Policy Analysis

Life-Cycle Assessment of Biodiesel Production from Microalgae

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This paper provides an analysis of the potential environmental impacts of biodiesel production from microalgae. High production yields of microalgae have called forth interest of economic and scientific actors but it is still unclear whether the production of biodiesel is environmentally interesting and which transformation steps need further adjustment and optimization. A comparative LCA study of a virtual facility has been undertaken to assess the energetic balance and the potential environmental impacts of the whole process chain, from the biomass production to the biodiesel combustion. Two different culture conditions, nominal fertilizing or nitrogen starvation, as well as two different extraction options, dry or wet extraction, have been tested. The best scenario has been compared to first generation biodiesel and oil diesel. The outcome confirms the potential of microalgae as an energy source but highlights the imperative necessity of decreasing the energy and fertilizer consumption. Therefore control of nitrogen stress during the culture and optimization of wet extraction seem to be valuable options. This study also emphasizes the potential of anaerobic digestion of oilcakes as a way to reduce external energy demand and to recycle a part of the mineral fertilizers.

1. Introduction

During the past ten years, fossil fuel depletion and global warming issues have strongly motivated research on fuel production from biomass. Biofuels based on vegetal oil or bioethanol have the key advantage of relying on existing distribution networks and current engine technology. In comparison to oil fuel, biofuel can represent an improvement in terms of emissions of fossil CO_2; however, such a technology can also induce negative environmental impacts, caused for instance by pesticides and fertilizers, and can also create a competition for land use with food crops. Therefore the use of first generation biofuel as a sustainable alternative to fossil fuels is questionable and has been the subject of controversy (*1*). On the other hand, microalgae seem to be an attractive way to produce biofuel due to their ability to accumulate lipids and their very high actual photosynthetic yields; about 3−8% of solar energy can be converted to biomass whereas observed yields for terrestrial plants are about 0.5% (*2, 3*). These interesting properties lead to potential productivities (in terms of oil production per ha and per year) which are far higher than those of rapeseed or sunflower (*4*). This high productivity combined with both the moderate competition with feed crop and the possibility to uptake industrial sources of CO_2 has motivated studies depicting microalgae as an alternative source of vegetal oil for biodiesel (*2, 4*).

Despite strong interest from economic and scientific actors, up to now, there is to our knowledge no industrial facility producing biodiesel from microalgae. The studies undertaken on the subject have been restricted to lab and pilot scales. Hence, no thorough Life Cycle Assessment of the production chain from microalgae culture to biodiesel is currently available, with the exception of LCA studies about the cofiring of microalgae with coal (*5*). The aim of this study is therefore to assess the environmental impacts of this technologically immature process. To do so, we extrapolated laboratory observations combined with known processes developed for first generation biofuel to design a realistic industrial facility. The potential pollution transfers are computed for various scenarios and guide the choice of selected steps in the process chain. In addition to the overall energetic balance of the production chain, the impacts of the combustion of algal biodiesel are compared to those produced by first generation biofuel and diesel fuel. The considered functional unit of the LCA is the combustion of 1 MJ of fuel in a diesel engine; the boundaries include extraction and production of raw materials, facility construction and dismantling, biofuel elaboration, and use in the engine. It is a "from cradle to combustion" analysis for the fuel and a "from cradle to grave" analysis for the facility. The key objective of this study is not to offer a LCA of the current microalgal biodiesel technology, but to identify the obstacles and limitations which should receive specific research efforts to make this process environmentally sustainable.

2. Production System Overview

As stated before, the analyzed process chain refers to a hypothetical system based on extrapolation from lab-scale studies. The inventory is based on figures derived from academic resources, communications with industrial producers, and inventories carried out on similar transformation units and processes described in the Ecoinvent database (*6*). Standard rules have been used for replacement of infrastructure: buildings have a 30-year lifespan, and are then dismantled, concrete is sent to ultimate landfill whereas steel-based and PVC products are recycled. Electrical engines are changed every 10 years. Electricity production is based on the European energetic mix, in which heat is produced with natural gas burned in industrial gas boilers. When a process leads to the production of several products, an energetic allocation has been done, sharing the environmental burden among coproducts according to their relative energetic content.

Figure 1 gives an overview of the process chain, from algae culture to the use of biodiesel in a diesel engine. Pure culture of *Chlorella vulgaris* is achieved in open raceways, in a facility covering about 100 ha. Like many other microalgae species, *Chlorella* is known to react to nitrogen deprivation by accumulating lipids and carbohydrates but at the cost of

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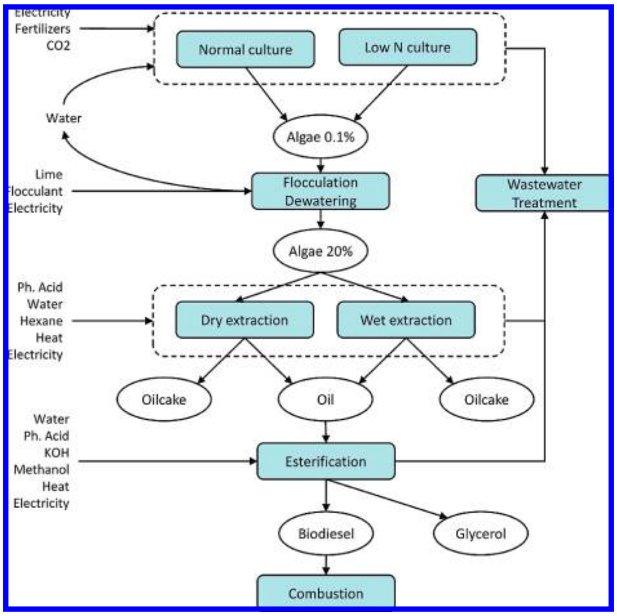

FIGURE 1. Process chain overview.

