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Biodiesel Production from Sunflower: an Environmental Study

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Biofuels, like bioethanol and biodiesel, are important alternatives to mineral fuels in order to reduce fossil fuel consumption in the transport sector. In this study, an environmental analysis of biodiesel production on pilot scale from sunflower oil was performed. The life cycle of biodiesel production involves different stages: 1) agricultural phases; 2) oil extraction from seeds; 3) transesterification to obtain the biodiesel; 4) distribution and 5) waste management. In this study, the system boundaries covered the agricultural stages, the industrial stages, the distribution and the waste management; the biodiesel usage was not considered. The chosen functional unit was 1 ton of biodiesel, and the life cycle assessment (LCA) study was performed using the SimaPro 8.0.4 software through the IMPACT 2002+ method. The environmental emissions were compared to the ones obtained producing 1 ton of diesel from fossil fuels. Data for the life cycle inventory (LCI) were obtained from the Ecoinvent database or experimentally.

1. Introduction

The problems related to climate changes, the increase in energy demand for transport and electricity and the interest in decreasing dependency on fossil fuels motivated the support for the use of biofuels (Barontini et al., 2015). Biofuels are most expensive with respect to fossil fuels, but the expected saving in greenhouse gas (GHG) emissions reduction are believed to reduce the importance of the cost gap, providing a remarkable alternative (Duer and Christensen, 2010). Biofuels can be of first-generation or second-generation (Naik et al., 2010). First-generation biofuels are made from sugar, starch, seeds and vegetable and animal oils and fats. The use of resources from agricultural sector for biofuel production, due to the generation of environmental issues like eutrophication, ecotoxicity, resource depletion and due to the competition with food crops for the use of arable land has been criticized for its impact on the food industry (Sims at al., 2010). Thus, the current strategy is the usage of second-generation fuels made from biomass consisting of the residual non-food parts of crops (Petersen et al., 2015). However, on local scale, if farmers' agricultural budget has to be improved, first generation biofuels can still be considered. The usage of biofuels stretched from the replacement of mineral diesel fuel in boilers to internal combustion engines (Qi et al., 2009) with a small decrease in performance, generating emissions comparable to those of mineral diesel (Puppan, 2012).
The European requirements reported in the Renewable Energy Directive 2009/28/EC (RED) (European Commission, 2009) wished for the reaching of the ambitious 20-20-20 targets for 2020: (1) reduction of GHG emissions at least 20% below 1990 levels; (2) 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency; (3) 20% of European Union (EU) energy consumption to come from renewable resources.
Italian biofuels production cannot supply a substantial contribution to the current energy production for transport without serious environmental implications, due to high costs in terms of land requirements (Russi, 2008). Therefore, large-scale biofuel production is not suitable for the Italian context, whereas biofuel production at farm scale could be considered a viable option (Barontini et al., 2015).
Different studies on the environmental impact of biodiesel produced from sunflower were published (Iriarte and Villalobos, 2013). Life cycle assessment (LCA) is an established methodology used to quantify environmental emissions (Iannone et al., 2014), in the last years very often used in different fields (De Marco et al., 2015). Different LCA studies were already published on biodiesel production from sunflower in different countries. Among them, Tsoutsos et al. (2010) studied the biodiesel production in Greece, Iriarte et al. (2010) the sunflower and rapeseed usage as energy crops in Chile and Spinelli et al. (2013) made a LCA of a biodiesel

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production line from sunflower in the province of Siena (Italy). Italian sunflower cultivation for biodiesel production were the object also of a LCA study made by Spugnoli et al. (2012) that focused the attention on the agricultural stages of the process. Other Italian regions sunflower cultivations and biodiesel productions were rarely been the object of LCA studies and, therefore, the aim of the present study is an environmental analysis of biodiesel production on pilot scale from sunflower oil in Campania. All the production stages (from agricultural stage to biodiesel production) were considered and a comparison in terms of environmental emissions among 1 ton of biodiesel produced from sunflower oil and 1 ton of diesel produced from fossil fuels was performed.

2. Methodology

LCA is a method for determining, using a broad set of collected and organized data, the environmental impact of a product through a life-cycle analysis. In that way, it is possible to compare different products or to individuate the most critical stages, from the environmental point of view, of a specific product. In the LCA methodology, some steps have to be pointed out: 1) goal definition and scope of the LCA analysis; 2) functional unit, system boundaries and life cycle inventory.

