Sustainability of Rapeseed Biodiesel Using Life Cycle Assessment

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ABSTRACT

The Kyoto protocol and the EU Directive 2009/28/EC focus their attention on the reduction of greenhouse gases (GHG) emissions. The use of biofuels in the transport sector is one of the main measures proposed. This paper evaluates the environmental impact, in terms of GHG emissions, of the production and use of rapeseed biodiesel, comparing the results with conventional diesel. The methodology used is the Life Cycle Assessment (LCA). The results of the analysis show that the production of rapeseed biodiesel entails a substantial reduction of the GHG emissions compared to the diesel production system. Furthermore, the agricultural phase is identified as the process which causes the largest amount of GHG emissions in biodiesel life cycle. Therefore it could be possible to improve further the environmental performance of biodiesel intervening properly at that stage.

Keywords: Biodiesel, Sustainability criteria, GHG emissions, LCA

1. Introduction

Alternative fuels for the transport sector are gaining growing attention as a means against fossil fuel dependence and towards greener forms of energy. At the same time, however, they are surrounded with doubts concerning sustainability of their production.

In recent years, the production of energy from renewable sources has been stimulated through policies both at international (Kyoto Protocol) and European level (Directive 2009/28/EC).

Biofuels for the transport sector (e.g. bioethanol, biodiesel) are today a subject of intense discussion and their role is ambivalent. On one hand, they represent an instrument against the dependence from fossil fuels and a key to reduce carbon emissions. On the other hand, biofuel production from crops is criticized for increases in food prices and food insecurity (Abbott et al., 2011). Furthermore, land use changes and intensification of cultivation following the increasing demand for biofuels may cause new GHG emissions and affect the biodiversity, the soil quality and the natural resources in a region (Perimenis et al., 2011).

The present paper, taking into account the debate concerning biofuels sustainability, evaluates the environmental impact of biodiesel in terms of GHG emissions, comparing the results of biodiesel from rapeseed with the ones of conventional diesel. The methodology used is the Life Cycle Assessment (LCA).

2. Sustainability criteria: from field to wheel

Biofuels, which can be solid, liquid or gas fuels derived from biomass, are internationally recognized as having a clear role in the reduction of greenhouse gas (GHG) emissions and for energy security (Khanna et al, 2010).

However, as the popularity of biofuels has grown, some authors point out that not all biofuels pathways guarantee the same net benefit for the environment (Sims et al., 2010; Lankoski et al., 2011).

Moreover, the current debate focuses on the possible negative social implications, especially land use change and "the fuel versus food" debate (Diaz-Chavez, 2011).

These considerations lead to the necessity to demonstrate the effective sustainability of biofuels given the fact that only the ones which are produced in a sustainable way can be considered truly renewable energy sources (Glenister and Nunes, 2011).

Biofuel pathways can be considered sustainable if they are technically efficient, economically sustainable, environmentally friendly and socially acceptable. The assessment of these sustainability dimensions is a complex task, because of the big number of biofuel options in terms of biomass and in terms of different economic, environmental and social impacts along the entire chain (Perimenis et al., 2011).

In June 2009, the European Union launched the Renewable Energy Directive (RED - Directive 2009/28/EC) with ambitious targets for all member states. The Directive endorsed a mandatory target of a 20% share of energy from renewable sources in overall Community energy consumption by 2020 and a mandatory 10% minimum target to be achieved by all Member States for the share of biofuels in the transport sector by 2020. Moreover, the RED introduces environmental sustainability criteria (Art. 17-18-19- Annex V) for biofuels that are to be taken into account for the achievement of the targets. In particular, the sustainability criteria introduced by RED are:

- The GHG emission saving shall be at least 35%;
- Biofuels shall not be made from raw material obtained from land with high biodiversity value as: a) primary forest and other wooded land, namely forest and other wooded land of native species; b) areas designated by law or by the relevant competent authority for nature protection purposes; threatened or endangered ecosystems or species recognized by international agreements or included in lists drawn up by intergovernmental organizations (IUCN); c) highly biodiverse grassland, natural or non- natural;
- Biofuels shall not be made from raw material obtained from land with high carbon stock[1] and peatland.

[1] Such as: wetlands, continuously forested areas, land spanning more than one hectare with trees higher than five metres.

Therefore, the Member States shall require economic operators to show that the sustainability criteria set out in Article 17 have been fulfilled.

Furthermore, Article 18 of the Directive provides, that the economic operators use a system (defined mass balance system) which allows consignments of raw material or biofuel with differing sustainability characteristics to be mixed requiring information about the sustainability characteristics and sizes of the consignments.

