Comparative LCA of fossil fuels and biofuels use for transportation – A literature review

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Abstract

This literature review investigates LCA studies carried out by different authors to evaluate the environmental impact of the use of traditional fossil fuels compared to the use of biofuels in the transport sector. The global warming potential of the studied fuels is analysed along with other impact categories such as acidification and human toxicity potentials. In general, biofuels are beneficial with respect to fossil fuels as regards greenhouse effect, since they are produced from vegetable systems that have assimilated CO_2. However, the use of fertilizers and land areas, not needed for fossil fuels production, represent some of the main drawbacks of biodiesel and bioethanol life cycle. Both the similarities and differences among the results of the different LCA studies analysed are discussed in order both to highlight the most critical features that arise by comparing the environmental impact of traditional and alternative liquid fuels, and to assess if biofuels are an effective and sustainable alternative to diesel and gasoline for transportation in the next years.

1. Introduction

Transport sector has a tremendous impact on greenhouse gas emissions, since it consumes almost one third of the total annual energy produced worldwide, which, in turn, comes mainly from liquid fossil fuels (BPSTATS, 2019). Motor gasoline remains the largest transportation fuel, even if its share of total transportation energy consumption should decrease from 39% in 2012 to 33% in 2040, according to the IEO2016 projection. In the same period, the total transportation market share of diesel fuel should decline from 36% to 33% (EIA, 2016). Indeed, the transition to a more sustainable and low-carbon mobility is mandatory to reach the main goal set in 2015 with the Paris Agreement, namely, to limit temperature increase to 1.5 °C and mitigate climate change (Erickson et al., 2019). This transition is based on the gradual replacement of vehicles fuelled by gasoline and diesel with those fuelled by alternative fuels such as bioethanol and biodiesel, or with hybrid and electric vehicles.

Biodiesel and bioethanol represent the typical alternative fuels for diesel and gasoline, respectively, since they can be directly used in already existing diesel and Otto engines as pure liquid fuels or blended with traditional fuels. Briefly, biodiesel, obtained from vegetable oils through transesterification process, has a higher density and a greater cetane number than commercial diesel oil. Also, since it contains very small amounts of phosphorus and sulphur, SO_X emissions from biodiesel combustion are negligible. Moreover, no aromatic compounds are present in biodiesel, limiting its carcinogenic impact. On the other hand, bioethanol is typically produced from raw materials rich of sugar, i.e. sugar beets and sugarcane, or starch, i.e. potatoes and cereals. The process of bioethanol production from biomass includes several steps, such as feedstock production, milling, saccharification, fermentation, distillation and dehydration, that largely depend on the type of feedstock. Bioethanol has a low vapor pressure, lower than that of gasoline, guaranteeing fewer evaporative emissions. Since average biofuels composition has a considerable amount oxygen, their heating value is lower than that of fossil fuels. However, due to the presence of oxygen atoms, the octane number of bioethanol is higher than the one of gasoline, leading to a larger anti-knocking property of the biofuel and preventing mechanical and thermal loads on the engine.

The global supply of biofuels has increased by 4% from 2012 to 2015. Brazil and United States produced approximately 70% of the global biofuels supply, consisting primarily of sugarcane-based and corn-based ethanol, respectively. On the other hand, European Union

focused on biodiesel from oil waste and fats, soybean, rapeseed and palm oil. In Asia, the biofuel feedstock is centred on sugarcane, corn and wheat (Souza et al., 2018). Therefore, it is evident the ever-growing interest in the use of biofuels worldwide, even if there is a still open debate about the effectiveness of their exploitation for replacing traditional fuels. For instance, while the carbon dioxide emissions are dramatically reduced by using biofuels instead of fossil fuels, the use of fertilizers and the need of new infrastructures suitable to produce a large quantity of biofuels represent a drawback for their exploitations.
In this context, the here presented work consists in a literature review of some LCA studies focused on the environmental impact of different liquid fuels, with the aim of evaluating the actual potential of biofuels to become a sustainable alternative to fossil fuels.

2. LCA studies selection

In principle, performing a consistent comparison requires that all the selected LCA studies have similar goal and scope, functional unit, system boundaries, co-product allocation method and are carried out through the same methodology.

