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Environmental impact of oil-based biofuels production processes

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Three scenarios of energy production from sunflower seeds in a rural context are compared. The analysis refers to the district of Pisa, in Italy, and it accounts for production of sunflower seeds, conversion of seeds into different biofuels (crude oil, refined oil and biodiesel) and production of thermal and electrical power from biofuels in CHP engines. The environmental impacts of each scenario were compared by applying the methodology of life cycle assessment (LCA).

The use of all the three types of biofuel allows a reduction of fossil CO2 emissions of 400-460 g/MJ of produced electricity respect to a traditional diesel fuel. On the other hand all biofuel scenarios have a higher impact than diesel in the categories respiratory inorganics, terrestrial ecotoxicity, terrestrial acidification/nutrification due to polluting emissions deriving from seed cultivation. The life cycle analysis shows that the biofuel upgrading processes (refining and transesterification) as well as crude oil transport have a low influence on the environmental performance, compared to seed cultivation, which is the most impacting step. On the other hand, crude oil upgrading allows a significant reduction in pollutant emissions during combustion. As a result, biodiesel results the most sustainable biofuel in the analysed context.

1. Introduction

In the next future, biomass is expected to become one of the major renewable resources for the production of chemicals, fuels, power and heat. In these fields the cultivation of oilseeds and the subsequent production of biofuels in plants called biorefineries may play an important role. Three different types of biofuels can be produced from oilseeds: raw oil, refined oil and biodiesel. High-grade fuels (i.e. biodiesel) guarantee high efficiency, low emissions and long operating life to engines, but they require a more complex plant and higher operating and capital costs (which may not be afforded by a small farm) than low-grade fuels (i.e. vegetable oil). The aim of this paper is to assess some aspects of feasibility in a rural context for a biorefinery based on the extraction of oil from oilseeds (sunflower) and a sequence of physical and chemical operations to produce a fuel suitable for the production of heat and power from internal combustion engines. Three scenarios for the production and utilization of different biofuels are defined and compared through life cycle assessment methodology.

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2. Scenarios definition

Three scenarios related to the production and utilization of three biofuel products (crude vegetable oil, refined oil, biodiesel) were defined. The district of Pisa was considered as the geographical context. Sunflower, the most common among oilseed cultures in this area, was chosen as biomass.

Mass and energy balances were set for each scenario, in order to compare the performance from an energetic and environmental point of view. Electric consumptions (oil press, centrifuges, pumps, impellers et cetera) were calculated from datasheet of commercial equipments.

2.1 Scenario 1

The first scenario represents a single farm in the district of Pisa, with a relatively wide cultivable surface (200 ha), which produces crude oil. *Table 1* reports data related to this production. Only 25% of the surface is cultivated with sunflower (a 4-years rotation is considered). The farm harvests sunflower seeds at the end of summer and it produces oil by mechanical pressing from September to November. The crude oil is burned in a CHP (combined heat and power) engine in winter, allowing the farm to reduce its energetic and thermal requirements in the cold season. The CHP engine has a thermal input of 330 kW, and no pollutant abatement system was considered except catalytic oxidation.

2.2 Scenario 2

The second scenario represents the production of high quality vegetable oil, obtained removing phosphorus (degumming), acids (neutralization) and moisture. The plant is made up of chemical operations which are not suitable to be operated in a small farm. For this reason, we referred this process to a consortium of 100 farms located in the Pisa district, similar to that of Scenario 1, each 50 km far by average from the refining plant. Each farm produces sunflower seeds that are transformed in situ in crude oil, which is then transported to the consortium refining plant. The plant operates continuously during the year and produces refined oil which is fed to a CHP engine with a thermal input of about 5 MW, equipped with catalytic oxidation and an SCR de-NO_x system. The thermal and electrical outputs are destined to local networks and they are partially used in the refining process. *Table 1* reports data related to this production.

2.3 Scenario 3

In the third scenario, the same consortium described in Scenario 2 performs the crude oil refining and transforms the refined oil in sunflower methyl-ester (biodiesel) via a transesterification reaction with methanol as main reagent and KOH as the catalyst (see *Table 1*) (Jungbluth et al, 2007). The produced biodiesel is then used in a CHP engine with a thermal input of about 5 MW, equipped with catalytic oxidation and an SCR de-NO_x system. As in the previous scenario, the thermal and electrical outputs are destined to local networks and partially used in the refining and trans-esterification process.

