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EXECUTIVE SUMMARY

Objectives

The objective of this report is to present the findings of a preliminary Life Cycle Assessment (LCA) of the current production practices of *Saccharina latissima* and *Ulva* spp., as well as its processing into products. This assessment is based on site-specific data provided by the producers, namely Seaweed Energy Solutions (SES) for *Saccharina latissima*, ALGAplus for *Ulva rigida* and Olmix for the processing of *Ulva* spp. The processing of *Saccharina latissima* is excluded from this assessment due to the lack of sufficient available data.

Rationale

This report is developed under task 5.4 that aims at evaluating the environmental performance of seaweed products by means of LCA, which is used in GENIALG as an instrument of refinement and optimization of both aquaculture and biorefinery. LCA is a standardized methodology that compiles and evaluates the environmental aspects and impacts of a product throughout its life cycle. A cradle-to-gate perspective was adopted, i.e., it includes the impacts from material acquisition up to the point at which the product leaves the producing company.

The cultivation of *Saccharina latissima* by SES takes place in off-shore farms in Norway and includes the steps of hatchery, transport of sporelings from the hatchery to the port, and off-shore farm (see Figure 2). *Ulva rigida* is cultivated by ALGAplus in a land-based Integrated Multi-Trophic Aquaculture system in Portugal (see Figure 3). The processing of wild *Ulva* spp. by Olmix in France gives origin to two products (Aralgae and Pasteurized Juice) and comprises the steps of wild seaweed harvesting and cleaning (including also transport to the processing factory), grinding, phase separation, solid fraction processing (Aralgae production) and liquid fraction clarification and pasteurization (see Figure 4).

The results of this preliminary LCA highlight the main environmental hotspots of the three systems analysed. The largest environmental impacts in *Saccharina latissima* cultivation derive mainly from the use of diesel, but the use of nylon nets and steel anchor chains is also relevant. The impacts from *Ulva rigida* cultivation are almost exclusively associated with the use of electricity. In the processing of *Ulva* spp., the largest contributions come from the use of gas and clay during Aralgae production. Several measures for improving the environmental performance of the systems were identified.

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1 INTRODUCTION

The GENIALG project aims to boost the Blue Biotechnology Economy by increasing the production and sustainable exploitation of the brown algae *Saccharina latissima* and the green algae *Ulva* spp. The Work Package 5 (WP5) assesses the economic feasibility and environmental sustainability of cultivating and refining this seaweed biomass in multiple use demanded products of marine renewable origin. In particular, task 5.4 aims at evaluating the environmental performance of these products by means of Life Cycle Assessment (LCA). This tool is used as an instrument of refinement and optimization of both aquaculture in WP3 and biorefinery in WP4.

The objective of this report is to present the findings of a preliminary LCA of the current production practices of *Saccharina latissima* and *Ulva* spp., as well as its processing into products. This assessment is based on site-specific data provided by the producers, namely Seaweed Energy Solutions (SES) for *Saccharina latissima*, ALGAplus for *Ulva rigida* and Olmix for the processing of *Ulva* spp. The processing of *Saccharina latissima* is excluded from this assessment due to the lack of sufficient available data. The assessment follows a cradle-to-gate perspective, i.e., it includes the impacts from material acquisition up to the point at which the product leaves the producing company. The results from this preliminary LCA are relevant to highlight environmental hotspots and to allow adjustment of processes.

This report is organized in 6 chapters. The first one presents the rationale and the objective of this report. Chapter 2 describes the LCA methodology applied, Chapter 3 presents the results obtained, Chapter 4 discusses the results and Chapter 5 gives the conclusions. Finally, Chapter 6 lists the references cited in the report.

2 METHODOLOGY

2.1 Life Cycle Assessment

LCA is a standardized methodology that compiles and evaluates the environmental aspects and impacts of a product throughout its life cycle (ISO, 2006). The life cycle may comprise extraction and processing of raw materials, production, use, and eventual reuse, recycling or disposal at end of life. LCA is generally considered the most suitable method for assessing the environmental impacts of products since it addresses both the entire life cycle of a product and the full spectrum of environmental impacts (Zamagni et al., 2009). The advantages of a life cycle approach to address sustainability are well known and relate with avoidance of shifting problems, for example, from one life cycle stage to another, from one geographic area to another and from one environmental medium (e.g. air) to another (e.g. water).

LCA is structured in four phases (ISO, 2006), as shown in Figure 1: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. This framework allows for iterative procedures among phases. As the assessment unfolds, data limitations and new insights or stakeholder views can lead to a redefinition of the study focus, goals or methods.

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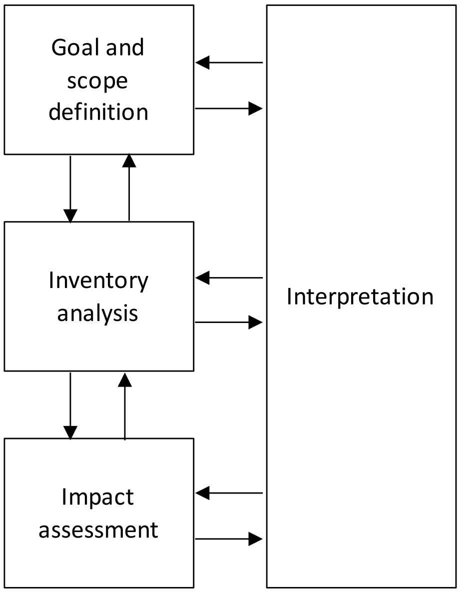

Figure 1. Structure of LCA.

The goal and scope definition mainly includes aspects such as:

- definition of the goal, including, the intended application, the reasons for carrying out the study and the intended audience;
- definition of the system boundaries, i.e., the unit processes along the life cycle to be included in the analysis;
- definition of the functional unit, which is the reference unit in relation to which the inventory and impact indicators are expressed;
- definition of the initial data quality requirements;
- selection of impact categories and respective methods for impact quantification.

The inventory analysis involves data collection for the processes previously identified within the system boundaries. These data comprise environmental aspects such as consumption of raw and ancillary materials and energy, as well as emissions to air, water and soil and solid waste generation. The inventory analysis also includes calculation procedures so that the data collected for each process are summed up and related to the functional unit.

During the impact assessment, the inventory data are processed in terms of their environmental impacts previously selected in the scope. This phase encompasses three mandatory elements, as follows:

- selection of impact categories, category indicators, and characterization models; there are currently several models available that include impact categories such as climate change, acidification, eutrophication, and resource depletion, among others;
- classification, where the inventory parameters are assigned to specific impact categories;

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- characterisation, where equivalency between inventory parameters within each impact category is done considering the cause-effect chain (environmental mechanisms) by means of so-called characterisation factors, resulting in an indicator for each impact category.

The impact assessment phase may also include the following optional elements:

- normalisation, where the results from the characterisation are compared to a reference situation that could be the total impacts of a country or a region, for each impact category;
- grouping, which consists of sorting and possibly ranking the impact categories;
- weighting, where the indicator results of the different environmental impacts are weighted relative to each other by using numerical factors based on value choices. Weighting may include aggregation of the weighted results into a single score.

Finally, the interpretation consists in the analysis of the results obtained both at the inventory and the impact assessment phases. This analysis allows the detection of the main impacts, their sources and improvement opportunities. In addition, the quantitative results obtained should be critically analysed and verified in terms of consistency, completeness, coherence, and agreement with the initial expectations.

