Article

Sustainability Assessment of Combined Animal Fodder and Fuel Production from Microalgal Biomass

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Abstract: We present a comparative environmental and social life cycle assessment (ELCA and SLCA) of algal fuel and fodder co-production (AF+fodder) versus algal fuel and energy co-production (AF+energy). Our ELCA results indicate that fodder co-production offers an advantage in the categories: climate change (biogenic, land use and land use change, total), ecotoxicity, marine eutrophication, ionizing radiation, photochemical ozone creation, and land use. In contrast, the AF+energy system yields lower impacts in the other 11 out of 19 Environmental Footprint impact categories. Only AF+fodder offers a greenhouse gas reduction compared to petroleum-based fossil fuel (-25%). Our SLCA results indicate that AF+fodder yields lower impacts in the categories: fair salaries, forced labor, gender wage gap, health expenditure, unemployment, and violation of employment laws and regulations. AF+fuel performs favorably in the other 3 out of 9 social indicators. We conclude that the choice of co-products has a strong influence on the sustainability of algal fuel production. Despite this, none of the compared systems has been found to yield a consistent advantage in the environmental or social dimension. It is therefore not possible to recommend a co-production strategy without weighting environmental and social issues.

Keywords: microalgae; biorefinery; fuel; fodder; feed; life cycle assessment; LCA; SLCA

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1. Introduction

Awareness of the detrimental impact that humanity has on the environment is growing worldwide and becomes increasingly relevant in the public debate. In 2015, 195 countries adopted the Paris Agreement - the first globally binding covenant on the climate - with the goal of limiting global warming to well below +2 °C compared to the pre-industrial era [1]. It is well known that the massive use of fossil fuels is a driver of climate change. In 2018, world primary energy demand amounted to 14.3 billion tonnes oil equivalent (Btoe) of which 81% were met by fossil fuels [2]. In the shift towards more sustainable energy sources, biofuels are expected to play a significant role [3]. Microalgal fuel in particular offers two advantages over first-generation fuels from soybeans or rapeseed: Microalgae offer potentially higher biomass yields per unit area [4,5] and they can be grown on marginal lands, thereby avoiding competition with the food and fodder sector [6].

Despite these advantages, no commercial microalgal fuel plant exists today. Whereas some authors explain this by the high cost of production [7–10] other authors have doubted the environmental benefits of algal fuel to begin with [11]. In pursuit of a remedy, the concept of the algal biorefinery was born. Apart from oil, which is the raw material for fuel production, some algae species are capable producing valuable co-products, such as cosmetic ingredients, pharmaceutical compounds, and pigments [12]. These could offer an additional income and share part of the production burden. However, apart from the technical difficulties of recovering co-products in sufficient quantity and quality [12,13], not all co-production strategies are compatible with algal fuel. Laurens *et al.* [14]

and Subhadra and Edwards [8] show that the small market volumes typically associated with high value commodities such as cosmetics, food supplements, and pharmaceuticals, are easily saturated by large-scale biorefineries. To avoid the uncertain socio-economic consequences of market glut, we prefer to combine algal fuel production with bulk co-products, such as chemicals and animal fodder. Several studies have investigated the suitability of algal biomass as a dietary supplement for poultry, pigs, ruminants and in aquaculture [13,15–17] with promising results. Observed benefits include improved overall health, better immune response, higher fertility, and increased body weight and product output [13]. Based on these findings and on the fact that a large part of today's algal biomass production is already used for fodder [12,13], our study will focus on this co-product specifically.

Before algal fuel and fodder co-production is employed at scale, it must undergo a stringent sustainability assessment. Life cycle assessments (LCA) found in the literature [18–22] typically focus on greenhouse gas (GHG) emissions and disregard or underrate other issues. Social aspects of biofuel production in particular have been shown to be hard to quantify because of supply chain complexity [23]. Existing studies address bioelectricity [23], bioethanol [24,25] or biohydrogen [26]. Notable studies dealing with microalgal fuel in particular include Tavakoli and Barkdoll [27], Rafiaani *et al.* [28]. Still, differences in the underlying methodology (e.g. background SLCA database and supply-chain definition) hamper comparisons. Furthermore, alternative co-production strategies are rarely explored.

It is the goal of our study to complement the existing literature by offering a broader view on the sustainability of algal fuel and fodder co-production. We present an environmental and social life cycle assessment (ELCA, SLCA), including all 19 indicators [1] of the Environmental Footprint (EF) 2.0 method [29], as well as 9 social indicators from the Product Social Impact Life Cycle Assessment (PSILCA) v3 database [30]. Reference for our comparison is an alternative algal fuel co-production pathway producing heat and electricity from the residual biomass. We further compare environmental impacts to those of petroleum diesel.

2. Materials and Methods

2.1. Goal Definition

The goal of our study is to quantify and compare the environmental and social life cycle performance of two algal fuel co-production systems. Both systems produce fuel via hydrotreatment of algal oil (hydrotreated esters and fatty acids, HEFA), but differ in the utilization of non-oil biomass fractions. The AF+energy system converts residual biomass into electricity and heat via anaerobic digestion and biogas combustion (Fig. 1). The AF+fodder system converts residual biomass into animal fodder via spray-drying (Fig. 2). We perform environmental life cycle assessment (ELCA) and social life cycle assessment (SLCA) for both systems in order to identify the more sustainable option. The highlighted environmental and social bottlenecks can further guide future development.

2.2. System Description

The process chain from algae cultivation to fuel final use is identical for both systems and is briefly recapitulated in Section 2.2.1. Note that this part of the system has been adapted from Portner *et al.* [31]. We refer to that study for an in-depth description and for an opportunity to download the original AF+energy model. The model has been adapted for this study as described in the supporting information (http://www.mdpi.com/1660-4601/1/1/0/s1). Finally, Section 2.2.2 describes the central focus of this study: the co-production of energy and fodder. A complete bill of materials for both systems is given in Table 1 and Table 2, respectively.

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[1] Note that the EF method consists of 16 indicators and 3 subindicators (climate change biogenic, climate change fossil, climate change land use and land use change). Throughout our study we will refer to them simply as 19 indicators for brevity.

