Methods in Molecular Biology
DOI 10.1007/7651_2018_203

Life Cycle Assessment of Seaweed Cultivation Systems

Michele Seghetta and Pietro Goglio

Abstract

Life cycle assessment (LCA) is a holistic methodology that identifies the impacts of a production system on the environment. The results of an LCA are used to identify which processes can be improved to minimize impacts and optimize production.

LCA is composed of four phases: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation.

The goal and scope define the purpose of the analysis; describe the system and its function, establish a functional unit to collect data and present results, set the system boundaries, and explain the assumptions made and data quality requirements. Life cycle inventory analysis is the collection, processing and organization of data. Life cycle impact assessment associates the results from the inventory phase to one or multiple impacts on environment or human health. The interpretation evaluates the outcome of each phase of the analysis. In this phase the practitioner decides whether it is necessary to amend other phases, e.g., collection of more data or adjustments of goal of the analysis. In the interpretation, the practitioner draws conclusions, exposes the limitations, and provides recommendations to the readers.

The quality of LCA of seaweed production and conversion is based on data availability and detail level. Performing an LCA at the initial stage of seaweed production in Europe is an advantage: the recommended design improvements can be implemented without significant economic investments. The quality of LCA will keep improving with the increase of scientific publications, data sharing, and public reports.

Keywords Climate change, Environmental impacts, Life cycle assessment, Macroalgae, Seaweed

1 Introduction

Seaweed cultivation is a promising activity in the European aquaculture sector [1]. Despite being widely used in the food and chemical sectors in Asia [2], seaweed occupies a niche market in Europe. The current demand in the food sector is satisfied mainly by wild harvest in Norway and France [3]. However, a stable biomass supply might ignite new business opportunities and boost the industrial development of cultivation and processing [4]. Extraction of valuable substances through successive refinery steps is technically feasible, and it has been tested in laboratory and pilot scale biorefineries [5]. Despite the absence of industrial scale cultivation sites and biorefineries in Europe, it is worth assessing the potential impacts on the environment to guide the industrial development and prevent harmful effects [4].

Different types of environmental assessments are available: environmental impact assessment [6], environmental risk assessment [7], and life cycle assessment (LCA). While the first two methods assess site-specific change in environmental conditions that could pose a threat to human health and well-being (e.g., concentration of specific pollutants), the third analysis is holistic and evaluates the local and global impacts through all stages of a product life cycle [8]. LCA can identify which stage of seaweed production has the highest impact on a series of environmental indicators and guide the designer to make choices that minimize the impacts.

The last decade has seen an increase of LCA studies about seaweed production and use. Researchers showed that biogas or bioethanol production have lower environmental impact than their fossil substitutes [9–15]. However, the energy price can hinder the development of production plants solely dedicated to biogas and bioethanol [4]. The economic aspect might be improved by the development of biorefineries that use the biomass in successive steps to extract multiple valuable products, i.e., biogas, bioethanol, fertilizer, and proteins [16–18]. High-value substances like proteins [19] or fucoidan [20] can increase the revenue of the production process and sustain the biorefinery economy.

At the current stage, Europe has several research projects on biorefineries but no industrial scale facility [4]. Performing a LCA based on laboratory data, also called anticipatory or prospective LCA [21–23], introduces uncertainty in results and is likely overestimating the impact compared with industrial optimized processes [23–25]. However, this should not discourage the LCA practitioners, who can still provide an informative result that can be used during the development process of pilot to large scale cultivation sites. Increasing the number of reports and publication will foster the data sharing and improve the reliability and quality of future studies.

This chapter describes how to perform an LCA following the protocol described by the ISO standard [8]. Through the description, seaweed cultivation will be used to provide examples and highlight features of particular relevance.

2 Methods

LCA methodology is constantly evolving and improving, thanks to the contribution of practitioners and scientists. While the concept of a holistic assessment—considering all the stages in a product manufacturing or service provision—is common in all LCAs, the procedure might differ, based on different purpose of the analysis and assumptions. The protocol to conduct an LCA is formalized in the ISO standard 14040:2006 [26] and 14044:2006 [8]. The standard offers a

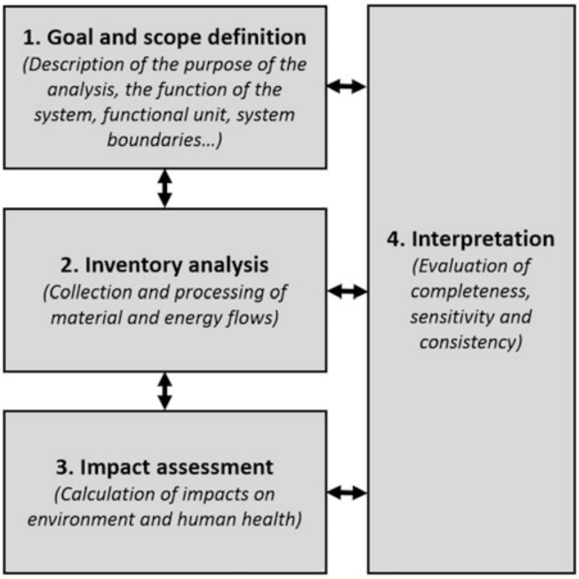

Fig. 1 The four phases that constitute a LCA according to the ISO standard 14044:2006

common ground for the development of LCA studies and reports and is used to develop specific certifications like environmental product declaration [27] or product carbon footprint [28]. In this chapter we follow the protocol described in the ISO standards 14040:2006 and 14044:2006 [8, 26].