Starting from the farmer, squeezer, processing plant, moving on to the trading companies that transport or adapt the product, to the fuel supplier who delivers it to a filling station and finally to the filling station, every supplier from the field to the end user must offer full traceability of sustainability. This chain of custody approach means that for any given consignment of biofuels, every detail of its production meets the required parameters.

In 2010, the European Commission published two Communications (COM (2010) 160/01 and COM (2010) 160/02) to assist the implementation of sustainability criteria.

In order to reduce the administrative burden for economic operators, the EU introduced two tools to show compliance to sustainability criteria:

- They can use recognized “voluntary schemes” or “bilateral and multilateral agreements” to show compliance with some or all of the sustainability criteria;
- They can use “default values” laid down in the Directive to show compliance with the sustainability criterion on greenhouse gas emissions savings.

Scarlat and Dallemand (2011) propose a review of the latest developments on the main initiatives and approaches for the voluntary sustainability certification for biofuels, showing the possible way to obtain the certification.

On July 19 2011, the European Commission announced the first seven schemes which have been approved. Each one has been rigorously checked to ensure that all the sustainability criteria are covered effectively by the economic organizations. The approval is valid for five years and confirms that the scheme can issue a certificate for a product that is fully assessed and meets all its criteria. These are the voluntary schemes approved by the Commission:

1. International Sustainability Carbon Certification (ISCC)
2. Bonsucro (previously the Better Sugar Cane Initiative)
3. Roundtable on Responsible Soy (RTRS)
4. Roundtable on Sustainable Biofuels (RSB)
5. 2BSvs Biomass Biofuels Sustainability
6. RED Bioenergy Sustainability Assurance Standard (RBSA)
7. Greenergy (Brazilian Bioethanol verification programme).

On April 23 2012, the European Commission also recognized the Ensus voluntary scheme for Ensus bioethanol production.

Novaol srl, which is an Italian biodiesel enterprise, adopted one of these schemes which is briefly described in the following paragraph.

2.1 The 2BSvs Scheme

The 2BSvs scheme has been developed by a Consortium of French raw materials and biofuels producers and it is one of the seven voluntary schemes recognized by the European Commission on 19 July 2011 (Commission Implementing Decision 2011/437/EU).

This voluntary scheme covers the whole biofuel industry's supply chain, from the biomass producer to the final biofuels distributor.

It is applicable to any type of biomass and biofuels worldwide and it covers all the sustainability requirements included in the European Directive 2009/28/EC.

This scheme includes the verification of:

1) sustainability criteria set out in Article 17(2) - 17(5) of the Directive:

- greenhouse gases emissions;
- conservation of biodiversity;
- conservation of carbon stocks;
- conservation of peatlands.

2) Chain of Custody (connection between raw materials, intermediate and final products) with the use of a mass balance system method and adequate standard of independent auditing.

In particular, for the assessment of greenhouse gas emissions criteria, the scheme provides that the first gathering entity and the economic operator shall demonstrate that the greenhouse gas emission savings from the use of sustainable biofuels is at least 35% in conformity with the EU Directive. The economic operator shall use the default value provided in part A or D of Annex V of European Directive, if their raw material has been produced in NUTS2 areas included in the list validated under article 19, point 2 of the European Directive, or if their raw material is imported from outside the Community, or if their raw material consists in waste or residues other than agricultural, aquaculture, fisheries or forestry residues. Whenever the economic operator wants to use calculated GHG values, the entity shall use a calculation methodology approved and recognized by the European Commission which is not available at the time of writing of the scheme (2BSvs, 2011).

Since GHG savings represent one of the main requirements of the sustainability assessment of biofuels and the 2BSvs scheme hasn't developed a methodology for the calculation of this parameter, the aim of the paper is to give an example of how to calculate GHG emission savings using the life cycle assessment (LCA) method.

LCA is considered as a commonly used tool for sustainability studies of biofuels, which includes evaluation of inputs, products and impacts in all stages of the life cycle. However, the LCA methodology cannot capture all the relevant impacts (land and water use and issues related to indirect land use changes and the competition for food products) which would require a broader approach (Requena et al., 2011; Silva Lora et al., 2011).

3. LCA methodology

Life Cycle Assessment is a technique used to assess the environmental impacts of a product, a process or a service during its entire life cycle from the "cradle", where raw materials are extracted from natural resources, through production and use to the "grave", the disposal or recycling.

The evaluation of the life cycle of a product can also be used to compare two different production processes in terms of use of resources and emissions.

As defined by ISO standards, a correct LCA analysis consists of four phases: 1) Goal and Scope Definition; 2) Inventory analysis; 3) Impact assessment; 4) Interpretation.