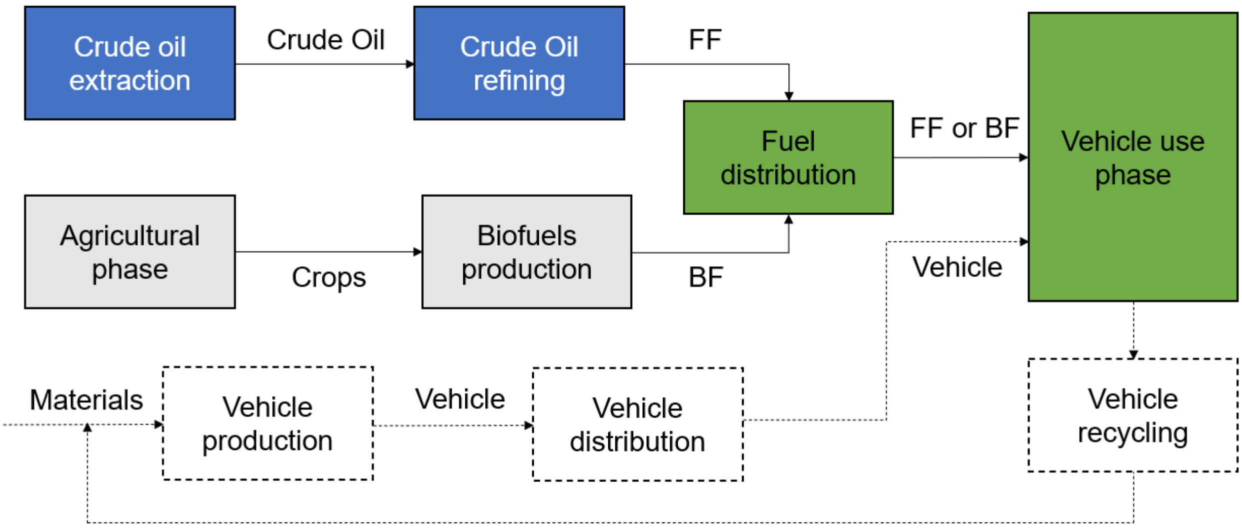

Figure 1: system boundaries of the selected LCA studies (Souza et al., 2018; Nanaki and Koroneos, 2012; De Nocker et al., 1998; Hou et al., 2011). FF indicates fossil fuels (diesel and gasoline); BF indicates biofuels (biodiesel and bioethanol). Dashed lines and blocks represent flows and processes considered only in (Souza et al., 2018).

In this literature review, four comparative LCA studies based on a cradle-to-grave attributional analysis on fossil fuels and biofuels are selected (Souza et al., 2018; Nanaki and Koroneos, 2012; De Nocker et al., 1998; Hou et al., 2011). These LCA studies were carried out with the goal of comparing the environmental performances of different type of fuels used in a "typical" middle-size vehicle, here considered as a vehicle able to use both fossil fuels and biofuels. The system boundaries considered in the three studies are similar, as schematized in Figure 1.

3. Environmental impact of biofuels and fossil fuels

3.1 Bioethanol vs gasoline

First of all, the comparative LCA study carried out by Souza in (Souza et al., 2018) is selected in order to assess the environmental impacts of gasoline and bioethanol from sugarcane used to run 1 km with a middle-size car in Brazil, by considering the cradle-to-grave product system shown in Figure 1. The analysis was conducted in accordance with the ISO 14040 standard (ISO 14040, 2006). Several impact categories were evaluated for three different scenarios:

- Scenario 1 consists in the use of internal combustion engine vehicle fuelled by gasoline.
- Scenario 2 consists in the use of internal combustion engine vehicle fuelled by a mixture of bioethanol (43.75%) and gasoline (56.25%).
- Scenario 3 consists in the use of internal combustion engine vehicle fuelled by bioethanol.