TABLE 1. Biomass Fractions

fraction	molar mass (g·mol-1)	net calorific value (MJ·kg^{-1})
protein $C_{4.43}H_7O_{1.44}N_{1.16}$	100.1	15.5
carbohydrate $C_6H_{12}O_6$	180	13
lipid $C_{40}H_{74}O_5$	634	38.3

a lower growth-rate (*7, 8*). As it is not evident which strategy will give better results, both options (normal and low N) will be evaluated. However it is assumed that in both cases culture is carried out in one step, without using a specific facility dedicated to nitrogen deprivation or inoculum's maintenance. Algae harvesting is achieved by continuous recirculation of culture ponds through a thickener; the flocculated stream is then dewatered. Oil extraction is subject to much discussion (*8*) and it is not clear now which technology would be the more efficient. As a consequence, two options have been evaluated: either advanced drying followed by hexane extraction (similarly to soybeans), or direct extraction from the wet algal paste. Water collected at the thickener and dewatering unit is redirected to the pond. An oil extraction unit located in the facility extracts oil from the algal paste. The oil fraction is then shipped to an industrial transesterification facility where it is transformed into biodiesel.

Performance and efficiency of the various steps in the process are highly dependent on the chemical composition of the algae. To assess the implication of the culture condition on the whole environmental impact, the biochemical fractionation (protein/carbohydrates/lipid content) is used to infer the CHON composition of different strains; this conversion is based on the gross elemental composition of biochemical classes for algae and cyanobacteria reported in ref *9*. In addition, experimental measurements reported in ref *7* for 4 strains of the genus *Chlorella* grown in two different conditions (normal or with low nitrogen) have been used to estimate net calorific values of each biomass fraction (summarized in Table 1).

On the basis of Table 1, it is possible to estimate nitrogen requirements and heating value of oil and oilcakes according to algae composition. Other nutrients (potassium, magnesium, phosphorus, and sulfur) are more closely associated to metabolic functions (e.g., photosynthesis) than to storage function. Their quota in the algae is thus assumed to be proportional to the protein content, and then indirectly to the nitrogen fraction of the biomass. Mineral balance among N, P, K, Mg, and S described for *Chlorella vulgaris* (*10*) has been used to determine the mineral composition depending on the protein content.

TABLE 2. Composition and Culture Parameters of *C. vulgaris*

parameter	normal	low N
protein (g·kg^{-1})	282	67
lipid (g·kg^{-1})	175	385
carbohydrates (g·kg^{-1})	495	529
lower heating value (MJ·kg^{-1})	17.5	22.6
C (g·kg^{-1})	480	538
N (g·kg^{-1})	46	10.9
P (g·kg^{-1})	9.9	2.4
K (g·kg^{-1})	8.2	2
Mg (g·kg^{-1})	3.8	0.9
S (g·kg^{-1})	2.2	0.5
CO_2 (kg·kg^{-1})	1.8	2.0
growth rate (day^{-1})	0.99	0.77
productivity (g·m^{-2}·day^{-1})	24.75	19.25

2.1. Algae Culture. The culture device consists of open raceways, operated with an algae concentration of 0.5 g·L^{-1}. Growth-rates observed in open raceways are usually lower than those in laboratory photobioreactors since it is more difficult to maintain optimal and stable growth conditions (*11*). Alternatively photobioreactors require much more energy for building and during processing compared to the increase in productivity that they offer (*12*). Assuming that the photosynthesis potential of a pond is equivalent to a 5-cm depth photobioreactor, growth-rates (expressed in day^{-1}) reported in ref *7* for photobioreactor lead to productivity rate between 20 and 30 g·m^{-2}·day^{-1}, which are in the range of usual performances of open raceways (*12*). Nutrient and CO_2 supply to produce 1 kg of algae are determined for both culture methods from the elementary composition proposed in Table 2 for both culture conditions. It is assumed that the total amount of nutrients is used with a perfect efficiency. Fertilizer mix has been chosen to minimize its environmental burden generated by its production or its use (e.g., nitrogen volatilization). Nitrogen is brought by calcium nitrate, phosphorus is brought by single superphosphate, potassium is brought by potassium chloride, and magnesium is brough by magnesium phosphate. Distance from production sites to regional storage has been assumed to be 100 km. Oligo-nutrients are usually provided in sufficient quantities by fresh water (*13*) and are therefore neglected.

