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Off-Shore and On-Shore Macroalgae Cultivation and Wild Harvesting: an LCA-Based Evaluation from Baltic Sea Region Case Studies

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***Abstract* – Seaweeds are organisms with unique characteristics. They contain a broad spectrum of micro and macro elements (i.e., minerals, carbohydrates, proteins, lipids, pigments, and vitamins). Furthermore, they have a very high growth rate and are present in large quantities and species in nature. Therefore, they represent an ideal feedstock for a biorefinery concept. Historically, macroalgae used in biorefineries have been harvested directly from the sea or the shores, i.e., off-shore technique. However, recent studies are analysing the possibility of creating on-shore cultivation facilities. This research aims to perform a Life Cycle Assessment (LCA) study that analyses and compares the environmental impact of two seaweed cultivation and wild harvesting techniques in the Baltic Sea Region conditions based on existing pre-commercial and commercial projects. Inventory data are collected directly from two macroalgae producers, one off-shore and one on-shore, integrated with literature, and then normalized to the selected functional unit, i.e., 1 ton of harvested fresh macroalgae. The results, implemented with *SimaPro 9.4* software, determine which of the two techniques has the highest environmental impact and which are the most sensitive environmental indicators. Furthermore, the results underline the critical parameters for the two cultivations (i.e., fuel consumption and electricity), contributing to identifying environmental benchmarks for further optimization strategies. The sensitivity analysis included in the study aims to explore and highlight the effect of the variation of selected input parameters or assumptions to provide a consistent assessment of the uncertainty of the model outputs and the main findings in terms of environmental impacts.**

***Keywords* – Environmental impact; Life Cycle Assessment; seaweed; sustainability.**

Nomenclature		
AP	Acidification	H+ eq.
AS	Alternative scenario	–
CC	Climate change	kg CO_2 eq.
ECF	Ecotoxicity freshwater	CTUe
EF	Eutrophication freshwater	kg P eq.
EM	Eutrophication marine	kg N eq.

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FU	Functional Unit	–
LCA	Life Cycle Assessment	–
LCI	Life Cycle Inventory	–
LU	Land use	Pt
ONS	On-Shore cultivation	–
OFS	Off-shore cultivation	–
PM	Particular matter	Disease inc.
Pt	Eco point	–
RF	Resource use fossil	Mj
RM&M	Resource use minerals & metals	kg Sb eq.
WH	Wild harvesting	–
WP	Water use	m^3 depriv.
Wp	Watt peak	–

1. INTRODUCTION

Global macroalgae production has been steadily growing for the last thirty years. The Food and Agriculture Organization of the United Nations reports 35.1 million tons for 2020 (+1.4 % compared to 2019), with China and Japan as the top-producing countries. This market generated a revenue of 264.6 EUR billion [1].

Seaweeds have historically been used as feed, food, or fertilizer. In the last decade, new applications have been undertaken to explore them as a great source of micro and macro elements (i.e., minerals, carbohydrates, proteins, lipids, pigments, and vitamins) [2]. Extensive attention has been paid to the production of biofuels and energy [2] or in the food [3], dietary products [4], cosmetic [5], pharmaceutical, and medical [6] industries, with an emphasis on using biorefinery conversion processes.

An idea of production on an industrial scale of this type requires a constant input of biomass feedstock to plump the process, which cannot be supported by the mere and simple handy collection of macroalgae from the beaches [7]. Nowadays, there are three possibilities. The first is the most straightforward collection of wild algae in the sea by vessels [8]. The other two fall into a cultivation design. One is a standard and consolidated process that considers biomass growth on substrates (i.e., ropes) in open waters [9]. The second includes cultivation on land in tank systems with the possibility to control the growing parameters precisely [10].

All these techniques have pros and cons. Harvesting in the open sea requires a lower consumption of resources but is susceptible to the seasonality of macroalgae [11], [12] and to the limitations in the catches imposed by national regulations [13]. Moreover, it can lead to problems for the sea or ocean ecosystem, with loss of habitat and shelter for animals, a decrease in nursery grounds for juvenile invertebrates and fish, and a loss of direct and indirect food sources for other species (e.g., mammals, birds, and piscivorous fish) [14].

Cultivation in marine farm systems allows the growth of organisms with simple operations [15] in a safer and more controlled environment than wild ones. Nevertheless, it has more productions limited by space [15] and troubles with the structures' resistance to the sea's extremely adverse conditions [16].

The land system is the one that most optimizes the production [17] thanks to the possibility of controlling the process parameters (i.e., salinity, light, pH, and CO_2) [16] individually.

However, it requires land that could be used for other purposes and energy to maintain the environmental conditions of growth at an optimal level [18], as well as high costs for constructing the plants [16].

It is thus difficult to define the absolute optimal technique for obtaining a macroalgae feedstock. Because the selection mainly depends on external factors (i.e., algae species, geography, production yield to reach, and final use of the biomass) that can make one lean towards one choice. To help in this decision, an analysis tool such as the Life Cycle Assessment (LCA) represents a quantitative framework to rank and screen more optimal and sustainable solutions. Through an LCA study, it is possible to draw a product's or system's environmental performance [19], [20]. In this study's case, the different types of systems for collecting or producing seaweed are described. There are already examples of LCA studies that include these aspects related to macroalgae [21]–[27]. However, as far as the authors of this work know, there is yet to be research in the literature whose main objective is to compare the different techniques for algae production.

This research reports a comparative LCA analysis, including three different possibilities for cultivating and harvesting red macroalgae. Data for wild harvesting of *Furcellaria lumbricalis* is gathered from an Estonian producer. Information about on-shore cultivation of *Schizymenia valentinae* species is obtained from an Icelandic company. Data concerning off-shore cultivation are integrated based on information collected from the literature [24]. This report contains an entirely exhaustive inventory that permits modeling the baseline scenarios. Once the initial calculation case is defined, alternative ones will also be performed to understand how the systems react to some parameters' changes.

2. METHODOLOGY

The LCA methodology is considered a quantitative and well-standardized approach to defining the environmental performance of a given service or system. It is based on the ISO 14044:2006 standard [19], [20] representing the main guidelines for the methodological approach setting the ground of this study. LCA is also used as a tool to support decision-making choices [28] when comparing different systems with the same function. LCA can identify the main environmental impact hotspots and the most sensitive system parameters in this case.

