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Comparative life cycle assessment study on environmental impact of oil production from micro-algae and terrestrial oilseed crops

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HIGHLIGHTS

- A comparative LCA of microalgae oil and terrestrial oilseeds crops was carried out.
- Microalgae oil has the greatest impact due to the electricity consumption.
- Three scenarios for micro-algae oil with renewable source was investigated.
- Photovoltaics compared to biogas shows the best environmental performances.
- Co-products valorization might reduce the impact of algae oil.

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ABSTRACT

In this study the LCA methodology is applied in order to satisfy two goals: i) to evaluate the hot spots in site-specific production chain of biodiesel from terrestrial and micro-algae feedstock; ii) to compare quantitatively, utilizing primary data, the impacts of the first generation in respect to the third generation bio-fuels. Results show that micro-algae are neither competitive yet with traditional oil crops nor with fossil fuel. The use of renewable technologies as photovoltaics and biogas self production might increase the competitiveness of micro-algae oil. Further investigations are however necessary to optimize their production chain and to increase the added value of co-products.

1. Introduction

In the past few decades, the idea of using bio-fuels, mainly for transport use, has been developed in order to achieve several goals: (i) to reduce fossil fuel dependency; (ii) to decrease greenhouse gas emissions; (iii) to generate new employment and new sources of income for farmers. It is important to point out that the introduction of biofuels in the transport market and further progress towards low-emission technologies have been both driven by policy decisions, especially in the EU (Directive EU 2015/1513 of the European Parliament and of the Council of 9 September 2015). The application of various biomass feedstock, such as rapeseed, soybean, canola, corn and lignocellulosic crops as bioenergy source has been a common topic in the literature (Spinelli et al., 2013, 2012; Forte et al., 2015; Roy et al., 2012 & Ref. therein). Some recent publications (Forte et al., 2016; Zucaro et al., 2016) are referred to site-specific studies evaluating the environmental performance of biofuels, more often in comparison with fossil counterpart and/or among several biofuels products. However, the evidence that first generation biofuels (produced from edible parts of agricultural crops) (Mamo et al., 2013) can generate several environmental burdens typically related to agricultural production (e.g. eutrophication, ecotoxicity, loss of biodiversity) and competition with food and land use change (EMPA, Technology and Society Lab report. http://publicationslist.org/data/zah/ref-6/070524_Bioenergie_ExecSumm_engl.pdf, 2007), has led to new solutions as second generation biofuels and third generation biofuels (Mamo et al., 2013), from lignocellulosic feedstock and algae-to-energy systems, respectively. Second generation biofuels produced from non-food lignocellulosic crops, agricultural residues or agro-

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industrial waste are considered more sustainable since they avoid land use change or competition with food crops. However, at the current state the production path to liquid biofuels from lignocellulsic materials is still far from the technical and economical sustainability (Sims et al., 2010).

Accordingly, algae-to-energy systems are receiving great attention from both academic and industrial sectors. The narrative identifies several advantages in using micro-algae for bioenergy production, compared with conventional crops, such as:

- Ability to be cultivated on marginal lands and therefore not incurring in land-use change (Searchinger et al., 2008).
- Semi-continuous to continuous harvesting.
- Variable lipid content in the range of 5–50% dry weight of biomass.
- High exponential growth rates potential to utilize carbon dioxide (CO_2) from industrial flue gas (1 kg of dry algae biomass utilizes about 1.83 kg of CO_2) and nutrients (especially nitrogen and phosphorus) from wastewater (Chisti, 2007; Cantrell et al., 2008).

For these reasons, they are an attractive feedstock for biofuel production (Chisti, 2007, 2008; Malcata, 2011). Moreover some authors consider that micro-algae can be cultivated in mudflats or deserts where the carbon stock is close to zero, furthermore they could be an interesting alternative to energy crops which often lead to carbon stock losses through land use change (Final report No SI2580403. The International Food Policy Institute IFPRI 2011). Although many efforts have been made to optimize both the medium and processes parameters, the development of cost-effective and highly efficient cultivation systems must be significantly improved for large-scale industrial production (Brentner et al., 2011; Soratana and Landis, 2011). According with forecasts of the International Energy Agency (IEA), world energy consumption is expected to increase by 53% between 2008 and 2035 (1.6% per year), stimulated in particular by the industrial and transport sector. Increasing demand for personal travel in the growing economies, freight and goods transportation system expansion along national and international routes are the main drivers of the utilization growth rate, which is expected to increase by 1.4% per year from 2008 and 2035 (IEA-International Energy Agency, World Energy Outlook 2011). Algae may play a key role in producing biofuels (biodiesel, ethanol, methane, hydrogen) in view of depletion of fossil resources. Large research efforts, in recent years, have led to a variety of micro-algae based life cycle assessments (LCA) (Brentner et al., 2011; Soratana and Landis, 2011; Huntley and Redalje, 2007; Collet et al., 2013; Clarens et al., 2010). Prior studies have shown that different algae harvesting options, reactor configurations, culture conditions, and cultivation assumptions yield divergent results concerning algae's environmental and energy performance. In any case, algae show higher environmental impacts than terrestrial crops in almost all the considered categories (Clarens et al., 2010). Many research efforts have been focused on this topic, among which the "EnerBiochem" project as a part of Italian National Operative Program (PON) for Research and Competitiveness, 2007–2013. The project aimed to study the feasibility of an integrated biorefinery, based on the opportunity of co-producing of biofuels together with bio-based chemicals, using marginal lands in the administrative scale of Campania Region (Southern Italy). The purpose of the project was also to identify an environmental and economical sustainable production for the development of a problematic region. Within the multidisciplinary framework and the several goals of this project, several biomasses (including micro-algae) have been considered as energy feedstock for the biorefinery. The results presented in this paper are part of the activities performed inside the EnerBiochem project. It is an attributional LCA applied to satisfy two goals: i) to evaluate the environmental hot spots in site-specific production chain of biodiesel from terrestrial oil seeds and micro-algae feedstock; ii) to evaluate quantitatively, utilizing primary data, if the first generation of bio-fuels is environmentally unfavorable respect to the third generation.

Furthermore, the study explored the possibility to enhance the environmental and economic performances of micro-algae oil through the application of renewable energies in the production process.

2. Materials and methods

2.1. Description of the analyzed systems

Primary data from the experimental plots of rapeseed and sunflower cultivated in Campania and from lab-to-pilot scale (100–3000 L) production of micro-algae (*Scenedesmus obliquus*) carried out in the framework of EnerBiochem project, form the basis for the life cycle inventories (LCI).

The LCA study was performed on the comparison of the oil production from terrestrial crops and algae. The oil extraction phase of terrestrial crops (via a chemical refining method) was referred to literature data (Figueiredo et al., 2012; Schneider and Finkbeiner, 2013). Data from literature were also used to determine the micro-algae oil recovery system by solvent extraction and the recovery system by a stripper column for separation of micro-algae oil/hexane stream (Stephenson et al., 2010).

2.1.1. Terrestrial crops oil system

This analysis has used average primary data of two crops (rapeseed and sunflower) grown in the years 2012–2014, using traditional farm practices, in experimental plots located in Campania Region (Southern Italy). The total cultivated area consists of 5 ha of flat land with sandy-loam soil texture, average annual rainfall 920 mm yr^{-1} and average annual sun insolation 10.8 MJ m^{-2} yr^{-1}. The two crops were cultivated in polluted marginal areas. Such areas, because of the adverse conditions for growing food crops were undergoing to a progressive abandonment. Experimental data relative to soil carbon storage are not presented in this study since, due to the short experimental period (3 years), they are poorly representative. The system boundaries of the vegetable oil system include agricultural step and oil extraction and treatment. The final outputs are cake and refined oil.