2.1 Goal definition and scope of the LCA analysis

Goal definition is one of the most important phases of the LCA methodology, because the choices made at this stage influence the entire study. The purpose of this study is to evaluate the environmental impacts of the production of biodiesel from sunflower oil on a local scale and to compare them with the emissions related to the production of fossil diesel. In Figure 1, the scheme of biodiesel production (from cradle to grave) according to the IDEF (Icam DEF for Function Modelling, where “ICAM” is an acronym for Integrated Computer Aided Manufacturing) methodology is reported.

2.2 Functional unit, system boundary and life cycle inventory

The definition of the functional unit (FU) is based on the mass of the product under analysis, and it is a reference to which all the inputs and outputs have to be related. The functional unit of this study was defined as 1 ton of biodiesel from sunflower oil. The boundaries of the system included the agricultural phase, the transportation of seeds to the extraction plant, the sunflower oil extraction, transesterification and the transportation of biodiesel to a refinery, as underlined by the dashed line in Figure 1. After transesterification, the glycerine is considered as a side product containing soaps, rests of catalyst, water and esters (Spinelli et al., 2013). In Table 1, the main activities of the observed process are reported. Activities as the potential impacts regarding the biodiesel usage were not taken into account.

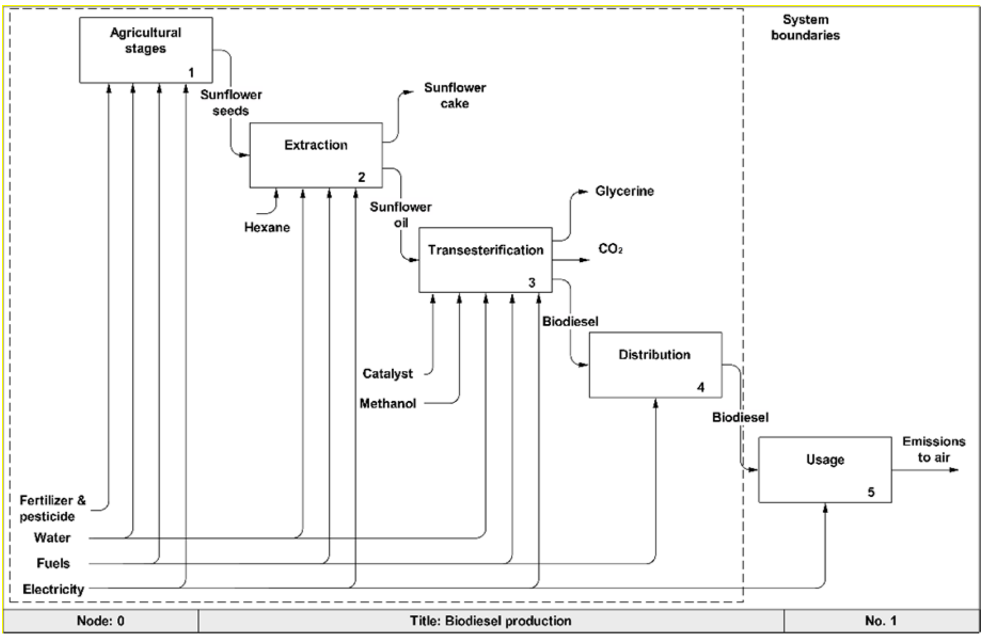

Figure 1: IDEF diagram for the biodiesel production.

Table 1: Process details and assumptions

Process	Characteristics and details
Agricultural stage	Energy and water supply Insecticide, pesticide and herbicide supply Nitrogen and phosphate fertilizers supply
Sunflower seeds supply to facility	Transport by truck, 28 t truck from Gesualdo (AV); distance = 80 km
Energy supply to facility	Italian energy mix low voltage
Extraction	Energy and water supply Hexane supply T = 50 °C
Transesterification	Energy and water supply Sodium methoxide and phosphoric acid addition Methanol addition T = 70 °C; t = 120 min
Distribution	Transport by lorry, 16-32 ton to Fiumicino (Lazio); distance = 240 km
Waste disposal	Energy supply, natural resources use for recycling and landfill

