Life cycle assessment of biofuels production from biomass

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June 2019

Abstract

The global warming and climate change effects that have been observed since the second half of the 20th century are directly related to the burning of fossil fuels, particularly in the transport sector. Continued emissions of greenhouse gases will aggravate the global warming effects and will cause lasting changes in all components of the climate system.

This study consisted of a life cycle analysis of the production of biofuels for transport, using biomass as feedstock and within the context of the European Union. The production processes were modeled based on the published literature, were implemented in the SimaPro software and were simulated with three different methods of analysis. More specifically, this study focused on the production of syndiesel, methanol, DME, ethanol, FAME and biodiesel through technologies such as wood gasification, black liquor gasification, hydrolysis and fermentation, transesterification, Soxhlet extraction and supercritical extraction using raw materials such as farmed wood, wood residues, straw, used cooking oil, animal fat and microalgae. The results show that syndiesel, methanol and DME are a potential alternative to conventional fossil fuels, particularly when produced by gasification of black liquor and using wood residues as feedstock. The production of ethanol showed the biggest impacts and is not environmentally viable. For the analysis methods used, the production of FAME presented somewhat contradictory impacts and is therefore no conclusions can be made. Technologies for producing biodiesel from microalgae need further investigation.

Keywords: biofuel, biomass, life cycle, greenhouse gases

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) states on its last report on climate change (AR5) that global warming is unequivocal and that many of the changes that have occurred since the middle of the 20th century have had no precedent over decades or even millennia. It also concludes that the evidence of the anthropogenic impact on climate change has increased compared to its previous report (AR4) and concluded that human influence has been the dominant cause of the observed warming.[1]

The increase in greenhouse gas emissions over the last decades is directly related to the increase in primary energy consumption and the burning of fossil fuels [2]. Currently the OECD countries still are responsible for the biggest share of this energy use and emissions [2], however this tendency is changing [3].

In the European Union the transport sector accounts for one third of the total final energy consumption [4]. To face this situation the EU has been issuing legislations to encourage the use of biofuels, like the Renewable Energy Directive (RED II) that sets a target for the use of advanced biofuels, requiring a minimum participation of 1,5% by 2021 that should increase gradually to 6.8% by 2030 [5]. Besides that, the use of biomass has been steadily increasing for the past 20 years because of its potential and availability [4]. Based on these factors the consumption of advanced biofuels must increase significantly from 2020.

2. LCA methodology

Life Cycle Assessment (LCA) is a methodology that performs the environmental evaluation of a product or service throughout its life cycle, from the extraction of raw materials to the final disposal of the product and waste treatment. The transparency and reliability of the LCA methodology is ensured by the fact that it is standardized by the International Organization for Standardization (ISO), namely by the standards ISO 14040: 2006 [6] and ISO 14044: 2006 [7]. These two standards define and describe the LCA methodology in four phases:

- Definition of the goal and scope
- Life Cycle Inventory (LCI)

- Life Cycle Impact Assessment (LCIA)
- Interpretation

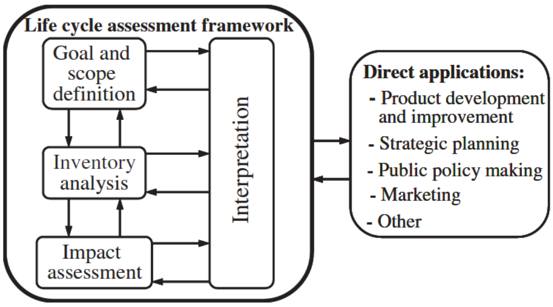

Figure 1 - Stages of an LCA (ISO 14040: 2006) [6]

The first stage consists of defining the purpose of the study, determining what type of outcome is sought, establishing the limits of the system, defining the functional unit and assuming the necessary assumptions. The functional unit is a key element of the LCA and it is crucial that it is clearly defined. It is a measure of the function of the system under study, whose purpose is to provide a reference unit that permits the entrances and exits of the processes to be related to each other and to provide a reference for which the inventory data is normalized. This reference is necessary to ensure comparability of the LCA results, particularly when several systems are being evaluated, to ensure comparisons are made on a common basis.[6]