2.2 Goal and scope definition

2.2.1 Goal

The goal of this study is to provide the first insights about the environmental performance of the current practices of: (1) *Saccharina latissima* cultivation in Norway, (2) *Ulva rigida* cultivation in Portugal and (3) wild *Ulva* spp. processing in France into Aralgae (a solid clay-based product) and Pasteurized Juice, using site-specific data provided by the producer companies SES, ALGAplus and Olmix, respectively.

The main purpose is to quantify the life cycle impacts and to identify the processes with the largest impacts. The intended audience are the partners of the GENIALG project and other interested parties in the topic.

2.2.2 System boundaries

The system boundaries for the cultivation of *Saccharina latissima* include the steps of hatchery, transport of sporelings from the hatchery to the port, and off-shore farm (Figure 2). For the cultivation of *Ulva rigida*, the boundaries include the process of cultivation in ponds under Integrated Multi-Trophic Aquaculture (IMTA) (Figure 3). The fish ponds of the IMTA system were left outside the boundaries as the corresponding environmental burdens are not affected by the seaweed production activity. The system boundaries of *Ulva* spp. processing into Aralgae and Pasteurized Juice (Figure 4) comprises the steps of wild seaweed harvesting and cleaning (including also transport to the processing factory), grinding, phase separation, solid fraction processing (Aralgae production) and liquid fraction clarification and pasteurization. The growing of the wild seaweed was excluded because it is a natural process not directly influenced by humans.

In all systems, the production of energy, fuels, water and materials consumed in all the processes was also considered. The production of capital goods (buildings, machinery and equipment) was excluded.

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However, in the *Saccharina latissima* system, the replacement of the infrastructure of the farm was included as data were available for the flows of materials replaced each year.

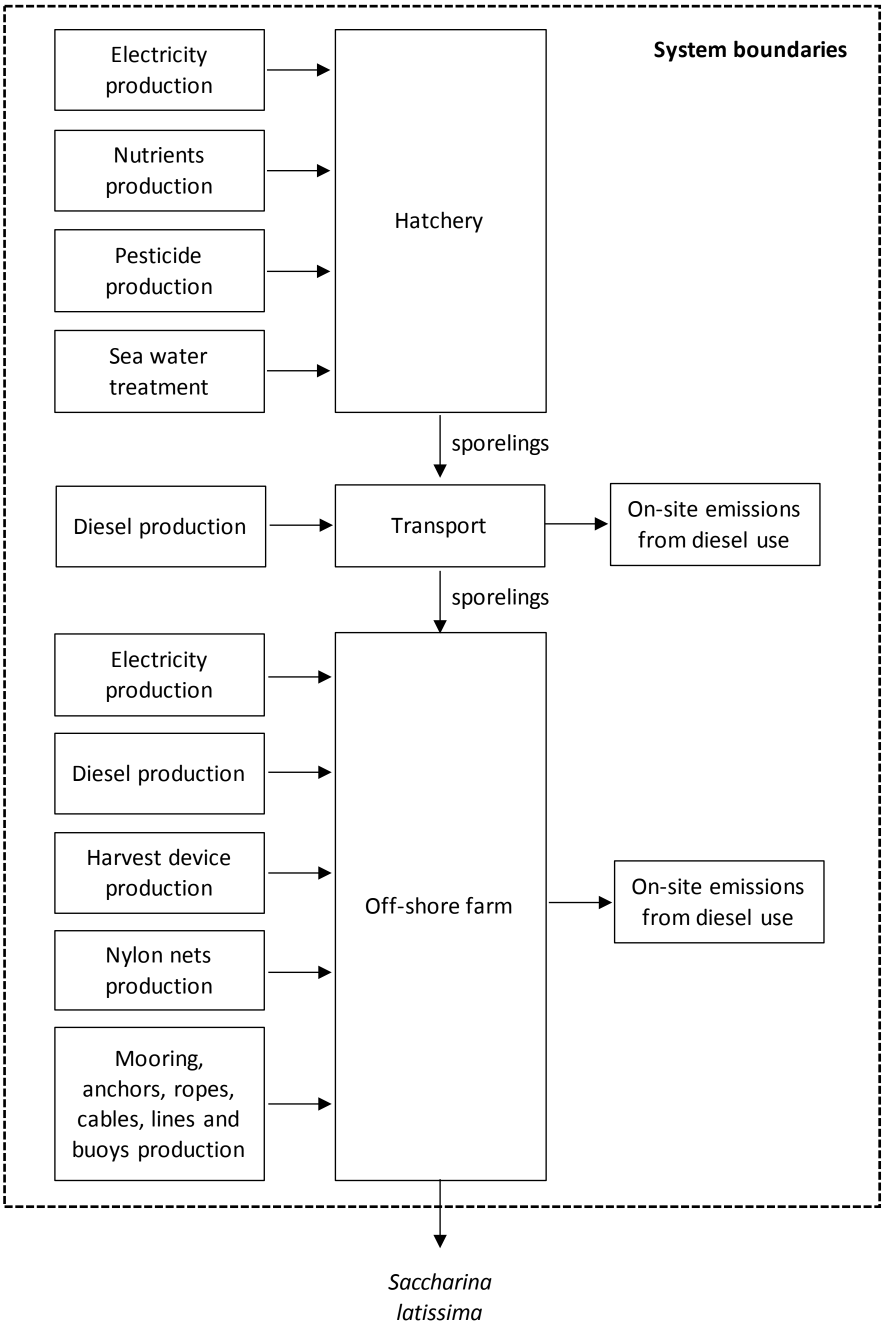

Figure 2. System boundaries for the cultivation of *Saccharina latissima*.

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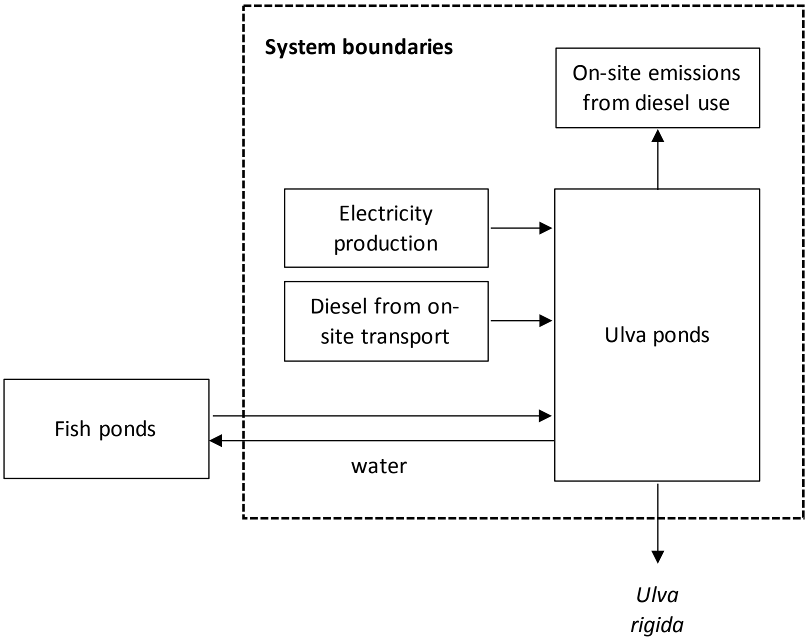

Figure 3. System boundaries for the cultivation of *Ulva rigida*.