The life cycle inventory (LCI) is one of the most effort-consuming step and consists on the activities related to the search, the collection, and interpretation of the data necessary for the environmental assessment of the observed system. The Ecoinvent 3.1 database was employed as the principal source of background data and the LCA study is conducted using the LCA software SimaPro 8.0.4 in accordance with the reference standard for LCA (i.e., ISO 14040-14044).However, the majority of the processes and materials information required for the analysis are specific of the observed system and the collection of these data was performed using personal interviews. For each unit process within the system boundary, input data, such as energy, water, natural sources and output data in terms of emission to air, water and soil were collected. Table 2 lists the main energy and direct material input to the product systems under the study of 1 ton of biodiesel.

Table 2: Life cycle inventory of the main inputs and outputs for biodiesel production (tkm is tonne-kilometre).

Industrial Phase	Input/Output	Unit	
Agricultural stages	Land area	m^2	7.52×10^{3}
	Rain water	ton	6.76×10^{3}
	Nitrogen fertilizer	ton	1.17×10^{-1}
	Phosphate fertilizer	ton	3.40×10^{-2}
	Insecticide, pesticide, herbicide	ton	1.80×10^{-3}
	Diesel	ton	1.39×10^{-1}
	Seeds	ton	5.70×10^{-3}
Transportation	Transport by truck	tkm	2.02×10^{2}
Extraction	Electricity	kWh	1.34×10^{2}
	Sunflower seeds	ton	2.41×10^{0}
	Water	ton	1.07×10^{-3}
	Hexane	ton	1.71×10^{-6}
	Output		
	Sunflower cake	ton	1.26×10^{-3}
Transesterification	Sunflower oil	ton	1.01×10^{0}
	Electricity	kWh	9.74×10^{1}
	Methane for heating	ton	2.63×10^{-2}
	Water	ton	6.05×10^{-3}
	Methyl alcohol	ton	1.06×10^{-3}
	Sodium methoxide	ton	1.00×10^{-5}
	Phosphoric acid	ton	2.05×10^{-5}
	Output		
	Glycerine	ton	1.01×10^{-2}
	Carbon dioxide	ton	7.17×10^{-1}
Distribution	Biodiesel	ton	1.00×10^{0}
	Transport by lorry	tkm	2.37×10^{2}

3. Results and discussion

The aim of this study is the interpretation of the data collected through the LCI phase and the evaluation and comparison of the impacts related to biodiesel and fossil diesel production. The results were interpreted utilizing the advantages of the use of both midpoint and damage categories, according to IMPACT 2002+ life cycle impact assessment methodology. All types of life cycle inventory results via 15 midpoint categories can be linked to four damage categories: human health, ecosystem quality, climate change and resources. In particular:

human health is affected by carcinogens (C), non-carcinogens (NC), respiratory inorganics (RI), ionizing radiations (IR), ozone layer depletion (OLD) and respiratory organics (RO);

ecosystem quality is affected by aquatic ecotoxicity (AET), terrestrial ecotoxicity (TET), terrestrial acidification/nitrification (TAN), land occupation (LO), aquatic acidification (AA) and aquatic eutrophication (AE);

climate change is quantified using the global warming potential (GWP);

resources are affected by non-renewable energy consumption (NRE) and mineral extraction (ME).

The contribution of the biodiesel and fossil diesel production on each midpoint category are reported in Table 3, from which it is possible to observe that biodiesel production instead of fossil diesel fuel produces advantages as well as disadvantages, depending on the midpoint category under study. In particular, observing the values in the last column of Table 3, where the ratio between biodiesel and diesel production emissions are reported, it is possible to note that:

- biodiesel emissions are higher in terms of non-carcinogens, land occupation, aquatic eutrophication, global warming potential and mineral extraction;
- biodiesel emissions are lower in terms of ionizing radiations, ozone layer depletion, respiratory organics, terrestrial ecotoxicity and non-renewable energy;
- finally, the two productions show comparable emission values in terms of carcinogens, respiratory inorganics, aquatic ecotoxicity, terrestrial acidification/nitrification and aquatic acidification.

