Journal of Cleaner Production 18 (2010) 328–335

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life Cycle Assessment for biodiesel production under Greek climate conditions

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ARTICLE INFO

Article history:
Received 13 June 2009
Received in revised form
1 November 2009
Accepted 9 November 2009
Available online 13 November 2009

Keywords:
Life Cycle Analysis
Biofuels
Biodiesel
Environmental impacts

ABSTRACT

The aim of this paper is to understand and to model the environmental performance of biodiesel produced by various Greek raw materials under current conditions. Three energy crops (rapeseed, sunflower and soybean) have been studied, with regard to their levels of biodiesel productivity. Throughout the entire process, current Greek climatic conditions and cultivation parameters have been taken into account. At the stage of assessment, we conclude that the environmental impacts per crop area indicate that soybean has the lowest environmental impacts. However, by assessing the results per quantity of produced biodiesel, the crop with the minimum environmental impacts is sunflower. This paper shows that environmental benefits from biodiesel have better results, compared to conventional diesel, thus leading to the conclusion that it is feasible to succeed improved environmental performance.

1. Introduction

Nowadays, the need for alternative and renewable fuels plays an important role, for both environmental and economic reasons. Biodiesel is a substitute of conventional diesel, which can be used alone or blended with conventional diesel. In this case, most emissions and pollutants known from the use of conventional diesel are reduced [1,2].

In addition, biodiesel is a non-toxic liquid, which is safer than conventional diesel, due to its higher ignition point; it has excellent lubricant characteristics, it biodegrades four times more rapidly and it also has a higher cetane number [3] than petrodiesel. Finally it can decrease dependence on fossil fuels, boost employment and prevent rural depopulation [4].

The disadvantages of biodiesel include increased NO_x emissions, higher coagulation and evaporation points, and less energy content [5]. However a major disadvantage of energy crops is their conflict with food, which is an economical and social matter rather than a technical one [6,7].

According to the last Renewable Energy Directive (2009/28/EC) it is mandatory that a 10% minimum target is to be achieved by all Member States for the share of biofuels in transport petrol and diesel consumption by 2020 [8]. In this paper, we analyze the Life Cycle [9–11] of biodiesel production from rapeseed, sunflower and soybean, which are amongst the most popular energy crops in Europe.

2. Methodology

2.1. The Greek case

Although the environmental impacts from biodiesel production can be evaluated at a European level [12–16], biodiesel production in Greece is required to take into account its mild Mediterranean climate, which favours many energy crops cultivations, as well as the importance of farming to the country. In addition, having in mind that olive oil production is essential to the Greek economy and tradition, but in parallel, Greece is characterized by high dependency on energy imports, biodiesel development can play a crucial role [17].

Biodiesel production in Greece reached 100 kt in 2007, and rose up to 565 kt in 2008 [18]. It seems that energy crops could also serve as a way of the agricultural sector to redefine its position, to move towards more sustainable cultivations, and to boost the Greek economy [19]. However, the environmental impacts from the production of biodiesel under Greek conditions are not well known; it is for this reason that a Life Cycle Assessment (LCA) is necessary, which will evaluate the potential environmental benefits and/or damages.

Abbreviations: DALY, disability adjusted life years; EU, European Union; LCA, Life Cycle Assessment; LCI, Life Cycle Impact; PDF, potentially disappeared fraction of plant species; WEQ, weighting factor for ecosystem quality; WHH, weighting factor for human health; WR, weighting factor for resources.

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doi:10.1016/j.jclepro.2009.11.002

2.2. Life cycle definition

The LCA approach is an effective method to select the environmentally optimum. There is a large variety of available relevant software tools (SimaPro, EMIS, GaBi, Regis, Umberto, etc), that not only focus on the assessment of the product production process, but also on its waste management [20,21].

The first stage of this work was data gathering on biodiesel production, based on international conditions [22,23]. The second stage involved data gathering from different reliable Greek sources [24] and the evaluation of local conditions, which led to the selection of the parameters and data used in this LCA. The third and final stage was the simulation of these parameters and data, followed by the comparison between the three different types of biodiesel (according to the three different crops: rapeseed, sunflower and soybean) and conventional diesel. Moreover, different scenarios were evaluated in order to assess methods to decrease potential negative environmental impacts.

For the simplification of the simulation the following five stages have been considered per energy crop: (i) soil preparation and cultivation; (ii) raw material transportation; (iii) crushing of the oilseed; (iv) seed oil refinery; (v) biodiesel production (Fig. 1).

The quantity of co-products and by-products from biodiesel production is relatively limited in Greece, due to the small production, and they are used as feedstock. Moreover glycerine, an important co-product of biodiesel production, is not retrieved as a co-product from the biggest part of biodiesel facilities of Greece. Its retrieval and later use, could reduce the total environmental impacts of biodiesel production [25].