Each stage is briefly described.

3.1. LCA stages

1) According to the ISO standards (ISO 14041 1998), the *Goal definition* "shall unambiguously state the intended application, the reason for carrying out the study and the intended audience" (Baumann et al., 2003). The *Scope definition* provides the basis of the study through 5 fundamental steps: a) Drawing of initial flowchart; b) Choice of functional unit and reference flow; c) Choice of impact assessment method and related impact categories; d) Definition of system boundaries; e) Decision on allocation problems.

The initial flowchart is the starting point of the study and it shows which processes are involved in the system and their connections.

The functional unit is the unit of measurement to which all the data relate. It allows the comparison among different systems which are functionally equivalent, determining energy and mass flows in relation to its value.

There are two different types of impact assessment methods: the methods which deal with the impacts caused by the production processes directly to the environment (mid points methods) and those dealing with the indirect effects to human health, ecosystem health and resources (end points methods). Both of them are characterized by impact categories.

System boundaries define the limits of the study stating for example the processes involved in the system (technical boundaries), the time horizon and the geographical boundaries.

Allocation problems arise when several products (inputs or outputs) share the same process (or more processes). The ISO standards state that, whenever possible, allocation problems should be avoided; the most popular method to achieve this goal is the System Expansion, which is based on the idea that the co-products of the system are considered alternatives to other products with equivalent functions, obtained by other processes (avoided processes) in systems external to the one under study. The emissions that would be released from the production of these alternatives are considered as a credit and subtracted from the total emissions of the system analyzed.

When allocation cannot be avoided, the Partitioning method should be used; this means that the resource consumption and the related emissions must be partitioned among the different products in a way which reflects the underlying physical relationships between them (i.e. mass, volume, lower calorific value etc.). Where physical relationship cannot be established as the basis for allocation, the environmental loads (resource consumption, energy consumption, emissions to air, soil and water etc.) should be allocated among the products in a way which reflects other relationships between them, for example the economic value.

2) The second phase of a LCA analysis is the *Inventory analysis* (LCI). This step includes: the construction of the flowchart according to the system boundaries decided in the goal and scope definition phase; the data collection of the inputs and outputs flows in each production process and the calculation of the environmental loads of the system in relation to the functional unit.

3) The *Impact Assessment* (LCIA) is a phase which aims to describe the environmental consequences of the environmental loads quantified in the Inventory Analysis. The ISO standard 14042 divides the Impact Assessment in four steps: Classification, Characterization, Normalization and Weighting, but only the first two are mandatory due to their objective results.

In the Classification step, all the emissions of a system are assigned to their respective impact categories; the Characterization step uses science-based conversion factors, called characterization factors, to convert and combine the LCI results into representative indicators of the impacts on human and ecological health (Curran M.A., 2006). The Characterization provides a way to directly compare the LCI results within each impact category.

4) Life cycle *Interpretation* analyzes the findings of the preceding phases of the LCA, reaching conclusions and providing recommendations to improve the environmental performances of the system studied.

4. Case study: LCA evaluation of GHG emissions of rapeseed biodiesel compared with conventional diesel

The goal of the study is to evaluate the GHG emissions of the entire life cycle of biodiesel from rapeseed comparing them with the GHG emissions related to the life cycle of conventional diesel.

Biodiesel from rapeseed has been chosen because it is the most produced biodiesel in Europe, mixed with soy, sunflower and palm oil.

The LCA has been implemented using a German software, GaBi4 and its databases, developed by the Institute for Polymer Testing and Polymer Sciences (IKP) of the University of Stuttgart.

Some default databases in GaBi4, such as Edu DB and Xergi, contain within them useful data to support the development of the life cycle of a product.

The data used in this study derive from different sources: some of them come from the databases mentioned above; others from the scientific literature, in particular from a study regarding the assessment of the impacts of rapeseed biodiesel (Mortimer et al., 2003); finally, part of the data derives from NOVAOL srl, an Italian company which produces biodiesel.

Goal and Scope definition

The main goal of the study is to quantify the GHG emission savings deriving from the use of rapeseed biodiesel replacing conventional diesel.

The functional unit of the study, which is the same for both systems, is 1 km travelled by a bus.

As provided by the goal definition step, it’s necessary to identify the general characteristics of both the production systems.