The LCI phase is an iterative process that involves the collection of data and calculation procedures that allow to quantify the relevant inputs and outputs of the various processes of a system. Due to the extensive data collection required, this is usually the most time consuming step compared to the other phases of an LCA. After the data collection, calculation procedures are necessary so that each process is modeled along the same line of thought and in coherence with the functional unit of the system being studied. Most processes generate more than one output, also producing co-products that can be recycled and by-products that need to be discarded. In these situations, it is necessary to consider the use of allocation procedures so that in each process there are no outputs that aren't accounted for in the impact assessment phase.[6]

The LCIA phase purpose is to evaluate the relevance of the possible environmental impacts from the information collected and processed in the LCI phase. It involves associating inventory data with categories and indicators of environmental impacts with specific meanings, in order to provide information that can be analyzed in the interpretation phase. The impact assessment phase is defined by a series of elements with a specific order, some of which are mandatory and others are optional. The first element is the selection of impact categories, category indicators and characterization models and should be duly substantiated and consistent with the purpose and scope of the LCA. The next step is called classification and consists of assigning the results of the inventory analysis to certain impact categories. The last mandatory element is the characterization phase and consists of converting the results of the inventory analysis into specific units (category indicators) through characterization factors, followed by aggregating the results of the category indicators into the corresponding impact categories. The optional elements are standardization, grouping and weighting. Standardization consists of calculating the magnitude of the results of the category indicators against a reference value known as the normalization factor. The grouping consists in ordering the impact categories according to their relevance. In the weighting stage the results of the category indicators or standardized results, depending on the relative importance of the impact categories considered, are converted and aggregated into a single final score representing the total environmental impact.[6] [7]

The last phase of an LCA is when the results of the inventory analysis and the impact are considered together and subjected to interpretation. This step should reflect the fact that the results of the impact assessment are based on a relative approach and are merely an indication of the potential environmental effects.[6]

Due to its complexity, in most cases it is completely impractical to perform a life cycle analysis manually. For this reason, performing an LCA is usually done with the help of specialized software to perform all the necessary calculations.

3. Study methodology

To perform an LCA it is necessary to model the life cycle of a product, service, or system. It is important to understand that a model is a simplification of an extremely complex reality, which implies the distortion of reality to a certain extent. One of the major challenges in performing an LCA is to develop the model so that the simplifications and distortions influence results as little as possible. A good starting point for trying to mitigate this problem is to carefully define the purpose and scope of the study.

The purpose of this study was to perform an LCA of the production of several biofuels, in order to compare the environmental impacts caused by them with the impacts of conventional gasoline and diesel production. For the system boundaries a Cradle-to-Gate approach was defined, that is, the entire biofuel production process was evaluated from the extraction of raw materials up to the vehicles tanks. Usually fuels are quantified in terms of volume, however the fuels studied have different energy densities and the comparison would not be direct if the studied processes were expressed in a unit of volume. For this reason, the production of 1 MJ of fuel was considered as the functional unit used for all processes.

The SimaPro 8 software was used as an assistance to perform the LCA. The database used for the inventory analysis was the "ecoinvent 3 - allocation, default - unit". Impact assessment was done using the "ReCiPe Midpoint (H), Europe ReCiPe H, Version 1.11" and "ReCiPe Endpoint (H), Europe ReCiPe H / H, Version 1.11" methods.

All the processes studied are organized in three stages: production, transformation and transport of raw material; transformation of raw material into biofuel; distribution of biofuels. Their composition can be seen in table 1.

Table 1 - Processes composition and listing

Raw material	Tecnology	Biofuel	Process #
Farmed wood	Wood gasification	Syndiesel	1
		Methanol	2
		DME	3
Waste wood		Syndiesel	4
		Methanol	5
		DME	6
	Black liquor gasification	Syndiesel	7
		Methanol	8
		DME	9
Straw	Hidrolisys and fermentation	Ethanol	10
Used oil	Transesterification	FAME	11
Animal fat			12
Algae	Soxhlet extraction	Biodiesel	13
	Supercritical extraction		14

The processes were structured based on the reports *"Definition of input data to assess GHG default emissions from biofuels in EU legislation, Version 1c – July 2017"* [8] *and "Solid and gaseous bioenergy pathways: input values and GHG emissions"* [9] and in the publication *"A biorefinery from* Nannochloropsis sp. *microalga – Energy and CO2 emission and economic analyses"* [10].