2.3. Software description

The software package SimaPro 7 has been chosen because it is a widely used LCA tool, both by professionals and researchers. Its main advantages are the several available databases and the ability to produce and evaluate results, which can be translated into a number of impact categories, such as acidification, climate change etc. (Fig. 3), and demonstrate the environmental impacts or loads. It is worth noting though, that SimaPro, like other relevant LCA software, does not automatically conform to the ISO standards, which are specifically designed for LCA application (ISO 14040, ISO 14041, ISO 14042, ISO 14043). The reason is that these standards are defined in a quite vague language, which makes it difficult to find out if LCA has been certified according to the standard [26].

The basic structure of the software methodology is:

(i) *Characterization*: Once the impact categories are defined and the Life Cycle Inventory (LCI) results are assigned to these impact categories, it is necessary to define characterization factors, which reflect the relative contribution of the LCI result to the impact category indicator result (Fig. 2). These impact categories are:

a. Depletion of fossil fuel (expressed as MJ Surplus energy);
b. Depletion of minerals (expressed as MJ Surplus energy);

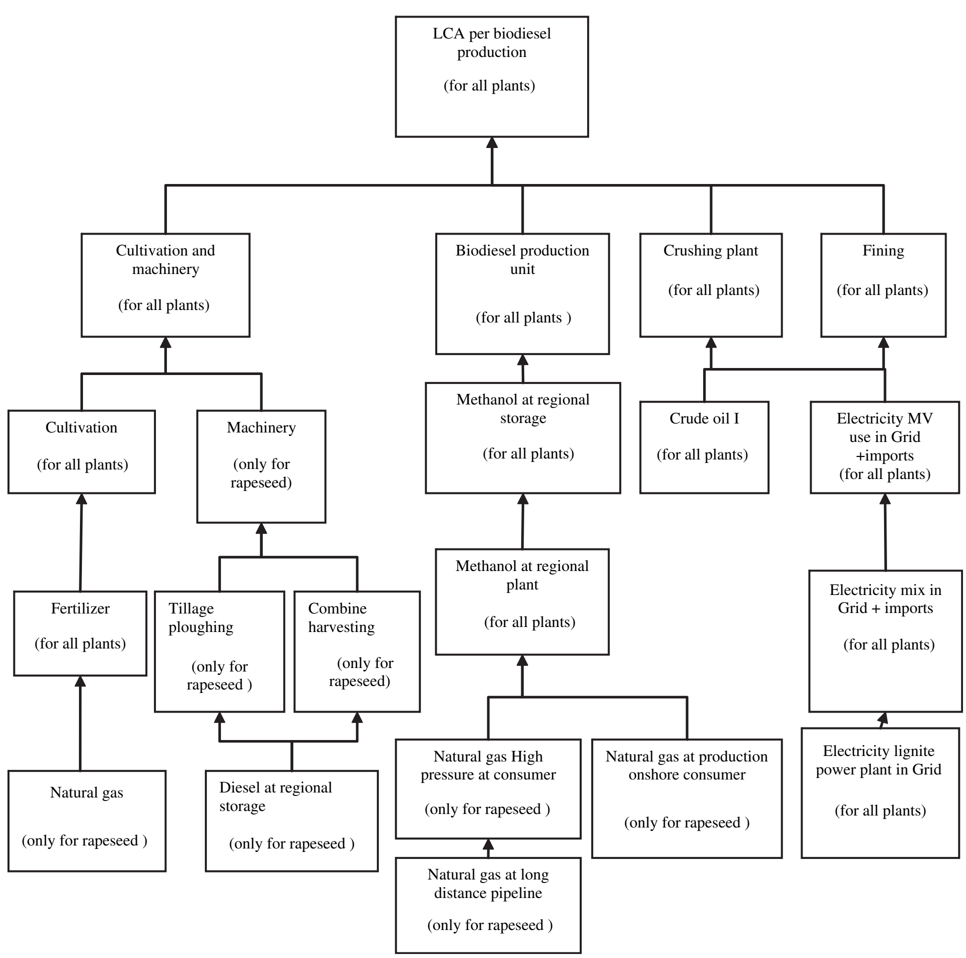

Fig. 1. Flowchart for rapeseed, sunflower and soybean energy crop.