The same amount of N and K fertilizer was provided to both crops, while sunflower crop has required 100% more phosphorous and 52% more fossil fuel than rapeseed and a rescue irrigation of 280 m^3ha^{-1}. Soil local N_2O emissions, due to N fertilization, were calculated by applying an emission factor (EF) of 0.8% measured in Mediterranean crops (Fierro and Forte, 2012). The oil extraction phase (via a chemical refining method) was referred to literature data (Figueiredo et al., 2012; Schneider and Finkbeiner, 2013).

2.1.2. Micro-algae oil system

As reported in literature, micro-algae biomass production using raceway pond shows a higher net energy ratio respect to the use of photo-bioreactors (Jorquera et al., 2010). Generally, open pond cultivation systems are the most frequently industrially applied because of their low cost of investment and operational capital. On the other hand, in more recent decades the development of different types of closed photo-bioreactors were considered and compared to open ponds; closed photo-bioreactors have increased photosynthetic efficiency and higher production of biomass (Wang et al., 2012). However, the main problems for closed photo-bioreactors are the high initial cost, the maintenance operations and the specificity of strains (only micro-algae strains with particular physiologies can be used) (Harun et al., 2010).

S. obliquus is a freshwater micro-alga that can grow in wastewaters of different origins showing good adaptability and is widely used for outdoor cultivation and application for biofuels production (Hodaifa et al., 2008). *S. obliquus* was chosen for its ability to grow on wastewater removing organic and inorganic contaminants, for its resistance to contamination and for its the lipid fatty acid profile (see Table 1SI) (Zhao et al., 2016; Álvarez-Díaz et al., 2017; Zhou et al., 2014; Ji et al., 2013).

Therefore the algae strain, *Scenedesmus obliquus* has been cultivated in a raceway pond with the use of livestock wastewater as nutrient source. The choice of this specific strain was due to the capability of *Scenedesmus obliquus* in purifying wastewater in order to minimize environmental impacts. Other strains should be preferred if the aim of the production is biofuels (increasing lipid content by cultivation under nitrogen starvation) (Lardon et al., 2009) or biogas (increasing carbohydrates content) (Baskar et al., 2012).

The quantities of materials required for cultivation and harvesting equipment, e.g., raceway pond, centrifuge, etc., were estimated to determine the environmental burden associated with the construction of the facilities. The lifetime of raceway pond and centrifuge were assumed to be 10 and 20 years, respectively. Livestock wastewater ($0.5\%_{v/v}$) was used as nutrient source instead of chemical fertilizers. After cultivation step, micro-algae slurry was sent to a flocculation step (recovery efficiency 88%). Natural illumination was used as light source for micro-algae growth. Micro-algae biomass was finally recovered by a centrifugation step (recovery efficiency 95%). All these treatments are high electricity consuming. The final outputs are cake and refined oil.

2.2. LCA assumptions and life-cycle inventory analysis

The first LCA parameters that have to be defined are: i) the functional unit and ii) the system boundaries. The definition of such parameters should be subjected to the precise identification of the goal and scope of the analysis. In the case of this study, the objective is the comparison between oil production processes from micro-algae and terrestrial oilseeds crops for energy purposes. Therefore, the chosen functional unit should be the embodied energy (MJ) in 1 kg of produced oil.

As far as the system boundaries are concerned, a “cradle-to-gate” analysis was performed including a cultivation phase and oil extraction phase (Figs. 1 and 2).

The facilities for the oil extraction (buildings, machineries, etc) are included in the system boundaries, but their input are negligible because of time spreading and utilization for other productions.

The life-cycle Inventory of oil from conventional crops is reported in Table 1. The cake in both crops was considered as substituted of soybean meal (avoided product) (D’Avino et al., 2015).

A detailed Inventory of the primary data of micro-algae cultivation and harvesting system (including parameters) is reported in Table 2. The corresponding parameters are reported in Supporting Information (Table 2 SI). The oil content for the selected micro-algae strain is 5.2% (primary data). This figure is at the lower limit, as the lipid content is dependent on the growing conditions and ranges from 5 to 15% in a open pond, while reaches 25% in a photo-bioreactor under N-starvation. Data from literature were used to determine the micro-algae oil recovery system by solvent extraction and the recovery system by a stripper column for separation of micro-algae oil/hexane stream (Stephenson et al., 2010). The total heat requirement of the re-boiler was estimated $\sim$1.6 kJ kg^{-1} oil entering in the distillation column (hexane recovery >99.5%). Electricity production is based on the Italian energetic mix and heat is produced with natural gas burned in industrial gas boilers (ecoinvent database v2.2, Swiss Centre for Life Cycle Inventories: http://www.ecoinvent.org/database, June 2013).

2.3. Method applied

The calculations were performed with the SimaPro software version 7.3.3 (SimaPro 7.3. Amersfoort, The Netherlands www.pre.nl/ 2011) and the main database used for this study is Ecoinvent version 2.2 (ecoinvent database v2.2, Swiss Centre for Life Cycle Inventories: http://www.ecoinvent.org/database, June 2013). The environmental characterization of the analyzed systems was performed with the following Life Cycle Impact Assessment (LCIA) methods: ReCiPe (ReCiPe 2008, Main Report Revised. PRè Consultants: http://www.pre-sustainability.com, 2012) and CED (Ecoinvent Report No. 3 2010).

The ReCiPe method allows the study at an impact (mid-point) or damage (end-point) category level. The environmental analysis is performed with the ReCiPe 2008 Midpoint level approach associated with a hierarchist perspective.

2.4. Sensitivity and uncertainty analysis

Sensitivity analysis was performed on micro-algae oil system changing the source of the most crucial parameter which is electricity consumption.

Therefore, three alternative scenarios for algae oil productions were proposed:

- Scenario 1 – conventional electricity,
- Scenario 2 – solar energy,
- Scenario 3 – electricity from biogas produced by algae cake.

The energy source in the scenario 1 is taken from ECOINVENT Database as “Electricity Medium Voltage Production IT, at grid” (ecoinvent database v2.2, Swiss Centre for Life Cycle Inventories: http://www.ecoinvent.org/database, June 2013).

In the Scenario 2 the use of renewable energy as photovoltaic (PV) systems was investigated using data from SimaPro 7.3.3 Ecoinvent 2.2 database. These devices absorb incident illumination and produce a supply of electrons which can be used by an external circuit with conversion efficiencies of up to 25% and 22% in small laboratory and full modules, respectively (Green et al., 2012; Beardall et al., 2009). Therefore, electricity can even be produced from this same solar resource via the use of photovoltaic modules connected to the grid (Parlevliet and Moheimani, 2014). Tredici et al. (2015) have shown positive results in terms of energy balance by integrating a PV system in the photo-bioreactor. The cake in both scenarios was considered as substituted of soybean meal (avoided product). The equivalent amount of avoided product was calculated as reported in the literature (Baliga and Powers, 2010).

In the scenario 3, the use of micro-algae cake for biogas production has been considered and was evaluated using data from literature (Collet et al., 2011). Biogas yield is affected by the composition of the algae biomass that in turn is partially determined by the algae growth conditions and by the biomass pretreatment (Sialve et al., 2009).