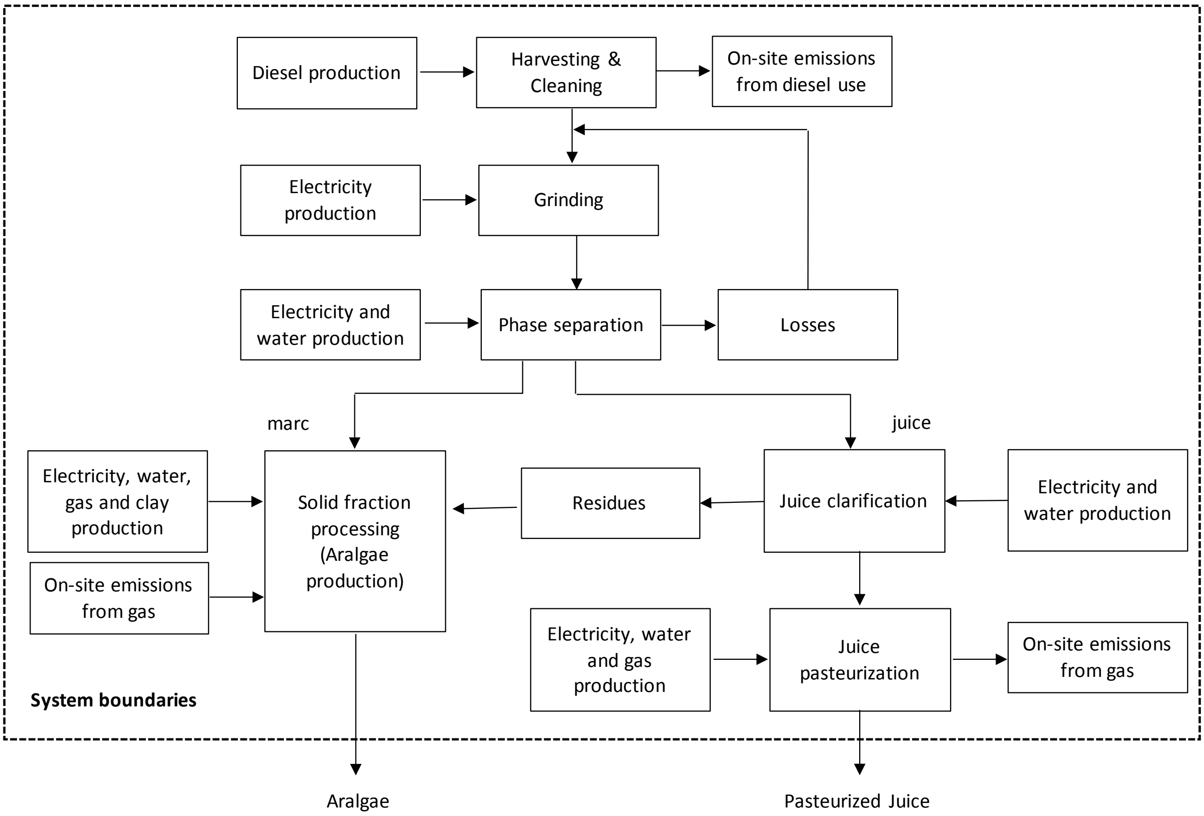

Figure 4. System boundaries for the processing of *Ulva* spp.

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2.2.3 *Functional unit*

For the *Saccharina latissima* and *Ulva rigida* cultivation systems, the functional unit is the provision of 1 kg of seaweed (wet basis) without any type of pre-processing.

For the processing of *Ulva* spp., the functional unit is the processing of 1 kg of seaweed (wet basis) into the production of both Aralgae and Pasteurized Juice.

2.3 *Cultivation of Saccharina latissima*

2.3.1 *Process description*

The perennial brown algae *Saccharina latissima* grows throughout the year with a period of maximum growth in the first half of the year followed by a period of reduced growth during summer (Handå et al., 2013). In the fjords of Norway, nutrients (especially ammonia) are well available near salmon farms (Handå et al., 2013). Quite some experience has accumulated in the cultivation of *Saccharina latissima* over the past years, also in southern Atlantic regions (Azevedo et al., 2016; Peteiro & Freire, 2013), with potential applications of biofuel (Ghadiryanfar et al., 2016), animal feed and fertilizer (Peteiro & Freire, 2013).

The *Saccharina latissima* for the GENIALG project comes from SES and is grown in off-shore seaweed farms in fjords in middle Norway, near Trondheim. Juvenile sporophytes are obtained from inducing soruses in full-grown blades to release their spores. Natural sorus (spore cluster) formation occurs from late autumn to early winter (Handå et al., 2013). In the current cultivation set up sporophytes are deployed in fall in the open sea attached to a structure where they grow until harvest in spring.

The cultivation of *Saccharina latissima* can be divided in the following steps: hatchery, transport of sporelings from the hatchery to the port, and off-shore farm.

The hatchery step comprises the following activities:

- Fertile seaweed seedlings are collected from the wild or from standing seaweed stock and transported to the hatchery lab, in which the release of spores is induced.
- The sporelings are allowed to grow in the lab to some millimetres in 1-2 months, in a growing solution containing some fertilizers and pesticide. They attach themselves to thin “seedling ropes” or they are actively attached onto the ropes.

A hatchery includes a lab and offices, and consumes also electricity and seawater that is filtered and treated with sodium hypochlorite solution and ultraviolet (UV) radiation.

The sporelings attached to the ropes are then transported by car to the port near the off-shore farm.

At the farm, two phases can be distinguished, a first one of deployment and growth, followed by harvest. The deployment and growth includes:

- The seedling ropes are wound around sturdy ropes and deployed in fall in the open sea attached to a structure of buoys, chains and anchoring material.
- The seaweed grows for 6 - 7 months until harvest in spring. Deployment and regular checks and maintenance requires significant amounts of transport by boat.

The harvest of seaweed can happen both manually and mechanically. Manual harvesting is the most common method globally, and can be used for both natural and cultivated macroalgae. In manual

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harvesting, devices such as sickle, fork, and net are used to uproot the algae, while mechanized harvesting methods, which can involve mowing, include rotating blades, suction, or dredging cutters (Ghadiryanfar et al., 2016). SES uses some level of mechanization and has adjusted boats and devices to operate, while a significant amount of manual handling of seaweed is required. The seaweed is taken to shore and washed, frozen and if necessary stored. However, these activities were left out of the boundaries as any pre-processing is excluded.

2.3.2 *Primary and secondary data & Inventory modelling*

Primary data on the input and output flows associated with each step of *Saccharina latissima* cultivation were provided by SES on an annual basis and then calculated to the functional unit, i.e., 1 kg of seaweed (Table 1). The nutrients added in the hatchery step consist of a modified enriched seawater (ES) medium prepared with seawater and chemicals. The outflow of seawater from the hatchery is assumed to have a quality similar to the seawater used as nutrients added to incubation water are all consumed by the sporelings.

The input flows include also materials from the maintenance of the infrastructure of the farm that are replaced. The corresponding outputs (the materials that are discarded) are assumed to be valorised (by recycling or energy recovery) and, therefore, are considered as coproducts and the associated environmental burdens were not accounted for by assuming cut-off allocation. Air emissions from the burning of diesel in vessels at the farm were estimated based on emission factors from EEA (2016).