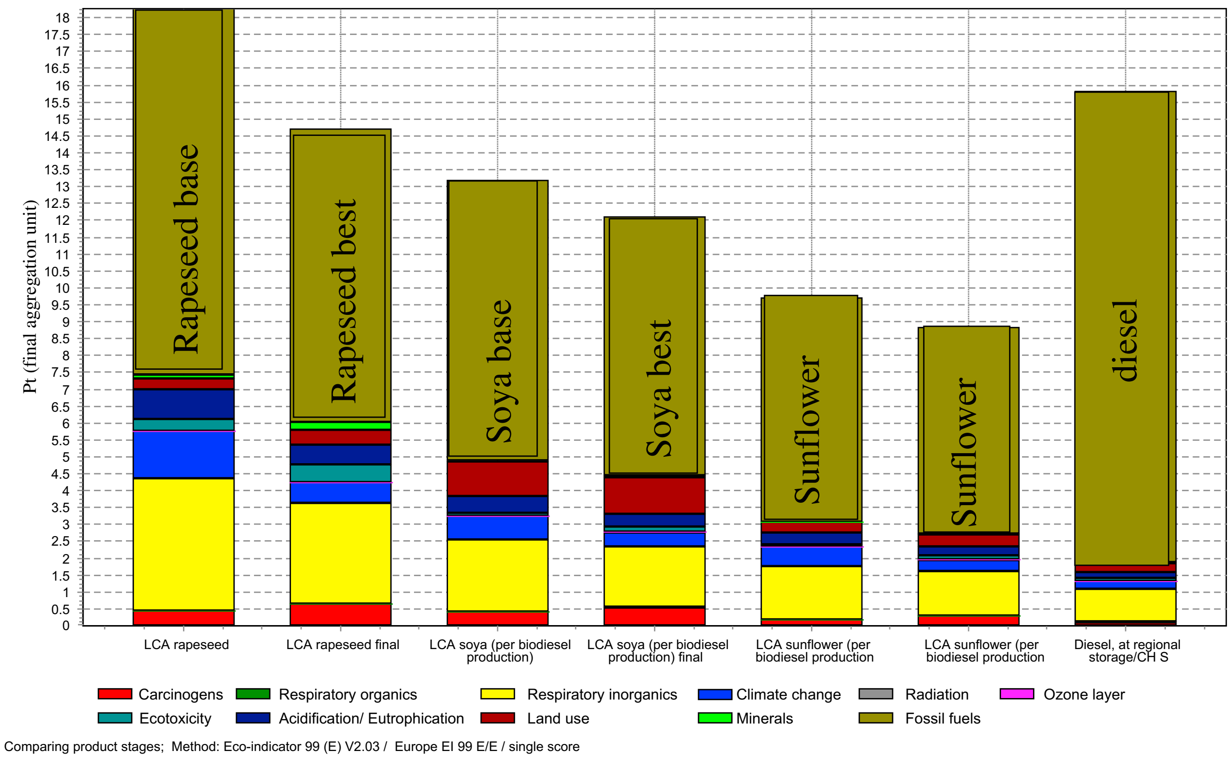

Fig. 2. Total environmental impacts of base scenarios and best scenarios for the three energy crops and conventional diesel, according to the 11 impact categories of Simapro.

c. Land use (expressed as PDF $\times$ m^2 $\times$ yr);
d. Acidification/eutrophication (expressed as PDF $\times$ m^2 $\times$ yr);
e. Ecotoxicity (expressed as PDF $\times$ m^2 $\times$ yr);
f. Climate change (expressed as DALY);
g. Ozone layer depletion (expressed as DALY);
h. Carcinogenic substances (expressed as DALY);
i. Respiratory effects (organic) (expressed as DALY);
g. Respiratory effect (inorganic) (expressed as DALY);
k. Ionising radiation (expressed as DALY).

(ii) *Damage assessment*: There is a wide range of impact category indicators, so a grouping procedure can be used in the Eco-indicator 99 methodology. The indicator results can be presented as three indicators at endpoint level without any subjective weighting.

(iii) *Normalization* is a necessary procedure to demonstrate to what extent an impact category has a significant contribution to the overall environmental problem. The most common procedure to normalize is by determining the impact category indicators for a region during a year and, if desired, dividing this result by the number of inhabitants in that area.

(iv) *Weighting* is the most controversial and difficult step in LCI assessment, especially for midpoint methods. The method used for comparing and presenting results is Eco-Indicator 99 v 2.1 [27], which includes the capability of analysis through damage evaluation step and can be used for the estimation of various environmental impacts. The final results can be shown in a single score. The categories that have been chosen as the main receivers of environmental impacts are:

- *Damage to human health*. The results are expressed in number of years of life lost and number of years of life in disability having as measuring unit Disability Adjusted Life Years (DALY) and include impact categories a and b.
- *Damage to ecosystem quality*. The results are expressed in number of species lost in a certain area during a certain period of time and include impact categories c, d and e.
- *Damage to resources*. The results are expressed in energy surpluses required for future fossil fuel extraction and include the last six impact categories.

The category indicators are defined close to one of the three endpoints to achieve an optimum environmental relevance. The impact category indicators that refer to the same endpoint are all defined in such a way that the unit of the indicator result is the same. This allows addition of the indicator results per group. Assuming that WEQ, WHH and WR are the weighting factors for Ecosystem Quality, Human Health and Resources respectively, any number of weighting set can be defined as far as $WEQ + WHH + WR = 100\%$. In Eco-Indicator 99 method used in this study, automatic generation of this combination has been used in order to avoid subjectivity.