LCA has four main phases (Fig. 1): (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

The goal and scope definition sets the basis on how to conduct the analysis, affecting the data collection in phase 2 and the evaluation of impacts in phase 3. However, the four phases should be considered flexible, meaning that the practitioner can use the results of each phase to revise the decisions and assumptions previously taken. For example, if the practitioner realizes that the lack of data affects the interpretation of an impact assessment category, he will either go back to inventory analysis and collect more data or modify the goal and scope definition to focus on another aspect that can be fully addressed.

3 Goal and Scope Definition

The first step in this phase is the definition of the goal of the analysis. Here, the practitioner describes the purpose of the analysis and identifies the target audience. Accordingly, he establishes the level of detail to be achieved in data collection and elaboration. This decision will deeply affect the approach to the following phases [8].

The goal can focus on the hotspots of a single production pathway or compare alternatives; it can focus on a specific problem, i.e., climate change, or account for several impacts on environment and human health.

In LCA focusing on seaweed, we can find the following examples of goals:

- Determine the most sustainable scenario for the cultivation and conversion of macroalgae to bioenergy in Chile [16].
- Identify the design that minimizes the environmental impacts of dried seaweed production [29].
- Assess the environmental impacts and energy balance of seaweed-based biofuels, and identify hotspots where design modifications can improve the system performance [17].

The definition of the scope establishes the limits of the LCA: system function, functional unit, processes, and system boundaries.

The system function is the purpose of the cascade of processes: deliver a product, e.g., production of seaweed, or provide a service, e.g., decrease eutrophication in a water basin. The same system can potentially deliver more than one function at the same time [30, 31]. The functional unit is the quantification of a system function, e.g., 1 mg of dried seaweed or 1 kg of nitrogen absorbed.

Examples of functional units in scientific papers are:

- 1 mg of dry seaweed [17]
- 1 ha of sea surface cultivation [18]
- 1 km driven using seaweed-based biogas [14]

A series of connected processes constitutes a system, which can be represented by a flow diagram (Fig. 2). The diagram shows the inputs of materials and energy, their transformation, processing and the final output(s). Offshore cultivation of seaweed usually follows four main phases [18, 32]: (1) seed line production, (2) deployment of lines, (3) maintenance during growth phase, and (4) harvest. During the seed line production, fertile material releases spores which settles on kuralone twines (polyvinyl alcohol fiber) and then incubated in cold room. Nutrients and sterile water support their growth. In the second phase, the kuralone twines are coiled around 8 mm diameter ropes, which provide support and surface for seaweed to attach during development. The combination of kuralone and 8 mm ropes are called seeded lines (or seeded ropes) and are deployed in the sea where seaweed will develop over several months, according to the local climatic conditions [18, 32]. In the third phase, the farmer visits regularly the cultivation site to assess the growth and maintain the lines. During the fourth phase, the farmer harvests the biomass using a mechanical arm to raise the

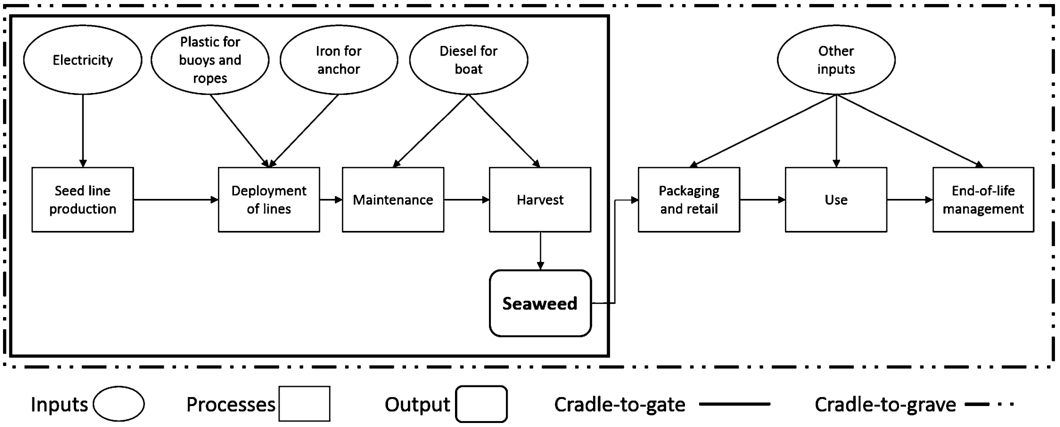

Fig. 2 Flow diagram of a seaweed production system based on Seghetta et al. [18]

lines from the water and manually collecting either part or the whole plant [33].

The system boundaries define which processes are necessary to deliver the product or service and set the limits of the analysis. There are two main types of system boundaries named after the limits of the analysis: cradle-to-gate and cradle-to-grave [34]. In a cradle-to-gate approach, the analysis stops when the product is created or service is delivered (Fig. 2). The system may present several possible gates according to the goal definition: harbor, storage warehouse (potentially including a preservation process like drying), and consumer table (therefore including the transport necessary for the distribution phase). In cradle-to-grave approach, the systems include the use and the end-of-life management (Fig. 2). In this case the analysis will include the emissions relative to the consumption of seaweed and, for example, the disposal of the materials used during the growth phase.