The higher emissions of biodiesel production are due to the high “land consumption” for the agricultural phase, to the carbon dioxide emissions from diesel engines, which burn the fuels in the agricultural phase, and to mineral fertilizers production processes. On the contrary, the smallest impact of biodiesel production on IR, OLD, RO, TET and NRE is due to the minor use of fossil fuel in the production line. To lower those emissions, different mineral fertilizers have to be proposed and the use of biodiesel instead of mineral diesel in agricultural phase can constitute a further improvement.

In order to make a comparison among different impact categories, the results were normalized. The IMPACT 2002+ method employs the emission values of Western Europe as reference values (Humbert et al., 2012); indeed, the total impact of a specific category is given by the sum of the products between all European emissions + resource consumption and the respective damage factors. The normalized characterization factors, then, are determined by the ratio of the impact per unit of emission divided by the total impact of all substances of the specific category per person per year. The unit of all normalized characterization factors is therefore [point/unit$_{emission}$] = [pers*y/unit$_{emission}$]. Figure 2 shows the values (in the case of biodiesel production) obtained for each category through the LCA analysis after the normalization process. It is evident that the midpoint categories mainly affected by biodiesel production are the ones of NC, AET and AE.

Table 3: IMPACT 2002+ midpoint results for biodiesel and diesel production. Data are referred to 1 ton.

Midpoint category	Unit	Biodiesel	Diesel	Biodiesel/Diesel
C	kg C_2H_3Cl eq	6.87×10^{0}	5.96×10^{0}	1.15
NC	kg C_2H_3Cl eq	5.85×10^{1}	1.37×10^{1}	4.27
RI	kg PM2.5 eq	6.78×10^{-1}	6.88×10^{-1}	0.99
IR	Bq C-14 eq	4.36×10^{3}	9.41×10^{3}	0.46
OLD	kg CFC-11 eq	1.21×10^{-4}	5.12×10^{-3}	0.02
RO	kg C_2H_4 eq	4.65×10^{-1}	5.22×10^{0}	0.09
AET	kg TEG water	3.38×10^{5}	3.99×10^{5}	0.85
TET	kg TEG soil	7.45×10^{3}	5.81×10^{4}	0.13
TAN	kg SO_2 eq	1.55×10^{1}	1.73×10^{1}	0.90
LO	m^2 org.arable	1.29×10^{2}	1.23×10^{1}	10.49
AA	kg SO_2 eq	5.85×10^{0}	4.84×10^{0}	1.21
AE	kg PO_4 P-lim	2.33×10^{0}	1.76×10^{-2}	132.39
GWP	kg CO_2 eq	1.24×10^{3}	5.44×10^{2}	2.28
NRE	MJ primary	1.79×10^{4}	5.09×10^{4}	0.35
ME	MJ surplus	1.14×10^{1}	3.87×10^{0}	2.95

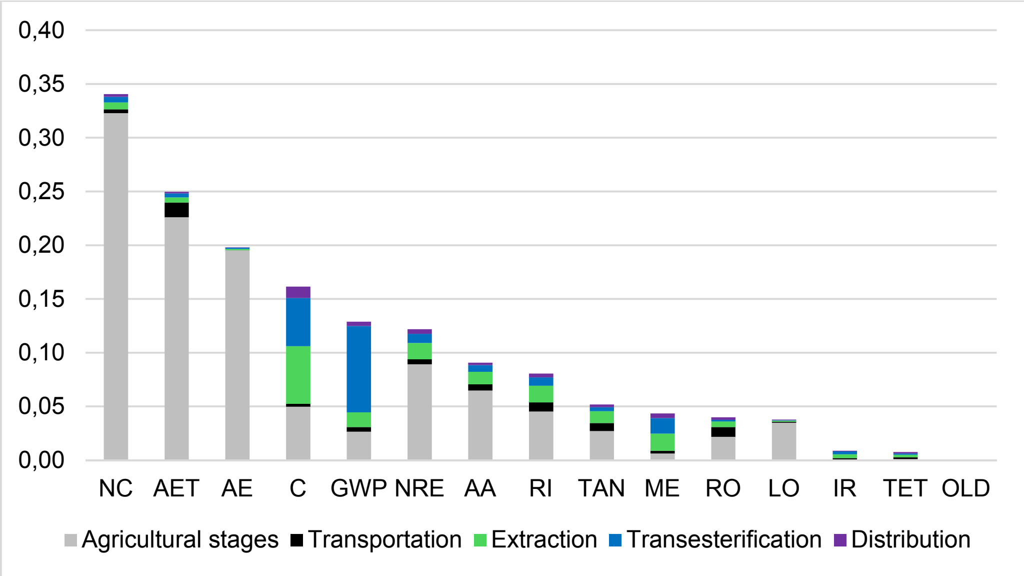

Figure 2: Normalized impact categories for biodiesel production per FU.