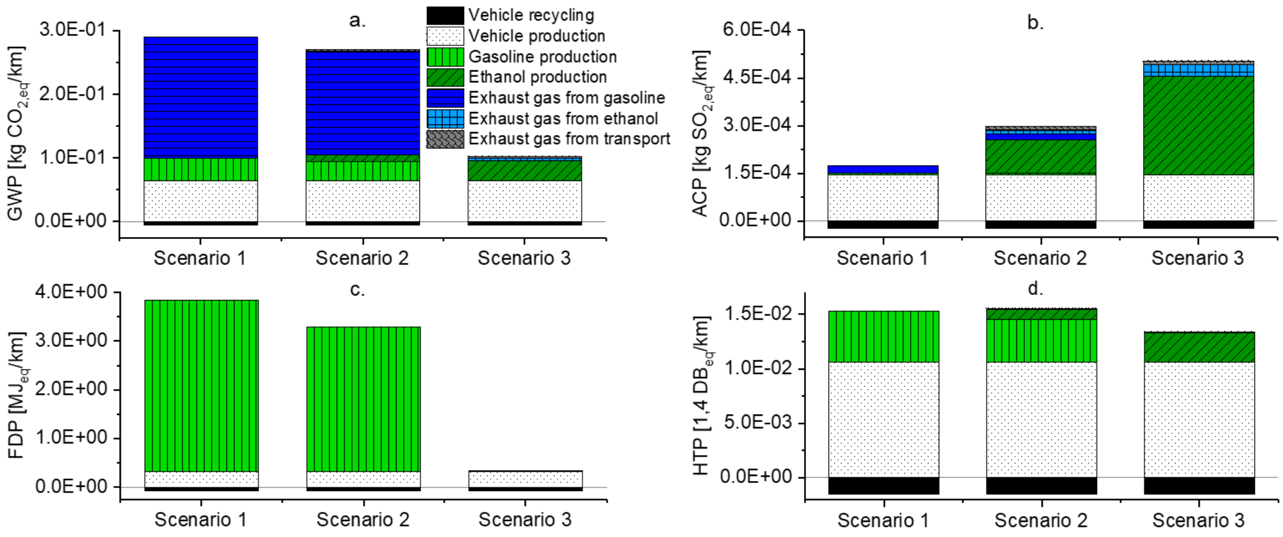

Figure 2: environmental and health impacts for the three different scenarios considered: a. Global Warming Potential (GWP); b. Acidification Potential (ACP); c. Fossil Fuel Depletion Potential (FDP); d. Human toxicity Potential (HTP). Adapted from (Souza et al., 2018).

In the life cycle inventory (LCI) carried out for gasoline production, inputs associated to facilities such as manufacturing, machinery and buildings were not included. On the other hand, in the agricultural phase of bioethanol life cycle, the use of fuels, fertilizers, herbicides, insecticides, lime and seeds is considered, as well as bioethanol production process, including sugarcane milling, juice clarification and treatment, fermentation, distillation, purification of ethanol and generation of steam and electricity used in the mill. The data used for the LCI of electricity production are retrieved from the Ecoinvent database.

The first impact category here analysed is global warming potential (GWP). The best environmental score is reached by Scenario 3 (9.72E-02 kg CO_{2eq}/km), even considering the whole CO_2 emissions of the sugarcane chain for bioethanol production. On the contrary, the worst case is represented by Scenario 1 (2.91E-02 kg CO_{2eq}/km) where pure gasoline is used, because of the large amount of CO_2 emitted from gasoline combustion. Indeed, the exhaust gases from gasoline are responsible for 65% and 60% of the total GWP impact of Scenario 1 and Scenario 2, respectively, as shown in Figure 2.a. Therefore, it is evident that the more the gasoline content in the fuel, the more the CO_{2eq}/km emissions. On the contrary, exhaust gases from ethanol have no relevance concerning greenhouse gas emissions. As regards vehicle production, it has a not negligible role in the total GWP impact; however, since it was assumed to use the same vehicle for the different fuels, the CO_{2eq}/km emissions related to this process does not vary in the three scenarios considered. For the same reason, the impact of vehicle production process is the same in the three scenarios for all the other impact categories analysed.

It should be noted that the sequence order of the environmental performance of GWP is the same for fossil fuels impact potential (FDP), as shown in Figure 2.c, since FDP refers to the use of non-renewable fuels such as petroleum, coal or natural gas during the life cycle of a product. Therefore, the use of pure fossil fuel in Scenario 1 leads, again, to the worst result (3.77E-01 MJ_{eq}/km), followed by Scenario 2 (3.22E-01 MJ_{eq}/km). Conversely, the renewable fuel used in Scenario 3 has a very high output-input energy ratio, which leads to the lowest FDP impact (2.57E-01 MJ_{eq}/km). However, ethanol production has a not negligible relative impact in this scenario, because of the diesel consumption in the agricultural phase.