The goal and scope section is also used to define all the operative details that characterize the analysis. For example, it should state if any processes has been excluded because considered negligible. In this case, the report/article should indicate the cut-off criteria and the reason for its application, e.g., exclude all the inputs that cumulatively do not reach more than 1% of the total mass input of the system based on previous analysis on the same site. Given the limited literature on seaweed production, a cut-off may reduce the accuracy of the results.

Goal and scope include the description of methodology used for the impact assessment and type of allocation used (if any). For reasons of clarity, these two concepts are explained in detail in Sects. 5 and 7, respectively.

4 Life Cycle Inventory Analysis

The life cycle inventory (LCI) analysis deals with the collection, elaboration, and organization of system inputs and outputs.

During the data collection, the practitioner uses the flow diagram (Fig. 2) as a guideline to register all the inputs and outputs of the system. Data can be primary, i.e., measured and gathered in person on the site, or secondary, i.e., collected from reports and literature as averages and statistical projections [34]. To increase the accuracy of the analysis, the major flows should be collected as primary data [26].

The data are presented in a table as exemplified in Table 1. The first column shows the list of material and energy used in the system

Table 1
Life cycle inventory table of seaweed cultivation in Denmark exemplified from Seghetta et al. [40]

Phases	Unit	Amount	Lifetime (year)	Amount year^{-1}	Material composition
Seed line production					
Electricity	kWh	5	1	5	Danish energy mix
Deployment of lines					
Screw anchor	kg	60	20	3	Iron
Buoys	kg	344	8	43	Polyethylene
Concrete block	kg	8,000	20	400	Concrete
Headline rope	kg	130	13	10	Polypropylene
Boat use	L	65	1	65	Diesel
Maintenance		0			
Diesel for boat	L	85	1	85	Diesel
Harvest		0			
Diesel for boat	L	65	1	65	Diesel
Industrial bags	kg	1	1	1	Polypropylene
Outputs	**Unit**	**Amount year^{-1}**			
Products					
Seaweed (dry weight)	kg	1,000			
Emissions to air					
Emissions during biomass conversion					
Methane loss	kg	2.45			
Ammonia loss	kg	0.02			

Functional unit 1 ha of sea surface

processes, as well as the products and emissions to different environmental compartments. The second column shows the unit of measure of each listed element. The third column shows the total amount of material and energy consumed by the system referred to the functional unit. The fourth column shows the lifetime. The fifth is the total amount normalized by its lifetime. The sixth shows the composition of the material or energy. To increase transparency and replicability, the practitioner should provide reference to specific flows [35].

Every energy or material input insisting on a process is a subsystem with its own inputs and outputs like branches in a tree diagram. A mix of primary and secondary data is usually used to prepare a complete inventory. Databases provide help in this time-consuming process by offering complete datasets, i.e., inputs, outputs, and emissions, of the most common industrial process, e.g., plastic and fuels. The most popular databases can contain up to 14,700 datasets, e.g., Ecoinvent [36] and Agri-Footprint [37]. Mixed sources can be used in the same study provided that they use the same set of assumptions and data quality standards. Incompatible sources may lead to significantly different results for the same system [38].

The data should respect energy and mass balance between inputs and outputs. The LCI table, together with the flow diagram, supports the practitioner to guarantee the respect of the balance within system boundaries. Consumption and emissions should also be referred to specific time frame, e.g., 100 years if evaluating climate change, and clearly describe data elaboration and assumption in the inventory analysis or goal and scope section.

5 Life Cycle Impact Assessment

The life cycle impact assessment phase associates the results from the inventory phase to one or multiple impacts on environment or human health. From a mathematical point of view, the emissions of different substances are converted to a single unit of measure (indicator) and summed to provide the magnitude of the impact (Fig. 3). For example, emissions of carbon dioxide and dinitrogen monoxide from electricity production are multiplied for a conversion factor, i.e., characterization factor, and converted into carbon dioxide equivalents. The sum of all carbon dioxide equivalents from system processes represents the impact on climate change [39].

The impact assessment consists of three steps: selection, classification, and characterization.

The selection of impact categories aims at including all the relevant environmental consequences of the system operations. In seaweed sector, the majority of scientists are interested in understanding the potential bioremediation of eutrophic waters and

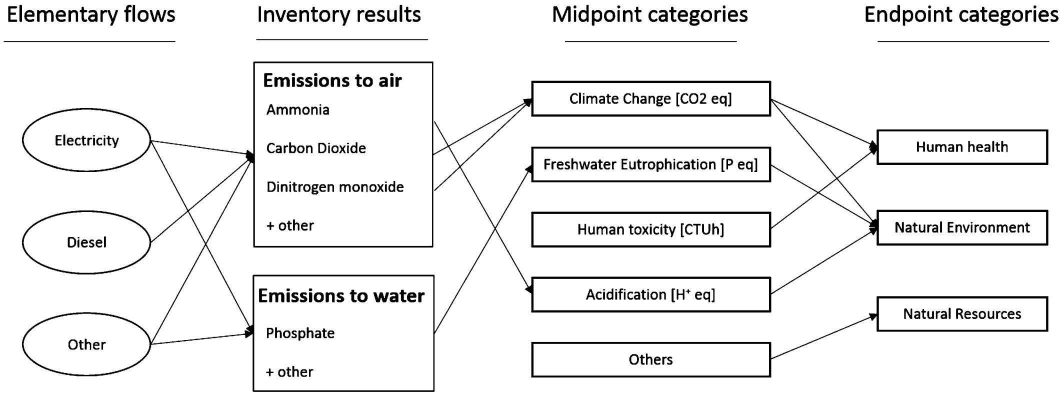

Fig. 3 Framework of impact assessment based on ILCD methodology [39]

carbon dioxide absorption; therefore, they select impact categories quantifying eutrophication and climate change [29, 40]. Studies dealing with biofuel production select, in addition to climate change and eutrophication, impact categories related to human health, eco-toxicity, fossil resources depletion, and cumulative energy demand [12, 14, 16, 18].