Four phases define an LCA study. The first is the goal and scope definition, in which the main discriminant of the study is declared. The second is the Life Cycle Inventory (LCI) phase, which focuses on collecting data necessary to characterize the phases of the chosen system. The third represents the transposition of the input data obtained in phase two into a series of environmental impact indicators. The last phase is the one that is responsible for the interpretation of the results. It also includes modifying some parameters susceptible to the system to understand how they can influence the final results. They are called sensitivity analysis or alternative scenarios [29].

Fig. 1 shows an outline of the methodology adopted in this study. It comprises three main parts:

- Represents the data collection needed to create the LCI. It was realized through bilateral meetings with a company that collects macro algae in Estonia and an enterprise that tests the possibility of developing on-shore seaweed cultivation in Iceland. A bibliographic analysis was used for the off-shore design. The data obtained were then integrated and refined through existing databases such as *Ecoinvent 3.8* [30];
- It is the LCA modelling phase. *SimaPro 9.4* software developed by *Pre' Consultants*

[31] was used. It also incorporates many calculation methods, including the one selected for this study, the Environmental Footprint (EF) 3.0 [32].

– It is the analysis of the results, initially, with the three basic scenarios and their comparison. Then, a sensitivity analysis modifies some critical process parameters. These alternative designs are described in subchapter 2.3.4.

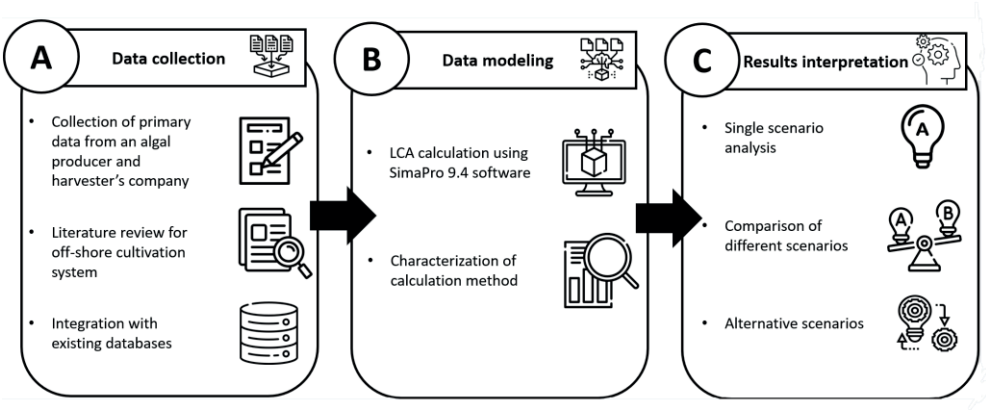


Fig. 1. Methodological research approach including the LCA perspective.

The study's major limitation concerns the scaling procedures of the primary data, from pilot plants, such as the case of on-shore cultivation, to the industrial ones of wild harvesting. Empirical scaling formulas were used, reported in the annexes, which may have some uncertainty. For this reason, the choice of sensitive analysis is fundamental to model the different scenarios in the most precise way possible.

2.1. Goal and Scope Definition

This LCA study aims to analyse seaweed harvesting and cultivation systems. For the cultivation ones, two options were selected: one is in the open sea called off-shore (OFS), and the second one is on the mainland called on-shore (ONS). Wild harvesting (WH) of seaweed was included in the analysis since it is the predominant method for obtaining local seaweed in Europe [33]. This research aims to identify the characteristics that influence the environmental performance of these three designs. By trying to identify the strengths and weaknesses of the different techniques, this study can be used as decision-support for the seaweed industry.

The functional unit (FU) selected is a quantitative expression of the product's system, setting the expected standard for direct comparison among the different techniques included in this study. The FU is defined as 1 ton of fresh seaweed harvested or produced. It considers an algal species purity of 100 %. This choice also aligns with similar literature studies about the LCA approach applied to macroalgae systems [23], [34].

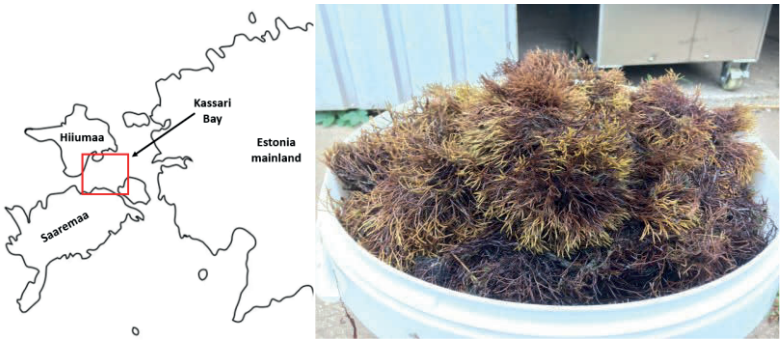
2.2. System Definition

The procedures used for collecting or producing macroalgae and the description of the selected species are included in the system definition. The system is developed for the Baltic Sea Region conditions. The data used will be characteristic of this regional situation.

2.2.1. Seaweeds Description

Two macroalgae species were selected for this study: *Furcellaria lumbricalis* and *Schizymenia valentinae*. The first is used for wild harvesting and cultivation in the open sea, while the second is for production through the on-shore farming system.

Furcellaria lumbricalis is a red macroalgae [35] widely distributed in the North Atlantic and Arctic oceans waters. It is one of the *rhodophytes* prevalent in the Baltic Sea Region [36]. It typically grows on hard substrates such as rocks, boulders, and stones. It then develops in an open environment, which can also be sandy or muddy, where it forms real monotypic dense meadows [35]. It is a species of perennial seaweed with a life span of 5–10 years. It can develop up to 30 m in depth, even if the greatest occurrence is around 8–12 m [37], and tolerate a low salinity environment [35]. The collection took place in the geographical confines of Estonia, more precisely in the Kassari Bay area (Fig. 2(a)) at 7 m deep, which contains a stock of up to 140 000 tons, largely unused. Fig. 2(b) shows a picture of the collected algae.



(a) (b)

Fig. 2. a) The geographical location of Kassari Bay (Estonia), b) Harvested *Furcellaria lumbricalis* with the kind permission of Vetik OÜ.