An investigation carried out with de-oiled micro-algae biomass obtained a biogas yield of 376 mL g^{-1} dry matter (DM) (0.376 m^3 kg^{-1}) from Chlorella sp. and 338 mL g^{-1} DM (0.338 m^3 kg^{-1}) from *Scenedesmus sp.* Ward et al. reported in their extensive reviews (Skorupskaite and Makareviciene, 2014; Ward et al., 2014) a methane yield of 240 mL g^{-1} VS (volatile solids) for *Scenedesmus obliquus*. Sialve et al. (2009) summarized different experimental results in which methane yield varies from 0.09 to 0.45 L g^{-1} VS (0.09–0.45 m^3 kg^{-1}) depending on the species and

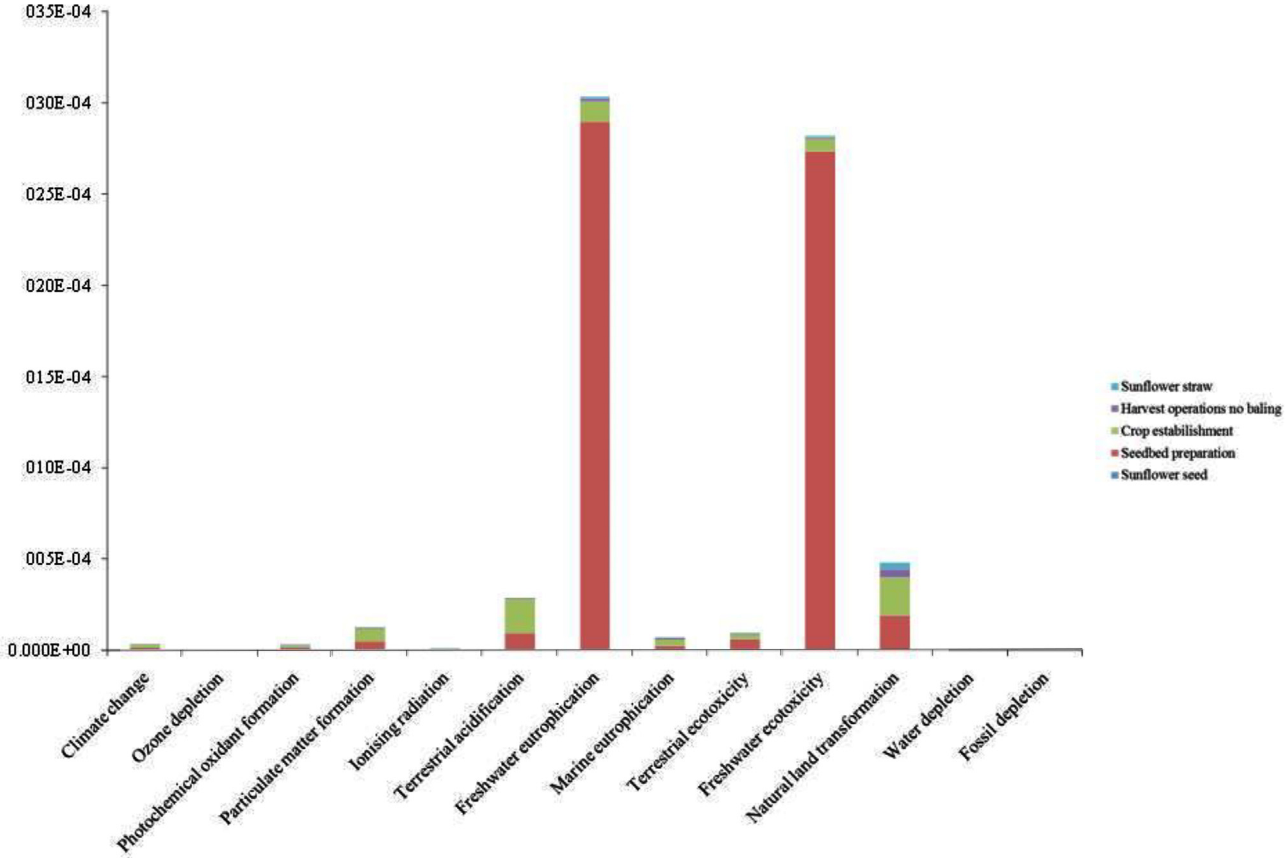

Fig. 1. Analysis of sunflower cultivation process (ReCiPe Midpoint (H) V1.04/Europe ReCiPe H/Normalization).

culture conditions. Biogas purification is usually achieved by bubbling it into pressurized water. Electricity potentially produced at cogeneration with biogas engine is assumed to substitute fossil energy in the production process of algae biomass.

Assuming a biogas production from anaerobic digestion of algae cake of 0.240 m^3 kg^{-1} VS in accordance with literature (Ward et al., 2014), the production of 3 m^3 of methane for 0.9 kg of algae oil has been calculated. As the electricity produced from 1 m^3 of purified biogas in a cogeneration unit is about 2 kWh (Piccini et al., 2007), only 20% of the electricity consumed in the micro-algae oil production process could be substitute from biogas-derived energy.

This scenario corresponds to a system expansion approach since the co-product (cake) is used inside the system boundaries.

Uncertainties were assessed by means of a Monte-Carlo simulation (Ecoinvent Report N. 1 2007). Most of the data used were obtained from the ecoinvent database and the variability of most of them was represented by a lognormal distribution around the central value specified, characterized by its standard deviation.

The uncertainty was calculated only on the data coming from the database Ecoinvent which are average data. On the contrary, the primary input data obtained from the project are provided as unique value.

3. Results and discussion

3.1. Environmental burden of oilseed crops

The choice of oilseeds crops as references in the comparison with algae were done because they are well-known and because of the availability of primary data.

Moreover, since the oil seeds crops are grown on marginal lands without generating Land Use Change (LUC), the advantage of algae in reducing LUC is mediated and the analysis should be concentrated on other resources consumption.

The starting point was to identify the critical step of the entire oil production chain and the cultivation phase of seeds has been detected as the heaviest environmental burdens. Comparing rapeseed with sunflower seed production, the latter shows the highest environmental impact in all observed categories as reported in details in Fig. 1SI in Supporting Information.

Cultivation phase of sunflower has the highest impact because of the heavier phosphate fertilizer input in seedbed preparation as demonstrated in Fig. 1.

In fact the world's phosphate fertilizers are based on phosphoric acid. Sulphuric acid is required for the production of phosphoric acid. The net emission from phosphate fertilizer manufacture (principally carbon dioxide) is largely determined by the method of sulphuric acid production. Most of these emissions are related to the consumption of fossil fuels as an energy source for the various processes involved in phosphate fertilizer production (Kongshaug, 1998).

3.2. Comparison between oil from conventional crops and micro-algae oil

The comparison between oil from sunflower and rapeseed and oil from micro-algae were performed with the ReCiPe Midpoint Method. A system expansion approach was applied in order to valorize the co-product (cake) and to minimize the low yield in oil of micro-algae. Results in Fig. 2, show that micro-algae oil production process has much higher environmental impacts compared with