2.4. Differences between energy crops

With regard to soil preparation processes, all three types of crops need tillage ploughing, hoeing and combine harvesting, while rapeseed also needs tillage harrowing. The data (concerning irrigation, fertilisers, biocide, pesticides, mass transport, and energy requirements [28] and biomass productivity) per hectare for three different energy crops under Greek conditions were acquired from farmers, local producers and biodiesel facilities of Agroinvest S.A., a Greek company established in 1978 which produces and trades edible seed oils and biodiesel. (Table 1).

The comparison of the different energy crops is made by assessing the environmental load per crop per:

- Hectare (ha);
- Quantity of produced biodiesel.

The three crops can flourish under the Greek climate conditions, while their introduction in the farming system is not expected to

Table 1
Energy–raw material requirements and factors for three different types of energy crops per hectare.

Irrigation through SimaPro 7 (m^3)	Rapeseed	Sunflower	Soybean
Water river	540	1080	2160
Fertiliser amounts (kg)			
N	230.00	70.00	40.00
K_2O	200.00	–	–
P_2O_5	90.00	–	–
MgO	25.00	–	–
Quantities of pesticides (kg)			
Biocide trifluralin	1.00	1.00	1.00
Pesticide pirimicarb	1.00	–	1.00
Pesticides dicofol	–	–	0.50
Transport of raw material (tkm)			
Truck 16t B250	130.00	105.00	120.00
Energy demand in the crushing plant			
Crude oil (kg)	100.30	84.00	76.80
Medium voltage electricity in Greece (MJ)	676.80	567.00	432.00
Energy requirements in the refinery			
Crude oil (kg)	58.70	50.40	25.90
Medium voltage electricity in Greece (MJ)	235.80	202.68	102.60
Reactants and required energy	Rapeseed oil	Sunflower oil	Soybean oil
Seed oil (kg)	980.00	840.00	432.00
MeOH (kg)	210.00	181.70	93.50
NaOH (kg)	7.80	6.70	3.50
H_2O (kg)	990.00	849.70	437.00
H_3PO_4 (kg)	6.10	5.20	2.60
Medium voltage electricity in Greece (MJ)	229.32	180.00	108.00
Biodiesel product per strema of cultivation	Rapeseed	Sunflower	Soybean
Produced quantity (kg)	971.20	834.40	429.10
Production factor	10.00	11.60	22.60
Mean yield of raw material (kg)	2507.00	2300	2710

cause any further environmental impacts, such as water, air and soil pollution or soil degradation and erosion since they can be cultivated with the existing machinery and need similar fertilisers as the existing cultivations of Greece.

In the first scenario (i), the reference point is the yield per hectare, while in the second scenario comparison is based on volume units, and more specifically, on biodiesel. The final produced quantities are shown in Table 1.

The yield of each crop and the productivity of biodiesel are very important due to the limited available field areas in Greece. Thus, for example, the production of 971.2 kg of biodiesel requires 1 ha when using rapeseed as raw material, 1.164 ha when using sunflower and 2.263 ha when using soybean; therefore, the final decision for the most appropriate cultivation depends on the volume of the desirable biodiesel production and on area availability.

2.5. Alternative scenarios

For the minimisation of the environmental impacts, some parameters were modified, so different alternative scenarios were made in order to find the best possible combination of these parameters [29]. These alternative scenarios are referred to the two main processes, during cultivation and biodiesel transformation. All alternative scenarios examined here are reasonable, feasible and have been adjusted to comply with Greek conditions. For every change in a parameter, a new alternative scenario was created, in order to distinguish the benefits or stresses (environmental impacts) arising from every diversification. For alternative scenarios are based on changes in different parameters, like the differentiation in fertilising. A possible diversification at the stage of cultivation is the use of alternative fertilisers, thus creating the following scenarios: LCA No 1 for NH_4NO_3, LCA No 2 for $(NH_4)_2SO_4$, LCA No 3 $Ca(NO_3)_2$, and LCA No 4 for KNO_3 (Table 2). Then the replacement of synthetic fertilisers with organic ones was considered, creating scenario LCA No 5. In the case of organic manure, the composition of Greek origin manure is approximately 4% N, 6% P and 4% K (the remaining 86% consists of organic material that helps further soil improvement). Another possible differentiation was in the amount of water used for irrigation. It fluctuated in the range of ±20%. In the biodiesel factory diversifications were made on the type of fuel consumption and several different scenarios were taken into account using different fuel types (crude oil, grid energy, conventional diesel), which are shown in Table 3. The total energy amount for each scenario must be stable, so the differentiation is in the quantities of each fuel type, since each type has different energy content. Moreover, another possible scenario was the differentiation in the grid energy; In 2007, the electricity mix in the Greek grid was 59.76% lignite, 6.27% oil, 25.40% natural gas, 6.05% hydroelectricity and 2.52% rest of the renewable energy [30], which is not environmentally friendly because of the high percentage of fossil fuels. A shift towards a less carbon intensive and more environmentally friendly mix, by using more renewable energy, would reduce the environmental impacts of grid electricity. Since this electricity is used in biodiesel production at the crushing, oil refining and oil-to-biodiesel conversion stages, the environmental impacts of the biodiesel production would be reduced too. Coherent to the target of renewable energy sources accounting for 20% of total energy consumption, by 2020 the contribution of renewable energy in the energy grid was decided to be 20%.