2.4 Main hypotheses

For the cultivation step, we considered a low-intensive cultivation, with no irrigation, no green manure and low dosage of fertilizers and pesticides, with a mean dry matter yield of 2500 kg/ha. A low moisture level of 9% can be obtained by harvesting in September, avoiding the need of drying the seeds before pressing them (Bonari et al., 1992).

Table 1. Data of each scenario

SCENARIO	*1*	*2*	*3*
Sunflower surface	50 ha	4000 ha	4000 ha
Sunflower seeds yield	2500 kg/ha	2500 kg/ha	2500 kg/ha
Product	Crude Oil	Refined Oil	Biodiesel
Production rate	98 kg/hr	270 kg/hr	270 kg/hr
Utilization rate	30 kg/hr	270 kg/hr	270 kg/hr
Production period and hours	Sept-Nov (420 hr)	Year (6500 hr)	Year (6500 hr)
Utilization period and hours	Winter (1360 hr)	Year (6500 hr)	Year (6500 hr)
Biofuel PCI (MJ/kg) (Altin et al., 2001)	39.6	39.6	40.6
Thermal Input to Engine (kW)	330	5340	5472

The crude oil production was supposed to happen via a two-step mechanical pressing producing about 33% of oil respect to seeds, 1% of solid waste and 52.5% of pellets usable as animal fodder, which are an important co-product for the operation economics. The refining step produces about 97 kg of refined oil from 100 kg of crude oil, but also an important amount of wastewater (about 20 kg) are produced. Finally, the assumed biodiesel plant have a biodiesel yield of 100% respect to input refined oil and co-produce crude glycerin, together with wastewater streams.

2.5 Process comparison

Table 2 reports some performance indicators of each biofuel scenario. Noteworthy the highest conversion of seeds into fuel is obtained for crude oil. The fuel upgrading leads to a lower conversion and a higher production of wastes (solid waste and wastewater) than the simple crude oil production, while only a small increase in the power requirements can be observed. The reason is that the power consumption of the mechanical pressing is large compared to the power requirements of the upgrading processes. Finally comparing the energetic yield of the three scenarios in terms of MJ per ha·yr, we can state that a major fuel quality leads to a higher efficiency in the use of agricultural soil to energetic purposes.

3. Life cycle assessment

Life cycle assessment is a technique for evaluating the environmental aspects associated with a product over its life cycle, i.e. from the extraction of raw materials to the final disposal. In this work LCA was applied to compare environmental performances of 4 scenarios of energy production in CHP internal combustion engines:

Table 2. Comparison of performance indicators of the three scenarios

Performance indicator		Scenario 1 (CSO)	Scenario 2 (RSO)	Scenario 3 (SME)
Mass conversion efficiency	kg_{fuel}/kg_{seed}	0.314	0.303	0.305
Waste production	Solid [kg/kg_{fuel}]	0.022	0.036	0.052
	Wastewater [kg/kg_{fuel}]	-	0.242	0.426
Power requirements [MJ_{el}/MJ_{fuel}]		0.022	0.023	0.027
Energy yield	Biofuel yield [MJ/ha·yr]	3.40	3.29	3.38
	Electric yield [MJ_{el}/ha·yr]	1.05	1.02	1.13
	Thermal yield [MJ_{th}/ha·yr]	1.27	1.23	1.24

- Scenario 1. Electricity, CSO (crude sunflower oil), at farm/IT.
- Scenario 2. Electricity, RSO (refined sunflower oil), at refinery plant/IT.
- Scenario 3. Electricity, SME (sunflower methyl-ester), at trans-esterification plant/IT.
- Scenario 4. Electricity, at cogeneration unit 200kWel, diesel/IT.

3.1 Methodology

The functional unit chosen for the analysis was 1 MJ of electrical energy produced. Mass and energy balances were performed on every defined scenario, in order to compile the inventory, which contains all of the inputs and outputs of the processes. Life cycle assessment was then carried out with the software SimaPro 7.1.8.