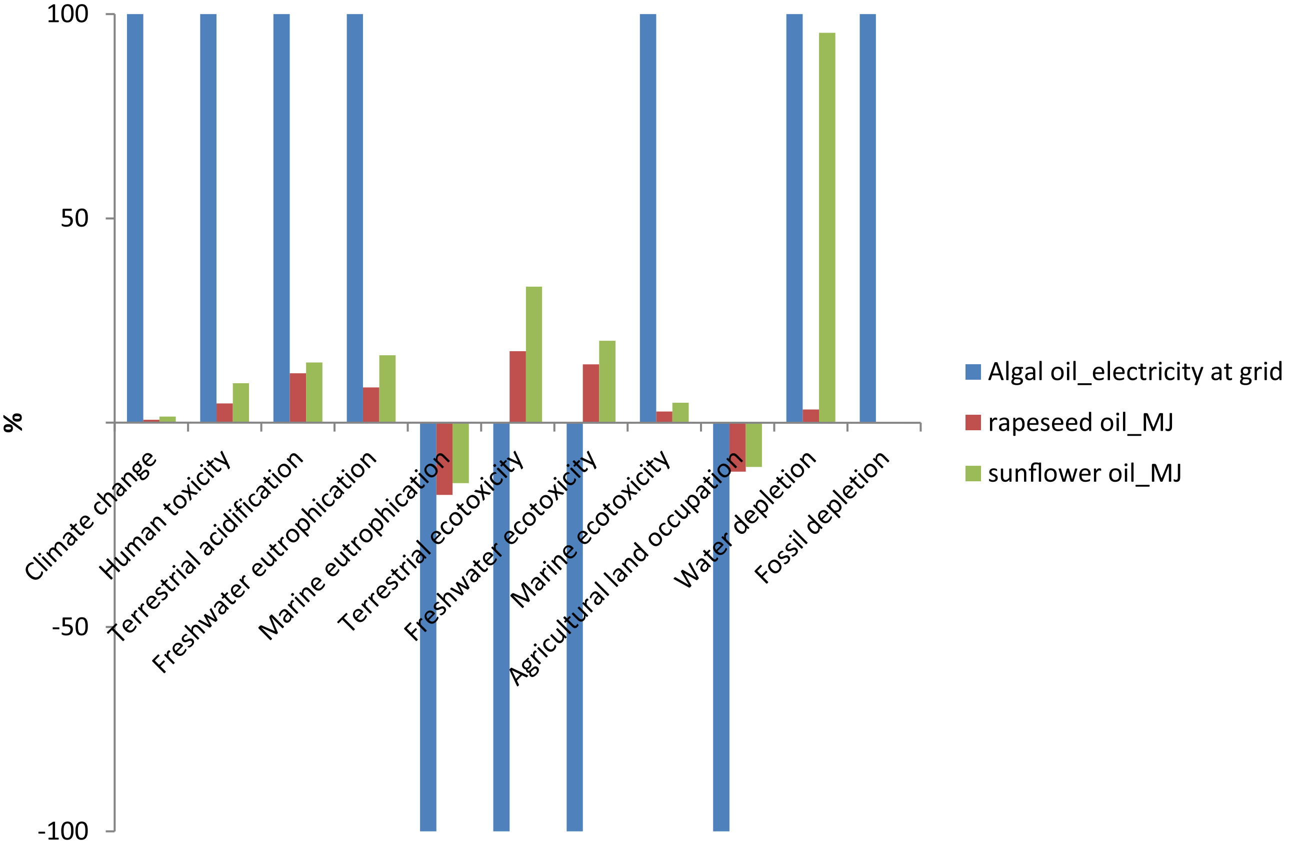

Fig. 2. Comparison among sunflower oil, rapeseed oil and micro-algae oil production processes (ReCiPe Midpoint (H) V1.04/Europe ReCiPe H/Characterization).

Table 1
Material and energy fluxes for the production of sunflower and rapeseed oil.

Seed production		Rapeseed	Sunflower
Input			
Nitrogen fertilizer	kg	174	174
Phosphate fertilizer	kg	109	217
Potash	kg	96.2	96.2
Diesel	kg	47	61.9
Lubricants	kg	0.603	0.76
Water for irrigation	kg	0.00	2.80
Steel for agricultural machinery	kg	5.29	5.10
Seeds	kg	2.00	4.76
Products and by-products			
Seed produced	kg	4400	3850
Residues in field as such (dry matter)	kg	9300	6500
Refined oil			
Input			
Seeds	kg	4400	3850
Water	kg	2090	2440
Bentonite	kg	9.71	8.90
Hexane	kg	4.56	4.18
Phosphoric acid	kg	1.47	1.30
Sulphuric acid	kg	3.61	2.44
Nitrogen liquid	kg	0.902	0.827
Charcoal	kg	0.361	0.331
Soda	kg	5.41	4.96
Heat natural gas	MJ	2940	2697
Electricity	kWh	174	159.87
Products and by-products			
Oil yield	%	41.0	43.0
Oil	kg/ha	1804	1655
Cake	kg/ha	2600	2195

Table 2
Mass and energy flow generated by the production and harvest of 1 kg/m^2 day of algae.

Input	Unit	Amount
Pond		
Concrete	kg	12,700
Steel (structure greenhouse)	kg	800
Copper (connection cables)	kg	18.4
PVC (pipeline connections)	kg	1320
PE (covering greenhouse)	kg	26,950
Electricity		
Air pumping	kWh	0.298
Nutrient pumping	kWh	1.06
Pump system		
Iron	kg	0.072
Fertilizer tank		
Concrete	kg	97.750
Nutrient		
N fertilizer	kg	0.029
K fertilizer	kg	0.02
P fertilizer	kg	0.011
Sedimentation/Flocculation system		
Sodium hydroxide	kg	0.232
Centrifugation (centrifuge model MSE 220 V, 2 A, 150 mL/min)		
Steel amount	kg	0.032
Electricity	kWh	0.065

sunflower oil and rapeseed oil. The large impacts are due to the heavy energy demand (electricity and heat) and material consumption for the algae biomass production. A deviation from this trend is shown in the case of Terrestrial Ecotoxicity and Freshwater Ecotoxicity. In the case of Terrestrial Ecotoxicity the better performance of micro-algae oil is due to the big amount of avoided product (soybean meal) which possesses a high environmental

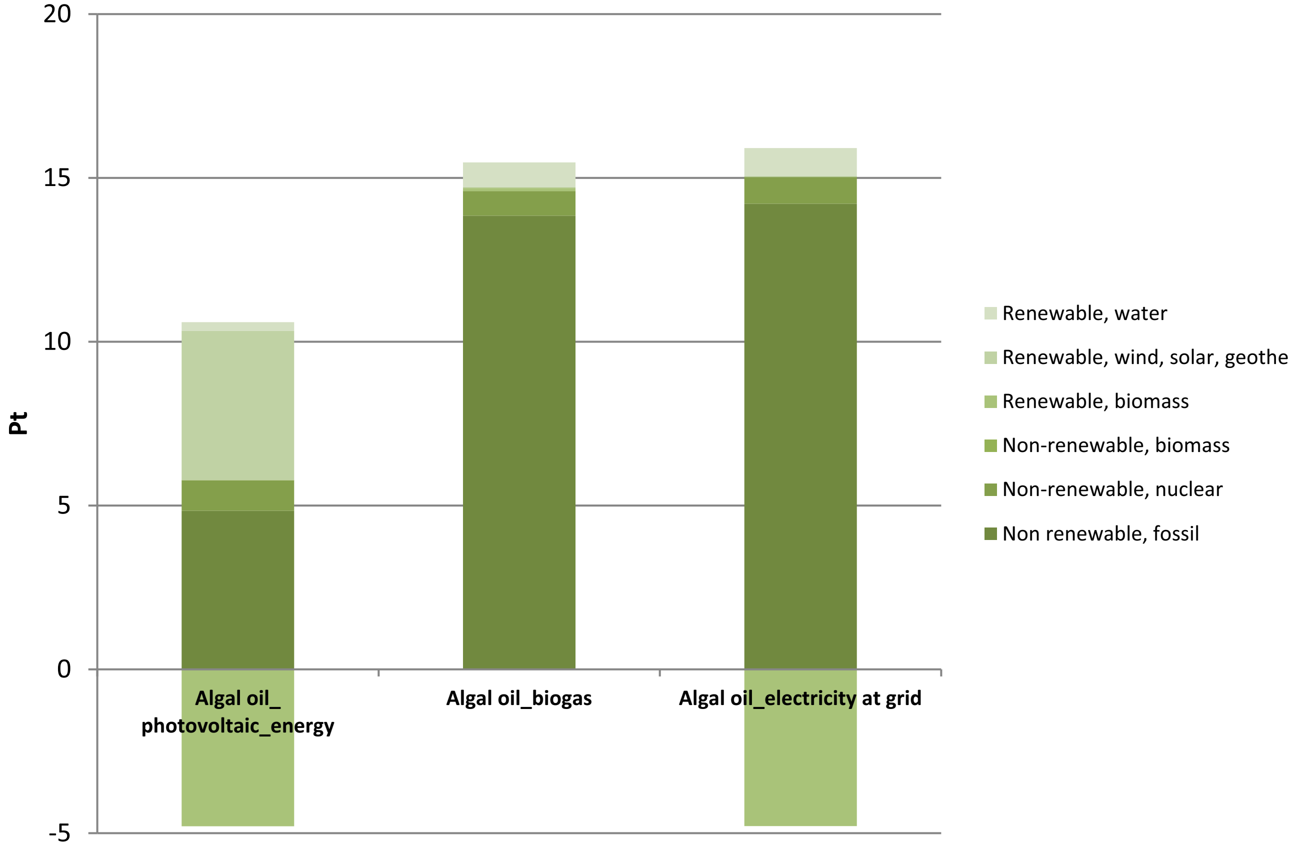

Fig. 3. Comparison of three scenarios of algae oil production with Cumulative Energy Demand V1.07/Cumulative energy demand/single point method.

burden. As far as Freshwater Ecotoxicity is highly influenced by the strong fertilization with phosphate as mentioned above.