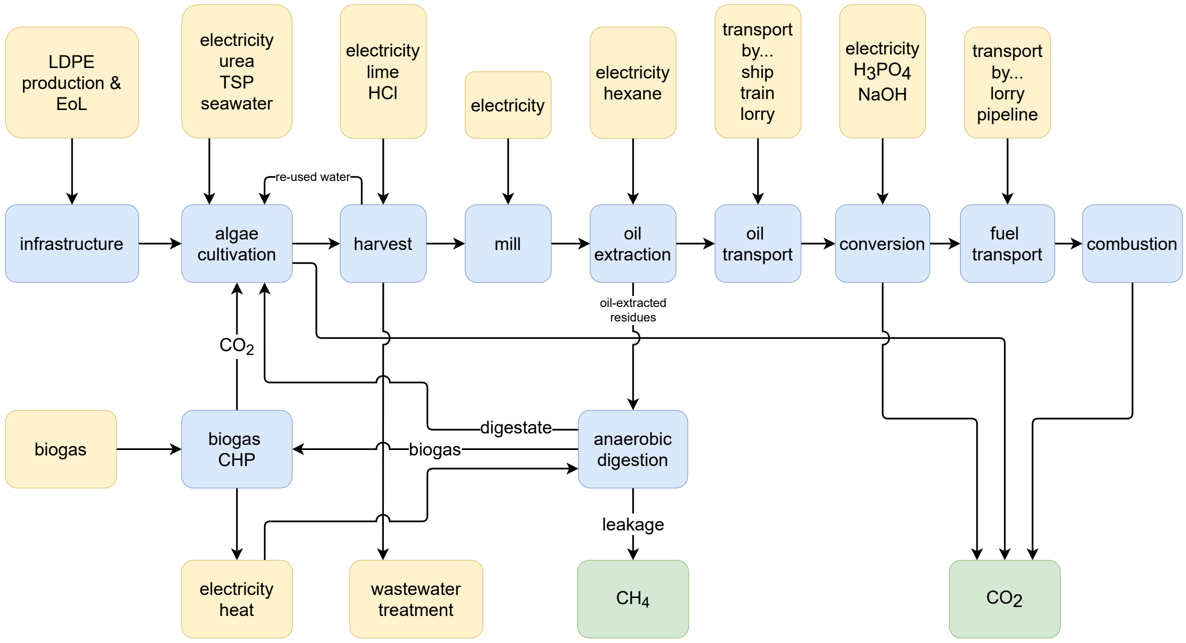

Figure 1. Scheme of the algal fuel + energy production system. Yellow - background system, green - biosphere, blue - foreground system. Abbreviations: LDPE - low density polyethylene, EoL - end of life, TSP - triple superphosphate, CHP - combined heat and power plant. Adapted from [31].

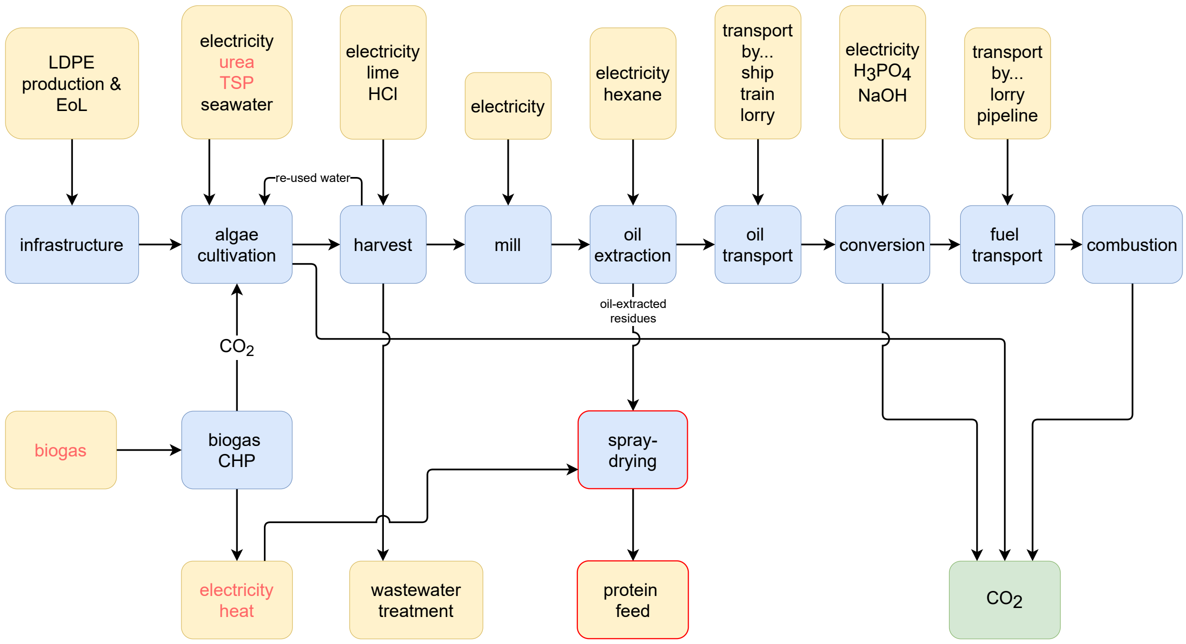

Figure 2. Scheme of the algal fuel + fodder production system. Yellow - background system, green - biosphere, blue - foreground system, red frame - newly introduced process, red font - existing process with different flow amount. Abbreviations: LDPE - low density polyethylene, EoL - end of life, TSP - triple superphosphate, CHP - combined heat and power plant.

2.2.1. Algal Fuel Production

Values and assumptions stated throughout this subsection are taken from [31] and explained therein.

Microalgae are cultivated in open raceway ponds (ORP) in a coastal area in Spain. The ponds are excavated from the ground and covered by plastic liners. The cultivation mode is autotrophic, meaning the microalgae thrive on photosynthesis. CO_2 is pumped into the pond after extraction from the flue gas of a combined heat and power plant (CHP), which uses biogas as its primary fuel. Electricity and heat produced by the CHP are treated as co-products of the fuel production process. Nitrogen and phosphorus are supplied in the form of commercial urea and triple superphosphate (TSP) fertilizers. To ensure homogeneous exposure to the sun, the pond is mixed by paddle wheels throughout the day (12 hours per day). The power demand for this is estimated at 4 000 W/ha, or 30.2 GJ per day for the whole cultivation area of 175 ha. The biomass yield is estimated at 15 $g_{DW}/(m^2\ d)$, or 6.3 kilotons during the cultivation season of 240 days per year. The algae cells are subjected to nitrogen-stress at the end of their growth cycle to raise the lipid content to 30% by weight. The cells also contain hydrocarbons and proteins, which are valuable nutrients for animals. Water evaporates continuously from the open ponds (1.3 $m^3/(m^2\ d)$) and needs to be replenished by pumping saltwater from the neighboring sea via a dedicated pipeline. The power demand for pumping is estimated at 160 kW, or 6.9 GJ per day. We assume that the algae cells can tolerate salt concentrations up to 5.3%-wt and that salt accumulation beyond this point is prevented by reducing the recycling rate. In this way, no external freshwater source is necessary.