Another impact category analysed is acidification potential, which derives from acidifying pollutants such as NH_3, NO_2 NO_x and SO_x reaching the atmosphere and reacting with water vapor to form acids. Figure 2.b shows the acidification potential of the three scenarios along with the relative impact of each process considered in the fuels life cycle. The worst case is represented by Scenario 3 (4.81E-04 kg SO_{2eq}/km). This behaviour is mainly due to the use of fertilizers and phosphate chemical products in the agricultural stage of the sugarcane production and because of acidifying substances emissions in the sugarcane bagasse combustion. Acidifying emissions are also related to combustion of fossil fuels, indeed the exhaust gases from gasoline are responsible for 11% of the total acidifying emissions in Scenario 1, while ACP related to fuel transportation is negligible. It should be noted that the vehicle production process is responsible for a major portion of the ACP impact category, because of the large consumption of metals, plastics and rubber contained in the vehicle body shell.

Finally, human toxicity potential (HTP) is investigated. It represents potential impacts on human health due to the emissions into the atmosphere of toxic species like benzene, dioxins, polycyclic aromatic hydrocarbons (PAHs) and particulate matter. Figure 2.d shows the potential impacts of vehicle technologies on HTP in terms of kg 1.4 dichlorobenzene equivalents per kilometre driven. Scenario 3 presents the best environmental result for the HTP impact category (1.19E-02 kg 1.4 DB_{eq}/km), followed by the Scenario 2 (1.40E-02 kg 1.4 DB_{eq}/km) and Scenario 1 (1.43E-02 kg 1.4 DB_{eq}/km). The vehicle production was found to contribute more than other processes to HTP due to toxic substances emissions. The ethanol production has a huge contribution to this category of impact for Scenario 3 due to the use of herbicides, pesticides and fertilizers in the agricultural activities. The exhaust gases emissions to air have low contribution to this category of impact, with a maximum around of 1%. The large amount of energy and materials saved by vehicle recycling and battery recycling will therefore significantly decrease emissions of substances that are harmful to human health, contributing to reduce by 10% in average the HTP.

3.2 Biodiesel vs diesel

On the other hand, the comparative LCA studies performed by De Nocker (De Nocker et al., 1998) and more recently by Hou (Hou et al., 2011)were selected in order to investigate the environmental impacts of biodiesel from biodiesel and diesel oil, required to drive 100 km in Belgium and to use 1 MJ of fuel in China, respectively . Similarly to the previous work analysed, these studies were carried out according to the ISO 14040 standard series (ISO 14040, 1997; ISO 14040, 2006), by considering the same system boundaries from the extraction of raw materials up to the combustion of the fuels in the car engine. Vehicle production and final transportation to the fuel station are not considered because the average distance and the means of transportation are the same for both fuels, while all other intermediary transportation steps are included.

The main impact categories evaluated for the selected biofuels compared to diesel oil are reported in Figure 3, where the fuel with the highest contribution to a specific environmental burden is indicated with the 100% bar.

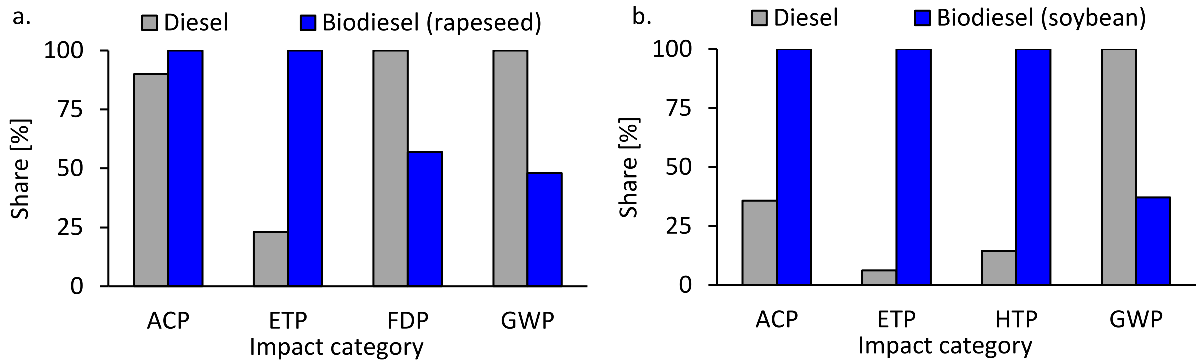

Figure 3: comparison between the environmental impacts of diesel and biodiesels adapted from a: (De Nocker et al. 1998) and b: (Hou et al., 2011). ACP: Acidification Potential; ETP: Eutrophication Potential; FDP: Fossil Fuels Depletion Potential; HTP: Human Toxicity Potential; GWP: Global Warming Potential.