The data for the processes that produce biodiesel was obtained in laboratory on a very small scale. For the sake of consistency, the distribution of biodiesel from microalgae was not considered in order to avoid that these processes were disproportionately related.

4. Single score analysis

The simplest and most direct method to compare the environmental impacts of the processes is the single final score, which is a simplification of the endpoint method. The single final score calculation uses the normalized results of the endpoint analysis to make a linear weighted sum between the three endpoint damage categories. The weighting coefficients were applied according to the hierarchical / average (H / A) perspective, which is a moderate perspective and generally accepted by the scientific community [11]. The three damage categories Human Health, Ecosystems and Resources were assigned weighting coefficients with a weight of 40-40-20% respectively. The single final scores for the processes studied are shown in figure 2. Processes 13 and 14 are not shown because they have much higher impacts than the other processes and overshadow their results.

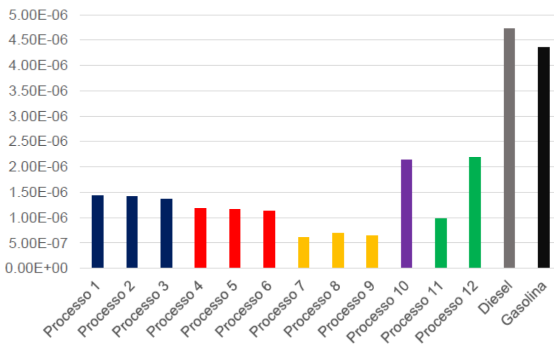

Figure 2 - Single final scores of the processes studied

Processes 1, 2 and 3 present the biggest impacts of all the processes that use wood as raw material. From this group, process 1 (syndiesel) has the greatest impact, followed by process 2 (methanol) and process 3 (DME). The group of processes 4, 5 and 6 has slightly less impacts than the previous group. Process 4 (syndiesel) has the highest impact, followed by process 5 (methanol) and process 6 (DME). Processes 7, 8 and 9 are the ones with the lowest impacts, with process 7 (syndiesel) having the lowest single final score, followed by process 9 (DME) and at last process 8 (methanol). Process 10 (ethanol) has a much higher impact than the general average. As for FAME production processes, process 11 presents a very low single final score, contrary to process 12 that shows the greatest impact of all the biofuels studied. Diesel and gasoline have the biggest impact among all processes, with diesel showing a single final score slightly higher than gasoline.

5. Endpoint analysis

The wide variety of raw materials, production technologies and types of biofuels of the 14 processes studied results in a certain complexity in the way results analysis can be performed, particularly in the comparison of environmental impacts between different processes. For this reason, the processes were analyzed in specific groups:

- Processes 1, 2 and 3
- Processes 4, 5 and 6
- Processes 7, 8 and 9
- Process 10
- Processes 11 and 12
- Processes 13 and 14
- Comparison with diesel
- Comparison with gasoline

5.1 Processes 1, 2 and 3

Processes 1, 2 and 3 respectively represent the production of syndiesel, methanol and DME from farmed wood and wood gasification. In figure 3 it is possible to observe that the effects are more noticeable in the Resources category with approximately the same proportion for the three processes. Compared to these values, the weight in the category Human health is about half and in the category Ecosystems is about a third. Although the difference is not significant, process 1 (syndiesel) is the one that represents the major environmental impacts associated with it, followed by process 2 (methanol) and last of process 3 (DME).

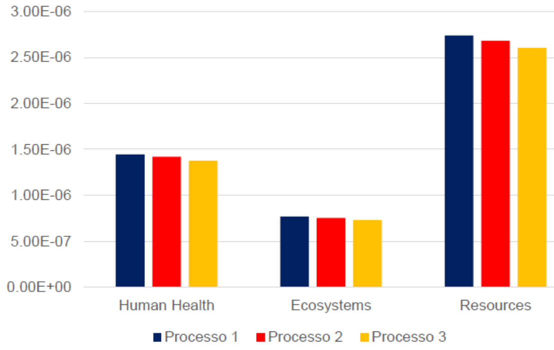

Figure 3 - Normalized endpoint results for processes 1, 2 and 3

5.2 Processes 4, 5 and 6

Processes 4, 5 and 6 respectively represent the production of syndiesel, methanol and DME from waste wood and wood gasification. Analyzing figure 4, the effects are more noticeable in the Resources category, roughly the same proportion for the three processes. Compared to these values, the weight in the Human health category is about half and in the Ecosystems category it is about one third, much like the results of processes 1, 2 and 3. Differences between the processes are not very relevant. Process 4 (syndiesel) has the highest impacts, followed by process 5 (methanol) and process 6 (DME).