After reaching the targeted cultivation density (0.5 g_{DW}/L) and cell lipid content (30% by weight), the microalgae are harvested in a two-step procedure: First, the medium is pre-concentrated by flocculation with magnesium hydroxide. After that, it is centrifuged, yielding a biomass concentration of 20% by weight. HCl is subsequently added to the centrate and to the supernatant to neutralize the pH and to recover the flocculation agent. The neutralized supernatant is then returned to the cultivation process if salt levels permit or discarded otherwise. Discarded medium is treated in a wastewater treatment plant and returned to the sea. Note that the composition of marine cultivation media after nitrogen deprivation and harvest is non-existent in the literature. For this reason, we chose a generic treatment model from the Ecoinvent database *treatment of wastewater, average, capacity 1.1E10l/year*[32].

After the centrifuge, the algae cells pass a mill, which breaks open the cell walls. The released lipids are then extracted using hexane and the extracted oil is shipped to the Netherlands, where it is converted into fuel via hydrotreatment (hydrotreated esters and fatty acids, HEFA). Finally, the fuel is distributed across Europe to its final users. Combustion emissions are treated as carbon neutral, as the released CO_2 is of biogenic origin.

2.2.2. Co-production of Energy and Fodder

Apart from algal oil, the extraction process produces an aqueous residue, which is rich in carbohydrates and proteins. This residue can be utilized in various ways. In our study, we compare two utilization scenarios: energy production and fodder production.

In the AF+fodder scenario, the residue is dried and sold as animal fodder. Not all drying processes are suitable for this task. The goal is to produce a durable product while conserving the bio-functionality of the algae proteins. On an industrial scale, spray-drying is employed for the production of baby formula and of Spirulina powder for food supplements [12,32]. We therefore chose Ecoinvent activity *milk spray-drying, CA-QC* [32] as the basis of our model. We adapted the model to account for the different water content of the raw material (85% instead of 50%) and for the changed location (inputs from Spanish markets instead of Canadian ones). We further added an efficiency term to model a loss rate of 10% of the nutritional value of the raw input. We assume that the remaining 90% of algal residues can displace soy meal on a 1:1 basis. Because no Spanish soy meal market was available from the Ecoinvent database, we approximated it by 55% imports from Brazil and 45% imports from the United States (US), based on data from UN COMTRADE [33]. Due to the high water content of the raw input, spray-drying requires a significant heat input, which is satisfied by a natural gas CHP. Overall, the AF+fodder system is a net heat *consumer*. In accordance with the Environmental Footprint method [29], we assign no dissipation impact to water evaporated from the algal residues, as it is mostly seawater. The resulting net inventory for the AF+fodder system, including fuel and fodder production, is reported in Table 2.

In the AF+energy scenario, the oil-extracted residue is used to produce biogas via anaerobic digestion (AD), which is then supplied to the biogas CHP to produce heat and electricity. Apart from biogas, AD produces digestate, which is rich in carbon, nitrogen and phosphorous and can be used as a nutrient source for algae cultivation. Our model is based on Portner *et al.* [31] with the adaptations described in the supporting information. In summary, the effect of AD is fourfold: 1) algae-derived biogas reduces market biogas demand (-13% compared to system without AD); 2) nitrogen in the recycled digestate reduces market urea demand (-45%); 3) phosphorus in the recycled digestate reduces market TSP demand (-45%); 4) carbon in the recycled digestate reduces cultivation-CO_2 demand (-16%). The reduced CO_2 demand has further consequences for the biogas-CHP plant: Because less CO_2 is consumed, less electricity and heat can be attributed to the algal fuel as by-products (-16% each). Furthermore, the reduced CO_2 demand leads to reduced market biogas consumption (-16% on top of the reduction induced by local biogas production). The resulting net inventory of the AF+energy system, including fuel and energy production, are reported in Table 1. Note that electricity production by the AF+energy system is *lower* than in the AF+fodder system due to the described effects of AD.

Table 1. Inventory of the AF+energy scenario (adapted from [31]).

Material	Ecoinvent 3.7.1 APOS activity, location (ELCA) [2]	PSILCA 3.0 sector, country (SLCA)	Amount per MJ	Unit	Cost per FU (USD)
Biogas	market for biogas, RoW	Agricultural and livestock services, ES	1.23E-01	m^3	1.42E-02
N-fertilizer	nutrient supply from urea, RER	Manufacture of pesticides and agrochemical products, ES	5.18E-03	kg N	2.89E-03
P-fertilizer	nutrient supply from triple superphosphate, RER	Manufacture of pesticides and agrochemical products, ES	1.04E-03	kg P_2O_5	2.96E-04
Pond liner	market for packaging film, low density polyethylene, GLO	Manufacture of plastic products, ES	5.46E-04	kg	1.91E-03
Water pipeline	market for water supply network, GLO	Civil Engineering, ES	5.07E-09	km	5.10E-03
Lime	market for lime, RER	Basic chemical products, ES	4.91E-02	kg	6.78E-03
HCl	market for hydrochloric acid, without water, in 30% solution state, RER	Basic chemical products, ES	4.83E-02	kg (undiluted)	7.24E-03
Hexane	market for hexane, GLO	Coke, refined petroleum products and nuclear fuel, ES	1.64E-04	kg	6.31E-05
Rail transport	market group for transport, freight train, RER	Railway transport, ES	3.16E-03	t km	9.68E-05
Sea transport	market for transport, freight, sea, tanker for petroleum, GLO	Water transport, ES	1.11E-01	t km	4.13E-05
Road transport	market for transport, freight, lorry 16-32 metric ton, EURO6, RER	Other transport material n.e.c., ES	2.74E-03	t km	9.34E-05
Pipeline transport	market for transport, pipeline, onshore, petroleum, RER	Other land transport; transport via pipelines, ES	9.25E-03	t km	5.17E-05
Electricity	market for electricity, medium voltage, NL	Electricity, gas, steam and hot water supply, NL	2.11E-03	kWh	2.49E-04
H_3PO_4	market for phosphoric acid, industrial grade, without water, in 85% solution state, GLO	Manufacture of industrial chemicals and fertilizers, IL	1.95E-05	kg (undiluted)	2.07E-05
NaOH	market for sodium hydroxide, without water, in 50% solution state, GLO	Manufacture of chemicals and chemical product, NL	5.84E-05	kg (undiluted)	1.32E-05

Electricity (avoided)	market for electricity, high voltage, ES	Production and distribution of electricity, ES	-1.45E-01	kWh	-1.68E-02
Natural gas (avoided)	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical, ES	Natural gas mix, ES [3]	-1.30E+00	MJ	-1.63E-02

Table 2. Inventory of the AF+fodder scenario.