The classification step connects substances emissions to categories where they manifest an impact, e.g., methane emissions to impact on climate change. This step is performed using characterization models that describe the relation between emissions and impacts through mathematical functions [34, 41, 42].

The characterization step is the mathematical conversion of a physical quantity to an indicator score, e.g., kg of methane into kg of carbon dioxide equivalents. This makes all processes comparable since they share the same unit of measure. Characterization provides results for midpoint impact categories (Fig. 3), which are defined as the point where a variety of substances have a common effect on the environment. For example, climate change is a point where all greenhouse gases produce an alteration of the radiative forcing in the atmosphere. The endpoint categories are created by a further characterization step which results in a broad category aiming at comparing multiple environmental impacts on a specific area, e.g., human health. The endpoint characterization is subject to higher uncertainties and then midpoint and, while providing a simple result, reduces the clarity of the mechanisms underpinning the calculation.

There are several available impact assessment methods that a practitioner can use. The most recent and harmonized indicators are provided by IPCC for climate change [43], ReCiPe [41], CML [42], ILCD [39] and Eco-indicator 99 [44]. All of them consider at least one impact category for the effects on climate change and eutrophication. ReCiPe provides two categories to differentiate between marine and freshwater eutrophication, which might be useful in studies focusing on the bioremediation service of seaweed cultivation [45].

The use of impact categories from well-known methods supports comparability of results among different studies. However, practitioners can create new impact categories to include aspects relevant for the aquaculture sector, such as sea surface occupation [46, 47], sea bottom impact [48], and phosphorus-limited marine eutrophication [45]. Other impacts such as on biodiversity have been developed for other systems; however, no characterization factors have been set up for marine environment yet [30, 49–51].

5.1 Impact Categories Used in Seaweed Sector

Climate change is the most common impact category used in LCA of seaweed production. Thanks to the photosynthesis, seaweed acts as a temporary storage of carbon and reducing the concentration of carbon dioxide in the atmosphere. The management of biomass defines where and when the carbon is released, the carbon balance of the system, and possible interaction with the nitrogen cycle. The end-of-life scenario is a key process to describe when calculating the net carbon balance. When modelling a biorefinery system for production of fuel, fertilizer, and fish feed, part of the carbon remains in the soil for more than 100 years, delivering a carbon sequestration service [52]. When seaweed is converted in an energy vector, the balance between absorption and emissions (during use phase) is considered neutral [53]. However, a thorough mass balance of the carbon and nitrogen within the system boundary can reveal if other greenhouse gases emissions occur, e.g., methane loss during storage [40].

Cumulative energy demand (CED) [54], energy return on energy investment (EROI), [55] and fossil depletion [41] are useful impact categories for studies focusing on biofuel production [12, 14, 16, 45]. These categories consider the total energy (or fossil resources) required from society to produce 1 unit of available energy. The result is a quantification of energy efficiency of the process and can highlight the best performance between seaweed-based biofuels and their fossil alternatives.

Seaweed cultivation is often considered as a bioremediation technology to reduce eutrophication [56, 57]. During the growth phase, seaweed can absorb up to 32 kg nitrogen and 17 kg phosphorus from the water per ton dry weight [45]. Eutrophication impact categories help the practitioner to evaluate the balance between seaweed bioextraction and system emissions during processing and end-of-life phases. The CML method offers a single impact category that converts both emissions of nitrogen and phosphorus in units of phosphate equivalents [42]. ReCiPe and ILCD methods differentiate between marine eutrophication, assumed to be nitrogen limited, and freshwater eutrophication, phosphorus limited. Marine eutrophication is therefore quantified in unit of nitrogen equivalents, while freshwater eutrophication in unit of phosphorus equivalents [39, 41].

Human toxicity, terrestrial, marine, and freshwater ecotoxicity quantify the effect of pollutant emissions and distribution within the system. The absorption of heavy metals from seawater during biomass growth may result in improved water quality [58]. However, the analysis should consider the pollutant flows in the system and identify potential reemissions. For example, production of fertilizers from seaweed may move heavy metals from seawater to agricultural field, modifying the potential exposure to humans and animals [18].

6 Interpretation

The interpretation phase identifies significant issues or hotspots of the system. The practitioner evaluates the completeness, sensitivity, and consistency of the study. Here, he draws conclusions, exposes the limitations, and provides recommendations for the readers.

Completeness is achieved when the conclusions satisfy the goal and scope of the assessment. Interpretation is an iterative phase: if a lack of data is observed, the practitioner might decide to either improve the data collected or adapt the goal and scope to what is practically achievable.

Uncertainty and sensitivity analyses help the practitioner to evaluate how reliable the results and conclusions are [8]. The uncertainty analysis should estimate the limits of the measurement and provide a range of final results. The sensitivity analysis applies variations to the input parameters to highlight which process will be mostly affected. For example, a sensitivity analysis can consider variations of input values by 10% increments varied from 50 to 150%. The key parameters can be transport distance, biomass moisture content, water reduction during drying phase, biomass yield, biomass composition, and material lifetime [29].