Data on the environmental impacts from the production of energy and materials were retrieved from the database Ecoinvent 3.4 (Ecoinvent, 2017). The name of the processes selected are presented in Table 1. When the exact processes were not available at the database, the most similar ones were selected. No data were available for the production of cartridge filters used for seawater treatment at the hatchery, some of the chemicals used in the preparation of the modified ES medium used at the hatchery, and the production of batteries for electricity generation at the farm. Thus, these processes were not accounted for. However, their contribution is not expected to be relevant for the total impacts.

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Table 1. Inventory data for the cultivation of *Saccharina latissima*, per 1 kg of seaweed (wet basis).

Parameter	Unit	Amount	Ecoinvent process
HATCHERY			
Inputs			
Electricity	kWh	1.10	Electricity, low voltage {NO}| market for | Cut-off, U
Seawater	L	365	-
Nutrients (modified ES medium)	L	2.53E-03	Sodium nitrate {GLO}| market for | Cut-off, U + EDTA, ethylenediaminetetraacetic acid {GLO}| market for | Cut-off, U + Ammonium sulfate, as N {GLO}| market for | Cut-off, U + Manganese sulfate {GLO}| market for | Cut-off, U + Zinc monosulfate {GLO}| market for | Cut-off, U
Pesticide (germanium oxide)	kg	1.46E-06	Pesticide, unspecified {GLO}| market for | Cut-off, U
Sodium hypochlorite solution (10%)	L	8.33E-06	Sodium hypochlorite, without water, in 15% solution state {GLO}| market for | Cut-off, U + Water, ultrapure {RoW}| production | Cut-off, U
Ultraviolet lamp	number	8.33E-06	Ultraviolet lamp {GLO}| market for | Cut-off, U
Outputs			
Sporelings in strings/ropes	km	3.33E-04	-
Seawater	L	365	-
TRANSPORT OF SPORELINGS TO PORT			
Distance by car	km	0.0267	Transport, passenger car, large size, diesel, EURO 5 {RER}| transport, passenger car, large size, diesel, EURO 5 | Cut-off, U

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Table 1 (cont.). Inventory data for the cultivation of *Saccharina latissima*, per 1 kg of seaweed (wet basis).

Parameter	Unit	Amount	Ecoinvent process
OFF-SHORE FARM			
Inputs			
Sporelings in strings/ropes	km	3.33E-04	-
Diesel for vessels	L	0.050	Diesel {RER}| market group for | Cut-off, U
Harvest device (aluminium)	kg	1.67E-03	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for | Cut-off, U
Food-grade harvest nets (nylon)	kg	5.00E-04	Nylon 6-6 {GLO}| market for | Cut-off, U
Anchor chains/cables (steel)	kg	5.13E-03	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, U
Mooring - rock bolts (steel)	kg	2.50E-05	
Mooring ropes/cables (PE/PP Danline)	kg	7.16E-07	Polypropylene, granulate {GLO}| market for | Cut-off, U
Structural ropes (PE/PP Danline)	kg	2.15E-06	
Structural lines (PE/PP Danline)	kg	1.59E-07	
Marker buoys (HDPE)	kg	6.25E-04	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U
Structural buoys (HDPE)	kg	5.00E-04	
Small buoys (PVC)	kg	3.33E-04	Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U
Cultivation/growth lines (polyester)	kg	1.44E-05	Maleic unsaturated polyester resin {GLO}| market for | Cut-off, U
Outputs			
Seaweed	kg	1	-
Air emissions – CO_2	kg	0.135	-
Air emissions – NO_x	kg	3.34E-03	-
Air emissions – CO	kg	3.15E-04	-
Air emissions – NMVOC	kg	1.19E-04	-
Air emissions – SO_2	kg	8.50E-05	-

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2.4 Cultivation of *Ulva rigida*

2.4.1 *Process description*

Ulva spp. is suitable for a range of applications since it is rich in sugars and proteins and has a relatively low salt content. Several studies have shown the successful cultivation of *Ulva* spp. under IMTA conditions (Korzen et al., 2016; Marinho et al., 2013; Mata et al., 2006).

The *Ulva* biomass for the GENIALG project comes from ALGAplus and is grown in a land-based IMTA system. Nutrient rich water (nitrate, carbon dioxide (CO_2) and ammonia) from the semi-intensive sea bream and sea bass farm provides the nutrients required. The water in the seaweed tanks is bottom-aerated with electricity powered turbines to facilitate nutrient assimilation and access to light. High biomass yields per surface area can be achieved without adding CO_2 or fertilizers. The cultivation of *Ulva rigida* is carried out according to the following steps:

1. Starting stock: clonal propagation is practiced so that no sexual reproduction is required, precluding a hatchery cycle in the propagation. Cultivation is started with a “starting stock” of a population of genetically related individuals from natural ocurrences within the property or from the previous cultivation cycle. Small portion of individual blades are maintained in controlled culture rooms in order to preserve the strains of *Ulva rigida* in cultivation. The support lab including the offices that support the R&D and hatchery operations requires electricity (artificial light, equipment functioning) and water for lab and office operations.
2. Growth phase: growth occurs in IMTA conditions from moulded plastic tanks of 1000 L up to concrete tanks of 20.000 L scale, today with a production capacity of up to 40 t (fresh weight) of Ulva per year. Within the GENIALG project and according to the company’s strategy, the production will be expanded in 2019 to a 6000 m^2 earthen pond that will hold several raceway units (ca. 4000 m^2 of effective productive area) – with an average expected capacity of 144 t (fresh weight) of *Ulva* per year. In this case, the main material to ensure water retention is PVC lining. Water and nutrients will continue to be supplied from the fish ponds. The incoming water is filtered before entry to the tanks. Today, the free-floating seaweed are kept in circulation by bottom aeration (in the raceways, paddle wheels will be used). Some on-site transport with a passenger car/tractor is required for checks and maintenance.
3. Harvest is done by draining the tanks and harvesting the seaweed with net-tools. The seaweed is collected and transported in perforated plastic boxes. This transport was excluded in the present study.
4. Pre-processing: the washing process uses seawater filtered down to 5 micron, UV sterilized and ozone treatment. The seaweed passes through a water bath with strong agitation, followed by spraying it in a conveyor belt system. The wet seaweed is dewatered in a centrifuge. Drying is done in air tunnel at room temperature (25 °C). Dried seaweed can be packed for sale into food markets (and stored if needed). This pre-processing requires electricity. If the seaweed is produced for further processing for nutraceuticals and animal and plant stimulants, the drying step will be skipped, and dewatered seaweed can be stored cold (2-7 °C) for a few days (up to 7 days according to a trial done with Olmix, where fresh algae were shipped from Portugal to France in refrigerated conditions). Exact shelf-life of dewatered and cooled seaweed needs to be determined. However, it should be noted that pre-processing was excluded from the system boundaries.

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2.4.2 *Primary and secondary data & Inventory modelling*

Inventory data for *Ulva rigida* cultivation were taken from Helmes et al. (2018), which presents data provided by ALGAplus. Table 2 shows those data, consisting in the consumption of electricity and on-site use of pick-up truck. Ecoinvent 3.4 was the source of the data on the environmental impacts of electricity production (Electricity, low voltage {PT}| market for | Cut-off, U) and on-site transport (Transport, passenger car, large size, diesel, EURO 5 {RER}| transport, passenger car, large size, diesel, EURO 5 | Cut-off, U).

Table 2. Inventory data for the cultivation of *Ulva rigida*, per 1 kg of seaweed (wet basis).