Material	Ecoinvent 3.7.1 APOS activity, location (ELCA) [2]	PSILCA 3.0 sector, country (SLCA)	Amount per MJ	Unit	Cost per FU (USD)
Biogas	market for biogas, RoW	Agricultural and livestock services, ES	1.72E-01	m^3	2.22E-02
N-fertilizer	nutrient supply from urea, RER	Manufacture of pesticides and agrochemical products, ES	9.44E-03	kg N	5.27E-03
P-fertilizer	nutrient supply from triple superphosphate, RER	Manufacture of pesticides and agrochemical products, ES	1.90E-03	kg P_2O_5	5.39E-04
Pond liner	market for packaging film, low density polyethylene, GLO	Manufacture of plastic products, ES	5.46E-04	kg	1.91E-03
Water pipeline	market for water supply network, GLO	Civil Engineering, ES	5.07E-09	km	5.10E-03
Lime	market for lime, RER	Basic chemical products, ES	4.91E-02	kg	6.78E-03
HCl	market for hydrochloric acid, without water, in 30% solution state, RER	Basic chemical products, ES	4.83E-02	kg (undiluted)	7.24E-03
Hexane	market for hexane, GLO	Coke, refined petroleum products and nuclear fuel, ES	1.64E-04	kg	6.31E-05
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Sea transport	market for transport, freight, sea, tanker for petroleum, GLO	Water transport, ES	1.11E-01	t km	4.13E-05
Road transport	market for transport, freight, lorry 16-32 metric ton, EURO6, RER	Other transport material n.e.c., ES	2.74E-03	t km	9.34E-05
Pipeline transport	market for transport, pipeline, onshore, petroleum, RER	Other land transport; transport via pipelines, ES	9.25E-03	t km	5.17E-05
Electricity	market for electricity, medium voltage, NL	Electricity, gas, steam and hot water supply, NL	2.11E-03	kWh	2.49E-04

H_3PO_4	market for phosphoric acid, industrial grade, without water, in 85% solution state, GLO	Manufacture of industrial chemicals and fertilizers, IL	1.95E-05	kg (undiluted)	2.07E-05
NaOH	market for sodium hydroxide, without water, in 50% solution state, GLO	Manufacture of chemicals and chemical product, NL	5.84E-05	kg (undiluted)	1.32E-05
Heat	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical, ES	Natural gas mix, ES [3]	6.10E-01	MJ	7.63E-03
Tap water	market for tap water, Europe w/o Switzerland	Collection, purification and distribution of water, ES	4.91E-02	kg	2.30E-05
Electricity (avoided)	market for electricity, high voltage, ES	Production and distribution of electricity, ES	-1.74E-01	kWh	-2.01E-02
Soybean (avoided)	soybean meal and crude oil production, BR	Processed soy oil, BR	-3.85E-02	kg	-2.40E-02
Soybean (avoided)	soybean meal and crude oil production, US	Soybean and other oilseed processing, US	-3.15E-02	kg	-1.96E-02

[2] Where no local Ecoinvent activity was available, the next-largest parent region was chosen (RER, Europe w/o Switzerland, GLO). If only CH and RoW were available, CH was preferred.
[3] Spanish natural gas mix: Algeria 33.11%; Nigeria 11.47%; Qatar 11.46%; US 11.04%; Russia 8.52%; Trinidad and Tobago 7.52%; France 7.02%; Norway 6.52%; Peru 1.43%; Angola 0.73%; Portugal, 0.25%; Cameroon 0.23% (source: www.ine.es)

2.3. Assessment Methodology

2.3.1. Environmental Life Cycle Impacts

Assessment of the environmental performance is based on the standardized Life Cycle Assessment (LCA) methodology [34,35]. The LCA methodology is becoming an essential tool to underpin evidence-based policies in the EU [36]. According to the ISO standards, it comprises four interrelated stages [34,35].

In the first stage ("goal and scope definition") key aspects such as the functional unit (FU) and the boundaries of the product system are defined. Since the main function of the systems under study is fuel production, we select 1 MJ of fuel (lower heating value) as the functional unit. Concerning the system boundary, a cradle-to-grave approach was followed, covering feedstock production (including infrastructure), feedstock preparation, conversion, fuel distribution, and fuel combustion (Figs. 1 and 2). The geographical scope of the foreground system comprises Spain (algal oil production) and the Netherlands (fuel production). The temporal scope is today, i.e. we consider state-of-the-art technologies.

The second stage ("life cycle inventory analysis", LCI) focuses on the acquisition of input and output data (bill of materials) describing the production system. Furthermore, an approach to deal with multifunctionality has to be detailed if the system under study produces more than one useful product. The bills of materials for the AF+energy system and the AF+fodder system are given in Table 1 and Table 2, respectively. The systems were modeled in Excel and a workbook containing the AF+fodder model is available in the supporting information of this paper. The AF+energy model is available from the supporting information of Portner *et al.* [31]. Modifications to the latter model were necessary and are described in the supporting information of this paper. The background system in our study is modeled using activities from the Ecoinvent 3.7.1 APOS database [32]. Multifunctionality in the foreground system is resolved following the substitution approach, in accordance with the ISO recommendation [34,35]. Each of the two systems produces three useful products (AF+energy: algal fuel, electricity, useful heat; AF+fodder: algal fuel, electricity, animal fodder). It is assumed that electricity displaces the current average Spanish grid mix, heat displaces heat generation from natural gas, and fodder displaces soybean meal. As no soybean meal market for Spain was available from the Ecoinvent database, we approximated it by 55% Brazilian imports and 45% US imports, based on data from UN COMTRADE [33]. We assume that 1 kg of spray-dried algae-residues are nutritionally equivalent to 1 kg of soybean meal.

The third stage of LCA ("life cycle impact assessment", LCIA) includes three mandatory components: (i) selection of impact categories, indicators and characterization models, (ii) linking of impact categories and inventory data (associating elementary flows with impact categories), and (iii) characterization of impacts (applying indicator-specific intensity variables, the characterization factors). The optional normalization and weighting step is omitted in our study. Given the European context of our study, the environmental life cycle performance is characterized using the Environmental Footprint 2.0 method (EF 2.0) midpoint indicators [29]. We use all 19 indicators to capture a broad view of the possible environmental consequences and trade-offs. Linking and characterization (components ii and iii) are performed in Brightway 2 [37].

The last stage of LCA ("interpretation") summarizes the findings of the LCI and LCIA stages, identifies critical life cycle phases and gives recommendations for future development. This stage corresponds to Section 3 of this article.