Moreover, Water Depletion is affected by auxiliary irrigation which in our primary data was made on sunflower only. As far as the impact category: Ozone Depletion, Photochemical Oxidant Formation, Particulate Matter, Ionizing Radiation, Urban Land Occupation, Natural Land Occupation, Metal Depletion were omitted because they reflect the general trend already discussed.

Including fossil fuel in the comparison, the CO_2 eq emissions of the micro-algae oil are higher than heavy fuel oil about two order of magnitude whereas the rapeseed oil shows a GHG reduction of 36%. It is evident that the production of micro-algae oil for energetic purpose is far to be acceptable. In fact the indicator IPCC GWP 100a shows for Algal oil_electricity at grid 1.007 kg CO_2 eq/MJ, for Heavy fuel oil, at regional storage 0.011 kg CO_2 eq/MJ and for Rapeseed oil 0.007 kg CO_2 eq/MJ.

3.3. Sensitivity analysis

The algae cultivation stage has the largest electricity requirement for air and nutrient pumping into the raceway pond, water pumping due to evaporation lost and pumping algae slurry for harvesting stage. The total process contributions to environmental impact categories are the following: micro-algae cultivation (56.4%), biomass harvest (4.5%) and oil extraction (39.1%).

For these reasons, as previously discussed in Section 2.4, two alternative energetic scenarios have been evaluated besides the base case of Italian electricity mix (scenario1): use of photovoltaic technology (scenario 2) and use of biogas produced from micro-algae cake (scenario 3). Fig. 3 shows the energy performance calculated with Cumulative Energy Demand Method (CED) for the three proposed scenarios. The Sensitivity Analysis is consistent with expectations: the most convenient is the photovoltaic scenario. As expected the photovoltaic scenario contains a higher contribution from the energy source "Renewable wind, solar, geothermal". The negative values of "renewable biomass" in the case of "photovoltaic energy" and "electricity at grid" are a consequence of the credit of avoided product. In the histogram the bar relative to "algal oil biogas" does not show negative values because cake is utilized for the production of biogas.

In Fig. 4 is reported the comparison of the three scenarios calculated with ReCiPe Midpoint Method.

The scenario with photovoltaic energy seems to be the most environmentally convenient in almost all the impact categories while the scenarios with biogas and conventional electricity are similar in five categories even if biogas is the worst. The difference between biogas and conventional electricity increases in the impact categories where the influence of the credits from the avoided product "soybean meal", highly affects the results: freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, agricultural land occupation.

Table 3 clearly shows the effect of soybean meal as avoided product on the indicator of freshwater eutrophication (as an example) quantified by ReCiPe method.

A decrease of about 68% in Climate Change and 66% in Fossil Depletion can be calculated if the energy source "Italian mix" is substituted by photovoltaic system.

Exception to this trend is represented by the following impact categories: Human Toxicity and Metal Depletion, due to heavy metals and chemical reagents necessary in panel production technology.

The following impact categories were not reported: Ozone Depletion, Photochemical Oxidant Formation, Particulate Matter, Ionizing Radiation, Urban Land Occupation, Natural Land Occupa-

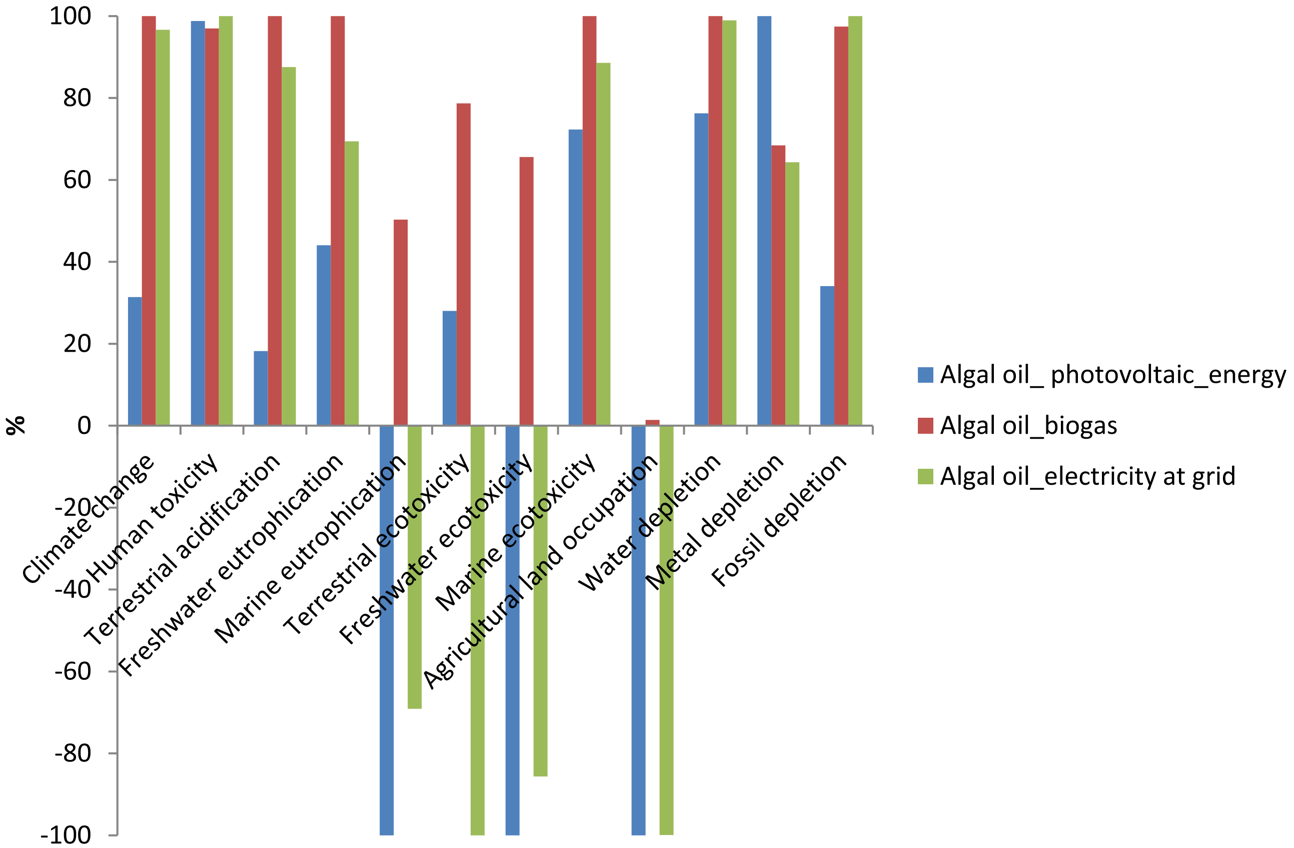

Fig. 4. Comparison among three scenarios for micro-algae oil production with different energy sources (electricity from biogas, photovoltaic, Italian electricity mix) (ReCiPe Midpoint (H) V1.04/Europe ReCiPe H/Characterization).

Table 3
Comparison among three scenarios for micro-algae oil production (electricity from biogas, photovoltaic, italian electricity mix) in freshwater eutrophication impact category (ReCiPe Midpoint (H) V1.04/Europe ReCiPe H/Characterization).