Parameter	Unit	Amount
Inputs		
Electricity	kWh	8.20
On-site use of pick-up truck *	km	0.0133
Outputs		
Seaweed	kg	1

* equivalent to 0.012 kWh of diesel

2.5 *Processing of Ulva spp.*

2.5.1 *Process description*

Olmix produces food additives for humans, feed additives for animals and stimulation products for plants, currently from wild harvested green and red seaweed from the coasts of Brittany in France. The seaweed contains macromolecules and trace elements that are important for Olmix' products.

The production at Olmix takes the following basic steps:

1. Pre-treatment and provision of seaweed: the seaweed is harvested from the beach in a special truck by a contractor located in Plouénan. The seaweed is washed with well water from a dedicated treatment plant. Sand and crustaceans are removed, and the seawater adjacent to the seaweed is removed.
2. Grinding: This step is done in Bréhan. The aim is to turn raw seaweeds into a puree. The output is hence more homogenous than the whole seaweed and can be processed more efficiently.
3. Phase separation: the ground seaweed contains both solids and liquids, which are separated by pressing.
4. Centrifugation and pasteurization of the liquid phase (juice): the liquid is cleared by centrifugation and pasteurized with heat produced from gas consumption. The sludge residue is reintegrated with the solid fraction. The liquid is sent off-site for formulation into end products.
5. The dry 'cake' (solid fraction) from the press phase separation is used as a protein-rich macroingredient. It is mixed with montmorillonite clay and dried on-site with gas consumption and packed. The evaporated water is removed as steam.

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The plant site also contains a laboratory where the same process steps can be accomplished at a small scale. This way the extraction process can be closely monitored, modified and tested, giving technicians the flexibility to adapt the treatment the seasonally and spatially variable chemical composition of the seaweed. Each step also consumes electricity for mechanised operations.

2.5.2 *Dealing with alternative process flows and multifunctionality*

Several side streams and coproducts are created and used at the Olmix facility, and were treated as follows:

- The losses from the belt press phase separation are re-introduced at the grinding step. This makes the grinding and the phase separation less efficient: although the amount of seaweed entering the grinding results in the same amount of material leaving the phase separation, 10% share has to be reworked in these steps, so that the electricity and water use are increased with a factor of 1/(1-0.1)=1.11 in both processes.
- The environmental impacts from the phase separation (and the steps before) need to be distributed between solid and liquid fraction, in order to link external inputs to these flows separately. This was done through mass allocation, because there is no reasonable other basis for substitution, system expansion or allocation for these intermediate products.
- The impacts from the clarification of the juice also need to be distributed between centrifugated liquid and the residue. This was also done by mass allocation for the same reasons. The residue from the clarification (and its environmental burden) goes to solid fraction processing and was assumed to replace solid fraction directly obtained.
- Little attention was paid to constructing full mass balances, but all recorded mass losses are accounted for with the above approaches. All consumed water was considered as going to waste water treatment. Evaporated water is not tracked.

2.5.3 *Primary and secondary data & Inventory modelling*

Quantitative data on gas, electricity, water and transport use, as well as on all process flows was collected in the fall of 2018 by an engineer from Olmix. The inventory data were calculated back to the functional unit of 1 kg of seaweed (wet basis), which corresponds to the production of 842 g of Aralgae and 510 g of Pasteurized Juice. Table 3 shows the process steps in which these inputs are used. The distribution of these usages between the Aralgae and the Pasteurized Juice derives from how the seaweed flows through the different process steps, and is shown in Figure 5. The allocation steps enable tracking the individual flows, while they are not required for the results on the basis of the functional unit.

The seaweed harvesting step comprises transport over the beach and from the beach to Plouénan, as well as the transport from Plouénan to Bréhan. Electricity is used in all steps and tap water is used during most steps.

The electricity use was linked to the Ecoinvent 3.4 process “Electricity, low voltage {FR}| market for | Cut-off, S”. The water use was linked to “Tap water {Europe without Switzerland}| market for | Cut-off, S” and all water was assumed to be treated after use, and this was modeled through linking with

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"Wastewater, average {RoW}| market for wastewater, average | Cut-off, S". Butane gas usage was reported in mass (kg) and converted to volume (m^3). The Ecoinvent 3.4 process "Heat, central or small-scale, natural gas {RoW}| heat production, natural gas, at boiler fan burner non-modulating <100kW | Cut-off, S" was used to represent the burning of butane gas in Olmix facilities with the following adjustments: burning of butane instead of natural gas, electricity use sourced from France, CO_2 emission calculated based on the carbon content of the gas. The reference flow of this process is 1 MJ of heat provided, and it was derived from the Ecoinvent process itself which volume was required to provide 1 MJ of heat. Road transport was modeled with "Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S".

Table 3. Input flows for the processing of *Ulva* spp., per process step.

Process step	Gas for heat	Electricity	Tap water	Transport
0 Seaweed Harvesting and Cleaning	-	yes	yes	yes
1 Grinding	-	yes	-	-
2 Phase Separation	-	yes	yes	-
3 Juice Clarification	-	yes	yes	-
4 Juice Pasteurization	yes	yes	yes	-
5 Aralgae production	yes	yes	yes	-

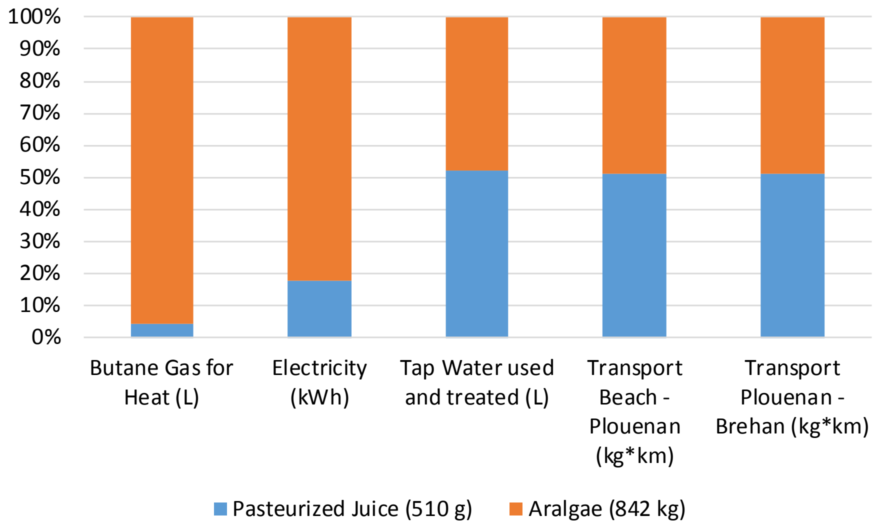

Figure 5. Distribution of external input usages over the two products in the processing of *Ulva* spp.

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2.6 Impact assessment

The impact assessment includes the mandatory elements up to the characterisation. The method selected was the hierarchist version of ReCiPe2016 at midpoint characterization level (Huijbregts et al., 2017). The following impact categories were considered: global warming (GW), ozone formation - human health (OF-HH), ozone formation - terrestrial ecosystems (OF-TE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). The optional elements of normalization, grouping and weighting were not applied because they are not necessary to achieve the goal defined for this study.