Different allocation criteria were used: for the co-production of crude sunflower oil (CSO) and sunflower meal at the oil mill, economic allocation was used, considering 900 €/t and 150 €/t respectively the price of the oil and of the meal in Italy. Economic allocation was performed even for the co-production of sunflower methyl-ester (SME, 1000 €/t) and glycerine (700 €/t). Allocation was executed on exergetic basis for electric power and heat cogeneration. In all the preceding cases, allocation for inputs and emissions of carbon dioxide from and to the air was done simply according to carbon balance for CO2 emissions. Any different approach would indeed lead to coarse mistakes in the evaluation of the environmental indicator “climate change”.

Life cycle impact assessment was performed using the method Impact 2002+. The weighting set used was 250 for Human Health, 200 for Ecosystem Quality, 300 for Climate Change and 250 for Resources.

For sunflower cultivation data in Tuscany, we referred to Bonari et al (1992) and Venturi & Venturi (2003), while for engines performances (pollutants emissions, lifetime), we referred to Altin (2001) and to data from engines producers. All other data necessary were taken from equipment producers or from the database Ecoinvent 2.0.

3.2 Life cycle inventory

The comparative analysis of the life cycle inventory (LCI) of the four scenarios gives a first indication of the processes sustainability. Main resources consumption are compared in *Figure 1a*. As far as the crude oil consumption is concerned, Scenario 4 exhibits the highest value due to the direct use of this resource in the production of the diesel fuel. The scenarios related to biofuels require about 25% of the crude oil consumed by Scenario 4, mainly due to heat production needed for vegetable oil storage. The coal consumption is due to high electrical demand for mechanical pressing, while the utilization of natural gas is mainly due to urea (used both as fertilizer and reactant in the SCR unit) and methanol production, which both involve methane steam reforming to produce synthesis gas. The iron consumption can be considered an indicator of the materials requirement due to equipment and infrastructure fabrication. The major need of this resource is in Scenario 1 (CSO) and it decreases with the enhancement of the quality of the fuel. This is due to the lower engine lifetime associated with a poor fuel quality.

Major airborne emissions are compared in *Figure 1b*. Emissions can be classified according to the major sources that originate them. Several compounds (CO, CO_2 , NO_x, PAH, Particulates total, SO_2, total hydrocarbons) are mainly produced by combustion, both directly in the considered CHP unit and during other “upstream” energy production processes. NH_3 and N_2O are mainly due to the use of fertilizers on agricultural soil.

The emissions related to combustion show a similar trend for the three biofuels scenarios: they decrease from Scenario 1 (CSO) to Scenario 3 (SME). The reason is that higher emission factors are associated to a poor fuel quality. The use of biofuels improves the abatement of CO, CO_2 and SO_2 respect to diesel, while Scenario 4 exhibits lower NO_x, PAH, Particulates and Hydrocarbons emissions. In fact biodiesel leads to smaller emissions of all the aforementioned pollutants other than NO_x, but the performances of Scenario 3 are anyhow worse than those of Scenario 4 because these emissions must be ascribed to "upstream" processes.

Waterborne emissions are compared in *Figure 1c*. There are three major sources for these pollutants: the use of fertilizers on the soil (NO_3, PO_4, P, Cr, Ni), the disposal (landfilling) of solid wastes (Cd, Cu, Pb, Hg, Ni, Zn), the production of fertilizers (Cd, Hg). As far as the emissions connected to the use of fertilizers are concerned a clear trend related to the overall efficiency of the scenario can be identified. Thus Scenario 2 (RSO) exhibits the higher emissions, followed by Scenario 1 and Scenario 3. The trend is similar for the emissions related to waste disposal, in this case Scenario 1 (CSO) exhibits very low emission values due to the small production of wastes.

3.3 Life cycle impact assessment

Figure 1d shows the results of the impact assessment for six categories that affect significantly the total environmental impact of the four scenarios.