The second seaweed is *Schizymenia valentinae*. It was described from the Icelandic coast as *Schizymenia jonssonii* in 2020 [38] but was later discovered in the Sea of Okhotsk and Bering Sea. Its correct name is *S. valentinae*, as it had previously been described as *Neoabottiella valentinae* [39]. It is found in the South, West, and North Icelandic coasts. It is distinguished from other species of *Schizymenia* species by molecular phylogeny, lack of glandular cells, and being strictly intertidal [38]. It grows mainly directly on the rocks, reaching its maximum size around July. This peculiarity makes it simple to collect and use as an initial inoculum for on-shore cultivation. The red circles of Fig. 3(a) show where *Schizymenia valentinae* can be found in Iceland [38]. This study focuses on a sample taken in Southwest Iceland. Fig. 3(b) displays a picture of the *Schizymenia valentinae* specimen.



(a) (b)

Fig. 3. a) Map of *Schizymenia valentinae* distribution in Iceland, b) A *Schizymenia valentinae* specimen from aquaculture with the kind permission of Hyndla Ltd.

2.2.2. System Boundaries for Scenario 1: Wild Harvesting

The scenario considered of wild harvesting relates to the collection of red seaweed *Furcellaria lumbricalis* in Kassari Bay in Estonia. Fig. 4a outlines the steps of the process. The operations begin with collecting wild seaweed using a trawling boat with a diesel engine. The harvesting area is located around 40 minutes from the harbour. This operation is performed using a specifically made trawling gear, a rectangular metal frame covered with a net, and carried behind the boat at a very low speed. Using this technique, the harvesting efficiency for the targeting species is 92.9 %. The capture of 5 % clamps and 2.1 % clay and mud is considered solid waste [40].

Afterward, the boat returns to the harbor, where it is unloaded using an electrically working unloader.

Finally, the *Furcellaria lumbricalis* is brought, using road transport, to a facility where it can be further processed.

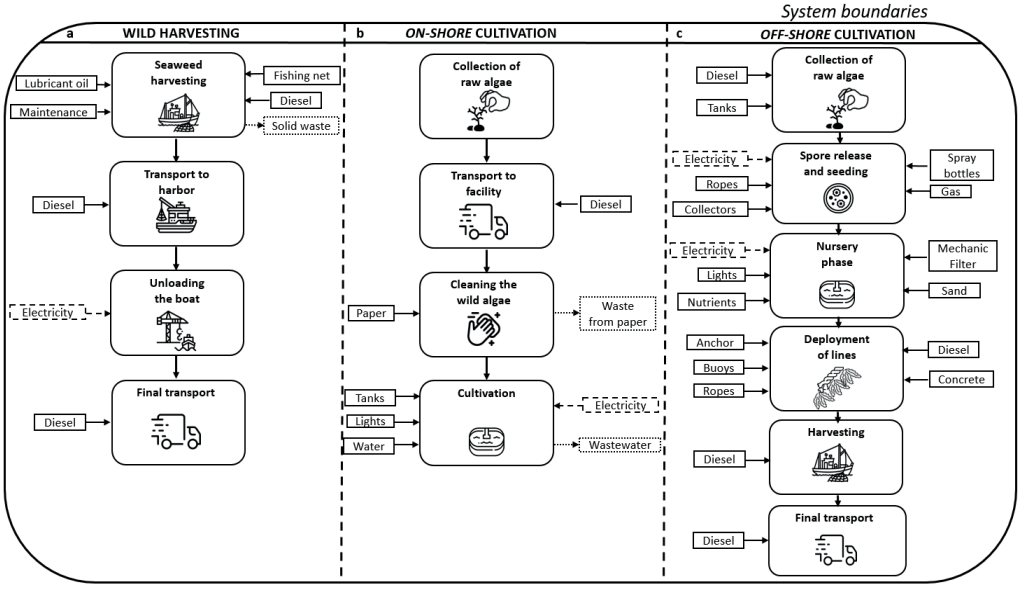


Fig. 4. a) System boundaries for WH, b) System boundaries for ONC and c) System boundaries for OFC. Note that the rounded boxes contain the main process steps, while the rectangular boxes contain the input and output regarding raw materials, energy, and waste. The continuous line of the boxes stands for "raw material", the dotted for "energy", and the pointed for "waste/wastewater".

2.2.3. System Boundaries for Scenario 2: On-Shore Cultivation

The scenario of the on-shore cultivation is summarized in Fig. 4b. The procedure begins with collecting *Schizymenia valentinae* specimens directly from their natural habitat (the area around Reykjavik, Iceland). The harvest occurs twice a year (spring and autumn) up to a maximum of 8 kg collected. The seaweed obtained is then transported for a 15 km road journey to where the cultivation phase will be carried out. There, the biomass is cleaned with paper towels and then weighed. The seaweed is placed inside fiberglass tanks where the growth phase begins for 6 weeks. The only input in this stage is seawater directly pumped from drill holes at a depth of 20–40 m. Given its richness in nutrients, no additional ones are needed. The growth rate obtained at the end of the 6 weeks is approximately 270 % [41]. The new specimens are harvested and manually cut into 36 mm sizes to encourage a new growth process. This growing-harvesting process continues throughout the year.

In the cultivation phase, the pump for the seawater and the lighting of the tanks to recreate the sunlight are the two main energy-consuming processes. All the electrical energy used has a geothermal energy source.

2.2.4. System Boundaries for Scenario 3: Off-Shore Cultivation

The system described for the off-shore cultivation (Fig. 4c) is based on the design described in the literature by the study of Seghetta (2016) [24]. This, even if not specifically for a species of macroalgae such as *Furcellaria lumbricalis* or *Schizymenia valentinae*, represents a complete inventory, as well integrated into a Baltic Sea Region scenario and which is similar to other designs present in the literature for red seaweed [42], [43].

The first phase for the OFC is creating a bioengineered cultivation system. Some algae specimens are taken from their natural environment and will serve as an initial inoculum for

the community's growth on the artificial substrate. It consists of Kuralon twine lines on which seaweed spores are deposited. Once the seeded lines have been prepared, they are deployed at sea. The operation is carried out with vessels. They are also used to maintain the lines and collect the algae produced. A final road transport is considered to standardize this technique to the WH scenario.