The reference system is the one which produces conventional diesel, with the following assumptions:

- Conventional diesel derives from crude oil refining. Crude oil extraction has been made through the conventional onshore process;
- The processes considered in this work and related data derive from a study on crude oil production conducted in USA (Sheehan et al., 1998) and from the database Xergi;
- Crude oil, extracted from the wells, is transported to the refining plants via pipelines, for an average distance of 100 km;
- Diesel, obtained by the refining process, is carried to the distribution plants via trucks with a capacity of 40 tons, for an average distance of 100 km;
- The last process, diesel consumption, refers to the emissions due to bus transport for 1 km (Mortimer et al., 2003).

The system studied is rapeseed biodiesel with the following assumptions:

- In 1 hectare of agricultural land, rape is cultivated; in the system of diesel production this area is maintained set aside;
- Land use changes, including the shifting from set aside to cultivation of rape, are not taken into account in the environmental impact calculations;
- Raw seeds, obtained in the agricultural phase, are carried via trucks with a capacity of 7,5 tons;
- The chemical extraction of oil from seeds takes place through the use of hexane as solvent;
- Biodiesel is carried from the transesterification plants to the distribution plants via trucks with a capacity of 40 tons, for an average distance equal to 100 km;

- It is considered the use of pure biodiesel (B100), that is not mixed with fossil fuels;
- Tailpipe CO_2 emissions during the combustion of biodiesel are considered to be equal to zero, assuming that the quantity of CO_2 released in the atmosphere is equal to the quantity absorbed by the plants during their growth[2];
- There are no emissions of sulphur dioxide (SO_2) because biodiesel doesn't contain sulphur.

Flowcharts analyze the entire life cycle of both systems (diesel and rapeseed biodiesel) (Figg.1 and 2).

Figure 1 shows the sum of the processes involved in the production and in the final use of conventional diesel (Well-to-Wheel approach). The first step is the extraction of crude oil from the wells which gives a mix of crude oil, natural gas and water. From the separation process, crude oil is obtained as the main product and natural gas as co-product. Crude oil is carried via pipelines to the refining plants in order to obtain diesel, which is carried to the distribution plants via trucks.

In the utilization phase, only the quantity of diesel needed to cover 1 km by bus (functional unit) is considered, that correspond to 0.3 kg of diesel (Razelli, 2009).

In Figure 2, the chain of production and utilization processes of rapeseed biodiesel is reported. In the agricultural phase, raw seeds are obtained as main product and straw as co-product. Raw seeds must be dried and stored before the extraction step that can be physical (pressing) or chemical (solvent extraction); in this study, a chemical extraction using hexane as solvent has been considered, obtaining raw oil as main product and rapeseed meal as co-product, which can be used for animal feeds.

Subsequently raw oil must be purified and refined with physical and chemical treatments, in order to achieve a high quality product and to remove impurities that can lead to low yield of biodiesel.

Refined oil can't be used in diesel engines because of its high viscosity and so the transesterification process is necessary to obtain a product with properties similar to conventional diesel.

The main co-product of the transesterification step is glycerine, which can be used in different fields such as industry (e.g. pharmaceutical and cosmetic sector) and agriculture as an additive for phytoiatric products.

Biodiesel is then carried via trucks to the distribution plants, in which only the quantity needed to cover 1 km by bus (functional unit) is considered, that is 0.4 kg of biodiesel (Branco et al., 2006).

[2] We underline that the CO_2 balance is not exactly zero, since the crop residues on the ground determine an emission of carbon dioxide.