The different feedstock-based biodiesels (and diesel oil itself), functional unit, specific processes and updated standards considered lead unequivocally to quantitative discrepancies in the results of the two studies. Nevertheless, it is possible to identify some analogies, such asfor the better score of biodiesels for GWP, since both soybean and rapeseed assimilates CO_2 during their growth, and their worse performances compared to diesel for ACP and ETP. This is due the use of fertilizers and herbicides employed in the agricultural phase, as shown in Figure 4, that provides an overview of the relative contribution of the different life cycle stages of biodiesel to the different impact categories considered. Firstly, it can be observed that the agricultural processes of the biodiesel chain contribute significantly to all impact categories. More specifically, the production and the use of fertilizers has an important contribution to greenhouse effect, while the crops growing process is responsible for almost 70% of biodiesel eutrophication load. Also, the use in the engine has a much larger impact to ACP and ETP rather than to GWP. Further comparisons between the results of the two studies become difficult and speculative, also because of the different specific processes classified to assess the environmental profile of the two biodiesels. For instance, the environmental loads of heat and power production (H&P) processes are classified only in (Hou et al., 2011). However, since they are almost fully related to oil extraction and esterification (O&E) processes according to the data of inputs in (Hou et al., 2011), it may be reasonable to compare H&P to O&E, which instead are accounted for in (De Nocker et al., 1998). Consistently, the sum of the contribution of H&P represents ~25-30% of the GWP, ~7% for ACP and ~2% for ETP in the case of soybean based rapeseed, just like that of O&E in the case of rapeseed-based oil. On the other hand, no comparisons can be accomplished for FDP and HTP considered only in (De Nocker et al., 1998) and (Hou et al., 2011), respectively. As shown in Figure 3, FDP of rapeseed-based biodiesel is lower than that of diesel since it is only related to the use of fossil fuel in the agricultural and production phases, while is null by definition when biodiesel is used in the engine. Conversely, the worse score of soybean-based biodiesel for HTP is due not only to chemicals production and use, not needed in the life cycle of fossil diesel, but also to steam and electricity production from coal combustion, which occupies a dominant role in primary energy supply in China and discharges much more heavy metals and hydrogen fluoride compared to oil.

It is interesting to compare the results of (De Nocker et al., 1998) with those obtained in (Nanaki and Koroneos, 2012), that considered the same functional unit, i.e. 100 km driven by a middle-size car, and very similar system boundaries, as schematized in Figure 1. The recycling and valorisation of by-products from transesterification, i.e. glycerol, is also considered, unlike the previous studies analysed.