7 Dealing with Allocation

The complex biological structure of seaweed allows the extraction and use of different components. For example, seaweed can be converted into bioethanol, fertilizer, and protein [18]. This process requires a first pretreatment step, i.e., milling, to increase active surface. Secondly the biomass is hydrolyzed and fermented in a reactor. It follows a separation of the solid and liquid fraction. The solid fraction is dried and used as high protein content ingredient for fish feed. The liquid fraction is distilled to obtain bioethanol and liquid fertilizer (Fig. 4). If the goal of the analysis is to evaluate the impact of a single output, e.g., only bioethanol, the practitioner has

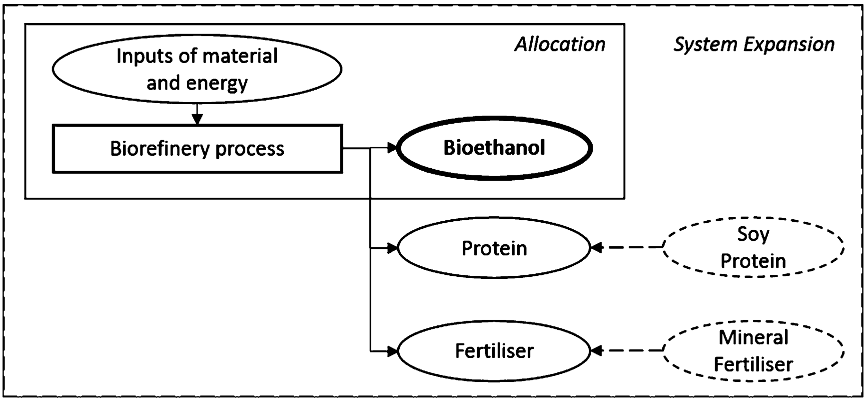

Fig. 4 The diagram shows the system boundaries when performing allocation (unbroken line) or system expansion (dashed line)

two main choices: allocation of impacts among the co-products or system expansion [8].

When allocation is performed—the impact of the system is distributed among the multiple products—the LCA is called attributional. Priority should be given to allocation according to physical relations between the co-products, e.g., mass or energy content. When this is not possible, other relations can be used, e.g., economic value.

Mass allocation requires impacts distribution according to the mass of the products. Following the biorefinery example (Fig. 4), fertilizers have the highest mass (due to high water content) and receive 91% of the impacts, while bioethanol and protein receive 7% and 1%, respectively (Table 2).

Energy allocation considers the energy content of the products. In this case, bioethanol has the highest energy content and receives 88% of the impacts, protein 12%, and fertilizer 0%, since this is mostly water and nutrients (Table 2).

Economic allocation considers the economic value of the products. Bioethanol has a lower price than proteins, but given the higher production, he receives the 78% of the impacts while protein the 22% (Table 2). Fertilizers have no commercial value, therefore no impacts are allocated to it.

Whenever possible, the practitioner should use the system expansion approach [8]. In the biorefinery example, when seaweed-based fertilizer and protein enter the market, a decrease in production of mineral fertilizers and soy proteins occurs, i.e., substituted products (Fig. 4). In the LCA calculation, the substituted product has a mathematically negative value on the total impact. Therefore, the impact of bioethanol is equal to the total impact of the system minus the avoided impact of the production of soy protein and mineral fertilizer (Table 2).

Table 2
Alternative impacts of bioethanol production according to mass, energy and economic allocation and system expansion

Outputs	Total	Fertilizer	Protein	Bioethanol
Weight (mg)	7.9	7.2	0.1	0.6
Energy content (MJ)	15,900.0		1,900	14,000
Economic value (€)	750.0		170	580
Impact on climate change (kg CO_2 eq)	1,300			
Mass allocation				
Percent	100%	91%	1%	7%
Impact (kg CO_2 eq)	1,300.0	1,186	19	**95**
Energy allocation				
Percent	100%	0%	12%	88%
Impact (kg CO_2 eq)	1,300.0		155	**1,145**
Economic allocation				
Percent	100%	0%	23%	77%
Impact (kg CO_2 eq)	1,300.0		295	**1,005**
System expansion				
Substituted products	Total	Mineral fertilizer	Soy protein	
Impact (kg CO_2 eq)	1,300	−160	−5	**1,135**

Values related to 1 ha of offshore cultivated seaweed exemplified from Seghetta et al. [18]

A more complex version of system expansion is called consequential approach. A consequential LCA aims at considering the future consequences of marginal changes [59, 60]. When these changes affect the market of a good, all the suppliers and competitors should be taken into account. For example, if seaweed is used as protein supplement, it will compete with all the other protein suppliers on the market that match the seaweed quality. Therefore, the analysis will take in consideration the potential scenario occurring: equal reduction among all the suppliers, only one supplier particularly affected, shift in prices, change in total demand, etc. Several models are available to describe the market behavior [61] and, combined with limitation of data, make this assessment more uncertain [62] but more realistic [60]. Consequential approaches are mostly used to define policy since the marginal effects can play a role on a regional or global level.

8 Discussion and Conclusions

The holistic approach of LCA provides a quantification of the impacts of an entire system. LCA can evaluate the seaweed value chain from cultivation, through processing, use, and end-of-life. The results can identify areas where the system can be improved. Each impact category can highlight a particular environmental problem and guide the designer to take action to reduce it.