The assumed pond design is consistent with industrial standards (*14*): 10 m wide, 100 m long, and 30 cm deep oval-shaped built in concrete blocks, on a 10-cm-thick sole. A PVC liner covers the concrete to decrease roughness and to avoid biomass attachment. Culture medium velocity is kept at 25 cm·s^{-1} with a paddlewheel. The pond's water is flushed every 2 months to control development of bacteria and to avoid accumulation of toxic or inhibiting compounds. Flush water is treated *in situ* in a classical wastewater treatment plant. In a Mediterranean context, the annual balance between rainfall and evaporation results in a water loss of 300 mm. Since the fraction of the water left in the harvest cannot be recycled, a significant part of water is lost for each kg of algae leaving the culture system. Consequently the total water needs are around 4 L per kilo of dry algae. A 750-W pump for murky water collects the growth medium with a 15m^3·hour^{-1} flow rate. CO_2 is pressurized and injected along the pond through PVC pipes. It is evaluated in ref *5* that CO_2 injection requires 22.2 Wh per kg of CO_2.

Harvesting has been pointed out as one of the main bottlenecks in algal culture (*15, 16*) because of their low diameter (i.e., from 2 to 20 μm). Centrifugation is usually efficient but too expensive for an energetic production purpose (*15*). However, it is often possible to flocculate algae by pH adjustment and addition of synthetic or biological flocculants (*17*–*19*). It is assumed here that the addition of 0.5 $g \cdot m^{-3}$ of a synthetic flocculant and the addition of lime up to a pH of 11 (i.e., 300 $g \cdot m^{-3}$) will flocculate 90% of the algal biomass. Resulting flocs are characterized by a settling speed of 2 $m \cdot h^{-1}$ and a concentration of 20 $kg \cdot m^{-3}$. The algae stream is processed through a rotary press producing an algal cake with a dry weight concentration of 200 $kg \cdot m^{-3}$.

2.2. Algae Oil Extraction and Transformation. Results on microalgal oil extraction are rare and difficult to extrapolate to industrial scale. According to ref *20*, algae oil extraction is very similar to soybean extraction. However soybean has a solid content around 90%. Hence to preserve consistency of the study, algal paste has to be dried up to a solid content of 90% before being processed in the oil mill. Comparison of different processes commonly used for wastewater treatment plant sludge shows that belt dryer is one of the less demanding drying processes able to reach a 90% solid content with an energetic consumption of 400 Wh of electricity and 13.8 MJ of heat per kg of dry matter processed (*21*). The oil mill has been modeled on the basis of the description of soybean mills provided in the Ecoinvent database. Oil is separated from the biomass by counter-current circulation of a solvent, usually hexane: 2 g of hexane are lost for each kg of dry algae. Some studies (*22*–*24*) suggest that direct extraction on the wet paste is possible. Whereas it was possible to use pre-existing LCA for dry extraction, there is, to our knowledge, no description of an industrial-scale wet process available. We have thus proposed an alternative scenario to dry extraction, assuming that heat consumption and hexane loss are proportional to the total volume of processed material. Data reported in the literature (*23*) use a volume ratio of 1:1 between solvent and the material to process and obtained an extraction yield of about 70%.

The oil mill leads to two products, crude oil and oilcake, which differ by their carbon and their energetic content. As a consequence energetic allocation does not match the mass flow; for instance in the case of the normal culture condition, the extracted oil represents 37.9% of the energy but accounts for only 27.4% of the initial carbon amount fixed in the algae. Therefore without proper correction, oil combustion will emit less carbon than it is supposed to have contributed to fix. Consistent with the use in the Ecoinvent database, a corrective emission term is hence added to correct the carbon balance. To determine the corrective term, ε, we write the equation describing the conservation of carbon fraction between two allocation rules:

$$\alpha(N_C + \varepsilon) = \beta N_C$$

where α is the chosen allocation coefficient, N_C is the amount of carbon in the initial product, and β is the fraction of carbon actually transferred to the product.

Oil has to be esterified with an alcohol to become a biodiesel. This transformation is usually performed in industrial facilities centralizing oil from different origins. We assume that processing yields and required facilities are similar to those used for other types of biodiesel (such as rapeseed or soybean oils).

2.3. Combustion. To compare biodiesel produced from microalgae to any other fuel, the chosen functional unit is the combustion of 1 MJ of fuel in a diesel engine. Impact assessment includes only emissions generated by the combustion and not the transport from storage to the distribution network. There is currently no data about the emissions of a petrol engine working with microalgal biodiesel. However, a related study (*25*) and algal biofuel characterization (*26*) let us assume that algal biodiesel has the same behavior in diesel engines as other biofuel.

TABLE 3. Most Impacting Flows Generated by the Production of 1 kg of Biodiesel

	normal		low N	
	dry	**wet**	**dry**	**wet**
algae culture and harvesting				
algae (kg)	5.93	8.39	2.7	3.81
CO_2 (kg)	10.4	14.8	5.32	7.52
electricity (MJ)	7.5	10.6	4	5.7
CaNO3, as g N	273	386	29.4	41.6
drying				
heat (MJ)	81.8		37.1	
electricity (MJ)	8.52		3.9	
oil extraction				
heat (MJ)	7.1	22.4	3.2	10.2
electricity (MJ)	1.5	8.4	0.7	3.9
hexane loss (g)	15.2	55	6.9	25
oil transeterification				
methanol (g)	114	114	114	114
heat (MJ)	0.9	0.9	0.9	0.9
total energy				
consumption (MJ)	106.4	41.4	48.9	19.8
production (MJ)	103.8	146.8	61	86
balance (MJ)	−2.6	105	12	66

3. Production Chain Analysis

3.1. Mass Flow. Table 3 summarizes the most impacting emissions and consumption generated by the production of 1 kg of algal biodiesel. Contrary to the standard LCI, this inventory is done without any allocation but reflects the flows really generated by the process chain. The distribution of energy production and consumption shows that all configurations have high energetic requirements compared to the energy contained in the biofuel (37.8 MJ/kg). However, it turns out that both fertilizers and energetic requirements are lower for the low-N culture condition. Wet oil extraction significantly reduces heat requirements but lower extraction yields erode slightly the benefit of this technique. It is worth noting that only the wet extraction on algae grown in low N condition requires less energy than the one obtained in the oil flow.