The alternative scenarios for grid energy were applied to the three examined energy crops (Tables 4–6).

Calculations and comparisons of the results were made with reference to the productivity of biodiesel per rapeseed hectare, which is 971.2 kg biodiesel.

3. Results

3.1. Results per crop

The results represent the environmental impacts from the whole process of biodiesel production under Greek conditions per crop. It is vital for developers and policy makers to know which processes affect the environment most and to be able to make the optimum decision. Finally, data are simulated and a baseline

Table 2
Alternative scenarios for the stage of cultivation for the three energy crops. Differentiations in the type and the quantity of fertilisers per hectare.

	Rapeseed		Sunflower		Soybean	
Fertiliser scenario (kg)	Fertiliser	Quantity (kg)	Fertiliser	Quantity (kg)	Fertiliser	Quantity (kg)
LCA No 1	NH_4NO_3	230	NH_4NO_3	70	NH_4NO_3	40
LCA No 2	$(NH_4)_2SO_4$	230	$(NH_4)_2SO_4$	70	$(NH_4)_2SO_4$	40
LCA No 3	$Ca(NO_3)_2$	230	$Ca(NO_3)_2$	70	$Ca(NO_3)_2$	40
LCA No 4	KNO_3	230	KNO_3	70	KNO_3	40
LCA No 5	Organic	5750	Organic	1750	Organic	1000

Table 3
Alternative scenarios for the stage of biodiesel plant. Differentiations in the type and the quantity of fuel used for the three different types of energy crops for the processing of the yield per hectare.

Fuel scenarios	Rapeseed			Sunflower			Soybean		
	Fuel type	Seed oil industry	Refinery	Fuel type	Seed oil industry	Refinery	Fuel type	Seed oil industry	Refinery
LCA No 6 (kg)	Crude oil	100.3	58.7	Crude oil	84	50.4	Crude oil	76.8	25.9
LCA No 7 (MJ)	Grid energy	5040	2740	Grid energy	5040	2740	Grid energy	5040	2740
LCA No 8 (kg)	Diesel	95.5	55.8	Diesel oil	80	48	Diesel	73.2	24.7

scenario is formulated, which shows the environmental impacts of the three different crops for the biodiesel production (Fig. 2). The following results focus on the main environmental impacts, while secondary impacts, like impacts from transportation and other processes, are relatively low (2.88%, 3.28% and 4.09% for sunflower, rapeseed and soya respectively).

3.1.1. Rapeseed

According to the adopted methodology, the maximum environmental impact is caused by the use of N as a fertiliser (32.1%) while the overall stress caused by the use of non-organic fertilisers exceeds 40% (40.32%). Major environmental impacts are high due to the use of MeOH, with a contribution of 12.9%. The second most important factor is energy requirements (21.27% on the total environmental load) for the processing of the raw material and the extraction of biodiesel, either in the form of fossil fuels or in the form of grid energy.

The above environmental impacts are caused mainly by the consumption of fossil fuels and the category “minerals”, which produce inorganic particles that harm the respiratory system.

3.1.2. Sunflower

In this case, we conclude that the largest part of the environmental impacts derives from the energy used in the crusher and oil refinery, which participates at a total of 39.3%. Other stresses are caused by the use of fertilisers (21.4%), and the use of MeOH in the biodiesel production facility (24.2%). In addition, the main receivers of the impacts per effect category are identical in both cases.

3.1.3. Soy

The impacts in this case derive from the energy used in the biodiesel production facility (totally 41.4%). The second most important environmental load arises from the use of MeOH (17.8%), while the use of fertilisers contributes 17.5%.

Soy has a similar Life Cycle to rapeseed and sunflower, so the structure and the LCA processes are similar. The main difference is in terms of yield per hectare; soy has limited potential for biodiesel production per area (in ha), but if the results are expressed in units of biodiesel production, then the outcome is much better. This is the reason why soy should be used when vast areas are available.

Table 4
Alternative scenarios for the cultivation of rapeseed in the biodiesel plant (20/80 renewable/conventional energy use).Differentiation in the type of energy used for the processing of the yield per hectare of rapeseed.