Process	Unit	Algal oil_photovoltaic_energy	Algal oil_biogas	Algal oil_electricity at grid
Triple superphosphate	kg P eq	1,12E−04	1,12E−04	1,12E−04
Electricity photovoltaic, at plant/IT S	kg P eq	6,80E−05	0,00E+00	0,00E+00
Copper	kg P eq	2,07E−05	2,07E−05	2,07E−05
Concrete block	kg P eq	1,47E−05	1,47E−05	1,47E−05
Urea ammonium nitrate	kg P eq	1,37E−05	1,37E−05	1,37E−05
Sodium hydroxide, 50% in H2O	kg P eq	1,31E−05	1,31E−05	1,31E−05
Glass fibre reinforced plastic, polyester resin, hand lay-up	kg P eq	3,55E−06	3,55E−06	3,55E−06
Potassium chloride, as K2O	kg P eq	2,44E−06	2,44E−06	2,44E−06
Polyvinylchloride	kg P eq	1,41E−06	1,41E−06	1,41E−06
Soybean meal, at oil mill	kg P eq	−1,16E−04	x	−1,16E−04

tion. Such categories were omitted for clarity and by analogy with Fig. 2.

Also in the context of sensitivity analysis, another key parameter to check at this point appears to be the avoided product. In fact the huge amount of residual biomass in the micro-algae oil production, which was considered as substitute of soybean meal, strongly affects many impact categories. For this reason scenario 3, where the biomass was used to produce biogas was penalized. Therefore, the convenience of using the residual cake for biogas production or as animal feed was evaluated moving the residual cake out of the system boundaries, as compost for 1 and 2. In Fig. 5 the results of the comparison with ReCiPe Method are shown. It is evident that with these last assumptions the biogas scenario improves its position in the trend.

3.4. Comparison of best cases

For the final comparison the photovoltaic scenario for micro-algae oil and rapeseed oil were chosen. Heavy fuel oil as reference was also compared. The results (Fig. 6) clearly show that any energetic application of micro-algae cannot compete with fossil oil neither with rapeseed oil in almost all impact categories where the environmental burden of electricity consumption is heavy.

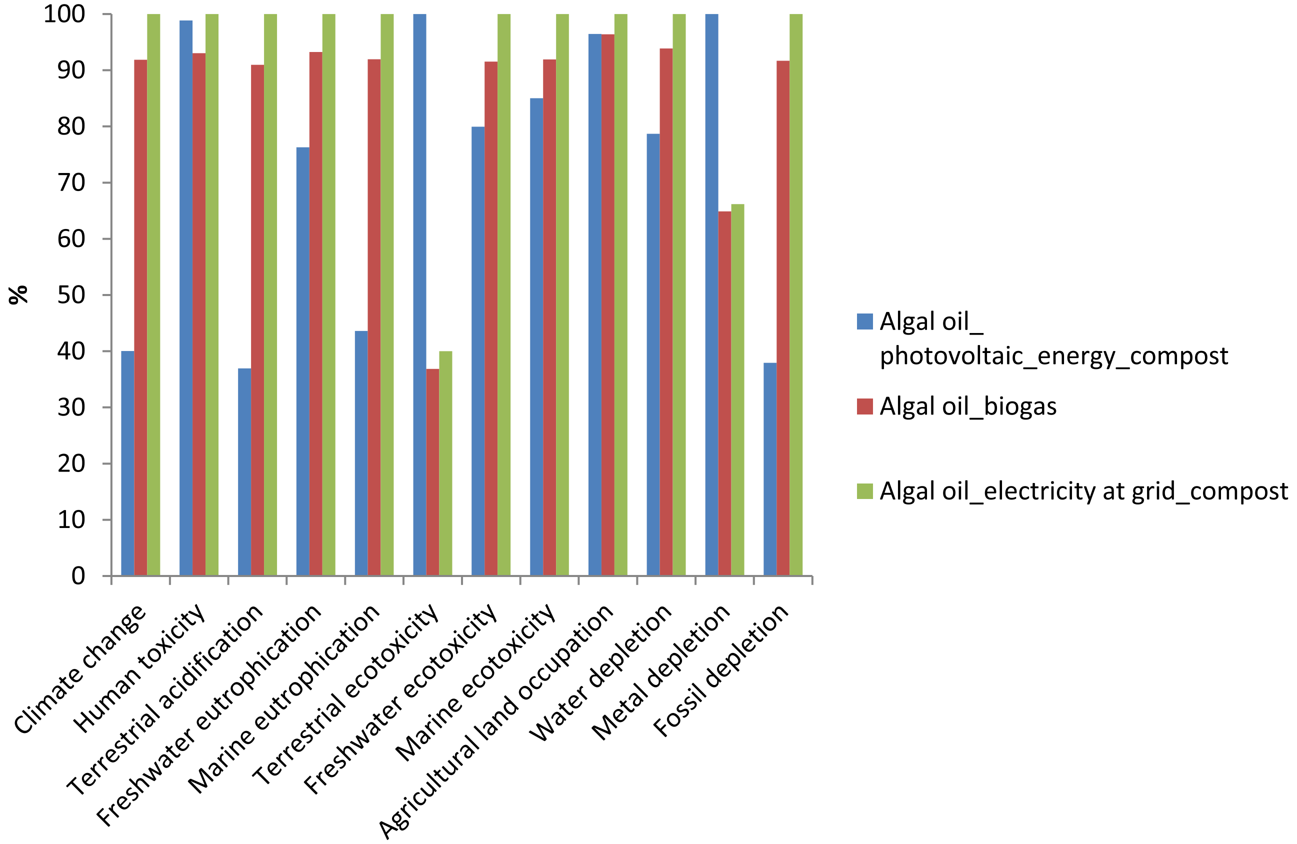

Fig. 5. Comparison of three scenarios for micro-algae oil production with different destination of residues for Scenarios 1 and 2 (ReCiPe Midpoint (H) V1.04/Europe ReCiPe H/ Characterization).

The inversion of the trend observed in the three categories Marine Eutrophication, Freshwater Ecotoxicity and Agricultural Land Occupation by the avoided product leads to conclude that the use of micro-algae for energetic purpose has to be coupled to other applications. In fact despite of the high biomass productivity of micro-algae, the lipid content is generally low.

Therefore, it is important to consider the possibility to increase the lipid content of micro-algae species using different nutrients composition (i.e. wastewaters with low nitrogen content). Since nitrogen is a fundamental element for the formation of proteins and nucleic acids, the limitation of these key nutrients shifts the metabolic pathway of the organism. For example, nitrogen and phosphorus starvation shifts the lipid metabolism from membrane lipid synthesis to neutral lipid storage. This in turn, increases the total lipid content of green algae or the energy density of biomass (Juneja et al., 2013; Sharma et al., 2012). As a consequence, an increase in the ratio between the amount of energy produced and energy required to produce micro-algae oil can be adequately modulated. Use of suitable (sterilized) waste water rich in N- and P-compounds, as well as alternative sources of carbon (CO_2, soluble carbonates) is essential for reducing the cost and impact of algae growing. Interestingly, sterilized waste water from a biogas fermenter has conveniently been used as nutrient-rich medium for growing microalgae, closing the cycle (Buono et al., 2016).

Finally the main hindrance to their application on industrial scale still consists on the high energy demand in terms of electricity, heat and nutrients. Use of renewable energy in algae oil production chain has shown that there is a significant possibility to reduce its environmental impact. Even if this is still not enough to match the performances of terrestrial oil-crops, the expected increase in world population resulting in growing need of arable land, will lead to favor second and third generation biofuels that do not compete with food production. From this perspective algae could play an important role.