A cumulative energy analysis has been performed to analyze the total energetic debt of 1 MJ of biodiesel and its distribution within the production chain (see Figure 2). The Cumulative Energy Demand (CED) includes energy used at the facility but also energy required for the production of the required inputs (fertilizers) and construction of infrastructure buildings (*27*). When taking into account all the energetic debt of the process chain, it appears that only the wet extraction on low-N grown algae has a positive balance. Other scenarios lead to negative energetic balance despite a 100% energy extraction from the oilcake. It can also be noticed that the application of a nitrogen stress improves the CED by 60% whereas CED is only increased by 25% with the wet extraction. Obviously low-N culture has lower fertilizer requirements but also implies a lower drying and extraction effort while the wet extraction needs a larger initial production due to its lower extraction yield.

3.2. Potential Impacts Analysis. Potential impacts are assessed by using the CML method, described in ref *28*. Several impacts have been chosen among the whole set of impacts described by CML, to evaluate potential effects on human health, ecosystem quality, and resources. Selected impacts are *abiotic depletion* (AbD), which is relative to the extraction of mineral and fossil fuels, *potential acidification* (Ac) by the emission of acidifying substances, *eutrophication* (Eu), which consists of the effect of releasing excessive amounts of nutrients, *global warming potential* (GWP), determined for a time horizon

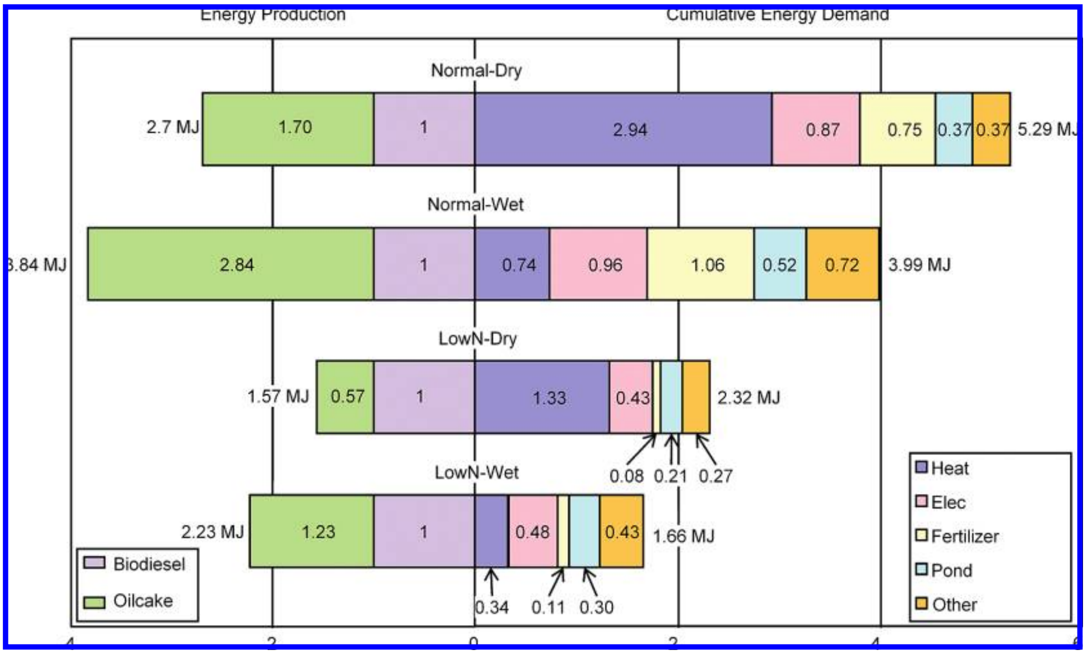

FIGURE 2. Cumulative Energy Demand and energy production associated with the production of 1 MJ of biodiesel.