3 RESULTS

3.1 Cultivation of *Saccharina latissima*

Table 4 presents the impact assessment results obtained for the cultivation of *Saccharina latissima*. The step of off-shore farm has the largest contribution to all impact categories, representing 81 to almost 100% of the total impacts, depending on the impact category (Figure 6). The step of hatchery contributes less than 4% for the impacts except for global warming, freshwater eutrophication and fossil resource scarcity for which it represents 10, 19 and 8% of the total impacts, respectively. The impacts of the transportation of the sporelings from the hatchery to the port are irrelevant for all impact categories, not exceeding 3%.

Figure 7 shows that the impacts of the hatchery are dominated by electricity use, ranging from 93% to almost 100% of the total impacts. Figure 8 shows that diesel use in vessels dominates the impacts of the off-shore farm in five impact categories: global warming, ozone formation - human health, ozone formation - terrestrial ecosystems, terrestrial acidification and fossil resource scarcity. In the later impact category, this contribution comes from the extraction of crude oil to produce diesel, while for the remaining categories the impacts are mostly (87 to 98% of total diesel-related impacts) due to air emissions from diesel combustion. The use of nylon harvest nets plays a major role (81%) for marine eutrophication mainly from ammonium ion emissions to water during nylon production. The use of steel anchor chains leads to a major contribution (87%) to mineral resource scarcity mainly because of nickel depletion. Finally, freshwater eutrophication is mainly caused by the use of steel anchor chains (42%) and aluminium harvest device (40%), due to phosphate emissions to water.

Table 4. Impact assessment results for the cultivation of *Saccharina latissima*, per 1 kg of seaweed (wet basis).

Impact category	Unit	Amount
Global warming (GW)	kg CO_2 eq	0.228
Ozone formation - human health (OF-HH)	kg NO_x eq	3.56E-03
Ozone formation - terrestrial ecosystems (OF-TE)	kg NO_x eq	3.58E-03
Terrestrial acidification (TA)	kg SO_2 eq	1.70E-03
Freshwater eutrophication (FE)	kg P eq	2.21E-06
Marine eutrophication (ME)	kg N eq	1.59E-06
Mineral resource scarcity (MRS)	kg Cu eq	2.71E-03
Fossil resource scarcity (FRS)	kg oil eq	0.0711

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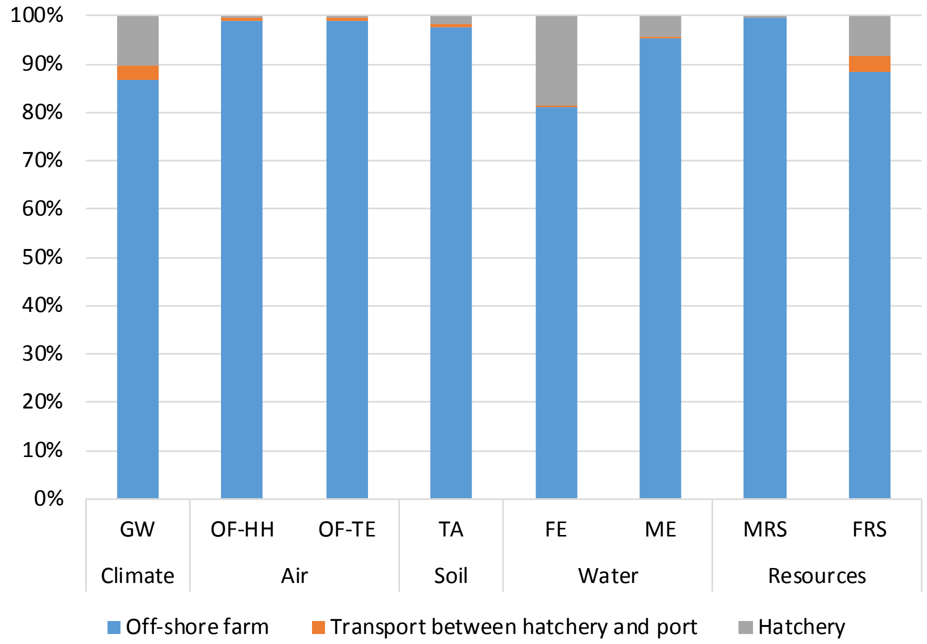

Figure 6. Contributions of the three steps of the cultivation of *Saccharina latissima*.

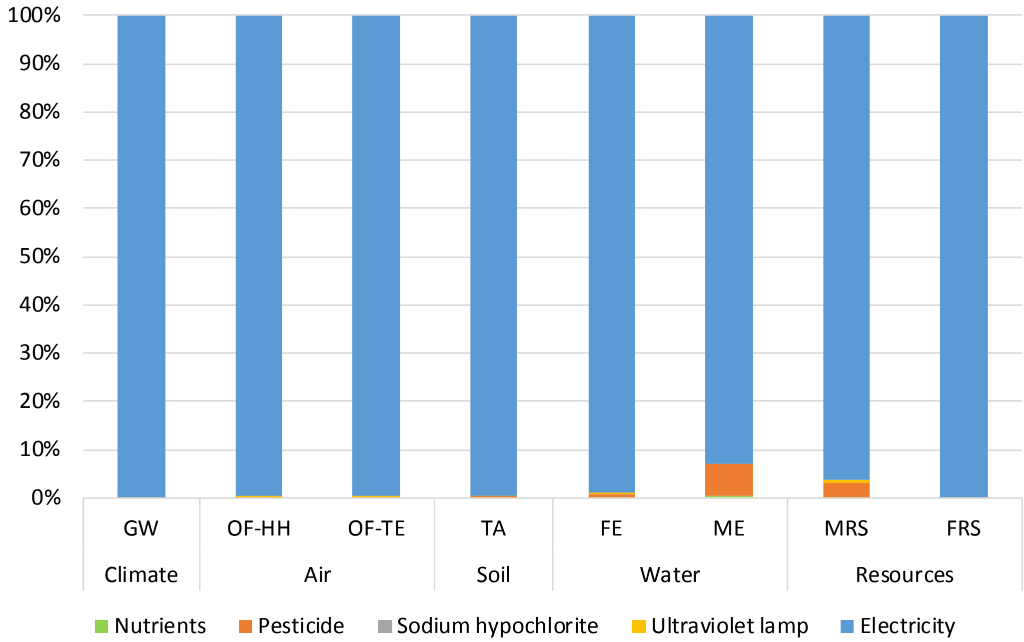

Figure 7. Contributions of the processes in the step of hatchery of *Saccharina latissima*.