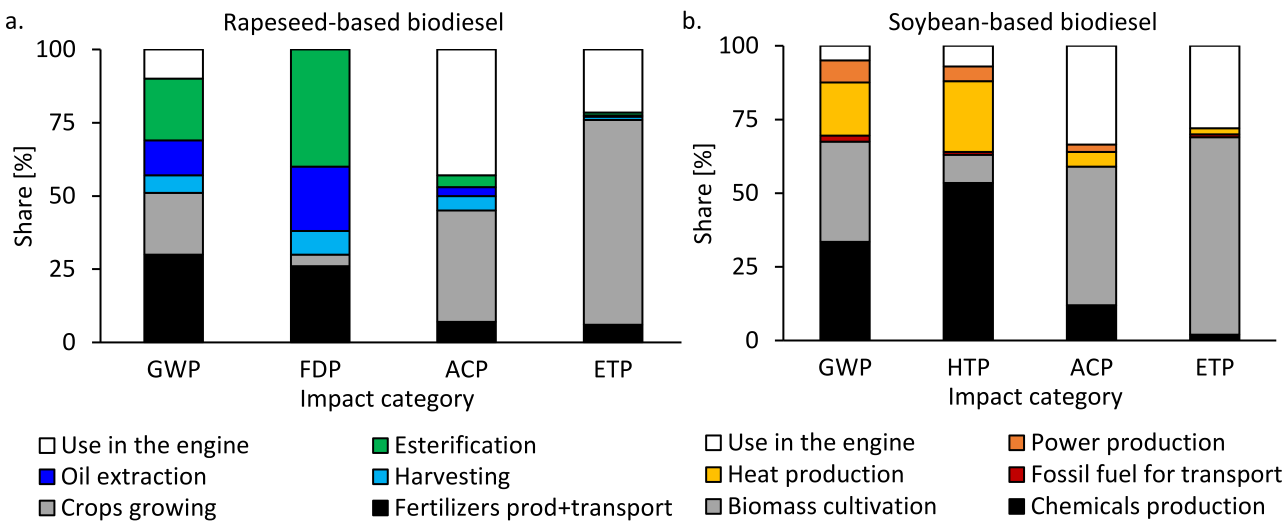

Figure 4: environmental profile of biodiesels. Adapted from a: (De Nocker et al. 1988); b: (Hou et al., 2011).

The methodology used to carry out the analysis is the same in the two LCA comparative studies. Biodiesel from rapeseed is again the selected alternative fuel to diesel and its environmental performances are also compared to the ones of gasoline. Different engines and thus vehicles must be considered, in principle, when comparing the use of diesel with gasoline. However, it is assumed that the production process of a vehicle fuelled by diesel or biodiesel has a similar impact than that of a vehicle fuelled by gasoline.
The environmental burdens of the different automotive fuels evaluated in (Nanaki and Koroneos, 2012) are reported in Figure 5. Again, the fuel with the highest contribution to a specific environmental effect is indicated with 100% bar.

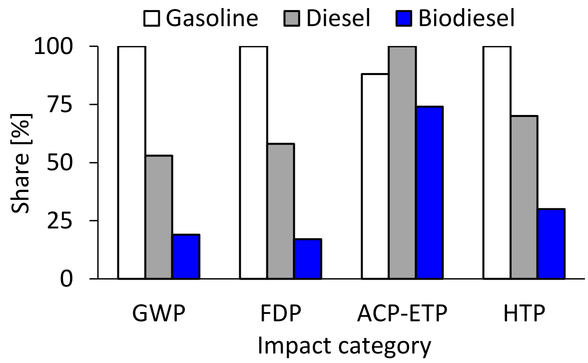

Figure 5: comparison of impact categories of different fuels. Adapted from (Nanaki and Koroneos, 2012)*.*

The better score reached by biodiesel for global warming (GWP) and fossil fuels (FDP) potentials with respect to diesel agrees with the results obtained in (De Nocker et al., 1998). However, Nanaki (Nanaki and Koroneos, 2012) computed a better score of biodiesel also for acidification-eutrophication potential (ACP-ETP), unlike De Nocker (De Nocker et al., 1998). This difference can be attributed to the fact that only in (Nanaki and Koroneos, 2012) the valorisation of glycerol as by-product is taken into account. Expanding the comparison to gasoline, it is observed that gasoline has an impact higher than diesel in terms of global warming and fossil fuels potentials, because of the higher emissions of CO_2 (16.6 kg/100km for gasoline and 13.4 kg/100 km for diesel). Conversely, NO_x emissions are higher if diesel (25.6 mg/100km) is used instead of gasoline (10.2 mg/100km). Higher NO_x emissions from diesel combustion also bring to worse inorganic respiratory effects than gasoline. However, the much larger emissions of polycyclic aromatic hydrocarbons (PAHs) due to gasoline combustion lead to the corresponding higher human health potential compared to diesel.

4. Discussion of the results

The results of the different LCA studies analysed pointed out the benefits of using bioethanol instead of gasoline as well as biodiesel instead of diesel in terms of global warming potential (GWP) and fossil fuels potentials (FPD). On the other hand, the agricultural phase necessary to grow and harvest biofuels leads to worse biofuels scores in human health (HTP) acidification (ACP) and eutrophication (ETP) potentials because of the use fertilizers and herbicides.
However, comparing and generalizing the global environmental impact of different fuels is a very difficult task, since it intrinsically implicates subjective evaluations. In this context, one of the most critical aspect of a comprehensive comparison between different products is the normalization and weighting procedures adopted, which can lead to completely different results, as shown in Figure 6. In (De Nocker et al., 1998), the environmental profile of the two compared fuels is normalized to the total impact of all Belgium economic activities in 1997 and the weighting was carried out by considering only the greenhouse effect, acidification, eutrophication, while no details about the normalization and weighting procedures adopted are provided in (Nanaki and Koroneos, 2012). The better score computed for diesel compared to biodiesel in (De Nocker et al., 1998) could be explained by the fact that two of the three impact categories weighted mostly depend on the agricultural phase, that is present only in biodiesel life cycle. Since the impact categories selected for the weighting in the two comparative LCA are different, it is reasonable to compute such different results.