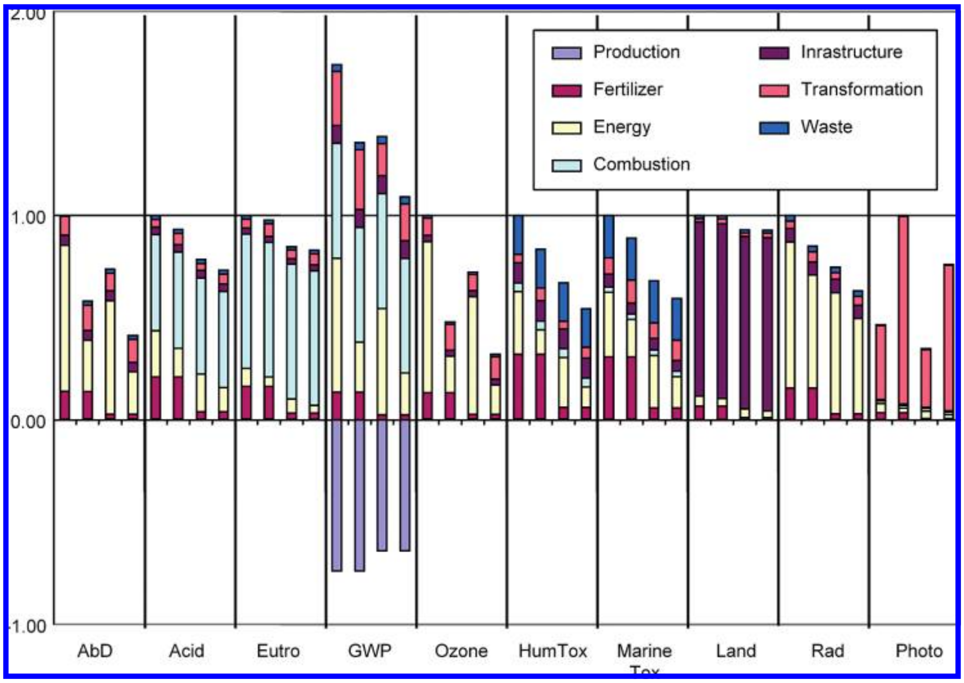

FIGURE 3. Distribution of impacts relative to the combustion of 1 MJ of algal fuel in a diesel engine. For each impact, the 4 bars refer to, respectively, Normal−Dry, Normal−Wet, LowN−Dry and LowN−Wet. Impacts are normalized by the impact value of the production with the highest impact.

of 100 years, *ozone layer depletion* (Ozone), determined on a time horizon of 40 years, *Human* (HumTox) and *marine* (MarTox) *toxicity* measuring impacts of emissions on humans and marine ecosystem over a period of 100 years, *land competition* (Land) accounting usage of earth surface, emission of *ionizing radiations* (Rad), and finally *photochemical oxidation* (Photo) referring to emissions of reactive substances injurious to human health and ecosystems. To analyze the contribution of the process chain to the different impacts, production steps have been grouped in 7 categories:

- Energy refers to the impacts created by the production of energy required on the facility (algae culture and oil esterification);
- Production includes emissions and consumption implicated in algae production, which includes harvesting and preparation of the biomass to a readily transformed product, but excludes fertilizer and energy;
- Fertilizer refers to the extraction and production of fertilizers;
- Transformation covers oil extraction and transesterification;
- Combustion is the use of fuel in a combustion engine;
- Infrastructure includes building and recycling of the facility;
- Waste is the treatment of wastewater produced during algae culture and processing.

The contribution of each step of the production chain is shown in Figure 3 for all culture configurations. Each impact

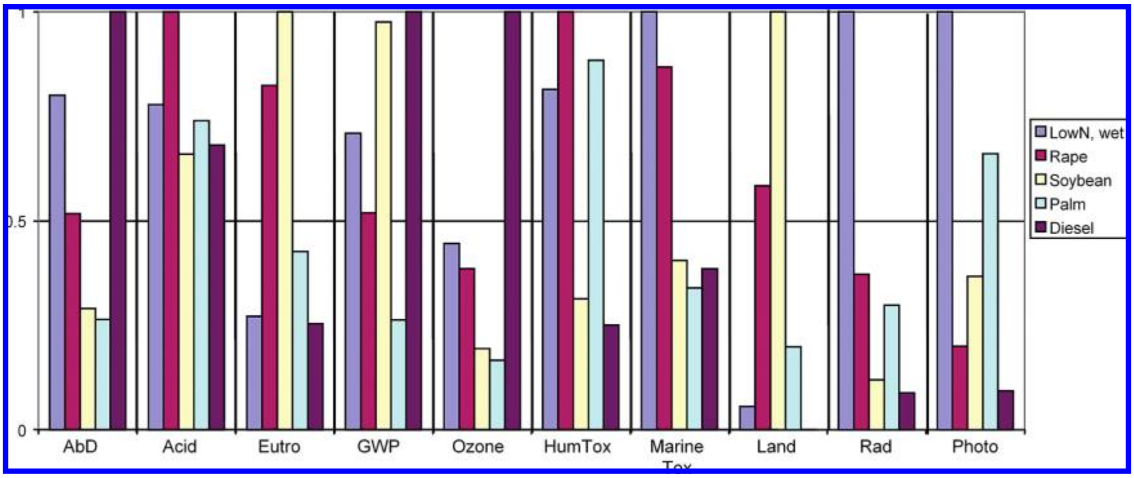

FIGURE 4. Comparison of impacts generated by the combustion of 1 MJ of different biodiesel and oil fuels.

is standardized with the value of the worst scenario for this impact. It is noticeable that most of the impacts are mainly driven by energy consumption, fuel combustion, and fertilizer use. Moreover, in agreement with conclusions brought by the mass-flow analysis, a low-N condition with a wet extraction scenario, which was characterized by lower energy and fertilizer needs, always showed lower impacts. Switching from normal to low-N always improved all the impacts; the wet extraction usually reduced the impact except for the photochemical oxidation which is directly related to the hexane emissions. Ozone depletion stems from emissions by a natural gas furnace used to provide heat; the radiation impact comes from the origin of the electrical energy used on the facility. Indeed the European energy mix includes 30% nuclear energy (*29*). It can also be noticed that the four scenarios have similar electricity consumption.