Accordingly, in the future these topics have to be approached by means of integrated and holistic methodologies, in order to evaluate the actual feasibility of bioenergy sources. In fact, many uncertainties still revolve around the technical and economic feasibility and the effectiveness of bioenergy to satisfy the energy demand of developed societies. These uncertainties and the complexity of the issue require multi-criteria studies to achieve representative results (Gomiero, 2015).

The need to produce an integrated site-specific assessment, is particularly obvious for complex production chain where natural capital (land availability, soil characteristics, solar input, water availability and so on) as well as typical local human managements (mainly agricultural managements and new technological improvements), can affect the overall production chain.

For these reasons, the decision to built a biorefinery production system in a territory, should be the subject of integrated evaluation with multi criteria approach to obtain a more reliable picture of the system.

3.5. Uncertainty analysis

Results of the uncertainty analysis are reported in Supporting Information (Table 3a–c SI).

In order to check the uncertainty for the comparisons of the best cases reported in Section 3.3 the Montecarlo Analysis were calculated on Rapeseed oil vs Algae oil photovoltaic scenario, Algae oil photovoltaic scenario vs Heavy fuel oil, Rapeseed oil vs Heavy

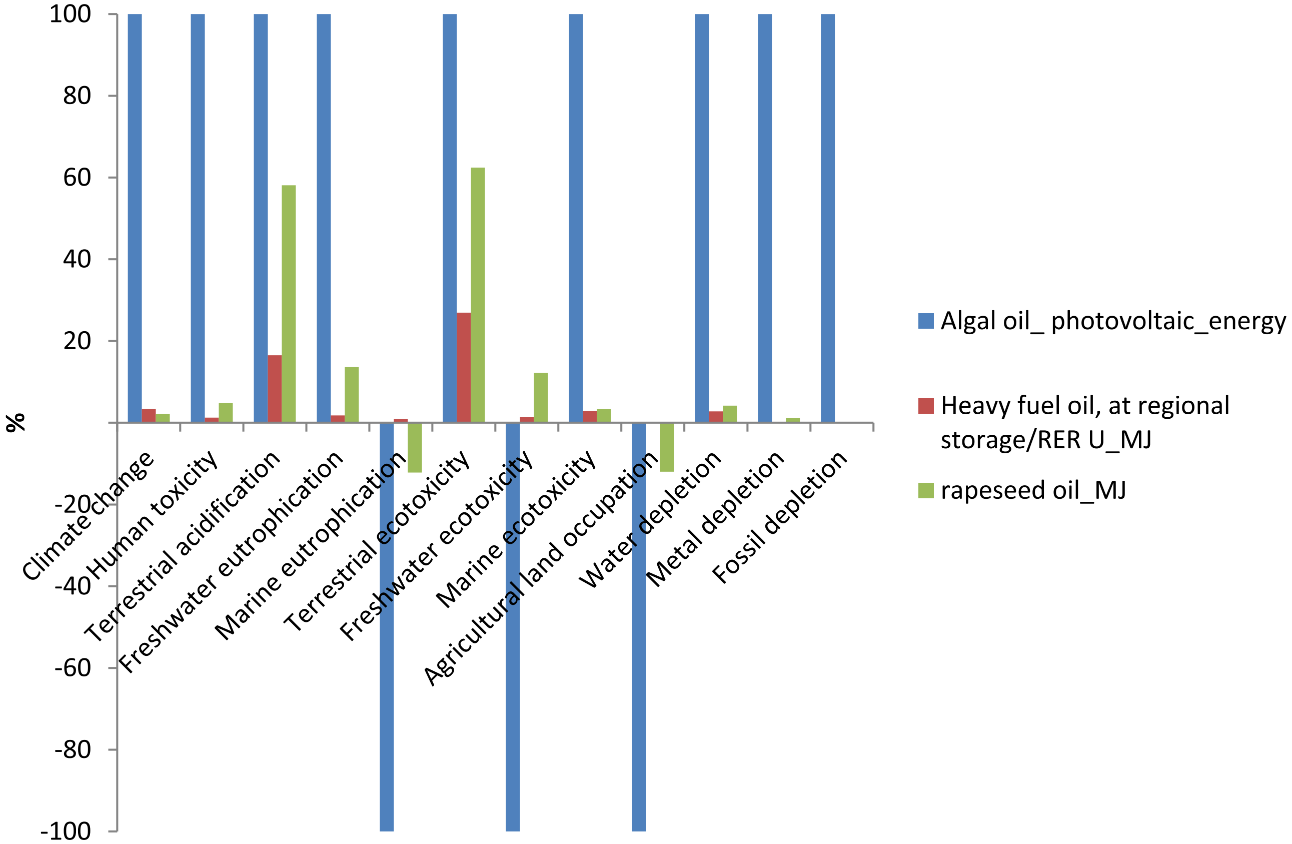

Fig. 6. Comparison of Algal oil (photovoltaic scenario) rapeseed oil and heavy fuel oil (ReCiPe Midpoint (H) V1.04/Europe ReCiPe H/Characterization).

fuel oil. In almost all cases the Uncertainty analysis confirms the results of LCA analysis.

4. Conclusions

Despite their high potential micro-algae are not yet competitive with the traditional oil crops. The main achievement of this work is to have got a confirmation of these findings by an LCA analysis based on primary data coming from a case study of an integrated biorefinery. An important result is that the use of renewable technologies could increase the competitiveness of micro-algae oil reducing its demand of non-renewable energy sources.

Further investigations are necessary to optimize their production chain and to increase the value of co-products as confirmed by the report of IEA "State of Technology Review–Algae Bioenergy" 2017.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2017.05.027.

References

Álvarez-Díaz, P.D., Ruiz, J., Arbib, Z., Barragán, J., Garrido-Pérez, M.C., Perales, J.A., 2017. Freshwater microalgae selection for simultaneous wastewater nutrient removal and lipid production. Algal Res. in press, http://dx.doi.org/10.1016/j.algal.2017.02.006.

Baliga, R., Powers, S.E., 2010. Sustainable algae biodiesel production in cold climates. Int. J. Chem. Eng., 13 Article ID 102179, Hindawi Publishing Corporation.

Baskar, C., Bskar, S., Dhillon, R.S., 2012. Biomass Conversion: The Interface of Biotechnology, Chemistry and Materials Science. Baskar, C., Bskar, S., Dhillon, R. S. (eds).

Beardall, J., Stojkovic, S., Larsen, S., 2009. Living in a high CO_2 world: impacts of global climate change on marine phytoplankton. Plant Ecol. Divers. 2, 191–205.

Brentner, L.B., Eckelman, M.J., Zimmerman, J.B., 2011. Combinatorial life cycle assessment to inform process design of industrial production of algae biodiesel. Environ. Sci. Technol. 45, 7060–7067.

Buono, S., Colucci, A., Angelini, A., Langellotti, A.L., Massa, M., Martello, A., Fogliano, V., Dibenedetto, A., 2016. Productivity and biochemical composition of *Tetradesmus obliquous* and *Phaeodactylum tricornutum*: effects of different cultivation approaches. J. Appl. Phycol. 28, 3179–3192.

Cantrell, K.B., Ducey, T., Ro, K.S., Hunt, P.G., 2008. Livestock waste-to-bioenergy generation opportunities. Bioresour. Technol. 99 (17), 7941–7953.

Chisti, Y., 2008. Response to Rejinders: do biofuels from microalgae beat biofuels from terrestrial plants? Trends Biotechnol. 26, 351–352.

Chisti, Y., 2007. Biodiesel from microalgae. Biotechnol. Adv. 25 (3), 294–306.

Clarens, A.F., Resurreccion, E.P., White, M.A., Colosi, L.M., 2010. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ. Sci. Technol. 44, 1813–1819.

Collet, P., Spinelli, D., Lardon, L., Helias, A., Steyer, J.P., Bernard, O., 2013. Life cycle assessment of microalgal-based biofuels. In: Pandey, A., Lee, D.J., Chisti, Y., Soccol, C.R. (Eds.), Biofuels From Algae. Elsevier, USA, pp. 287–312.