Scenario name	Energy type (MJ)	Seed oil industry	Refinery	Production unit
LCA No 9	Energy from conventional fuels	676.80	235.80	229.32
LCA No 10	Energy from conventional fuels	541.44	188.64	183.60
	Hydroelectric energy	135.36	47.16	45.72
LCA No 11	Energy from conventional fuels	541.44	188.64	183.60
	Solar energy	135.36	47.16	45.72
LCA No 12	Energy from conventional fuels	541.44	188.64	183.60
	Wind energy	135.36	47.16	45.72

3.2. Comparison between the three available crops

3.2.1. Comparison per area (ha)

When comparing the environmental impacts, which arise from biodiesel production expressed per unit area, we conclude that cultivation of rapeseed will cause greater environmental impacts. According to the results, soybean seems to be the best raw material. As it is observed in all three crops, the highest environmental impacts arise from three identical factors, which are:

i. The use of fertilisers (mainly N);
ii. The use of MeOH during the process of seed oil conversion to biodiesel;
iii. Energy requirements (seed oil refinery and crushing for the production of seed oil).

In rapeseed cultivation, the extensive use of fertilisers and particularly the large quantities of N cause a rapid increase in the environmental load. Between sunflower and soybean, soybean has smaller requirements for all three factors.

Environmental impacts can be allocated in three main damage categories: human health, ecosystem quality, resources (Fig. 2). It is observed that impacts in various ecosystems are extremely scarce and then follow those on human health. The part of the whole process with the highest environmental impacts is that of “sources” because the manufacturing of both fertilisers and MeOH is energy intensive.

3.2.2. Comparison per biodiesel production

Summing up the results per quantity of produced biodiesel generates different outcomes than the comparison per cultivated area. Due to the low yield of soy per hectare, for the same quantity of biodiesel the other two cultivations require almost half this area. Calculating the impacts, the cultivation of rapeseed remains more harmful for the same reasons as stated in the previous comparison. However, sunflower crops damage the environment, the least.

Similar to the previous comparison, the distribution of environmental impacts in the three categories (damage categories) has no major differences; moreover, the part of the process that is important is also “sources”. As we have already mentioned, significant amounts of energy are required for the production of fertilisers and MeOH.

3.2.3. Comparison with conventional diesel

The impacts, due to the biodiesel production, were compared with those caused by conventional diesel. The energy content of biodiesel is less than the energy content of conventional diesel, since the energy produced by the combustion of one biodiesel unit is equivalent to 0.873 units of conventional diesel [16]. Thus, to acquire the same amount of energy 847.8 kg of conventional diesel corresponds to 971.2 kg of biodiesel, which is the quantity

Table 5
Alternative scenarios for the cultivation of sunflower in the biodiesel plant (20/80 renewable/conventional energy use). Differentiation in the type of energy used for the processing of the yield per hectare of sunflower.

Scenario name	Energy type (MJ)	Seed oil industry	Refinery	Production unit
LCA No 9	Energy from conventional fuels	567.00	201.60	196.92
LCA No 10	Energy from conventional fuels	453.60	162.00	157.68
	Hydroelectric energy	113.40	40.68	39.24
LCA No 11	Energy from conventional fuels	453.60	162.00	157.68
	Solar energy	113.40	40.68	39.24
LCA No 12	Energy from conventional fuels	453.60	162.00	157.68
	Wind energy	113.40	40.68	39.24

Table 6
Alternative scenarios for the cultivation of soy in the biodiesel plant (20/80 renewable/conventional energy use). Differentiation in the type of energy used for the processing of per hectare of soy.

Scenario name	Energy type (MJ)	Seed oil industry	Refinery	Production unit
LCA No 9	Energy from conventional fuels	432.00	102.60	101.52
LCA No 10	Energy from conventional fuels	307.20	82.08	81
	Hydroelectric energy	86.40	20.52	20.72
LCA No 11	Energy from conventional fuels	307.20	82.08	81
	Solar energy	86.40	20.52	20.72
LCA No 12	Energy from conventional fuels	307.20	82.08	81
	Wind energy	86.40	20.52	20.72

produced per hectare of rapeseed. Apart from biodiesel production from rapeseed, the environmental impacts resulting from the production of biodiesel from sunflower and soybean are less than the corresponding impacts caused by the extraction, transportation and processing of conventional diesel (see Fig. 2).

3.3. Alternative scenarios

After the base scenarios for the three energy crops were formulated, the next step was the formulation of alternative scenarios with differentiation in the two main processes, the stage of cultivation and the biodiesel plant.

3.3.1. Stage of cultivation

3.3.1.1. Differentiations in fertilisers

3.3.1.1.1. Rapeseed. In all alternative scenarios of the stage of cultivation, the same amounts of N were used, as a safe comparison basis; the quantities of fertilisers in the first four scenarios remained the same, as they were calculated according to their overall N content.

The overall environmental impacts from the use of fertilisers can be reduced with the use of $(NH_4)_2SO_4$ as the main ingredient, scenario LCA rapeseed No 2 (reducing output by 11%) or using an organic fertiliser, scenario LCA rapeseed No 5 (decrease output by 17.1%).