Figure 1: Initial flowchart of diesel life cycle

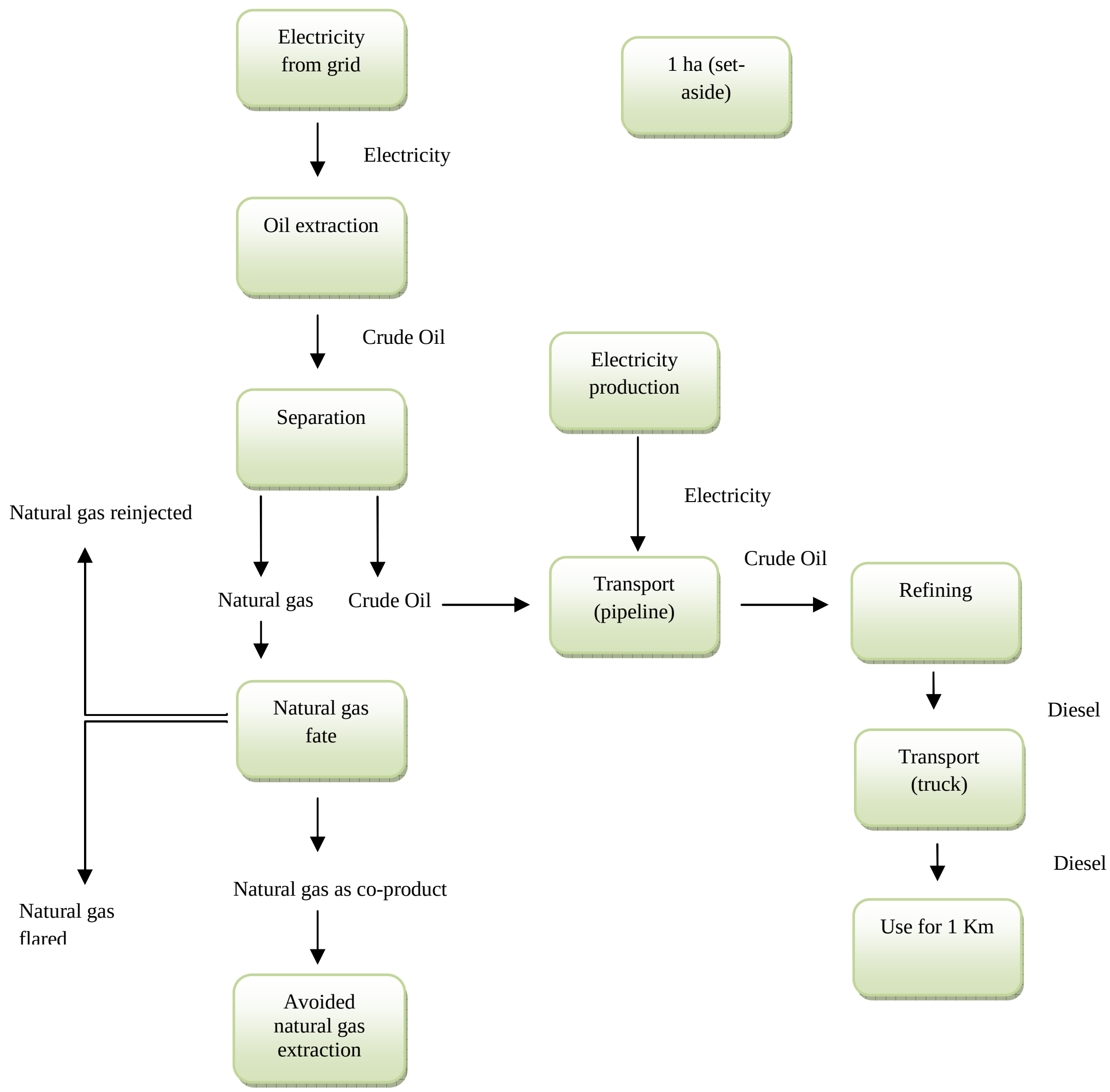
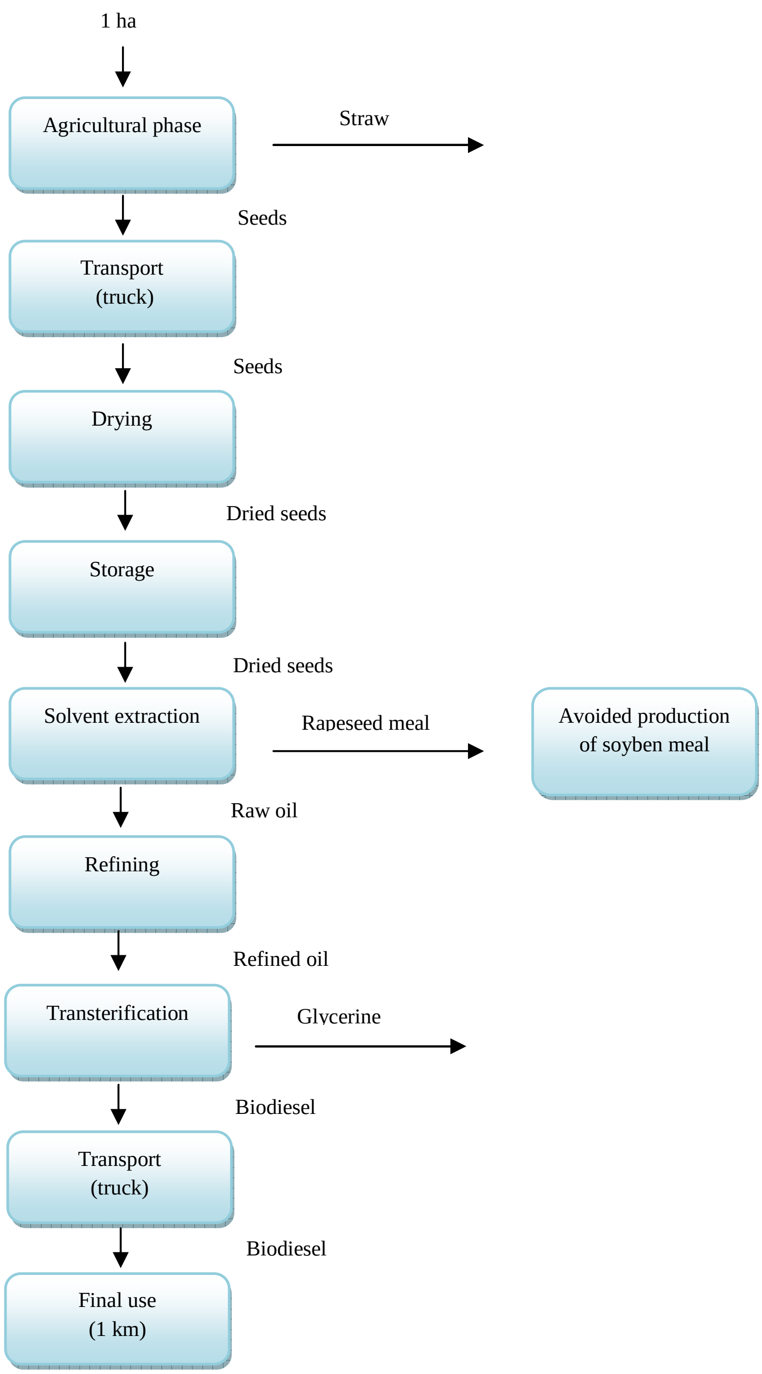