2.2.5. Alternative Scenarios

This study considers the possibility of modifying a few parameters with respect to an initial baseline scenario, creating alternatives (AS). From the analysis of the AS, it is possible to evaluate potential improvements in the environmental system's performance. The considered AS are:

- AS1 – Use of solar energy for 50 % of the electricity production in ONC and OFC scenarios. Because the electricity consumption for these designs seems to be a key parameter for the environmental impact;
- AS2 – Consider an ONC system based on natural sunlight instead of artificial LED light;
- AS3 – Select an environmentally friendly antifouling agent (its composition is described in the annex) instead of copper oxide base one for the WH scenario;
- AS4 – Reduce diesel consumption by 10 % for scenario WH and OFC vessels.

2.3. Environmental Impact Assessment

The Environmental Footprint (EF) 3.0 impact assessment method [32] was selected to analyse the three scenarios' environmental performance. In particular, the most representative indicators included in it have been chosen, namely:

- Climate change (CC), expressed in kg CO_2 eq., is ideal for evaluating a material or process's Global Warming Potential (GWP).
- Particular matter (PM), expressed in disease inc., and it is particularly interesting to quantify the emissions related to the extensive boat use during the harvesting and seaweed cultivation.
- Acidification (AP), quantified in mol H+ eq., is the atmospheric pollution from anthropogenic activities derived from sulfur, nitrogen, and NOx or ammonia [44], [45]. It is essential to evaluate their release during all the vessels' operations.
- Eutrophication freshwater (EF) and marine (EM), expressed in kg P eq. and kg N eq. respectively. Since most of the operations are carried out in the aquatic environment, it is crucial to quantify how significant the impact on these habitats is.
- Ecotoxicity freshwater (ECF), given in CTUe (Comparative Toxic Unit for aquatic ecotoxicity). Similar to EF and EM, it is particularly interesting since both WH and OFC operations act directly on marine ecosystems.
- Land use (LU) and water use (WP), reported in Pt and m^3 depriv. respectively. They are relevant for framing the impacts of ONC as there is the intensive use of land and water to enable on-shore cultivation.
- Resource use fossil (RF) and minerals & metals (RM&M). Expressed in MJ and kg Sb eq. respectively. They quantify the impact of the use of resources, particularly fossils since it is one of the most considerable inputs among raw materials.

2.4. Life Cycle Inventory (LCI)

The data quality of an LCA study is a crucial point. Primary data gives added value to the results because they are more realistic and peculiar to the analysed system. This paper collects most of the WH and ONC scenarios inputs directly from seaweed producers. While the OFC case comes from the literature, the data are then adapted and scaled to the FU of this study to permit a comparable scenario.

2.4.1. LCI for Scenario 1: Wild Harvesting

The data used are shown in Table 1. The values are scaled by the functional unit and lifetime (when applicable) and depend on the total seaweed collection for 2021 by the company [40].

TABLE 1. LIFE CYCLE INVENTORY FOR THE WILD HARVESTING SCENARIO

	Category	**Material/ component**	**Function**	**Quantity**	**Unit**	**Lifetime, y**	**Data source**
Seaweed harvesting							
Inputs	Raw materials	Nylon	Harvesting net	0.11	kg	5	Primary data
		Diesel fuel	For harvesting	5.00	L		Primary data
		Lubricant oil	Operation	0.18	kg		Primary data
		Epoxy paint	Maintenance of boat	0.083	kg		Primary data
		Antifouling agent	Maintenance of boat	0.028	kg		Primary data
		Steel	For the boat	0.27	kg	50	[46]
Outputs	Raw materials, waste	Seaweed	*Furcellaria lumbricalis*	1	ton		Primary data
		Sand, clay, and mud	From harvesting	21	kg		Primary data
Transport to the harbor							
Inputs	Raw materials	Diesel fuel	For transport to harbor	1.39	L		Primary data
Unloading the boat							
Inputs	Energy	Electricity	For unloading the boat	0.69	kWh		Primary data
Final transport							
Inputs	Transport	Freight lorry	Capacity > 12 ton	53.20	km		Primary data

2.4.2. LCI for Scenario 2: On-Shore Cultivation

Table 2 gives the inventory for the ONC. The values indicated are scaled by the functional unit and lifetime (when applicable) and depend on the total seaweed produced for the year 2021 by the company [41].

TABLE 2. LIFE CYCLE INVENTORY FOR THE ON-SHORE CULTIVATION SCENARIO

	Category	Material/ component	Function	Quantity	Unit	Lifetime, y	Data source
Collection of raw algae							
Outputs	Raw materials	Seaweed	*Schizymenia valentinae*	3	kg		Primary data
Transport to the facility							
Inputs	Transport	Passenger car	Euro 4 engine	15	km		Primary data
Cleaning the wild algae							
Inputs	Raw materials	Paper tissues	For cleaning	0.34	kg		Primary data
Outputs	Waste	Paper waste	From the cleaning	0.34	kg		Primary data
Cultivation							
Inputs	Raw materials	Polystyrene	For tanks	1.40	kg	20	Primary data
		Sea water	For cultivation	32.00	m^3		Primary data
		Water	For cleaning	1.12	m^3		Primary data
		Soap	For cleaning	0.446	L		Primary data
		LED lights	To create sunlight	47	pieces	10	Primary data
		Iron	Pump	12	kg	10	Primary data
	Energy	Electricity	For lighting	4652	kWh		Primary data
		Electricity	For pumping seawater	2.22	kWh		[47]
	Land use	Cultivation facility		333	m^2		Primary data
Outputs	Wastewater	Wastewater	From cleaning procedures	1.12	m^3		Primary data
		Seaweed	*Schizymenia valentinae*	1	ton		Primary data

The electricity consumption for pumping water was modelled following the equation reported in the work of Piccino (2016) [47]. This is because the company uses pumps shared with another plant. Therefore, it was difficult for them to disaggregate the energy utilization. All the electricity used in the ONC is obtained from a geothermal power plant.

2.4.3. LCI for Scenario 3: Off-Shore Cultivation

Table 3 reports the data used for the inventory for the OFC. They are taken from the inventory of Seghetta (2016) [24] and then scaled to this study's FU.