The pollution from respiratory inorganic compounds and the terrestrial acidification are dominated by the emission of NO_x, thus Scenario 1 shows the worst performance in this category. As far as "terrestrial eco-toxicity" and "land occupation" are concerned Scenario 2 exhibits the worst performance followed by Scenario 1 and Scenario 3, due to the minor overall efficiency, which leads to a higher use of soil and fertilizers. Scenario 1 is the biofuel scenario with the worst performance in "global warming", followed in order by Scenario 2 and Scenario 3, as a consequence of the thermal requirement (oil storage) within the process, while Scenario 3 has the highest demand of "non-renewable energy" (due to the methanol production).

Generally speaking, the production and use of biofuels give better results in term of contribution to the global warming and use of non-renewable sources than Scenario 4. However the diesel production and use show better performances in terms of land occupation, terrestrial pollution and production of respiratory inorganics.

Finally, the aggregated results can be properly used to compare in a direct way similar scenarios, like scenarios 1, 2, 3 (see *Table 3)*. Among these, Scenario 3 turns out to be the less impacting in all of the damage categories but "Resources", due to the use of methanol, and the more environmentally convenient according to the global indicator.

Table 3. LCIA weighted scores for damage categories, method Impact 2002+.

	Scenario (E+03)			
Damage category	1 (CSO)	2 (RSO)	3 (SME)	4 (Diesel)
Human health	12.8	5.7	4.9	1.9
Ecosystem quality	11.1	11.5	9.7	0.2
Climate Change	3.3	3.2	2.9	6.0
Resources	2.2	2.0	2.3	4.9
Total	29.4	22.4	19.7	13.0

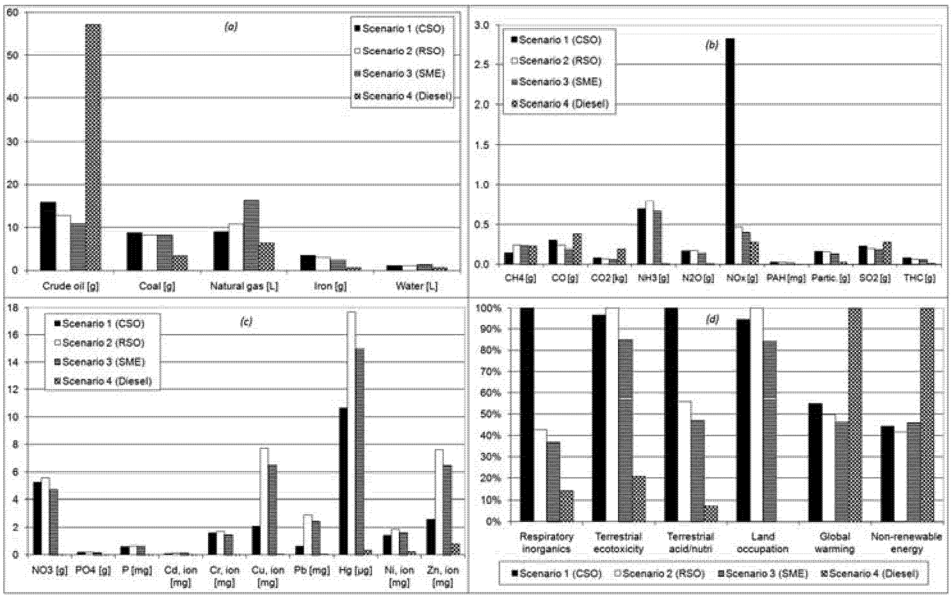

Figure 1. LCI and LCIA results: (a) major resources consumptions, (b) major airborne emissions, (c) major waterborne emissions, (d) percentage comparison for main impact categories (method Impact 2002+), for 1 MJ of electrical power produced

4. Conclusions

The influence on environmental impact of biofuels upgrading processes (refining and trans-esterification), as well as that of oil transport, results to be low compared to that of seed cultivation; on the other hand fuel upgrading allows a significant reduction in polluting emissions during combustion. As a consequence LCA results show that Scenario 3 (biodiesel) is the most sustainable biofuel scenario, because of the high efficiency of fuel utilization (minimum seeds requirements for produced energy unit) and high fuel quality (minimum emissions respect to oil and even to fossil diesel).

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