2.3.2. Social Life Cycle Impacts

The SLCA methodology is defined in the UNEP/SETAC Guidelines for Social Life Cycle Assessment [38] and is largely analogous to the LCA framework. The social life cycle inventory is defined in terms of work-hours per functional unit and characterization factors describe the risk of a specific social issue occurring in a country-specific sector. Inventories can be defined explicitly by the SLCA practitioner or they can be taken from economic databases. We chose the first approach for the foreground system and the second approach for the background system.

For the foreground inventory, the source country of each exchange was first identified based on global commodity trade statistics reported in the UN COMTRATE database [33]. In a second step, the sector associated with each flow was selected among those available in the PSILCA 3.0 database [30]. Physical exchange were converted to monetary units based on price data from the Ecoinvent APOS 3.7.1 database [32]. Prices in EUR were converted to USD using a conversion factor of 1.179 EUR/USD. The labor demand at the algal plant was estimated at 240 days per year, 12 hours per day, and 10 workers per shift. Normalized by the fuel production rate ($5.15 \cdot 10^7$ MJ per year), this yields a labor demand of $5.59 \cdot 10^{-4}$ work-hours per MJ fuel.

Linking and characterization was carried out in OpenLCA [39]. The PSILCA v3.0 database [30] was used to model sector and country specific background inventories, as well as their social risk levels. There are 55 social performance indicators available in PSILCA 3. We selected a subset of 9 based on the following considerations: (i) relevance to central subjects of the SDGs; (ii) recommendations set by previous SLCA studies on alternative fuels in the European and Spanish context [26,40–42]; (iii) socio-economic specifics of countries involved in the supply chain. The 9 chosen indicators are: Child labor (CL), Contribution of the sector to economic development (SED), Fair Salary (FS), Frequency of forced labor (FL), Gender wage gap (GWG), Health expenditure (HE), Unemployment (U), Violations of employment laws and regulations (VEL), and Women in the sectoral labor force (WLF).

3. Results and Discussion

3.1. Environmental Life Cycle Impacts

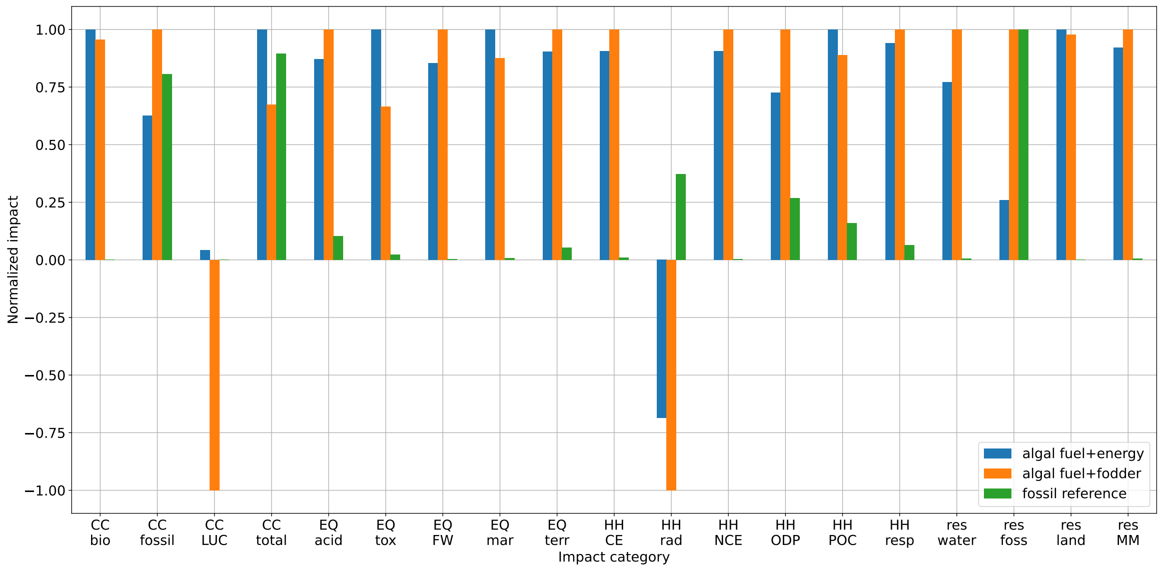

Figure 3. Comparison of environmental impacts: AF+energy (blue), AF+fodder (orange) and petroleum diesel (green). Note that the bars are normalized by the maximum in each category. Abbreviations: CC - climate change, EQ - ecosystem quality, HH - human health, res - resource depletion, bio - biogenic, LUC - land use and land use change, acid - freshwater and terrestrial acidification, tox - freshwater ecotoxicity, FW - freshwater eutrophication, mar - marine eutrophication, terr - terrestrial eutrophication, CE - carcinogenic effects, rad - ionizing radiation, NCE - non-carcinogenic effects, ODP - ozone depletion potential, POC - photochemical ozone creation, resp - respiratory effects, water - water dissipation, foss - fossil, land - land use, MM - minerals and metals

Fig. 3 compares the calculated environmental impacts of the AF+energy system (blue) and the AF+fodder system (orange). The AF+energy system performs better in 11 out of the 19 indicators (climate change - fossil, ecosystem quality - acidification, freshwater & terrestrial eutrophication, human health - carcinogenic & non-carcinogenic effects, ozone depletion, respiratory effect, resource depletion - water dissipation, fossil, materials and metals). In the remaining 8 categories, the AF+fodder pathway shows a lower impact (climate change - biogenic, land use and land use change, total, ecosystem quality - freshwater ecotoxicity, marine eutrophication, human health - ionizing radiation, photochemical ozone creation, resource depletion - land use). Thus, we find no systematic environmental advantage for either co-production strategy. The figure further shows the environmental impact of petroleum diesel (green), which outperforms both algal fuels in 14 out of the 19 indicators. Our results demonstrate that decisions based on one indicator alone can lead to increasing burdens in the ignored environmental compartments. Whether burden shifts are acceptable or not is a question of weighting, which is inherently value-based and not further discussed here. Instead, we move on to clarify the origin of impacts within our systems, based on the breakdown in Fig. 4.