TABLE 3. LIFE CYCLE INVENTORY FOR THE OFF-SHORE CULTIVATION SCENARIO

	Category	Material/component	Function	Quantity	Unit	Lifetime, y	Data source
Collection of raw algae							
Inputs	Raw materials	Diesel fuel	Transport of seaweed	1.38	L		[24]
		PET	Tanks for SW	0.017	kg	10	[24]
Spore release and seeding							
Inputs	Raw materials	PET	Plastic jug	0.035	kg	5	[24]
		PEHD	Block of collectors	1.382	kg	5	[24]
		Polyvinyl alcohol	Kuralon twine	3.71	kg		[24]
		PET	Spray bottles	0.014	kg	5	[24]
	Energy	Natural gas	Preparation of collectors	0.33	kg		[24]
		Electricity	Autoclave	5.18	kWh		[24]
		Electricity	Refrigerator	1.62	kWh		[24]
Nursery phase							
Inputs	Raw materials	Sand		0.77	kg		[24]
		Polypropylene	Mechanical filter	0.18	kg		[24]
		UV filter (bulb)	Light emitting diode	0.00031	piece		[24]
		F2 medium	Specific nutrients for algae	0.83	L		[24]
	Energy	Electricity	Air pump	0.51	kWh		[24]
		Electricity	Water pump	0.13	kWh		[24]
		Electricity	Sand filter	0.08	kWh		[24]
		Electricity	UV filter	0.57	kWh		[24]
Deployment of lines							
Inputs	Raw materials	Iron	Screw anchor	0.933	kg	20	[24]
		Polyethylene	Black buoys	14.77	kg	8	[24]
		Nylon	Thin rope	7.98	kg		[24]
		Concrete	Concrete block	138.23	kg	20	[24]
		Polypropylene	Ropes for buoys	3.11	kg		[24]
		Polypropylene	Headline rope	3.36	kg	13	[24]
		Concrete	Concrete block rope	5.18	kg		[24]
	Consumption	Boat use		311	km		[24]
Harvesting							
Inputs	Consumption	Boat use		311	km		[24]
	Sea use			0.0003	ha		[24]
Final transport							
Inputs	Transport	Freight lorry	Capacity > 12 ton	53.20	km		Primary data

2.4.4. LCI for the Alternative Scenarios

For the AS1, the addition of solar panels and inverters for producing electricity from solar energy was considered. Multi-Si photovoltaic panels in the *Ecoinvent* database were taken as input materials, consisting of 60 solar cells of 156×156 cm with a capacity of 210 Wp. Even the inverters are contained in the *Ecoinvent* database and have a capacity of 0.5 kW. The photovoltaic system has been attributed a lifetime of 25 years [48]. The input values obtained, scaled according to FU and useful life and to produce 50 % of electricity, are 0.243 m^2 of solar panel and 0.031 pieces of inverter for ONC, and 0.00042 m^2 of solar panel and 0.031 pieces of inverter for OFC.

The AS2 was supposed to be a scenario where artificial light is replaced by natural sunlight, so it was considered a null energy consumption for that.

In the AS3 analyses, the standard antifouling agent made on a copper oxide base, particularly harmful to the environment, was replaced with a new one that is environmentally friendly, based on the publication of Lin and Usino [49].

For the AS4, there is a hypothetical improvement in the fuel consumption by the vessels in scenarios WH and OFC. For the WH, the new diesel consumption per FU is 4.48 L. While for the OFC, the consumption is 0.0224 kg/tkm of heavy fuel oil.

Deeper calculations of the values for the alternative scenarios are reported in the Annex.

3. RESULTS

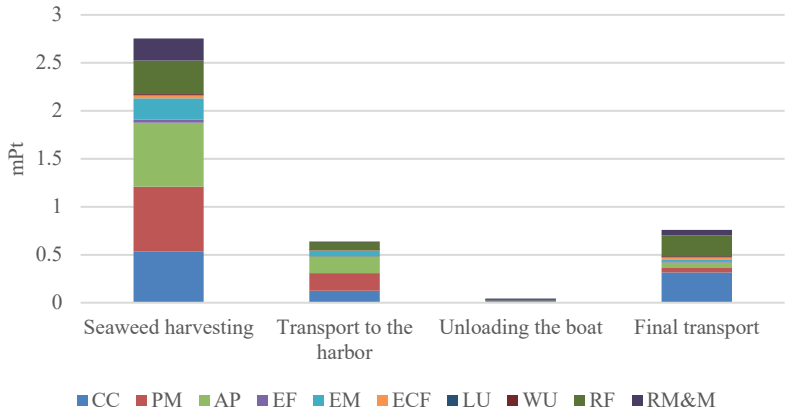
3.1. Results for the Wild Harvesting Scenario

Table 4 gives the environmental impact of the WH scenario for the selected midpoint indicators. On grey is the step with the highest values.

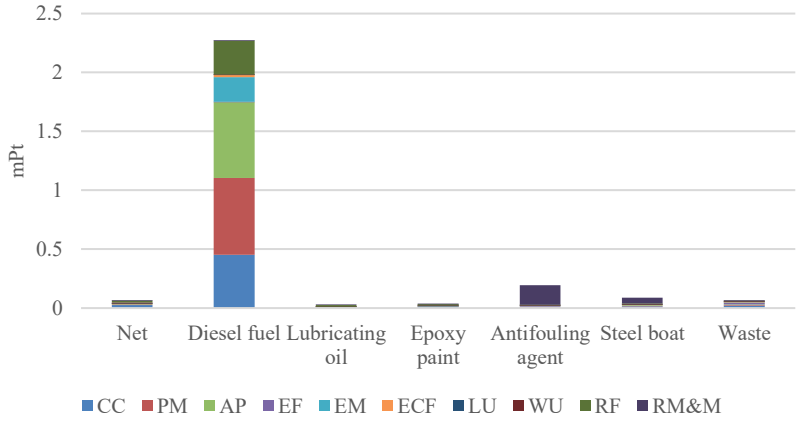
TABLE 4. MIDPOINT RESULTS FOR THE WH SCENARIO

Impact category	Unit	Seaweed harvesting	Transport to the harbor	Unloading the boat	Final transport
CC	kg CO_2 eq	1.90E+01	4.51E+00	5.99E–01	1.14E+01
PM	disease inc.	4.51E-06	1.20E-06	5.19E–08	8.60E–07
AP	mol H+ eq	5.98E-01	1.60E-01	5.53E–03	4.54E–02
EF	kg P eq	1.88E-03	4.75E-05	4.26E–05	8.45E–04
EM	kg N eq	1.45E-01	3.87E-02	8.16E–04	1.32E–02
ECF	CTUe	2.05E+02	3.00E+01	7.00E+00	1.39E+02
LU	Pt	3.82E+01	7.81E+00	3.81E+00	1.02E+02
WU	m^3 depriv.	1.86E+00	1.01E-02	4.43E–02	6.05E–01
RF	MJ	2.68E+02	6.22E+01	8.21E+00	1.70E+02
RM&M	kg Sb eq	1.92E-04	8.15E-07	8.08E–07	4.72E–05