Impact on climate change shows that the infrastructure necessary to offer support for seaweed cultivation has a significant impact. In particular, the plastic manufacture and consumption for buoys have high emission of greenhouse gases with respect of the quantity of biomass produced. Therefore, the material consumption should be reduced or the lifetime increased [18, 29].

CED can highlight the importance of storage design. Energy consumption for drying seaweed is a high energy-intensive process and affects the overall energy balance when producing biofuels [18, 29]. Storage of seaweed as ensilage—a process that reduces the biomass degradation by lowering the pH to acid environment—is an alternative method to reduce the energy consumption [63]. However, while it might represent a solution for biogas production, it is not recommended for bioethanol, since the ensilage process reduces the quantity of fermentable sugars in the biomass.

The impacts of seaweed cultivation can be reduced by improving productivity of the species so that the efficiency of material and energy use is increased [18, 40]. Currently, test sites are cultivating specimens collected in the wild, adapted to local environmental conditions [64]. A continuous selection and genetic improvement during successive generations will likely increase yields, similarly to historical development in agriculture sector.

Overall, despite a structured and standardized approach, LCA is highly affected by data quality [35]. Seaweed cultivation and conversion are still at its infancy, and consequently data are often based on pilot scale trials or laboratory experiments. On one hand, this makes LCA results more uncertain, but on the other hand, this allows LCA to provide recommendation at the development phase where changes can be applied without significant economic investments.

With the progress of research and industrial development, we expect to obtain more and more representative data and further improve the quality of LCA.

References

1. BIM (2014) The European market for sea vegetables. Bord Iascaigh Mhara
2. Zemke-White WL, Ohno M (1999) World seaweed utilisation: an end-of-century summary. J Appl Phycol 11:369–376
3. FAO (2014) The state of world fisheries and aquaculture: opportunities and challenges. Food and Agriculture Organization of the United Nations, Rome
4. Buschmann AH, Camus C, Infante J, Neori A, Israel Á, Hernández-González MC, Pereda SV, Gomez-Pinchetti JL, Golberg A, Tadmor-Shalev N, Critchley AT (2017) Seaweed production: overview of the global state of exploitation, farming and emerging research activity. Eur J Phycol 52:391–406. https://doi.org/10.1080/09670262.2017.1365175
5. Jung KA, Lim S-R, Kim Y, Park JM (2013) Potentials of macroalgae as feedstocks for biorefinery. Bioresour Technol 135:182–190. https://doi.org/10.1016/j.biortech.2012.10.025
6. Noble B, Nwanekezie K (2017) Conceptualizing strategic environmental assessment: principles, approaches and research directions. Environ Impact Assess Rev 62:165–173. https://doi.org/10.1016/j.eiar.2016.03.005
7. European Commission (2003) Technical Guidance Document on Risk Assessment. European Commission—Joint Research Centre Institute for Health and Consumer Protection European Chemicals Bureau (ECB), Office for Official Publications of the European Communities L-2985 Luxembourg
8. International Organization for Standardization (2006) Environmental management—life cycle assessment—requirements and guidelines. BS EN ISO 14044:2006+A1:2018
9. Cappelli A, Gigli E, Romagnoli F, Simoni S, Blumberga D, Palerno M, Guerriero E (2015) Co-digestion of macroalgae for biogas production: an LCA-based environmental evaluation. Energy Procedia 72:3–10. https://doi.org/10.1016/j.egypro.2015.06.002
10. Cappelli A, Gigli E, Muzi L, Renda R, Simoni S (2010) Energetic and environmental impacts related to transport and assembling processes in a biogas production plant from marine macroalgae (FP7 Project BioWALK4Biofuels). Sci J Riga Tech Univ Environ Clim Technol 5:16–27. https://doi.org/10.2478/v10145-010-0030-7
11. Czyrnek-Delêtre MM, Rocca S, Agostini A, Giuntoli J, Murphy JD (2017) Life cycle assessment of seaweed biomethane, generated from seaweed sourced from integrated multi-trophic aquaculture in temperate oceanic climates. Appl Energy 196:34–50. https://doi.org/10.1016/j.apenergy.2017.03.129
12. Giwa A (2017) Comparative cradle-to-grave life cycle assessment of biogas production from marine algae and cattle manure biorefineries. Bioresour Technol 244:1470–1479. https://doi.org/10.1016/j.biortech.2017.05.143
13. Jung KA, Lim S-R, Kim Y, Park JM (2017) Opportunity and challenge of seaweed bioethanol based on life cycle CO_2 assessment. Environ Prog Sustain Energy 36:200–207. https://doi.org/10.1002/ep.12446
14. Langlois J, Sassi J-F, Jard G, Steyer J-P, Delgenes J-P, Hélias A (2012) Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels Bioprod Biorefin 6:387–404. https://doi.org/10.1002/bbb.1330
15. Pilicka I, Blumberga D, Romagnoli F (2011) Life cycle assessment of biogas production from marine macroalgae: a latvian scenario. Sci J Riga Tech Univ Environ Clim Technol 6:69–78. https://doi.org/10.2478/v10145-011-0010-6
16. Aitken D, Bulboa C, Godoy-Faundez A, Turrion-Gomez JL, Antizar-Ladislao B (2014) Life cycle assessment of macroalgae cultivation and processing for biofuel production. J Clean Prod 75:45–56. https://doi.org/10.1016/j.jclepro.2014.03.080
17. Alvarado-Morales M, Boldrin A, Karakashev DB, Holdt SL, Angelidaki I, Astrup T (2013) Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. Bioresour Technol 129:92–99. https://doi.org/10.1016/j.biortech.2012.11.029
18. Seghetta M, Hou X, Bastianoni S, Bjerre A-B, Thomsen M (2016) Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers—a step towards a regenerative bioeconomy. J Clean Prod 137:1158–1169. https://doi.org/10.1016/j.jclepro.2016.07.195
19. Jensen A (1993) Present and future needs for algae and algal products. Hydrobiologia 260/261:15–23