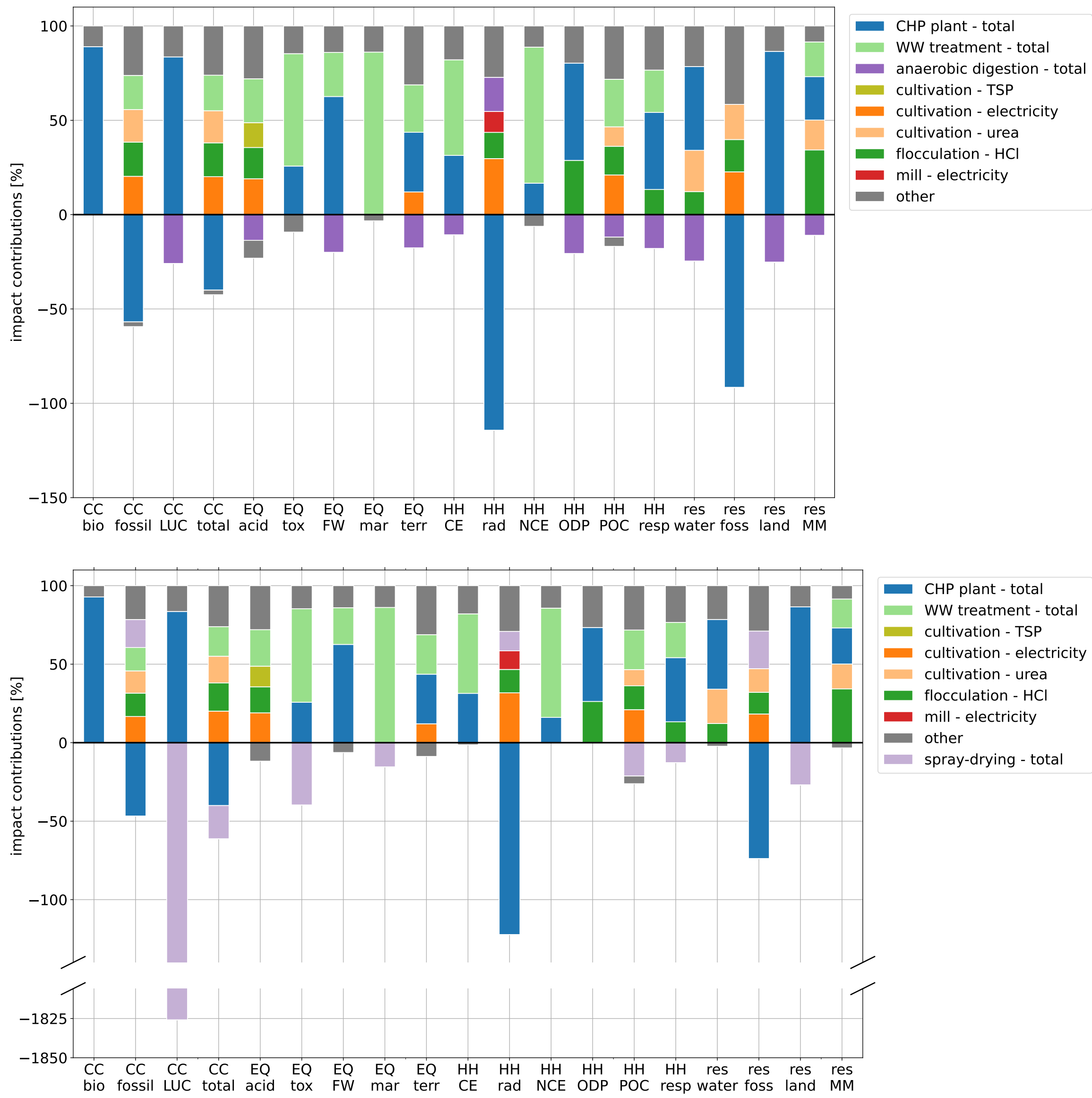

Figure 4. Break-down of environmental impacts: (**a**) AF+energy (**b**) AF+fodder. Note that the bars are normalized by the sum of positive (i.e. damaging) impacts. Abbreviations: CC - climate change, EQ - ecosystem quality, HH - human health, res - resource depletion, bio - biogenic, LUC - land use and land use change, acid - freshwater and terrestrial acidification, tox - freshwater ecotoxicity, FW - freshwater eutrophication, mar - marine eutrophication, terr - terrestrial eutrophication, CE - carcinogenic effects, rad - ionizing radiation, NCE - non-carcinogenic effects, ODP - ozone depletion potential, POC - photochemical ozone creation, resp - respiratory effects, water - water dissipation, foss - fossil, land - land use, MM - minerals and metals

3.1.1. Climate Change

The climate change subcategory comprises the aggregated indicator *cliamte change - total* (CC total), as well as three subcompartments for biogenic methane emissions (CC bio), fossil GHG emissions (CC fossil), and land use change effects (CC LUC).

AF+fodder shows the lowest total climate change impact thanks to credits for the displacement of soybean meal. Displacement of soybean cultivation in Brazil in particular yields a significant credit in the CC LUC subcategory. Both algal fuel pathways further profit from the displacement of fossil electricity (CC fossil). Despite these substantial credits, the AF+fodder fuel achieves only 25% GHG reduction compared to petroleum diesel, which is insufficient for RED II accreditation. GHG intensity of the AF+energy fuel surpasses that of petroleum diesel.

Impacts in both algal fuel systems stem mainly from the consumption of electricity, urea fertilizer, hydrochloric acid and from the treatment of discarded cultivation medium [2]. Note that the release of CO_2 from the cultivation ponds into the atmosphere has no impact, as the CO_2 is of biogenic origin. Biogenic methane leaking from the anaerobic digestion (AD) process on the other hand causes a climate impact and is accounted for in the *anaerobic digestion - total* credit.

3.1.2. Ecosystem Quality

Both algal fuels show substantially higher ecosystem quality (EQ) impacts than petroleum diesel in all five subcategories. These impacts stem mainly from the treatment of discarded cultivation medium and from the CHP supply chain. The former causes eutrophication by releasing nitrogen- and phosphorous-rich compounds into water and into the atmosphere (EQ FW, EQ mar, EQ terr). The CHP contributions are caused by the burning of digester sludge, which is a by-product of biogas generation. Acidification impacts (EQ acid) are governed by the consumption of grid electricity (SO_2 emissions during hard coal combustion), P-fertilizer (release of SO_2 from land-filled gypsum, which is a by-product of TSP production) and hydrochloric acid (various SO_2 sources along the supply chain).

EQ credits are given to the AD process primarily for the displacement of market biogas (reduced release of N- and P-rich compounds during digestion and sludge incineration). The spray-drying process profits from the displacement of market soy (reduction in pesticide and fertilizer use). The former yield an advantage for the AF+energy system in the subcategories acidification, freshwater eutrophication, and terrestrial eutrophication. The latter yield an advantage for the AF+fodder system in the categories marine eutrophication and ecotoxicity.

3.1.3. Human Health

Both algal fuels show substantially higher impacts than petroleum diesel in five out of six Human Health (HH) subcategories. The only exception is ionizing radiation (HH rad) where they achieve an overall negative impact (environmental benefit) due to the displacement of nuclear electricity from the Spanish grid.

