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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 lignocellusic 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 opera-