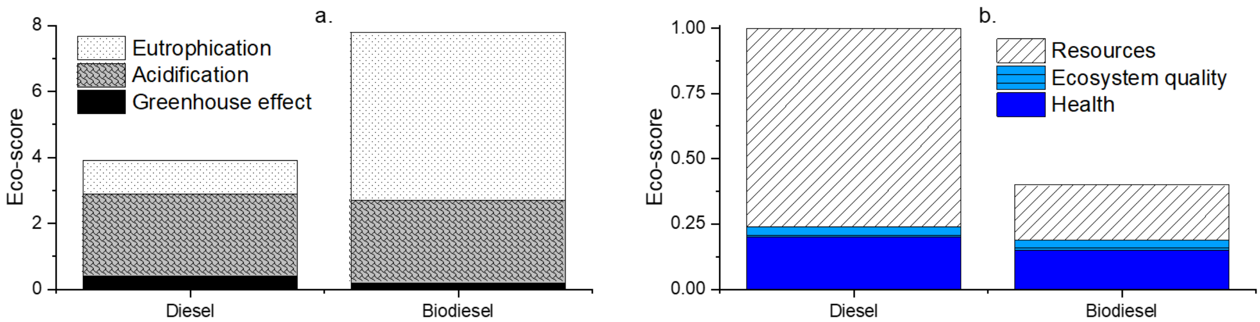

Figure 6: environmental impact after weighting in a. (De Nocker et al., 1998) *and b.* (Nanaki and Koroneos, 2012).

Concerning biofuels, their environmental impact depends on several factors, like the raw materials used, the type of soil and weather. Additionally, other significant factors are the past land-use, the production of by-products, the technological process path as well as the relative use of the end fuel either in a mixed or in a pure mode. For instance, a limit of the comparative LCA studies here analysed, hence of this report itself, is that land use change is not accounted for. As highlighted by Hou et al., it may be a source of significant additional greenhouse gases emissions from soils. According to the work of Fargione et al. direct and indirect land use change in the life cycle of biofuels may be responsible of much more CO_2 emissions than CO_2 reduction owing to displacing fossil fuels with biofuels.
Finally, it must be mentioned that if the life cycle assessment for a specific product is extended also to the social (S-LCA) or economic (LCC) life cycle assessments, the results in terms of most sustainable product final use can vary. As an example, the results of the case study analysed in (Sobrino et al., 2011) about the evaluation of the potential applications of citrus waste show that producing electricity is more convenient than producing bioethanol, since the first process saves more oil and is more profitable from the economic point of view than producing the biofuel.

5. Conclusions

The aim of this literature review was to investigate the environmental impact of biofuels compared to traditional liquid fuels used in the transport sector, which has been dominated by diesel and gasoline in the last decades. All the LCA studies here selected were characterized by similar features. They were carried out with the aim of evaluating the environmental performances of biofuels compared to liquid fossil fuels, by using the same methodology, i.e. according to the ISO 14040 standard, and by considering a cradle-to-grave product system. Specifically, raw material extraction, fuel production and use in the car engine were considered in the life cycle of all the fuels analysed. The results of the comparative LCA studies investigated show that biofuels are beneficial with respect to fossil fuels as regards greenhouse effect, since produced from vegetable systems that have assimilated CO_2. Also, the computed human health potential of gasoline and diesel was higher than the one related to bioethanol and biodiesel, respectively. This is mainly due to the lower emissions of carcinogenic compounds coming from biofuels production. However, the use of fertilizers and herbicides used in the agricultural phases in the biofuels life cycle makes the acidification and eutrophication potentials of bioethanol and biodiesel higher than that of the corresponding fossil fuel. Therefore, reducing the environmental impact related to crops cultivation while developing new technologies aimed to transform agricultural and food wastes into renewable fuels on an industrial scale, will definitively make biofuels an effective and sustainable alternative to fossil fuel in the future.

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