Figure 2: Initial flowchart of biodiesel life cycle



The impact assessment method (EDIP 1997[3]) has been used in thist study. Considering the goal, only the Global Warming Potential category (GWP) has been taken in account, which depends on the level of greenhouse gases in the atmosphere, measured in CO_2 equivalents, following the Characterization indicators provided by IPCC (100 years range). The greenhouse gases quantified are: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

In the diesel life cycle, just one allocation problem has been identified, which raises in the process of crude oil separation from natural gas, in which crude oil is obtained as main product and natural gas as co-product.

The System expansion method has been used to solve this allocation problem, including in the system the process of Avoided natural gas extraction, taken from the database Xergi in GaBi. In other words, the production of natural gas during the extraction of crude oil, means that it won't be necessary to use further energy and raw materials to obtain that specific quantity of gas, eventually produced by another system.

While three allocation problems occur in the biodiesel life cycle.

The first one appears in the agricultural phase, where rapeseeds is obtained as main product, which become an input in the subsequent drying phase and straw as co-product.

This allocation problem has been solved through the Partitioning method, determining the percentage of rapeseeds and straw (in terms of mass) with respect to the total; subsequently, all the inputs and outputs of the process have been re-calculated using the percentage relative to rapeseeds.

The second one occurs in the solvent extraction phase, in which raw oil is produced as main product and rapeseed meal as co-product. Rapeseed meal can be used as feed for animals substituting another feed. In this case, the System expansion method has been applied to substitute soybean meal, produced in another system with other processes, with rapeseed meal.

The third allocation problem arises in the transesterification process, where biodiesel is the main product and glycerine is produced as co-product. This problem has been solved through Partitioning, calculating the percentage of biodiesel and glycerine, in terms of mass, respect to the total. All the inputs and outputs of the process have been re-calculated using the percentage of biodiesel.

The partitioning method states that this allocation percentage must be use to re-calculate all the inputs and the outputs of the previous processes until reaching another process which produces a different co-product. In this case, the inputs and the outputs of the refining process have been re-calculated.

5. Discussion of results

The life cycle impact assessment (LCIA) aims at describing the environmental consequences of the environmental loads quantified in the inventory analysis (LCI).

[3] This impact assessment method, belonging to the mid points methods, is divided in seven different impact categories: global warming potential, nutrient enrichment potential, human toxicity, ecotoxicity, ozone depletion potential, acidification and photochemical oxidant potential.

In this phase, the most significant results are those deriving from the Classification and Characterization steps.

Figure 3 shows the results of the Characterization, elaborated with software GaBi4, which states that the diesel life cycle, from its production to the final use in a bus covering a distance equal to 1 km, produces 1.1 kg of CO_2 equivalents.