These LCA results have been compared to LCA results of other fuels to have a better insight of advantages and drawbacks of algal biodiesel. These assessments are based on inventories already published (*30, 31*) and included in the Ecoinvent database and deal with rapeseed methylester, soybean methylester, palm methylester, and oil diesel. Rapeseed biodiesel is supposed to be produced in Europe, analysis of palm tree biodiesel refers to Malaysian production, and soybean biofuel analysis refers to U.S. context. Consistently with the rest of this study, energetic allocation has been chosen. Since low-N culture condition has shown the better performance in this study, only this system will be compared to others.

Figure 4 compares impacts of the combustion of 1 MJ of fuel. Algal biodiesel based on existing technologies appears as the worst option regarding ionizing radiation, photochemical oxidation, and marine toxicity, and the second worst regarding abiotic depletion. However, it shows very low impacts for eutrophication and land use, and average impacts for acidification, human toxicity, and ozone depletion. Lower eutrophication and human toxicity effects can be attributed to better control of fertilizers fate as well as the absence of pesticide. Extremely low land use is easily explained by high biomass production yields reached by algae. Indeed, annual oil production can reach 26 t/ha/year for algae while soybean annual production is 0.47 t/ha/year, rapeseed reaches 1.3 t/ha/year, and palm tree yields 4.7 t/ha/year (*32*). Due to heat and electricity requirements, the algal biodiesel is outcompeted by other biofuels in terms of global warming, mineral resource, and ozone depletion. The high radiation impact is directly related to the electricity consumption which is a specific feature of algal cultures compared to other biomasses. However no other biodiesel source outperforms algal biodiesel in every impact.

4. Discussion

As a reminder, this work assesses the life cycle of a process which does not exist at this stage at industrial scale, and for which many technological problems are still unsolved. Moreover when relevant technological solutions exist, they still need to be strongly revisited during the optimization phase of the process. In this study we used reasonable assumptions and tried to minimize the proportion of arbitrary choice to design the best microalgal-based biofuel process based on current available technology. *Chlorella vulgaris* has been chosen as a model species mainly because it was significantly studied and quantitative estimates of both composition and productivities in various conditions were available. This work must therefore not be interpreted as a real and stable assessment of microalgal-based biodiesel impacts, but more as a LCA driven study to identify the bottlenecks in such processes. The main objective of our LCA study is to identify the parameters or the transformation steps which have the most impact on the energy balance and the environmental performance of the whole chain. Finally, we highlighted the key research pathways that must be further investigated to make microalgal-based biofuel production environmentally relevant.

Energetic balance of biodiesel production from microalgae shows that it can be rapidly jeopardized ending up with a counter-productive production chain. Whereas production of fuel differs slightly from the simple production of energy (production of a storable product useable in automotive engine requires specific properties), it is mandatory to have at least positive energetic balance. In our analysis, we showed that any improvement of oil extraction technique would have a direct impact on the sustainability of this production; indeed 90% of the process energy consumption is dedicated to lipid extraction (70% when considering the wet extraction). It is then clear that specific research must investigate new processes in lipid recovering with limited drying of the biomass. The dry extraction is possible only with an alternate method for drying the algae; solar drying is regularly cited, as in ref *5*, but its practical feasibility has never been demonstrated whereas lipid stability during solar drying is also questionable. The wet extraction seems promising; however data used here to estimate impacts and mass flows of wet extraction are questionable. Finally, the choice of the microalgal species must probably be considered in agreement with this factor, and species for which oil recovery is easier must be considered in priority.

Analysis of the distribution of environmental impacts and their comparison to impacts generated by other biofuels also demonstrate that a better control of the energetic consumption not only improves the energy balance but would also significantly decrease numerous impacts (abiotic depletion, ozone depletion, radiation, global warming potential, and to a lower extent acidification and human toxicity) and will hence improve the overall environmental performance compared to other biofuels. Comparison of low-N and normal culture conditions for both extraction modes shows the high sensitivity of results to the algal lipid productivity. Similar effect would have been observed with selected or modified strains harboring high lipid content and expressing decent growth rates. Depending on the considered hypotheses, some authors (*11*) have assumed very high productivities (up to 110 tons per ha of raceways). Such figures, which have not been obtained on the long-term at pilot scale, would of course considerably decrease the process impact per produced oil MJ. However, there is a clear and underestimated difficulty to reach these productivities. The nitrogen deficiency is necessary to induce a significant lipid production (*33*), but such culture conditions strongly affect the growth rate, and thus the net productivity (*34*). Looking for a species which can maintain a high productivity under nitrogen-limiting conditions is thus a key challenge. It is shown in ref *34* that the eustigmatophyte *Nannochloropsis* could have such a property, leading to extrapolated productivities of 20 tons of lipids per hectare and per year under the Mediterranean climate. On the other hand such a small size (2−5 μm) might make harvesting and extraction steps more difficult.