From Fig. 5(a), seaweed harvesting is the process that contributes primarily to the impact. It is mainly related to the indicators CC, PM, and AP. Fig. 5(b) focuses on the harvesting procedure step, highlighting that the fuel diesel is the material that has the most significant environmental impact (2.27 mPt), followed by the antifouling agent (0.19 mPt).



(a)



(b)

Fig. 5. a) Endpoint results for the WH, b) Results of the seaweed harvesting procedures.

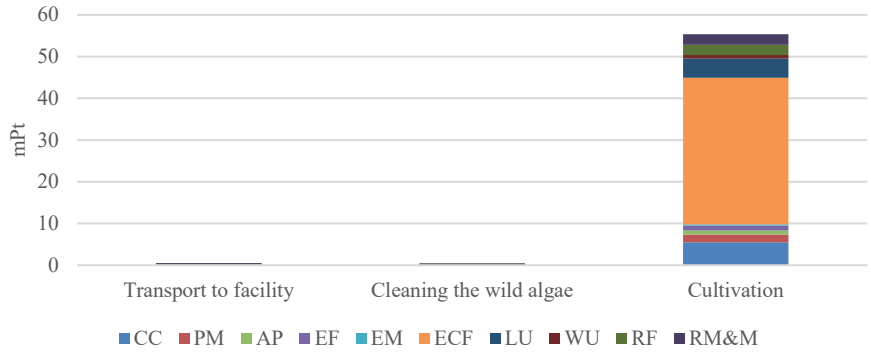
3.2. Results for the On-Shore Cultivation Scenario

Table 5 gives the environmental impact of the ONC scenario for the selected midpoint indicators. The stage of collecting the original raw algae to start the cultivation is not reported because it is null since it is supposed to be executed manually. In grey is the step with the highest values.

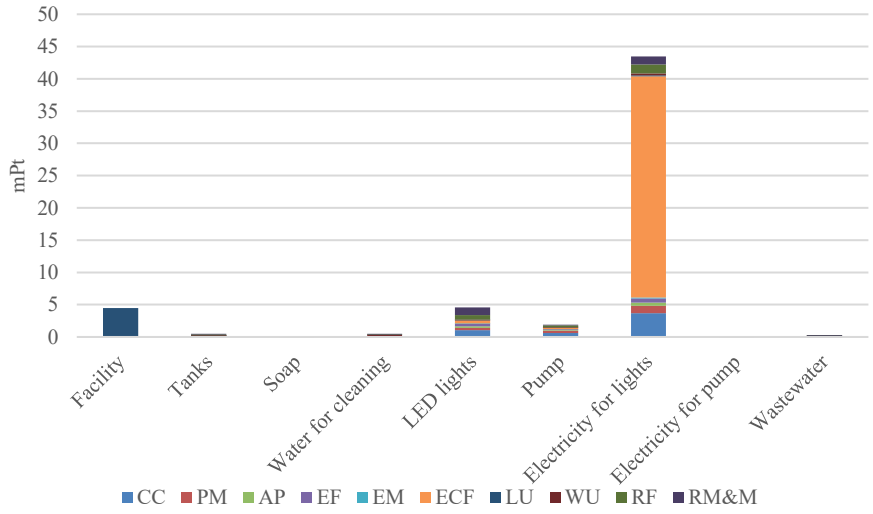
Fig. 6(a) confirms that the cultivation procedures are the most impactful for the ONC scenario (56.206 mPt). Fig. 6(b) shows how this is mainly connected to the electricity needed to create the artificial sunlight (43.49 mPt) on the ECF indicator. They are related to the infrastructure and processes for geothermal electricity production, particularly the drilling waste generated during the operations.

TABLE 5. MIDPOINT RESULTS FOR THE ONC SCENARIO

Impact category	Unit	Transportation to facility	Cleaning	Cultivation
CC	kg CO_2 eq	4.96E+00	2.70E+00	2.13E+02
PM	disease inc.	3.08E–07	2.46E–07	1.22E–05
AP	mol H+ eq	2.00E–02	1.58E–02	8.11E–01
EF	kg P eq	6.93E–04	1.08E–03	6.82E–02
EM	kg N eq	4.38E–03	3.47E–03	2.00E–01
ECF	CTUe	9.47E+01	1.63E+02	7.83E+04
LU	Pt	2.99E+01	8.56E+01	4.76E+04
WU	m^3 depriv.	5.09E–01	3.06E+00	1.11E+02
RF	MJ	6.78E+01	5.09E+01	1.96E+03
RM&M	kg Sb eq	6.52E–05	5.25E–05	2.15E–03



(a)



(b)

Fig. 6. a) Endpoint results for the ONC, b) Results of the cultivation procedures.

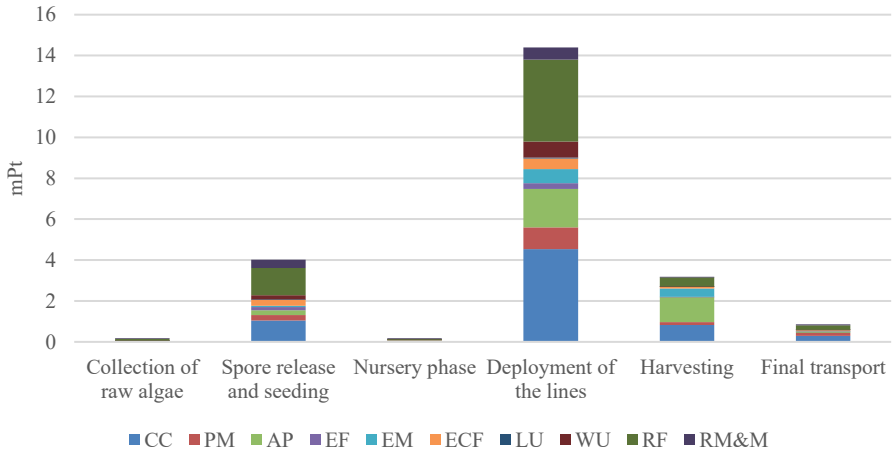
3.3. Results for the Off-Shore Cultivation Scenario

Table 6 shows the midpoint results for the OFC. The coloured column is the step with the highest values.