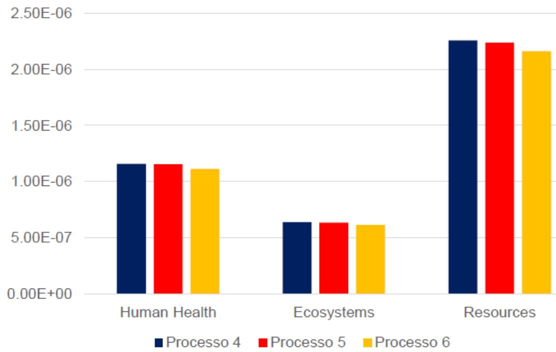

Figure 4 - Normalized endpoint results for processes 4, 5 and 6

5.3 Processes 7, 8 and 9

Processes 7, 8 and 9 respectively represent the production of syndiesel, methanol and DME from waste wood and black liquor gasification. In figure 5 it's possible to observe the results of these three processes, once again the proportions between them remain approximately constant. The category with the greatest impacts is Resources, followed by the

Human health category with about half of the impacts and by the Ecosystems category with approximately one-third of the impacts of the first category. Contrary to what happened in the analysis of processes 1 to 6, in this case the differences between the impacts are a little more expressive. Process 8 (methanol) is responsible for the greatest environmental impacts, followed by process 9 (DME) and lastly by process 7 (syndiesel). In contrast to processes 1 to 6, in which syndiesel production processes (processes 1 and 4) were the ones with the greatest impact, in this case the syndiesel production process (process 7) was the one that showed the most reduced impacts. This is due to the fact that in processes 7, 8 and 9, because of the black liquor gasification, the amount of raw material used is lower and the impact weight of the biofuels distribution remained constant. In the case of process 7 (syndiesel) this was sufficient to show total impacts lower than process 8 (methanol) and process 9 (DME), since the syndiesel is the one with the highest energy density and consequently has the lowest distribution impacts.

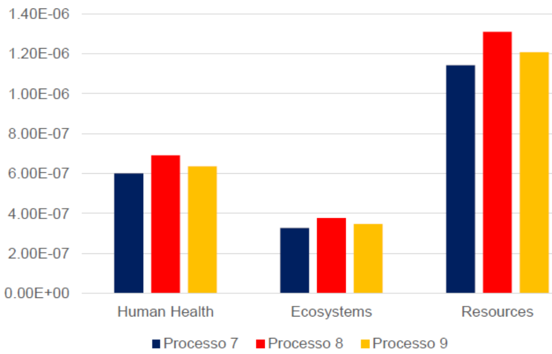

Figure 5 - Normalized endpoint results for processes 7, 8 and 9

5.4 Process 10

Process 10 represents the production of ethanol using straw as the raw material and through hydrolysis and fermentation. In figure 6 we can observe that the impact of this process is more noticeable in the Resources category, followed by Human Health category with just over half the impact of the first. Less significant is the Ecosystems category, which has an impact almost four times lower than the impact of the most relevant category. For all three categories the raw material used represents about 70% of the total impacts, the transformation of straw into ethanol through hydrolysis and fermentation accounts for approximately 20% and the ethanol distribution influences only about 10%.