Another clear evidence is that agricultural stages are the ones that mainly affect the emissions; their contribute is higher than 50% with respect to the total of the normalized emissions on NC, AET, AE, NRE, AA, RI, TAN, RO and LO. The environmental impacts were then grouped, according to IMPACT 2002+ method, considering the damage on endpoint categories: human health, ecosystem quality, climate change and resources. Figure 3 shows for biodiesel and fossil diesel productions the four global environmental impact categories. Emissions related to diesel production are higher considering the total effect on the four categories (505 mPt vs 350 mPt). The higher difference between the two productions is related to the resources category. Biodiesel production requires less consumption of resources (118 mPt) with respect to diesel production (335 mPt), because in the production line there is less depletion of fossil fuel and minerals. Biodiesel shows higher emissions on climate change because of the high quantities of organic solvents used in the transesterification step. The effect on ecosystem quality and on human health are more or less comparable between the two productions.

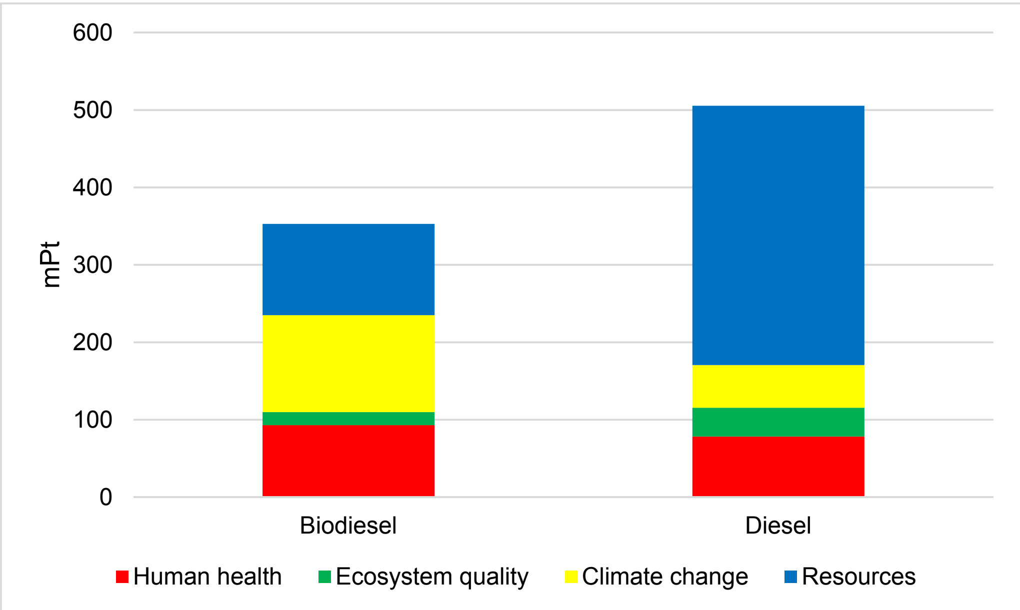

Figure 3: Total environmental impact according to the four main endpoint categories of IMPACT 2002+ method on relative scale (millipoint, mPt).

4. Conclusions

In this work, a comparative LCA analysis on biodiesel and fossil diesel productions was performed, considering a “from cradle to grave” analysis, where only the consumption was not considered in the system boundaries. It is clear that, in the biodiesel production, the agricultural stages are the most impacting ones, due to the usage of fertilizers and the work of agricultural machines. The lowering of that emissions can be achieved using different mineral fertilizers and using, as fuel in the agricultural machines, biodiesel in substitution to mineral diesel fuel. Considering the global damages on human health, ecosystem quality, climate change and resources, it is possible to note that fossil diesel production generates higher emissions, mainly caused by the high consumption of resources, whereas, for the biodiesel production, human health, climate change and resources are more or less equally damaged.

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