Impacts in the algal fuel pathways can be traced back to electricity consumed in the cultivation and milling processes (nuclear grid electricity), to HCl consumption in the harvesting stage (electricity demand and Cl-gas and SOx emissions along the HCl supply chain), and to the CHP supply chain (release of toxic substances during biowaste digestion and sludge incineration). Emissions from the wastewater treatment process (zinc, chromium VI, NOx), are a product of the generic wastewater composition (cf. Section 2.2.1) and the actual HH impact of cultivation medium treatment might be lower than shown here.

AF+energy credits in the subcategories carcinogenic effects (HH CE), non-carcinogenic effects (HH NCE), and ozone depletion (HH ODP) are driven by the displacement of market biogas, whereas fodder co-production yields no significant benefit. AF+energy further performs favorably in the respiratory effects category (HH resp) for the same reason. AF+fodder shows lower impacts in the subcategories ionizing radiation (HH rad) and photochemical ozone creation (HH POC), where it profits from the displacement of market soy (reduced slash and burn in Brazil) and from its higher net electricity production (cf. Section 2.2.2).

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[2] Note that both algal fuel systems are net electricity *producers*. Subtracting the CHP credit (blue bar) from the electricity burden (dark orange bar) yields a net credit. Similarly, urea consumption is partially offset by digestate recycled from the anaerobic digestion process (violet bar). We decided to show both sides of the balance for transparency.

3.1.4. Resource Depletion

Compared to petroleum diesel, the algal fuels perform unfavorably in 3 out of 4 resource depletion categories (res). In the fossil depletion category (res foss), the AF+energy system achieves significant impact reduction compared to petroleum diesel (credits for internal urea demand reduction and market biogas displacement), whereas AF+fodder is on par (impact from additional heat demand for spray-drying).

Water dissipation (res water) is driven by embedded impacts in the form of market biogas (biomass irrigation) and market urea (steam used as energy- and hydrogen-source in ammonia production). As the AF+energy system consumes less of both, it has the lower impact. Note that seawater evaporation is not associated with a dissipation impact, as seawater is not a critical resource.

Both algae pathways have a similar land footprint (res land), dominated by the biogas supply chain (composting of biomass). The credit for market biogas substitution (AF+energy) is marginally bigger than the credit for soy meal substitution (AF+fodder), giving AF+energy a small advantage. Note that the land demand for algae cultivation itself is negligible in comparison.

Minerals and metal depletion (res MM) in both algal fuel systems is caused by the use of copper and zinc in buildings and appliances throughout various supply chains - most notably the production of HCl, biogas, fertilizer, and the treatment of wastewater. Soybean meal displacement in the AF+fodder pathway is rewarded a significant credit (displaced harvesting equipment and fertilizers), which is partially consumed by the additional energy demand of spray-drying. The AF+energy pathway on the other hand receives credits for the displacement of market biogas and the reduction of the urea demand, and is slightly more favorable.

3.2. Social Life Cycle Impacts

Fig. 5 compares the social life cycle impact of the AF+energy and AF+fodder system (normalized with respect to the highest score between the two). Note that the indicator *sector contribution to economic development* is the only indicator expressed in medium *opportunity* hours (higher is better) whereas all other impact categories are expressed in medium *risk* hours (lower is better). Overall, the benefits of energy co-production, although relevant, appear less evident than those of fodder co-production. Whereas AF+energy features lower social risks in 3 out of 9 categories (child labor, CL; sector contribution to the economic development, SED; women in the sectoral labor force, WLF), AF+fodder shows a favorable performance in the other 6 categories (fair salary, FS; forced labor, FL; gender wage gap, GWG; health expenditure, HE; unemployment, U; violations of employment laws and regulations, VEL).

Fig. 6 shows a breakdown of risks according to location, distinguishing between Spain and the rest of the world (RoW). On average, energy co-production yields social benefits in Spain but creates burdens in the rest of the world. The opposite is true for fodder co-production, which primarily benefits the rest of the world and burdens Spain. The notable exception is economic development (SED), which is fostered internationally by the AF+energy pathway and domestically by the AF+fodder pathway. Note that activities located in the Netherlands were found to contribute less than 5% of the impact for all of the selected social life cycle indicators.

Table 3 further refines the breakdown by listing the main risk and benefit drivers in each category according to their country and industrial sector. Whereas algal fuel production in Spain creates burdens in most of the categories, displacement of soy and energy carriers are the most important benefit drivers. Clearly, co-production is an important means to improve the social performance of algal fuels. Again, the SED category poses an exception, indicating that the displacement of energy and soy from the market can exert significant pressure on established suppliers. This trade-off should be kept in mind in a potential decision-making context.

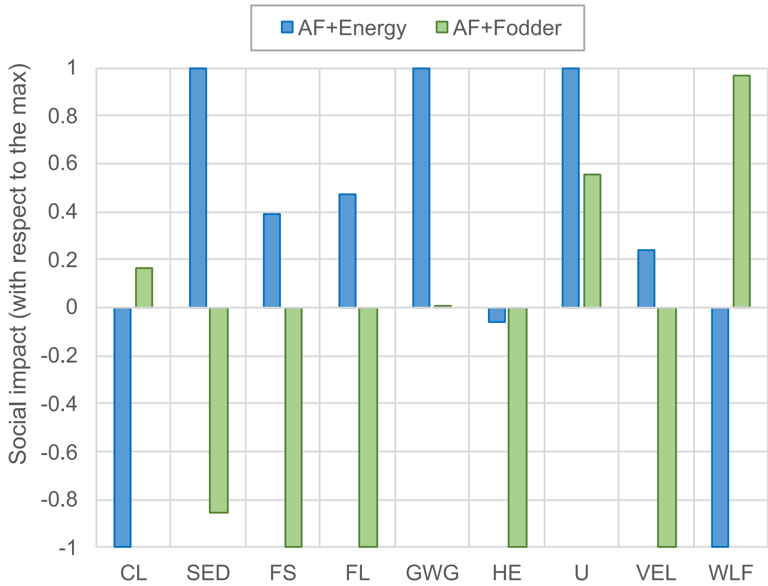

Figure 5. Social life cycle impacts of the AF+energy and AF+fodder systems. Scores are normalized by the highest absolute score in each impact category. Abbreviations: CL - Child Labor; SED - Sector contribution to Economic Development; FS - Fair Salary; FL - frequency of Forced Labor; GWG - Gender Wage Gap; HE - Health Expenditure; U - Unemployment; VEL - Violations of Employment Laws and regulations; WLF - Women in the sectoral Labor Force. Note that SED is the only positive indicator (higher is better) and all other indicators should be interpreted as "lower is better".