Collet, P., Hélias, A., Lardon, L., Ras, M., Goy, R.A., Steyer, J.P., 2011. Life-cycle assessment of microalgae culture coupled to biogas production. Bioresour. Technol. 102, 207–214.

D'Avino, L., Dainelli, R., Lazzeri, L., Spugnoli, P., 2015. The role of co-products in biorefinery. J. Cleaner Prod. 94, 108–115.

Fierro, A., Forte, A., 2012. Measurement of CO_2 and N_2O emissions in the agricultural field experiments of the MESCOSA GR project. In: Piccolo, A. (Ed.), Carbon Sequestration in Agricultural Soil. Springer-Verlag, Berlin Heidelberg, pp. 229–259.

Figueiredo, F., Castanheira, E., Freire, F., 2012. LCA of sunflower oil addressing alternative land use change scenarios and practices, 8th International Conference on LCA in the Agri-Food Sector, Rennes, France, 2-4 October 2012.

Forte, A., Zucaro, A., Basosi, R., Fierro, A., 2016. LCA of 1,4-butanediol produced via direct fermentation of sugars from wheat straw feedstock within a territorial biorefinery. Material 9, 563.

Forte, A., Zucaro, A., Fagnano, M., Bastianoni, S., Basosi, R., Fierro, A., 2015. LCA of Arundodonax L. lignocellulosic feedstock production under Mediterranean conditions. Biomass Bioenergy 73, 32–47.

Gomiero, T., 2015. Are biofuels an effective and viable energy strategy for industrialized societies? a reasoned overview of potentials and limits. Sustainability 7, 8491–8521.

Green, M.A., Emery, K., Hishikawa, Y., Warta, W., Dunlop, E.D., 2012. Solar cell efficiency tables (version 39). Prog. Photovoltaics Res. Appl. 20, 12–20.

Harun, R., Danquah, M.K., Forde, G.M., 2010. Micro-algal biomass as a fermentation feedstock for bioethanol production. J. Chem. Technol. Biotechnol. 85, 199–203.

Hodaifa, G., Martinez, M.E., Sànchez, S., 2008. Use of industrial wastewater from olive-oil extraction for biomass production of *Scenedesmus obliquus*. Biores. Technol. 99, 1111–1117.

Huntley, M., Redalje, D., 2007. CO_2 Mitigation and renewable oil from photosynthetic microbes: a new appraisal. Mitig. Adapt. Stratigr. Global Change 12, 573–608.

Ji, M.K., Abou-Shanab, R.A.I., Hwang, J.H., Timmes, T.C., Kim, H.C., Oh, Y.K., Jeon, B.-H., 2013. Removal of nitrogen and phosphorus from piggery wastewater effluent using the green microalga Scenedesmus obliquus. J. Environ. Eng. 139 (9), 1198–1205.

Jorquera, O., Kiperstok, A., Sales, E.A., Embiruçu, M., Ghirardi, M.L., 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photo-bioreactors. Biores. Technol. 101, 1406–1413.

Juneja, A., Ceballos, R.M., Murthy, G.S., 2013. Effects of environmental factors and nutrient availability on the biochemical composition of algae for biofuels production: a review. Energies 6, 4607–4638.

Kongshaug, G., 1998. Energy Consumption and Greenhouse Gas Emission in Fertilizer Production, IFA Technical Conference, Marrakech, Morocco, 28 September-1 October, pp. 18–24.

Lardon, L., Helias, A., Sialve, B., Steyer, J.P., Bernard, O., 2009. Life-cycle assessment of biodiesel production from microalgae. Environ. Sci. Technol. 43, 6475–6481.

Malcata, F.X., 2011. Microalgae and biofuels: a promising partnership? Trends Biotechnol. 29, 542–549.

Mamo, G., Faryar, R., Nordberg Karlsson, E., 2013. In: Gupta, W.K., Tuhoy, M.G. (Eds.), Biofuel Technologies: Recent Developments. Springer, pp. 171–188.

Parlevliet, D., Moheimani, N.R., 2014. Efficient conversion of solar energy to biomass and electricity. Aquatic Biosystems 10, 4–9.

Piccini, S., Bonazzi, G., Fabbri, C., 2007. Energia dal biogas prodotto da effluenti zootecnici, biomasse dedicate e di scarto. – C.R.P.A., Ed. AIEL Legnaro (PD), 17–18 (in italian).

Roy, P., Tokuyasu, K., Orikasa, T., Nakamura, N., Shiina, T., 2012. A review of life cycle assessment (LCA) of bioethanol from lignocellulosic biomass. JARQ 46 (1), 41–57.

Schneider, L., Finkbeiner, M., 2013. Life Cycle Assessment of EU Oilseed Crushing and Vegetable Oil Refining: FEDIOIL Report, May 2013.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319 (5867), 1238–1240.

Sharma, K.K., Schuhmann, H., Schenk, P.M., 2012. High lipid induction in microalgae for biodiesel production. Energies 5, 1532–1553.

Sialve, B., Berneta, N., Bernard, O., 2009. Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable. Biotechnol. Adv. 27 (4), 409–416.

Sims, R.E.H., Mabee, W., Saddler, J.N., Taylor, M., 2010. An overview of second generation biofuel technologies. Bioresour. Technol. 101, 1570–1580.

Skorupskaite, V., Makareviciene, V., 2014. Green energy from microalgae: usage of algae biomass for anaerobic digestion. J. Int. Sci. Pub. Ecol. Saf. 8, 71–77.

Soratana, K., Landis, A.E., 2011. Evaluating industrial symbiosis and algae cultivation from a life cycle perspective. Bioresour. Technol. 102, 6892–6901.

Spinelli, D., Jez, S., Pogni, R., Basosi, R., 2013. Environmental and life cycle analysis of a biodiesel production line from sunflower in the Province of Siena (Italy). Energy Policy 59, 492–506.

Spinelli, D., Jez, S., Basosi, R., 2012. Integrated environmental assessment of sunflower oil production. Process Biochem. 4, 1595–1602.

Stephenson, A.L., Kazamia, E., Dennis, J.S., Howe, C.J., Scott, S.A., Smith, A.G., 2010. Life-cycle assessment of potential algal biodiesel production in the united kingdom, a comparison of raceways and air-lift tubular bioreactors. Energy Fuels 24, 4062–4077.

Tredici, M.R., Bassi, N., Prussi, M., Biondi, N., Rodolfi, L., Chini Zittelli, G., Sampietro, G., 2015. Energy of algal biomass production in 1-ha "green wall panel" plant: how to produce algal biomass in a closed reactor achieving a hight net energy ratio. Appl. Energy. http://dx.doi.org/10.1016/j.apenergy.2015.01.086.

Wang, B., Lan, C., Horsman, M., 2012. Closed photo-bioreactors for production of micro-algal biomasses. Biotechnol. Adv. 30, 904–912.

Ward, A.J., Lewis, D.M., Greenb, F.B., 2014. Anaerobic digestion of algae biomass: a review. Algal Res. 5, 204–214.

Zhao, Y., Ge, Z., Lui, H., Sun, S., 2016. Ability of different microalgae species in synthetic high-strength wastewater treatment and potential lipid production. J. Chem. Technol. Biotechnol. 91 (11), 2888–2895.

Zhou, G.J., Ying, G.G., Liu, S., Zhou, L.J., Chen, Z.F., Peng, F.Q., 2014. Simultaneous removal of inorganic and organic compounds in wastewater by freshwater green microalgae. Environ. Sci. Processes Impacts 16 (8), 2018–2027.

Zucaro, A., Forte, A., Basosi, R., Fagnano, M., Fierro, A., 2016. Life cycle assessment of second generation bioethanol produced from low-input dedicated crops of arundo donax L. Bioresour. Technol. 219, 589–599.