20. Bilan MI, Grachev AA, Shashkov AS, Kelly M, Sanderson CJ, Nifantiev NE, Usov AI (2010) Further studies on the composition and structure of a fucoidan preparation from the brown alga *Saccharina latissima*. Carbohydr Res 345:2038–2047. https://doi.org/10.1016/j.carres.2010.07.009
21. Bichraoui-Draper N, Xu M, Miller SA, Guillaume B (2015) Agent-based life cycle assessment for switchgrass-based bioenergy systems. Resour Conserv Recycl 103:171–178. https://doi.org/10.1016/j.resconrec.2015.08.003
22. Hospido A, Davis J, Berlin J, Sonesson U (2010) A review of methodological issues affecting LCA of novel food products. Int J Life Cycle Assess 15:44–52. https://doi.org/10.1007/s11367-009-0130-4
23. Miller SA, Moysey S, Sharp B, Alfaro J (2013) A stochastic approach to model dynamic systems in life cycle assessment. J Ind Ecol 17:352–362. https://doi.org/10.1111/j.1530-9290.2012.00531.x
24. Liska AJ, Yang HS, Bremer VR, Klopfenstein TJ, Walters DT, Erickson GE, Cassman KG (2009) Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol. J Ind Ecol 13:58–74. https://doi.org/10.1111/j.1530-9290.2008.00105.x
25. Shibasaki M, Fischer M, Barthel L (2007) Effects on life cycle assessment—scale up of processes. In: Takata S, Umeda Y (eds) Advances in life cycle engineering for sustainable manufacturing businesses. Springer, London, pp 377–381
26. International Organization for Standardization (2006) ISO 14040:2006 Environmental management—life cycle assessment—principles and framework
27. International Organization for Standardization (2010) ISO 14025:2010 Environmental labels and declarations—type III environmental declarations—principles and procedures
28. PAS (2011) PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI, London
29. van Oirschot R, Thomas J-BE, Gröndahl F, Fortuin KPJ, Brandenburg W, Potting J (2017) Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. Algal Res 27:43–54. https://doi.org/10.1016/j.algal.2017.07.025
30. Goglio P, Brankatschk G, Knudsen MT, Williams AG, Nemecek T (2017) Addressing crop interactions within cropping systems in LCA. Int J Life Cycle Assess 1(9). https://doi.org/10.1007/s11367-017-1393-9
31. Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G (2011) Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agr Syst 104:217–232. https://doi.org/10.1016/j.agsy.2010.10.002
32. Werner A, Dring M (2011) Aquaculture explained, cultivating *Palmaria palmata*. Bord Iascaigh Mhara
33. Bak UG, Mols-Mortensen A, Gregersen O (2018) Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. Algal Res 33:36–47. https://doi.org/10.1016/j.algal.2018.05.001
34. European Commission, Joint Research Centre, Institute for Environment and Sustainability (2010) International Reference Life Cycle Data System (ILCD) handbook general guide for life cycle assessment: detailed guidance. Publications Office, Luxembourg
35. Henriksson PJG, Guinée JB, Kleijn R, de Snoo GR (2012) Life cycle assessment of aquaculture systems—a review of methodologies. Int J Life Cycle Assess 17:304–313. https://doi.org/10.1007/s11367-011-0369-4
36. Weidema B, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo CO, Wernet G (2013) The ecoinvent database: overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent Rep 1(v3):169
37. Durlinger B, Tyszler M, Scholten J, Broekema R, Blonk H (2014) Agri-footprint; a life cycle inventory database covering food and feed production and processing. San Francisco, USA, p 8
38. Takano A, Winter S, Hughes M, Linkosalmi L (2014) Comparison of life cycle assessment databases: A case study on building assessment. Build Environ 79:20–30. https://doi.org/10.1016/j.buildenv.2014.04.025
39. European Commission, Joint Research Centre, Institute for Environment and Sustainability (2011) International Reference Life Cycle Data System (ILCD) handbook framework and requirements for life cycle impact assessment models and indicators. Publications Office, Luxembourg
40. Seghetta M, Romeo D, D'Este M, Alvarado-Morales M, Angelidaki I, Bastianoni S, Thomsen M (2017) Seaweed as innovative feedstock for energy and feed—evaluating the impacts through a Life Cycle Assessment. J Clean Prod 150:1–15. https://doi.org/10.1016/j.jclepro.2017.02.022
41. Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R (2013)

ReCiPe 2008, a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report 1 characterization. Minist Hous Spec Plan Environ 133