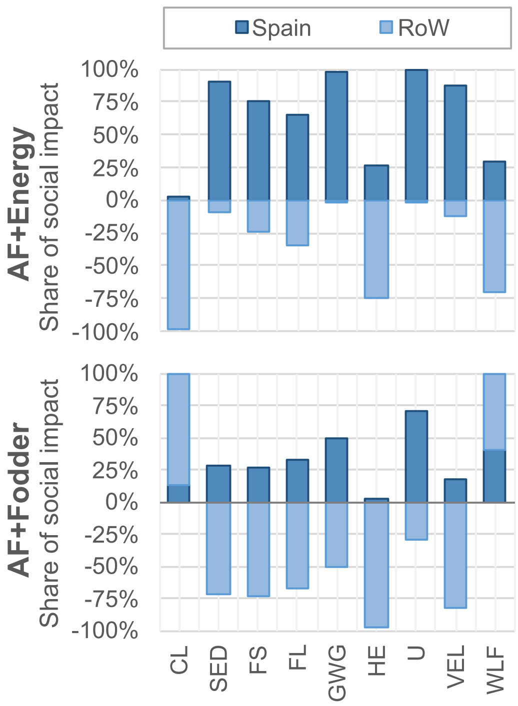

Figure 6. Breakdown of impact origins by domestic (Spain) and foreign (Rest of the World, RoW) activities. Abbreviations: CL - Child Labor; SED - Sector contribution to Economic Development; FS - Fair Salary; FL - frequency of Forced Labor; GWG - Gender Wage Gap; HE - Health Expenditure; U - Unemployment; VEL - Violations of Employment Laws and regulations; WLF - Women in the sectoral Labor Force. Note that SED is the only positive indicator (higher is better) and all other indicators should be interpreted as "lower is better".

Table 3. Summary of social impact drivers.

Social indicator	Main benefit driver AF+Energy	Main impact driver AF+Energy	Main benefit driver AF+Fodder	Main impact driver AF+Fodder
Child labor, total	Displacement of natural gas from Nigeria, Russia	Chemicals production in Spain	i) Displacement of soy from Brazil ii) Displacement of Spanish grid electricity	i) Natural gas production in Nigeria, Russia ii) Chemicals production in Spain
Sector contribution to economic development (positive indicator)	Algal fuel production in Spain	Displacement of energy carriers from Nigeria, Russia, South Africa	Production of biogas and chemicals in Spain	Displacement of soy from Brazil.
Fair Salary	Displacement of activities in Spain, Algeria related to energy products	Production of biogas and chemicals in Spain	Displacement of soy from Brazil, USA	Production of chemicals in Spain
Frequency of forced labor	Displacement of activities in Spain, Algeria, Russia related to energy products	Production of biogas and chemicals in Spain	Displacement of soy from Brazil	i) Natural gas production in Nigeria, Algeria, Russia ii) Production of biogas and chemicals in Spain
Gender wage gap	Displacement of Spanish grid electricity	Chemicals production in Spain	i) Displacement of soy from Brazil, USA ii) Displacement of Spanish grid electricity	i) Production of biogas and chemicals in Spain ii) Natural gas production in Peru
Health expenditure	Displacement of natural gas from Nigeria	Chemicals production in Spain	Displacement of soy from Brazil	Algal fuel production in Spain
Unemployment	Displacement of Spanish grid electricity.	Production of biogas, chemicals, water in Spain	Displacement of Spanish grid electricity	Production of biogas and chemicals in Spain
Violations of employment laws and regulations	Displacement of natural gas from USA, Peru	Production of biogas, chemicals, water in Spain	Displacement of soy from USA	Production of biogas and chemicals in Spain
Women in the sectoral labor force	Displacement of economic activities in France, Peru, Algeria related to energy products	Production of biogas and chemicals in Spain	Displacement of Spanish grid electricity	Economic activities in France related to natural gas

3.3. Limitations

The models used in this study are subject to limitations, which should be kept in mind when interpreting the ELCA and SLCA results.

We assume that algae can be grown in open ponds without applying pesticides. If pesticide use is necessary, the ecotoxicity impact of algal biomass production will be bigger than shown in our study.

Although power demand for raceway pond operation is frequently reported, values in the literature vary by orders of magnitude. Furthermore, the correlation between mixing power and biomass yield is rarely explored. As the two presented systems are net power exporters, they benefit from the displacement of grid electricity. Thus, impacts would go up if grid electricity is greener than modeled or if power demand goes up (i.e. less power can be exported). Such changes would mainly affect the impact categories climate change, ionizing radiation and fossil resource depletion.

Our anaerobic digestion model does not account for the release of nitrogen- or phosphorus-rich compounds to water and air. Although digestate recycling should reduce this risk, our study might underestimate it. Impacts in the ecosystem quality and human health categories would be exacerbated by the release of these compounds.

We assume that digestate can be recycled wholly and infinitely without impacting biomass yields - a practice which has yet to be proven at scale. If algae toxins are found to accumulate in the digestate, the recycled ratio would have to be reduced. In turn, fertilizer demand would increase and an alternative digestate disposal route would have to be found, likely increasing impacts in all categories.

Treatment of discharged cultivation medium presents a significant source of environmental impacts in our study. To the authors' best knowledge, no public data on the composition of spent algae cultivation media exists. Thus, we had to rely on a generic model from the Ecoinvent database to model its treatment. In particular, it is conceivable that impacts in the human health category are significantly lower than presented in this study. We recommend to close this knowledge gap in future studies.

Our models rely on socio-economic background data, which are highly specific to the geographical and temporal scope of this study. The obtained results should neither be applied to other countries nor be extended into the long-term future.

4. Conclusion

The presented study compares the potential environmental and social life cycle performance of microalgal fuel and fodder co-production (AF+fodder) against microalgal fuel and energy co-production (AF+energy) in Spain. Our environmental impact assessment shows a mixed picture, indicating that energy co-production outperforms fodder co-production in 11 out of 19 indicators. In contrast, the social impact assessment favors fodder co-production in 6 out of 9 categories. We conclude that there is no systematic environmental or social benefit of fodder co-production over energetic utilization of the oil-extracted biomass. Preference for either option can only be established by weighting the environmental and social issues, which is inherently value-based and not further investigated. Despite this, our results show that co-production strategies have a decisive impact on the environmental and social performance of algal fuel. Our comparison of algal fuel to petroleum diesel identified needs for improvement in several environmental impact categories. We hence recommend exploring new technologies and system configurations, which enable truly sustainable algal fuel production.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/1/1/0/s1 : PDF document: Modifications to the AF+energy model, Excel workbook: AF+fodder model.

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