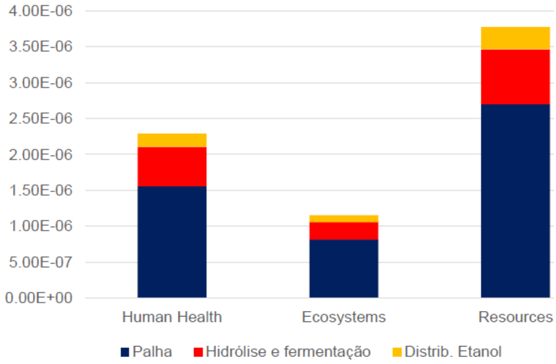

Figure 6 - Normalized endpoint results for process 10

5.5 Processes 11 and 12

Processes 11 and 12 respectively use used oil and animal fat as feedstock, which are used for the production of FAME by transesterification. In figure 7 we can see the most relevant difference is in the Resources category, where process 12 has an impact more than twice as high as process 11. This difference is caused by the raw material used, since in the transesterification and distribution phases of FAME processes 11 and 12 are exactly the same. Much less relevant are the Human Health and Ecosystems categories, with both impacts of process 12 being greater than those of process 11.

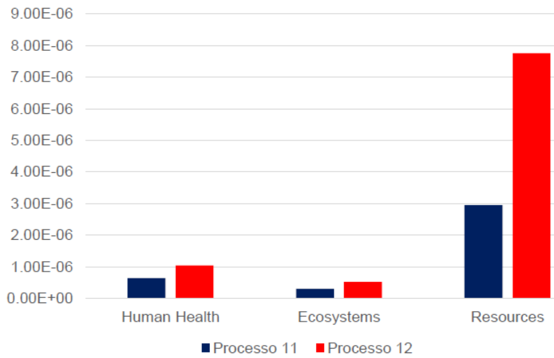

Figure 7 - Normalized endpoint results for processes 11 and 12

5.6 Processes 13 and 14

Processes 13 and 14 represent the production of biodiesel from microalgae through Soxhlet extraction and supercritical extraction respectively. It should be recalled that for the sake of consistency with the other processes studied, both processes do not include biodiesel distribution because they are based on a laboratory-scale study. The most relevant observation to be made from figure 8 is that the results are of an order of magnitude far superior to all other processes analyzed so far. This was already expected because of the reduced scale on which the processes were modeled. The Resources category is where the impacts are most relevant, closely followed by the Human Health category. With about half of the impacts of the previous two is the Ecosystems category. In all three categories, process 13 has the lowest impacts. As processes 13 and 14 are the same except for the technology used to transform microalgae into biodiesel, we can conclude that Soxhlet extraction has fewer impacts than supercritical extraction.

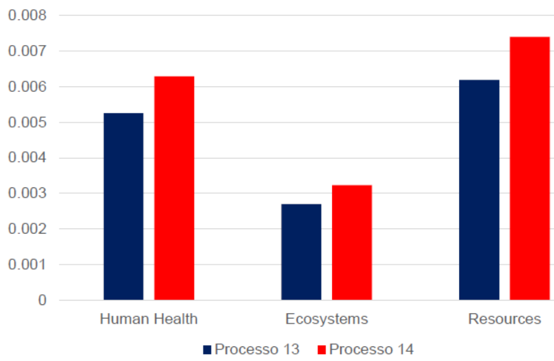

Figure 8 - Normalized endpoint results for processes 13 and 14

5.7 Comparison with diesel

The biofuels studied in this work that can replace conventional diesel are syndiesel, DME, FAME and biodiesel. For each type of biofuel, only the processes with the lowest impacts were compared with the diesel. In the case of syndiesel it was process 7 that had smaller impacts, for DME it was process 9 and for FAME it was process 11. Process 13 (biodiesel) was not compared because its impacts are of an order of magnitude a lot higher. In Figure 9 the results of the endpoint analysis can be visualized for these processes. The greatest contrast is in the Resources category, where diesel has a far greater impact than other processes, including its own impacts on the other two categories. Also, in the categories Human Health and Ecosystems diesel has bigger impacts than the other processes, however the difference between them is not as noticeable.

