. hang-drying and ensiling [24], it should be considered if the preservation step in production chains could be removed by having geographical and temporal closeness between processing and seaweed harvesting.

One important characteristic of seaweed is that their chemical composition, e.g. levels of alginate and protein, varies with growth period and time of harvest [31,33]. Since yield of extraction is an important parameter for the environmental performance, time of harvest may have a significant effect on this and should be studied in more detail in future sustainability assessment studies of seaweed value chains. The benefits of algal uptake of CO_2 and nutrients have here been left out as the effects are only temporary in the studied production chain. The uptake has however been shown to considerably mitigate eutrophication and climate change if applying a shorter time perspective, or when the carbon and nutrients removed from the atmosphere and marine environment are prevented from reentering the same [24,32]. On the other hand, a change in the marine environment, i.e. through increased concentration of nutrients, may affect both the growth rate and composition of seaweeds [34,35]. Thus, to develop a sustainable blue bioeconomy more research is needed.

4.1. Conclusions

Seaweed has the potential to become a sustainable raw material for biorefinery purposes. However, the technologies are still not well defined and substantial improvements must be made before seaweed-based systems are competitive with land-based systems. Using ultrasound in the 3rd process step gave the highest yield of extraction and thus, this process option has the lowest environmental impact per kg alginate despite the higher energy use. Efforts to lower impacts from line cultivated seaweed should be directed towards reducing fossil fuel use in farming, and most importantly, to find energy effective ways of drying seaweed. The purification of extracted sodium alginate is an important hot-spot in the value chain, and a process that avoids using organic solvents would be preferable.

CRediT authorship contribution statement

Anna Ekman Nilsson: Conceptualization, Methodology, Writing - Original Draft, Visualization, Writing - Review & Editing **Kristina Bergman**: Conceptualization, Methodology, Writing - Original Draft, Visualization, Writing - Review & Editing. **Laura Pilar Gomez Barrio**: Investigation, Writing - Review & Editing. **Eduarda M. Cabral**: Investigation, Writing - Review & Editing. **Brijesh Kumar Tiwari**: Investigation, Writing - Original Draft.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2022.102725.

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