42. Guinée G (2002) Handbook on life cycle assessment, operational guide to the ISO standards. Springer, Dordrecht
43. Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Zhang H, Takemura T (2013) Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK
44. Goedkoop M, Spriensma R (2001) The eco-indicator 99, a damage oriented method for life cycle impact assessment. Methodol Rep. Plotterweg 12, 3821BB Amersfoort, Netherlands, pp 144. https://www.pre-sustainability.com/download/EI99_methodology_v3.pdf
45. Seghetta M, Tørring D, Bruhn A, Thomsen M (2016) Bioextraction potential of seaweed in Denmark—an instrument for circular nutrient management. Sci Total Environ 563–564:513–529. https://doi.org/10.1016/j.scitotenv.2016.04.010
46. Langlois J, Fréon P, Steyer J-P, Delgenès J-P, Hélias A (2014) Sea-use impact category in life cycle assessment: state of the art and perspectives. Int J Life Cycle Assess 19:994–1006. https://doi.org/10.1007/s11367-014-0700-y
47. Taelman SE, De Meester S, Schaubroeck T, Sakshaug E, Alvarenga RAF, Dewulf J (2014) Accounting for the occupation of the marine environment as a natural resource in life cycle assessment: an exergy based approach. Resour Conserv Recycl 91:1–10. https://doi.org/10.1016/j.resconrec.2014.07.009
48. Abdou K, Aubin J, Romdhane MS, Le Loc'h F, Lasram FBR (2017) Environmental assessment of seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*) farming from a life cycle perspective: a case study of a Tunisian aquaculture farm. Aquaculture 471:204–212. https://doi.org/10.1016/j.aquaculture.2017.01.019
49. Knudsen MT, Hermansen JE, Cederberg C, Herzog F, Vale J, Jeanneret P, Sarthou J-P, Friedel JK, Balázs K, Fjellstad W, Kainz M, Wolfrum S, Dennis P (2017) Characterization factors for land use impacts on biodiversity in life cycle assessment based on direct measures of plant species richness in European farmland in the 'Temperate Broadleaf and Mixed Forest' biome. Sci Total Environ 580:358–366. https://doi.org/10.1016/j.scitotenv.2016.11.172
50. Milà i Canals L, Bauer C, Depestele J, Dubreuil A, Freiermuth Knuchel R, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007) Key elements in a framework for land use impact assessment within LCA. Int J Life Cycle Assess 12:5–15. https://doi.org/10.1065/lca2006.05.250
51. Milà i Canals L, Romanyà J, Cowell SJ (2007) Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA). J Clean Prod 15:1426–1440. https://doi.org/10.1016/j.jclepro.2006.05.005
52. Seghetta M, Marchi M, Thomsen M, Bjerre A-B, Bastianoni S (2016) Modelling biogenic carbon flow in a macroalgal biorefinery system. Algal Res 18:144–155. https://doi.org/10.1016/j.algal.2016.05.030
53. European Parliament (2009) Directive 2004/39/Ec of the European Parliament and of the Council of 21 April 2004. Off J Eur Union L 140/16:47
54. Frischknecht R, Jungbluth N, Althaus N, Bauer C, Doka G, Dones G, Hischier R, Hellweg S, Humbert S, Köllner T (2007) Implementation of life cycle impact assessment methods. Ecoinvent Rep 151
55. Mulder K, Hagens NJ (2008) Energy return on investment: toward a consistent framework. AMBIO J Hum Environ 37:74–79. https://doi.org/10.1579/0044-7447(2008)37[74:EROITA]2.0.CO;2
56. Chung I-K, Kang Y-H, Yarish C, George PK, Lee J-A (2002) Application of seaweed cultivation to the bioremediation of nutrient-rich effluent. ALGAE 17:187–194. https://doi.org/10.4490/ALGAE.2002.17.3.187
57. Quilliam RS, van Niekerk MA, Chadwick DR, Cross P, Hanley N, Jones DL, Vinten AJA, Willby N, Oliver DM (2015) Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land? J Environ Manage 152:210–217. https://doi.org/10.1016/j.jenvman.2015.01.046
58. Sudharsan S, Seedevi P, Ramasamy P, Subhapradha N, Vairamani S, Shanmugam A (2012) Heavy metal accumulation in seaweeds and sea grasses along southeast coast of India. J Chem Pharm Res 4:4240–4244

59. Ekvall T, Weidema BP (2004) System boundaries and input data in consequential life cycle inventory analysis. Int J Life Cycle Assess 9:161–171. https://doi.org/10.1007/BF02994190
60. Schmidt JH (2008) System delimitation in agricultural consequential LCA: outline of methodology and illustrative case study of wheat in Denmark. Int J Life Cycle Assess 13:350–364. https://doi.org/10.1007/s11367-008-0016-x
61. Vázquez-Rowe I, Rege S, Marvuglia A, Thénie J, Haurie A, Benetto E (2013) Application of three independent consequential LCA approaches to the agricultural sector in Luxembourg. Int J Life Cycle Assess 18:1593–1604. https://doi.org/10.1007/s11367-013-0604-2
62. Dale BE, Kim S (2014) Can the predictions of consequential life cycle assessment be tested in the real world? Comment on "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation...". J Ind Ecol 18:466–467. https://doi.org/10.1111/jiec.12151
63. Herrmann C, FitzGerald J, O'Shea R, Xia A, O'Kiely P, Murphy JD (2015) Ensiling of seaweed for a seaweed biofuel industry. Bioresour Technol 196:301–313. https://doi.org/10.1016/j.biortech.2015.07.098
64. Bruhn A, Tørring D, Thomsen M, Canal-Vergés P, Nielsen M, Rasmussen M, Eybye K, Larsen M, Balsby T, Petersen J (2016) Impact of environmental conditions on biomass yield, quality, and bio-mitigation capacity of *Saccharina latissima*. Aquac Environ Interact 8:619–636. https://doi.org/10.3354/aei00200