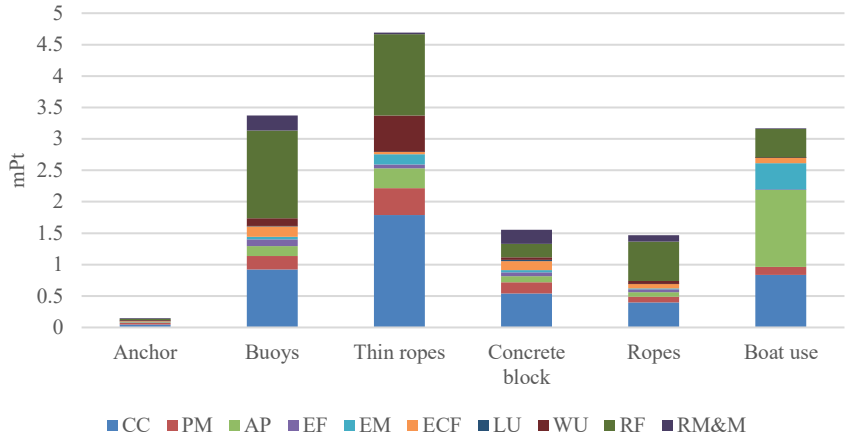
TABLE 6. MIDPOINT RESULTS FOR THE ONC SCENARIO

Impact category	Unit	Collection of raw algae	Spore release and seeding	Nursery phase	Deployment of lines	Harvesting	Final transport
CC	kg CO_2 eq	7.28E–01	4.00E+01	1.89E+00	1.74E+02	3.21E+01	1.14E+01
PM	disease inc.	4.67E–08	1.80E–06	1.30E–07	7.09E–06	8.49E–07	8.60E–07
AP	mol H+ eq	8.47E–03	2.14E–01	1.38E–02	1.69E+00	1.10E+00	4.54E–02
EF	kg P eq	6.39E–05	9.07E–03	2.23E–04	1.63E–02	3.11E–04	8.45E–04
EM	kg N eq	1.07E–03	3.79E–02	2.90E–03	4.51E–01	2.76E–01	1.32E–02
ECF	CTUe	3.76E+01	6.77E+02	2.73E+01	1.16E+03	1.87E+02	1.39E+02
LU	Pt	8.92E+00	1.40E+02	8.84E+00	3.62E+02	4.53E+01	1.02E+02
WU	m^3 depriv.	3.88E–02	2.77E+01	4.29E–01	1.06E+02	7.89E–02	6.05E–01
RF	MJ	7.07E+01	1.04E+03	3.19E+01	3.13E+03	3.56E+02	1.70E+02
RM&M	kg Sb eq	1.51E–06	3.38E–04	8.75E–06	5.12E–04	5.06E–06	4.72E–05

The step of the OFC that gives the most noticeable environmental impact is the deployment of the lines (Fig. 7(a)). Focusing on that, Fig. 7(b) demonstrates that the thin nylon ropes are the most impactful material (4.69 mPt), followed by the buoys (3.37 mPt) and the boat use (3.16 mPt). This is also in line with the literature because nylon production is one of the most harmful in terms of emissions and embodied energy [50].



(a)



(b)

Fig. 7. a) Endpoint results for the OFC, b) Results of the seaweed harvesting procedures.

4. DISCUSSION

4.1. Comparison of the WH, ONC and OFC Scenarios

Table 7 addresses the total results of each midpoint indicator. The coloured ones are the highest value among the different techniques. ONC has the maximum amount in CC, EF, ECF, LU, WU, RM&M. OFC in PM, AP, EM, RF.

TABLE 7. TOTAL MIDPOINT RESULTS OF THE WH, ONC, OFC SCENARIOS

Impact category	Unit	WH total	ONC total	OFC total
CC	kg CO_2 eq	3.56E+01	2.20E+02	2.60E+02
PM	disease inc.	6.63E-06	1.28E–05	1.08E–05
AP	mol H+ eq	8.09E-01	8.47E–01	3.07E+00
EF	kg P eq	2.81E-03	7.00E–02	2.68E–02
EM	kg N eq	1.98E-01	2.08E–01	7.82E–01
ECF	CTUe	3.81E+02	7.86E+04	2.23E+03
LU	Pt	1.51E+02	4.77E+04	6.67E+02
WU	m^3 depriv.	2.51E+00	1.15E+02	1.34E+02
RF	MJ	5.09E+02	2.08E+03	4.80E+03
RM&M	kg Sb eq	2.40E-04	2.27E–03	9.13E–04

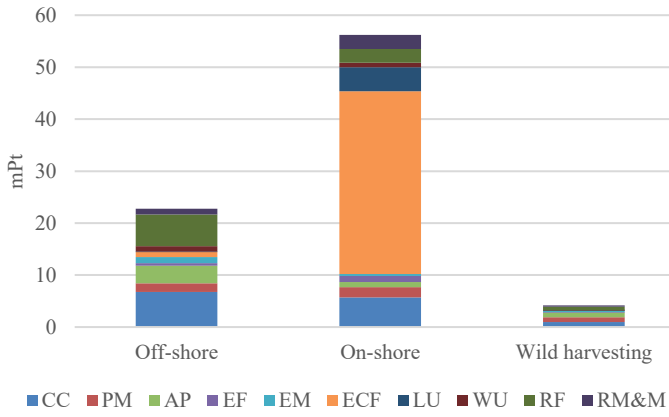


Fig. 8. Comparison between WH, ONC, OFC scenarios.