3.3.1.1.2. Sunflower. In the case of sunflower, the fertiliser requirements are 70 kg N per hectare; to meet that demand using organic fertilisers the required quantity should be 1750 kg.

In this case, as in the previous one, the more efficient and environmentally friendly alternative scenarios are those using either a fertiliser which has $(NH_4)_2SO_4$ as main ingredient, scenario LCA sunflower No 2 (reduction of the output at 6.8%) or the one that uses an organic fertiliser, scenario LCA sunflower No 5 (reduction of output by 4.8%). In these scenarios, the decrease of the environmental impacts is equally satisfactory as the case of rapeseed. Moreover, in the case of sunflower, the organic fertiliser is not the optimal solution. In the case of rapeseed, $(NH_4)_2SO_4$ can replace only the necessary quantities of N as a fertiliser, while to cover the overall fertilising demands P and K fertilisers must be used. On the contrary, with the use of organic manure those needs are covered, further reducing the environmental load of rapeseed. In the case of sunflower (as in soy), P and K fertilisers are not used, and for that reason, organic fertilisers are not expected to minimise the environmental impacts.

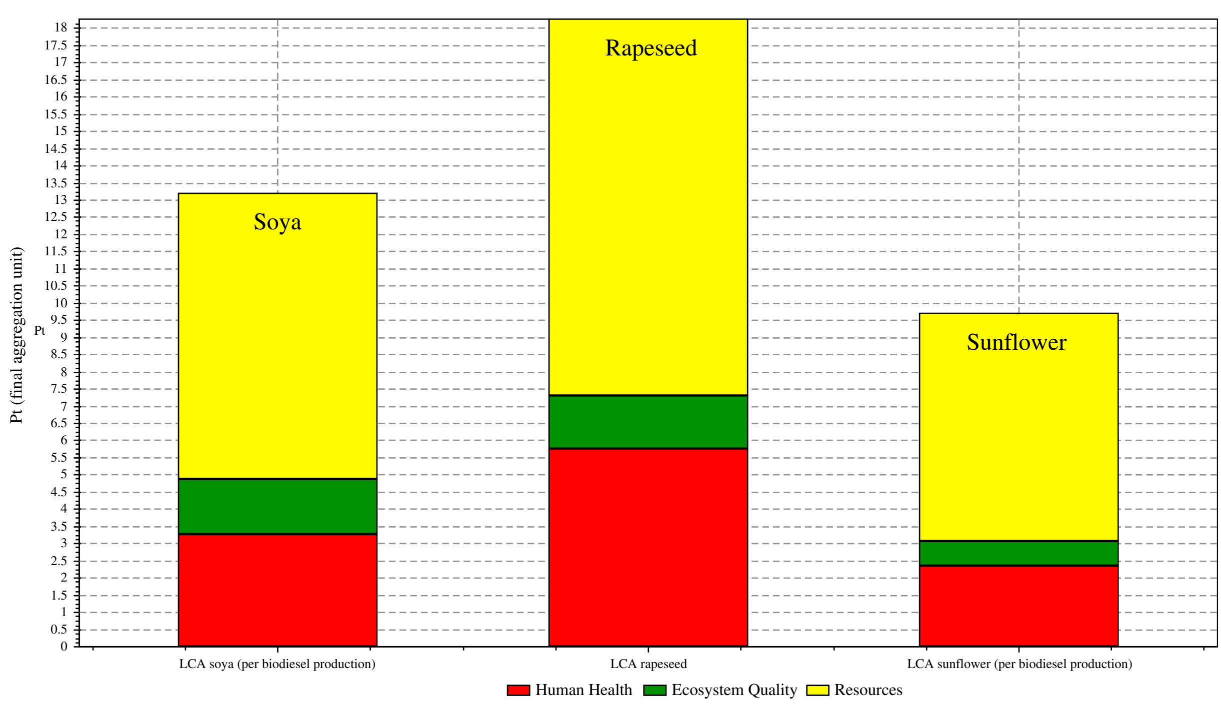

Fig. 3. Total environmental impacts for the three energy crops according to the 3 main impact categories of Simapro.

Table 7
Optimum factors, which are used in Fig. 2, for each energy crop.

Differentiations	Rapeseed	Sunflower	Soybean
Fertilisers	LCA No 5	LCA No 2	LCA No 2
Fuel	LCA No 8	LCA No 8	LCA No 8
Grid energy	LCA No 10	LCA No 10	LCA No 10

3.3.1.1.3. Soy. In the case of soy crop, the required fertilisers are 40 kg N/ha. Reductions in this crop are similar to the case of sunflower, as their basic characteristics remain the same. As in the previous alternative scenario, the most effective and environmentally friendly scenario is (i) using $(NH_4)_2SO_4$, LCA soy (per biodiesel production) No 2 (reduction of the output by 6%) or (ii) using organic fertiliser, scenario LCA soy (per biodiesel production) No 5 (a cut of 4.5%).