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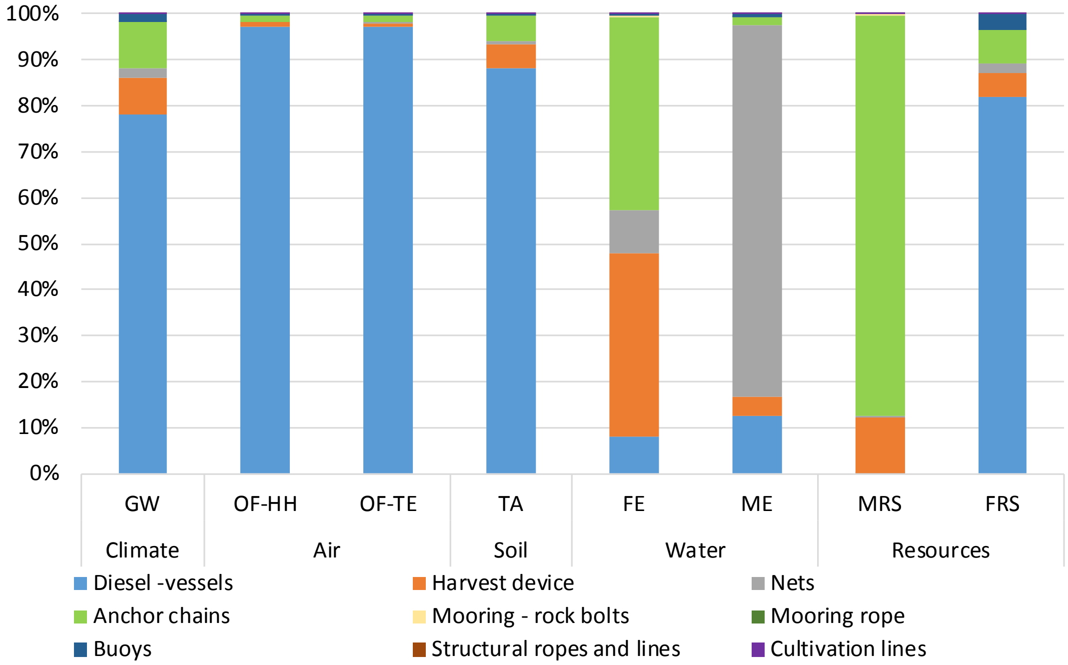

Figure 8. Contributions of the processes in the step of off-shore farm of *Saccharina latissima*.

3.2 *Cultivation of Ulva rigida*

The total impact assessment results obtained for the cultivation of *Ulva rigida* are presented in Table 5. The use of electricity contributes to almost 100% of the impacts in all the categories (Figure 9), as the contribution of on-site transport is irrelevant and no other inputs are needed under IMTA conditions.

Table 5. Impact assessment results for the cultivation of *Ulva rigida*, per 1 kg of seaweed (wet basis).

Impact category	Unit	Amount
Global warming (GW)	kg CO_2 eq	3.33
Ozone formation - human health (OF-HH)	kg NO_x eq	8.04E-03
Ozone formation - terrestrial ecosystems (OF-TE)	kg NO_x eq	8.06E-03
Terrestrial acidification (TA)	kg SO_2 eq	0.0206
Freshwater eutrophication (FE)	kg P eq	1.00E-03
Marine eutrophication (ME)	kg N eq	6.64E-05
Mineral resource scarcity (MRS)	kg Cu eq	2.99E-04
Fossil resource scarcity (FRS)	kg oil eq	0.698

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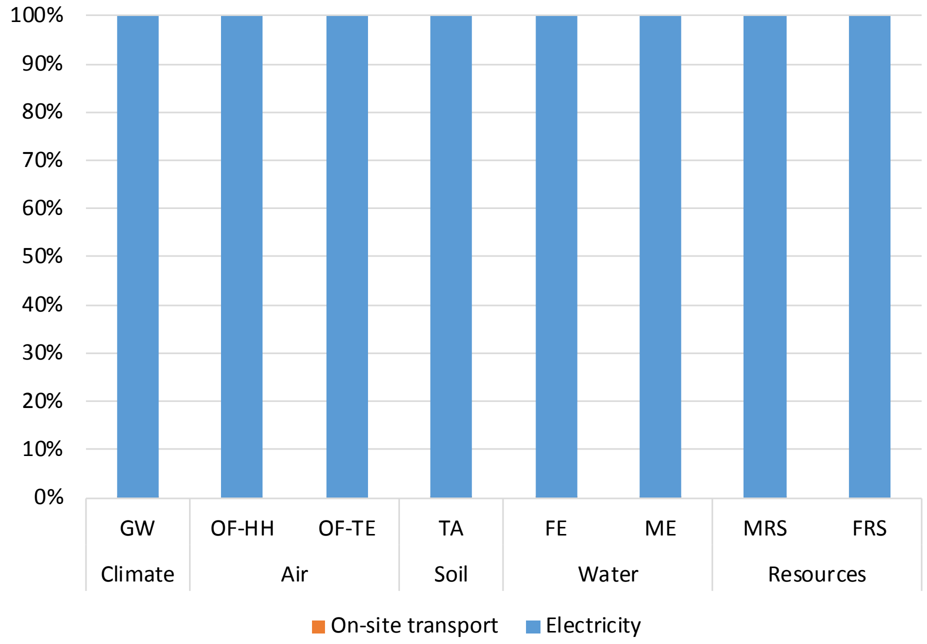

Figure 9. Contributions of inputs to the environmental impacts of *Ulva rigida* cultivation.

3.3 Processing of Ulva spp.

Table 6 shows the impact assessment results for the processing of *Ulva* ssp. In Figure 10, the different contributions of the process steps can be distinguished. In Figure 11, the contributions from the external inputs are shown. Almost every external input is used in different process steps.

The step of producing Aralgae, the solid clay product, has the largest impact for all categories except marine eutrophication. The contribution of this step is particularly relevant for global warming and resource scarcity (75 – 97%). In the case of global warming and fossil resource scarcity, this is because most of the gas is used during this step. For mineral resource scarcity, this contribution is mainly due to the clay used. This step is also important for the ozone formation categories, terrestrial acidification, and freshwater eutrophication, with contributions ranging from 58 to 64%, mainly due to emissions from the combustion of gas. In these categories, the harvesting and cleaning step has also important shares (29 –36%), mainly as a result of the transport of seaweed to Olmix facility.

In the seaweed harvesting and cleaning step, the largest amount of water use also takes place, and the wastewater treatment of this water use contributes most to marine eutrophication. Because the nitrogen (N) emissions causing this result are modelled in the secondary data source (the Ecoinvent process of waste water treatment), this number is quite unrepresentative. It is very likely the N emissions from this wastewater will be low, because the water is used for rinsing seaweed and does not contain much N.

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Table 6. Impact assessment results for the processing of 1 kg of *Ulva* spp. at Olmix facilities

Impact category	Unit	Amount
Global warming (GW)	kg CO_2 eq	0.344
Ozone formation - human health (OF-HH)	kg NO_x eq	5.79E-04
Ozone formation - terrestrial ecosystems (OF-TE)	kg NO_x eq	6.60E-04
Terrestrial acidification (TA)	kg SO_2 eq	5.28E-04
Freshwater eutrophication (FE)	kg P eq	3.59E-05
Marine eutrophication (ME)	kg N eq	4.26E-05
Mineral resource scarcity (MRS)	kg Cu eq	7.92E-03
Fossil resource scarcity (FRS)	kg oil eq	7.66E-02