The trend of Table 7 is also reflected in Fig. 8, which shows the normalized comparison of the three designs. ONC is the technique that has the highest absolute environmental impact (56.206 mPt), succeeded by OFC (22.76 mPt) and WH (4.18 mPt), which results in the best environmental solution. For the ONC, the most sensitive indicators were ECF (35.22 mPt) and CC (5.73 mPt). For the OFC, the indicators with the most remarkable values were CC (6.77 mPt) and RF (6.14 mPt). Finally, the indicators with the most significant input to the total impact were CC (0.98 mPt) and PM (0.91 mPt) for WH.

4.2. Comparative Analysis for the Baseline and the Alternative Scenarios

Fig. 9 shows a comparison between all the scenarios included in this study. For the WH, the alternative scenarios do not provide a significant change. 3.96 mPt is obtained with AS4 (−5.26%), and it is the most significant decrease. These results suggest that the WH scenario is already well optimized, and there is no big margin for improving the performance. The only solution could be to completely change the diesel engine with an electrical one since diesel fuel is the most impactful input.

Regarding the off-shore cultivation, the parameters selected in the OFC_AS1 and OFC_AS4 scenarios do not influence the final results. On the contrary, using solar energy through solar panels leads to a slight increase in the impact since the materials have a more significant impact than the electricity savings gained. This study does not consider the carbon sequestration capacity and nutrient removals from the water of the seaweed. It aligns with the work of Seghetta *et al.* (2016) [24], which generated the LCI. Nevertheless, recent research includes these factors [51]–[53]. So only when future studies focus on the carbon sequestration and nutrient removal properties of *Furcellaria lumbricalis* will it be possible to include their benefits to the system. This could lead to a decrease in the environmental impacts of the OFC scenarios.

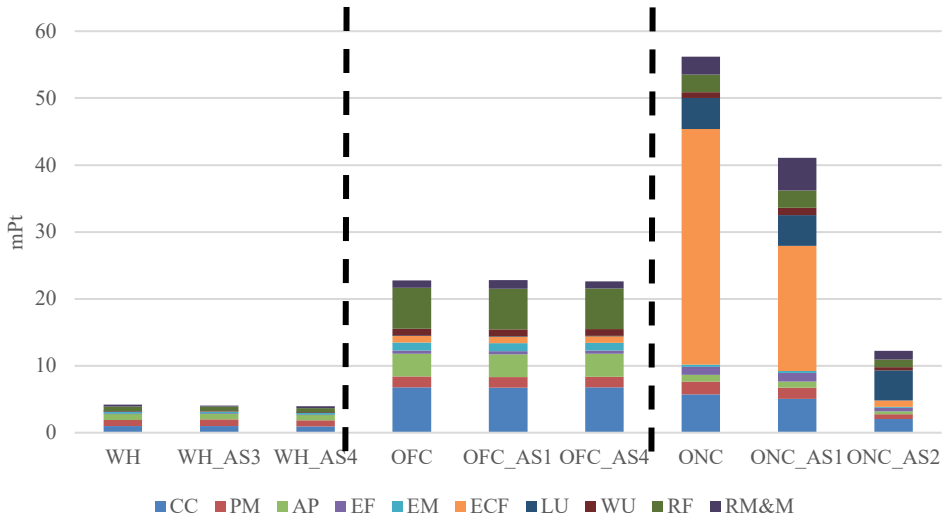


Fig. 9. Comparison of the baseline and alternative scenarios.

For on-shore cultivation, it shows how the use of solar energy for lighting in the ONC_AS2 scenario is very influential, with a 78.25 % decrease in impact compared to the base scenario, almost reaching WH levels. An improvement is also obtained in the case of the use of solar panels (−26.9 %). However, it is limited by the environmental impact given by the materials necessary for the plant's construction. An exciting point further accounted for the ONC scenario is that it assumes a 100 % use of electricity produced by a geothermal plant. Considering the electricity of the usual Icelandic national energy mix (hydropower production for 71 %), the impact of the ONC baseline scenario is 36.38 mPt, a decrease of 35.28 %. So, using electricity produced by geothermal energy is not the most efficient solution to reduce the impacts of this system.

The scenario with the lowest environmental impact is WH_AS4, which involves an improvement in the diesel consumption (3.96 mPt). The highest impact is with the on-shore cultivation in the baseline condition (56.21 mPt).

The most critical decrease (−78.25 %) was seen in the ONC_AS2. This demonstrates how electricity consumption is a vital parameter for this design. Nonetheless, this scenario is hardly applicable to a system developed in Iceland since it has limited availability of sunlight during the year. It can be instead decisive for uses at lower latitudes.

The WH must also consider that it had a reasonably favourable algae collection area (40 minutes from the harbour), which may not be the case for other situations. And since diesel fuel is the first impact input for this technique, the results could change significantly considering greater distances.

These results should not be taken as an absolute environmental impact value on macroalgae's cultivation/harvesting technique but rather as a general indication of the parameters that must be considered in the planning phase. This is because, in addition to the environmental aspect, other factors also come into play, such as the total production of biomass and the possibility of better controlling the process parameters, which are fundamental in choosing a system.

5. CONCLUSION

This study estimated the environmental impacts of two macroalgae cultivation techniques (one on-shore and one off-shore) and the seaweed wild harvesting. A Life Cycle Assessment analysis determined the environmental impact on indicators representing climate change, use of resources, and aquatic ecosystem damages. It identifies the critical parameters of each system, favouring an improvement in performance with information that can be useful in implementing one of the following techniques at an industrial level.

The system with the highest environmental impact is ONC (56.21 mPt), followed by OFC (22.76 mPt) and WH (4.18 mPt).

Investigating the AS was possible to improve the performance of the baseline scenarios. Using sunlight instead of LED light for the ONC allows a 78.25 % decrease in impacts. At the same time, implementing a solar panel system for producing electricity is more limited. Using the electrical energy from the national grid instead of the 100 % geothermal produced will be even better. As far as WH is concerned, the most critical parameter turned out to be the diesel used in the vessels. In fact, by improving the diesel consumption by 10% decrease, it is possible to cut the environmental performance by 5.26 %, obtaining the lowest absolute environmental impact result (3.96 mPt). For OFC, however, the AS did not improve the final results.

The considerations obtained can be an excellent starting point for further studies, which perhaps also implement the use of the biomass produced in a biorefinery concept to reduce further the environmental burden given by the production or collection of seaweed.

ANNEX

Annex is available at: https://zenodo.org/records/10036914

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