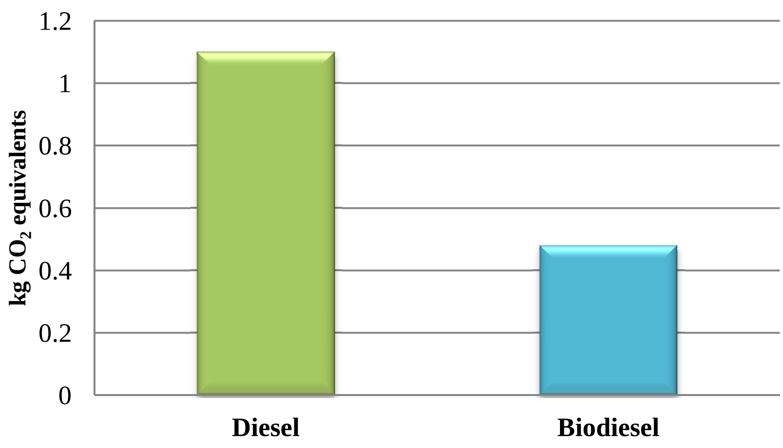
In the biodiesel life cycle, using the same parameters, a lower value is obtained, since greenhouse gases are released for a total of 0.48 kg of CO_2 equivalents.

In substance, the use of rapeseed biodiesel instead of conventional diesel entails a 56% saving of greenhouse gases emissions.

It's important to underline that this result doesn't consider the impact caused by land use change, which would bring to an increase of CO_2 emissions and therefore to a reduction of the saving percentage presented above (Edwards et al., 2010).

This percentage is in line with the standard and default values reported in the European Directive 2009/28 (Annex V), in which the average saving due to the use of rapeseed biodiesel is between 38% and 45% and with the study conducted by Rutz et al., 2008, which shows that saving of emissions of rapeseed biodiesel compared to diesel vary from 40% to 70%.

Figure 3: Characterization – Global warning potential (GWP 100 years) [kg CO_2 equiv.]



It seems to be relevant also to identify the processes in the life cycles of diesel and rapeseed biodiesel that have a major influence on GHG emissions.

LCA analysis gives significant results for both the production systems (diesel and rapeseed biodiesel) shown in Figures 4 and 5.

Figure 4: GHG emissions in every process of diesel life cycle

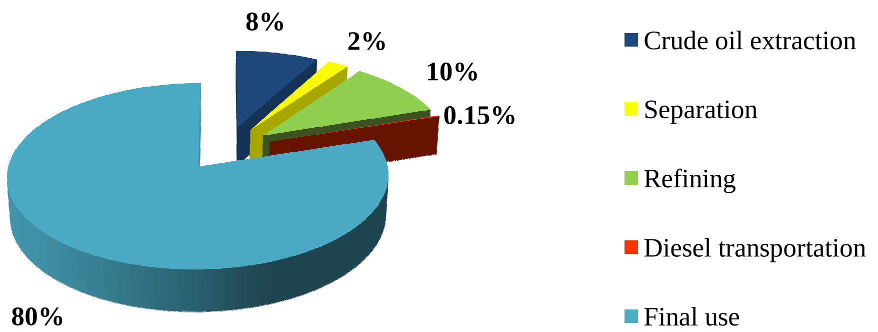
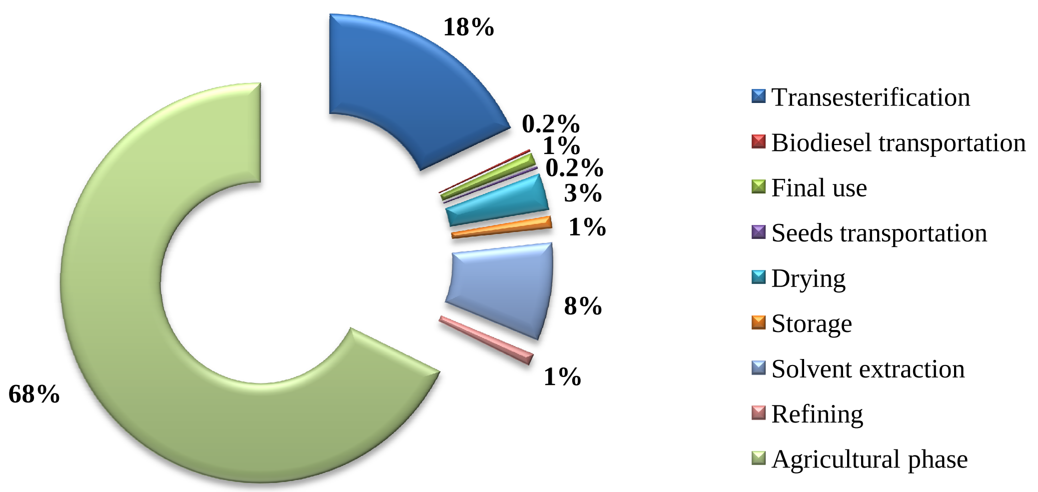


Figure 4 shows that the process which emits the most quantity of GHG is the Final use, that represents the combustion of diesel in a bus during a ride 1 km long, with a percentage of almost 80% of the total; it is followed with percentages much more lower by the Refining process (10.4%) and the Crude oil extraction process (8.1%). While the Separation phase and, in particular, the Diesel transportation phase seems to have a very marginal importance respect to the total.