3.3.1.2. Differentiations in irrigation. In order to assess the importance of irrigation on the total environmental impacts, two alternative scenarios were evaluated, by changing water consumption by 20% (increase and decrease respectively). Changes in the end result in all three crops were almost negligible. The conclusion is that the environmental load caused by the consumption of water is several orders lower than that of other parameters.

3.3.2. Process in the biodiesel plant

3.3.2.1. Differentiations in the fuel type. In the LCA of the three crops, the fuel type used in the biodiesel facility was crude oil; two additional energy sources were taken into account, conventional diesel and grid energy. As a unit, the mean yield per hectare of rapeseed was used, which is 2507 kg. Fuel requirements, per case and per scenario are shown in Table 2. In comparison with the final results, these do not vary significantly, as the fuel source and its nature remain the same in all three cases.

3.3.2.2. Energy grid differentiations. According to data gathered, assumptions and Greek conditions, three different forms of renewable energy were examined (hydroelectricity, solar energy and wind energy), as electricity provision alternatives for the production stage of biodiesel. As it is expected, the increase in the share of renewable energy sources improves the final result in all cases. The major reduction derives from the use of hydroelectricity, followed by wind power, and then by photovoltaic systems.

3.3.2.3. Optimum factors. We differentiated the inputs per scenario and per crop in order to minimise the environmental impacts. For each scenario, the differentiated input with the maximum reduction is called optimum factor. By combining the calculated optimum factors, we created the optimum scenario and the final results for all three crops (Fig. 3) have the maximum environmentally friendly performance. In the case of rapeseed the optimum scenario has the biggest decrease of the environmental load (19.5%), then the case of sunflower (9.1%); soy has the smallest decrease on the environmental load (8.2%). All the optimum factors and the optimum scenario, which is their combination, are presented in Table 7 and the best scenarios are represented in Fig. 2.

4. Discussion and conclusion

Comparing the three energy crops, rapeseed turns out to be the most preferable, due to its high biodiesel productivity; however, it has the largest environmental load, due to the increased amount of fertilisers used for plant growth. Comparing the other two energy crops, in terms of cultivated area, soy is clearly more advantageous, due to the reduced requirements for fertilisers, the reduced amount of MeOH for the oil conversion and for the reduced consumed energy in the rest of the stages of production and refining of oil. But when comparing the results per biodiesel quantity, the results differ because of the most favourable ratio of required fertilisers, MeOH and consumed energy per volume of produced biodiesel. This is expected because major environmental impacts are caused by the consumption of fossil fuels and the use of fertilisers. By evaluating the crops per biodiesel production, the production of biodiesel from rapeseed has the largest environmental impacts, while sunflower is more favourable and environmentally friendly (Fig. 3).

As to environmental impacts, mineral raw materials account for the largest share followed by the emissions of particulates and substances, harmful to human health and particularly to the respiratory system, with a larger share of NO_x and SO_2 emissions. NO_x emissions in biodiesel LCA are mainly caused by the combustion of the end product, 92% [14], while secondary NO_x emissions are caused from the machines that use diesel in the stage of cultivation and in the biodiesel facilities and by the transportation of the raw material. SO_x emissions are caused mainly by steam production and indirect emissions associated with methanol production. For example the soybean crushing step generates SO_x through the consumption of steam, natural gas, and electricity [14]. Moreover the stage of cultivation can produce SO_x emissions through consumption of diesel in the machinery and through the use of nitrogen fertilisers.

We note that biodiesel production from rapeseed is estimated to cause the worst environmental impacts compared to conventional diesel, without taking into account the negative implications of combustion. In all three cases, high environmental impacts on the emissions and particulates exists (respiratory inorganics and organics). The category of respiratory organics is not so important as it comes up to 1.6% at most, while the respiratory inorganics are considerably high ranging between 13.5% and 22.2%. Nevertheless, the general outcome is environmentally favourable, in comparison with conventional diesel (except from the standard scenario of rapeseed), especially from sunflower.

Comparing alternative scenarios with the standard (Fig. 2), if fertilisers are replaced with an organic fertiliser in the case of rapeseed or fertiliser $(NH_4)_2SO_4$ in the cases of the other two crops, the environmental impacts can be significantly reduced, while significant reductions can also be achieved by the use of renewable energy.

Based on the discussion above, the sunflower crop seems to be the optimum solution for biodiesel production, because it combines the relation between the volume of production and the corresponding implications. Soy follows, comparing the positive results with conventional fuels, while rapeseed shows negative results.

As can be seen, although biodiesel can be an option for the transition to cleaner fuels, analyzing and studying the complete chain of energy crops and their requirements may demonstrate different results than biofuel supporters expect. Thus, the whole Life Cycle should be taken into account before choosing and applying cultivation patterns of energy crops for biodiesel production.

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