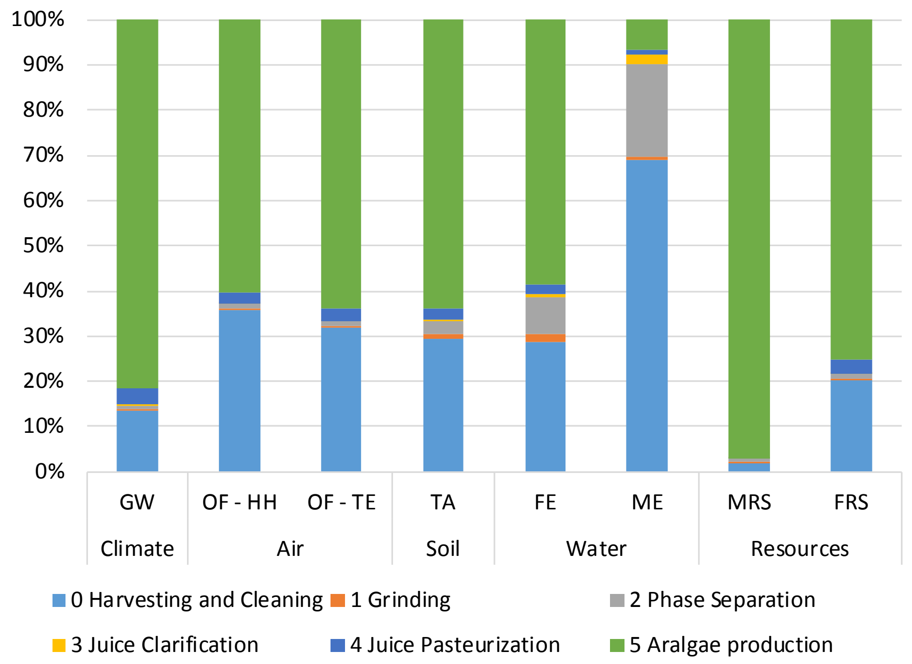

Figure 10. Contributions of process steps to the environmental impacts of Olmix products.

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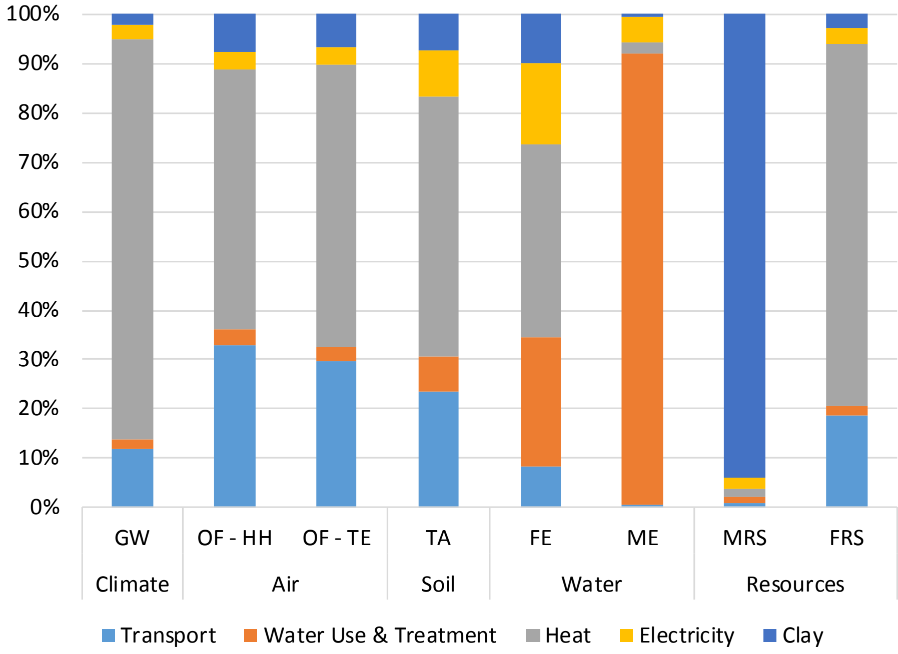

Figure 11. Contributions of external inputs to the environmental impacts of Olmix products.

4 DISCUSSION

The results of this preliminary LCA highlight the main environmental hotspots of the current practices of cultivation of the two seaweeds and processing of *Ulva* spp., and, thus, allow the identification of measures for improving the environmental performance of these systems.

In the case of *Saccharina latissima* cultivation, the largest impacts for most impacts categories are related to diesel use in vessels for several activities such as harvest, deployment, maintenance and inspections. However, the amount of fuel consumed was roughly estimated and given its importance for the environmental impacts, efforts should be developed to obtain more accurate amounts. Measure to decrease diesel-related impacts may include the optimization of vessels use aiming at decreasing travelled distances, and the choice of vessels with lower diesel consumption. The use of harvest nets in nylon and anchor chains in steel are also relevant, and their use should be reduced. For example, nets could be reused more intensively, and anchor chains could be replaced with cables of lighter weight.

In the *Ulva rigida* cultivation system, the impacts are almost totally due to electricity consumption. This result indicates that measures for decreasing electricity use should be a priority for improving the environmental performance of this system. Electricity use optimization is already under implementation by shutting down water pumping system at night time, by implementing optimized equipment and re-dimensioning pipe system (mainly air supply). Also, with the planned expansion using paddle wheels instead of bottom aeration is expected to reduce energy consumption. Moreover, the implementation of photovoltaic panels for energy production is also foreseen. These are actions planned within the project GENIALG with the contribution of partner INEGI. It should be noted that in

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the current scenario, all the electricity consumed comes from the Portuguese grid. Data taken from Ecoinvent refer to the electricity mix from 2014 with almost 40% of electricity being produced from fossil sources. For example, the emission factor of greenhouse gases was 406 kg CO_2 eq/kWh.

For *Ulva* spp. processing into Aralgae and Pasteurized Juice, gas use in the step of Aralgae production is the main hotspot for all impact categories other than marine eutrophication and mineral resource scarcity. Measures to decrease gas-related impacts may include energy saving methods like condensing evaporated water or installing a heating circuit with (superheated) steam. However, it should be noted that the direct emissions from burning butane gas should be modelled more accurately (the Ecoinvent process should be replaced). Besides, the quantity of gas used should be confirmed another time, and sensitivities in their estimation should be evaluated, although they have been verified. Variability analysis or alternative scenarios of changing heat demand would be also interesting. Clay use in the Aralgae production is important for the mineral resource scarcity impact. The wastewater discharge in the harvesting and cleaning step contributes most to marine eutrophication, but as explained before, this result is quite unrepresentative. A recommendation is that wastewater modelling should be based on the most likely contaminant concentration in the actual wastewater. Still in the harvesting and cleaning step, the transport of seaweed to Olmix facility plays an important role in some impact categories (ozone formations, terrestrial acidification, and freshwater eutrophication) and, therefore, should be optimized. In this context, it should be further evaluated what are the improvements obtained from changing locations of specific unit operations to decrease the amount of water transported in solutions, and limit logistic steps. The modelling of the transport processes is reasonably reliable, but it should be determined how representative they are for the current vehicles. Future work in the modelling of Olmix activities to obtain higher certainty in the results should also comprise a critical evaluation of dry mass and wet mass balances.

5 CONCLUSION

This report presents a preliminary LCA of the current cultivation practices of *Saccharina latissima* and *Ulva rigida*, as well as *Ulva* spp. processing into products, based on primary data provided by the companies SES, ALGAplus and Olmix, respectively. The results show that the main environmental hotspots in *Saccharina latissima* cultivation derive from the use of diesel, nylon nets and steel anchor chains. The impacts from *Ulva rigida* cultivation are almost exclusively associated with the use of electricity. In the processing of *Ulva* spp., the largest contributions come from the use of gas and clay during Aralgae production. Several measures were proposed in an attempt to reduce the impacts of these processes and, consequently, improve the global environmental performance of the systems.

Future work should entail the refinement of some data used in the current assessment, as described in the Discussion Section. It should also focus on the integration of *Ulva rigida* biomass cultivated by ALGAplus in the Olmix process. In the same way, the integrated system composed by *Saccharina latissima* cultivation by SES and processing taking place at Algaia should be assessed. Moreover, LCA will be carried out for the most promising applications of seaweed that are most likely to enter the market.

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