Figure 5: GHG emissions in every process of rapeseed biodiesel life cycle



In the rapeseed biodiesel system, the process that causes major GHG emissions is the Agricultural phase for the production of rapeseeds (68%), which includes the emissions due to the production of nitrogen fertilizer (Figure 5). It is followed by the Transesterification process (18%) and by Solvent extraction (8%). All the other processes present much lower percentages of emissions.

The emissions released through combustion in a biofuel engine are similar to those in a diesel engine. However, the value of GHG emissions registered in the biodiesel system is lower because it has been assumed that tailpipe emissions of carbon dioxide are equal to the quantity of CO_2 absorbed by plants during the agricultural phase.

The use of biodiesel, instead of diesel, also entails advantages in terms of other gases emissions, such as a 40% reduction of carbon monoxide emissions (CO) and a 15-20% reduction for hydrocarbons emissions (HC).

Particulate emitted by biodiesel is less dangerous than the one emitted by diesel because it is made by bigger particles and it is more difficult to inhale. Moreover, biodiesel doesn't contain sulphur, avoiding problems of sulphur dioxide emissions (SO_2).

The only disadvantage connected to the use of biodiesel, is an increase of nitrogen oxides emissions (10-13%) with respect to diesel, which are one of the most dangerous compounds (CTI[4], 1999).

6. Conclusions

The GHG savings is one of the major indicators identified to assess the environmental sustainability of biofuels, respecting the provisions of EU Directive RED.

Economic operators could satisfy the sustainability criteria through certification which is able to assure a market advantage and to make them recognizable to the society.

The GHG calculation is necessary to implement a certification scheme and LCA tool represents one of the common methods used for this purpose.

The present study demonstrates that the use of rapeseed biodiesel represents a good opportunity for the achievement of the European goals in terms of GHG emissions reductions, considering a saving of emissions, measured in CO_2 equivalents, of 56% respect to conventional diesel.

However, this result does not take into account the negative environmental impacts caused by land use changes (direct and indirect), which would lead to a worsening of the budget of the greenhouse gases emissions, resulting in a decrease in the percentage of the estimated saving.

The estimated results of the analysis of the GHG emissions in every single process in both production systems, are similar to the conclusions that can be found in literature.

As Table 1 shows, in the conventional diesel life cycle, the estimated percentages per process (Figure 4) are similar to the ones reported in the study of Gerdes K. et al., 2008.

[4] Comitato Tecnico Italiano (CTI): http://www.cti2000.it

Table 1: GHG emissions in every production process of diesel

Life Cycle Stage	Diesel
Crude Oil Extraction	7%
Crude Oil Transport	1%
Refinery Operations	10%
Diesel Transport	1%
Combustion of Diesel	81%

Source: Gerdes K. et al., 2008

On the other hand, in the rapeseed life cycle, the process which causes the highest GHG emissions is the Agricultural phase (68%). This result is coherent with the results showed in the study of Mortimer (Mortimer et al., 2003), summarized in Table 2. Despite some differences, the results of this study are not so different to the ones obtained through the present LCA application.

Table 2: GHG emissions in every production process of biodiesel

Life Cycle Stage	Biodiesel
Agricultural phase	57%
Transestesterification	25%
Solvent extraction	8%
Drying	3%
Transportation	2%
Refininig	2%
Distribution	2%
Storage	1%

Source: Mortimer et al., 2003

High levels of GHG emissions in the agricultural phase depend mostly from the production and the use of nitrogen fertilizer. From a simulation with GaBi4, it resulted that total GHG emissions of the system including the production process of nitrogen fertilizer (0.48 kg of CO_2 equivalents) are almost twice the emissions of the same system without that process (0.26 kg of CO_2 equivalents).

Therefore, the saving percentage of GHG equal to 56%, could be improved intervening properly in this phase, for example limiting the use of nitrogen fertilizer, but also of other chemical products as pesticides, fungicides, herbicides ensuring a sustainable production process.

Moreover, it's relevant to underline, looking at these results, that the use of a biomass different from rapeseed, such as soybean, could avoid emission problems due to nitrogen fertilization (Pimentel and Patzek, 2005).

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