Importance of fertilizers and the high energetic debt due to the pond construction had a significant impact on the cumulated energetic balance. Process optimization could have opposite dynamics on these two expenses, as nitrogen deprivation will reduce the fertilizer consumption but will also reduce production yields and then potentially increase the share of the energetic debt supported by each kilogram of algae. When fertilizer flows are reduced, numerous impacts are reduced (abiotic depletion, acidification, and toxicity). Here only the low-N culture has been evaluated as a way to reduce fertilizer consumption; however other options are possible, as shown by the successful culture of Chlorella on hydroponic wastewater, reported in ref *35*. Another improvement we believe to be promising is the in situ anaerobic digestion of algal oilcakes, as suggested in refs *11 and 36*. According to the scenario, between 35 and 73% of the accumulated energy is stored in the oil cake, mainly under nonlipid form (carbohydrate and proteins). Despite technical obstacles (low bioavailability of particulate matter and the high N content, known as inhibiting anaerobic digestion), direct anaerobic digestion of oilcakes should produce biogas which can be directly used to provide heat and electricity to the oil extraction unit but also remineralize part of the nutrients stored into the algae, mainly under the form of ammonium and phosphate. Hence, a proper recirculation of the liquid fraction of the digestate into the algal pond would recycle part of mineral fertilizers and could reduce their net consumption.

Biodiesel production from microalgae is an emerging technology considered by many as a very promising source of energy, mainly because of its reduced competition for land. However the impact assessment and the energy balance show that algal biodiesel suffers from several drawbacks at the current level of maturity of the technology. In comparison to conventional energetic crops, high photosynthetic yields of microalgae significantly reduce land and pesticide use but not fertilizer needs. Moreover, production, harvesting, and oil extraction induce high energy consumption, which can jeopardize the overall energetic balance. It appears that even if the algal biodiesel is not really environmentally competitive under current feasibility assumptions, there are several improvement tracks which could contribute to reduce most of its impacts. A large-scale production can be seriously considered under the achievement of the following improvements: the choice of microalgal species maintaining high lipid and low protein contents with sustained growth-rates (e.g., low-N culture, strain selection, or modification), the setup of an energetically efficient extraction method, and the recovery of energy and nutrients contained in the oilcake. More generally, LCA appears as a relevant tool to evaluate new technologies for energy production. Even when dealing with young and immature technologies, this tool identifies the technological bottlenecks and therefore supports the ecodesign of an efficient and sustainable production chain.

Acknowledgments

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Supporting Information Available

Data detailing the model of the production chain and graphics presented in this paper; normalized results of the same inventory. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Crutzen, P. J.; Mosier, A. R.; Smith, K. A.; Winiwarter, W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* **2008**, *8*, 389–395.

(2) Huntley, M. E.; Redalje, D. G. CO_2 Mitigation and Renewable Oil from Photosynthetic Microbes: A New Appraisal. *Mitigat. Adapt. Strat. Global Change* **2007**, *12*, 573–608.

(3) Li, Y.; Horsman, M.; Wu, N.; Lan, C. Q.; Dubois-Calero, N. Biofuels from microalgae. *Biotechnol. Prog.* **2008**, *24*, 815–820.

(4) Chisti, Y. Biodiesel from microalgae beats bioethanol. *Trends Biotechnol.* **2008**, *26*, 126–131.

(5) Kadam, K. *Microalgae Production from Power Plant Flue Gas: Environmental Implications on a Life Cycle Basis*, Technical Report; National Renewable Energy Laboratory, 2001.

(6) Frischknecht, R.; Althaus H.-J.; Doka, G.; Dones, R.; Heck T.; Hellweg, S.; Hischier, R.; Jungbluth N.; Nemecek, T.; Rebitzer, G.; Spielmann, M. *Overview and Methodology*; Final report ecoinvent v2.0 No. 1; Swiss Centre for Life Cycle Inventories, 2007.

(7) Illman, A. M.; Scragg, A. H.; Shales, S. W. Increase in Chlorella strains calorific values when grown in low nitrogen medium. *Enzyme Microb. Technol.* **2000**, *27*, 631–635.

(8) Converti, A.; Casazza, A. A.; Ortiz, E. Y.; Perego, P.; Del Borghi, M. Effect of temperature and nitrogen concentration on the growth and lipid content of *Nannochloropsis oculata* and *Chlorella vulgaris* for biodiesel production. *Chem. Eng. Process.: Process Intensification* **2009**, *48*, 1146–1151.

(9) Geider, R. J.; La Roche, J. Redfield revisited: variability of C: N: P in marine microalgae and its biochemical basis. *Eur. J. Phycol.* **2002**, *37*, 1–17.

(10) Oh-Hama, T.; Miyachi, S. In *Microalgal Biotechnology*; Borowitzka, M. A., Borowitzka, L. J., Eds.; Cambridge University Press: Cambridge, 1988.

(11) Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25*, 294–306.

(12) Sheehan, J.; Dunahay, T.; Benemann, J.; Roessler, P. *A look back at the US department of energy's aquatic species program—biodiesel from algae*; National Renewable Energy Laboratory (NREL), 1998.

(13) Geldenhuys, D. J.; Walmsley, R. D.; Toerien, D. F. Laboratory Studies on the Suitability of a Fertilizer Tap Water Medium for Mass-Culture of Algae. *Biotechnol. Bioeng.* **1985**, *27*, 1572–1576.

(14) Richmond, A. *Handbook of Microalgal Culture: Biotechnology and Applied Phycology*; Wiley-Blackwell: Oxford, 2003.

(15) Molina Grima, E.; Belarbi, E. H.; Acien Fernandez, F. G.; Robles Medina, A.; Chisti, Y. Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnol. Adv.* **2003**, *20*, 491–515.

(16) Carlsson, A.; van Beilen, J.; Möller, R.; Clayton D. Micro and macro-algae: utility for industrial applications, University of York, 2007.
(17) Oh, H. M.; Lee, S. J.; Park, M. H.; Kim, H. S.; Kim, H. C.; Yoon, J. H.; Kwon, G. S.; Yoon, B. D. Harvesting of *Chlorella vulgaris* using a bioflocculant from Paenibacillus sp AM49. *Biotechnol. Lett.* **2001**, *23*, 1229–1234.
(18) Yahi, H.; Elmaleh, S.; Coma, J. Algal Flocculation-Sedimentation by Ph Increase in a Continuous Reactor. *Water Sci. Technol.* **1994**, *30*, 259–267.
(19) Gutzeit, G.; Lorch, D.; Weber, A.; Engels, M.; Neis, U. Bioflocculent algal-bacterial biomass improves low-cost wastewater treatment. *Water Sci. Technol.* **2005**, *52*, 9–18.
(20) Sazdanoff, N. Modeling and Simulation of the Algae to Biodiesel Fuel Cycle; The Ohio State University, Department of Mechanical Engineering, 2006.
(21) Hassebrauck, M.; Ermel, G. Two examples of thermal drying of sewage sludge. *Water Sci. Technol.* **1996**, *33*, 235–242.
(22) Shen, Y.; Pei, Z.; Yuan, W.; Mao, E. Effect of nitrogen and extraction method on algae lipid yield. *Int. J. Agric. Biol. Eng.* **2009**, *2*, 51–57.
(23) Lee, J.-Y.; Yoo, C.; Jun, S.-Y.; Ahn, C.-Y.; Oh, H.-M., Comparison of several methods for effective lipid extraction from microalgae. Bioresour. Technol. 2009, In Press (doi:10.1016/j.biortech.2009.03.058).
(24) Rodríguez-Ruiz, J.; Belarbi, E.-H.; García Sánchez, J. L.; Alonso, D. L. Rapid simultaneous lipids extraction and transesterification for fatty acid analysis. *Biotechnol. Tech.* **1998**, *2*, 689–691.
(25) Scragg, A. H.; Morrison, J.; Shales, S. W. The use of a fuel containing *Chlorella vulgaris* in a diesel engine. *Enzyme Microb. Technol.* **2003**, *33*, 884–889.
(26) Xu, H.; Miao, X.; Wu, Q. High quality biodiesel production from a microalga *Chlorella protothecoides* by heterotrophic growth in fermenters. *J. Biotechnol.* **2006**, *126*, 499–507.
(27) Frischknecht R.; Jungbluth N.; Althaus H.-J.; Doka, G.; Dones, R.; Hellweg S.; Hischier R.; Humbert S.; Margni M.; Nemecek, T.; M., S. *Implementation of Life Cycle Impact Assessment Methods*; Final report ecoinvent v2.0 No. 3; Swiss Centre for Life Cycle Inventories, 2007.
(28) Guinée, J. B. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*; Springer: New York, 2002.
(29) *UCTE Annual Report*; Union for the Co-ordination of Transmission of Electricity (UCTE), 2007.
(30) Jungbluth, N.; Chudacoff, M.; Dauriat, A.; Dinkel, F.; Doka, G.; Emmenegger, M. F.; Gnansounou, E.; Kljun, N.; Spielmann, M. *Life Cycle Inventories of Bioenergy*; Final report ecoinvent v2.0 No. 17; Swiss Centre for Life Cycle Inventories, 2007.
(31) Hischier, R.; Zah, R.; Wäger, P.; Lehmann, M.; Gauch, M. *Life Cycle Assessment of Energy Products: Environmental Impact Assessment of Biofuels - Executive Summary* (Ökobilanz von Energieprodukten: ökologische Bewertung von Biotreibstoffen - Schlussbericht), 2007.
(32) Zah, R.; Böni, H.; Gauch, M.; Hischier, R.; Lehmann, M.; Wäger, P. *Life Cycle Assessment of Energy Products: Environmental Assessment of Biofuels*; EMPA, 2007.
(33) Spoeher, H. A.; Milner, H. W. The chemical composition of Chlorella: effect of environment conditions. *Plant Physiol.* **1949**, *24*, 120–149.
(34) Rodolfi, L.; Zittelli, G. C.; Bassi, N.; Padovani, G.; Biondi, N.; Bonini, G.; Tredici, M. R. Microalgae for Oil: Strain Selection, Induction of Lipid Synthesis and Outdoor Mass Cultivation in a Low-Cost Photobioreactor. *Biotechnol. Bioeng.* **2009**, *102*, 100–112.
(35) Bertoldi, F. C.; Villela, M.; Sant Anna, E. S.; Oliveira, J. L. B. Lipids, fatty acids composition and carotenoids of *Chlorella vulgaris* cultivated in hydroponic wastewater. *Grasas Aceites* **2006**, *57*, 270–274.
(36) Sialve, B.; Bernet, N.; Bernard, O. Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable. *Biotechnol. Adv.* **2009**, *27*, 409–416.

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