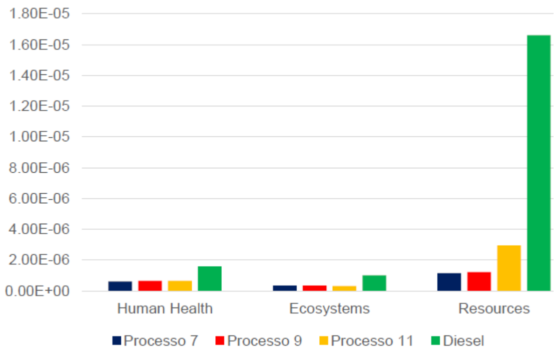

Figure 9 - Normalized endpoint results for processes 7, 9, 11 and diesel

In the previous figure the results of processes 7, 9 and 11 were practically indistinguishable due to the inadequate scale needed to visualize the enormous impacts caused by diesel. For this reason, the same graph but without the diesel was designed to allow a more detailed analysis of the other processes, as can be seen in figure 10. Again, the greatest contrast occurs in the Resources category, in which process 11 presents an impact more than twice as high as the impacts of processes 7 and 9. In this category, although very close, process 7 has a slightly lower impact than process 9. In the Human Health category, although very similar, process 11 have a higher impact on processes 9 and 7, in that order. However, in the Ecosystems category the same is no longer true, since the greatest impact is caused by process 9, followed by process 7 and last of process 11, although the impacts do not differ much between them.

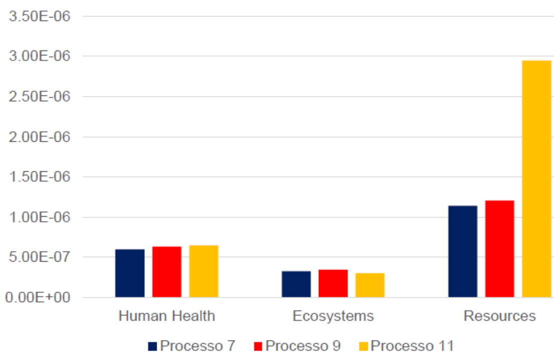

Figure 10 - Normalized endpoint results for processes 7, 9 and 11

5.8 Comparison with gasoline

The biofuels in this work that can replace conventional gasoline are methanol and ethanol. Only one process was studied for the production of ethanol, in this case process 10. However, there were three processes for the production of methanol, of which only process 8 entered this comparison because it was the one with the lowest impacts. Figure 11 shows the endpoint analysis results for these processes. The greatest contrast is visible in the Resources category, in which gasoline has a far greater impact than other processes and its own impacts on the other two categories. In the Ecosystems category, the impacts of gasoline and process 10 are relatively balanced and are higher than the impact of process 8. In the Human Health category, process 10 has the greatest impact, being slightly higher than gasoline and much higher than process 8.

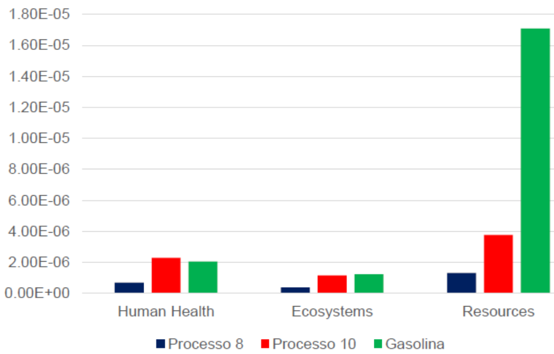

Figure 11 - Normalized endpoint results for processes 8, 10 and gasoline

6. Midpoint analysis

Only the processes that showed the least impacts on the previous single score and endpoint analysis were compared to the conventional biofuels with the midpoint analysis.

6.1 Comparison with diesel

The results of the midpoint impact analysis for the processes 7, 9, 11 and diesel are represented in figure 12. The impact of diesel in the natural land transformation category is so much higher than the impacts in the remaining categories that it completely eclipses them. In the fossil depletion category, although in a much smaller proportion, it is also much higher than the impacts of the remaining processes.

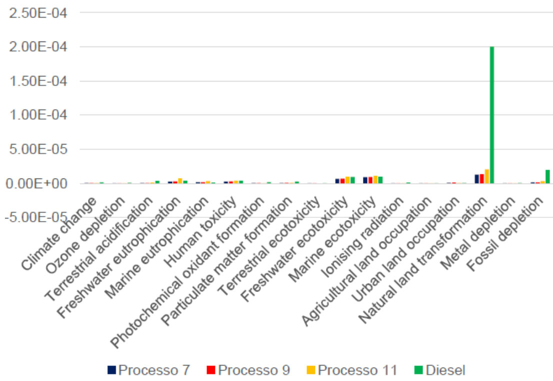

Figure 12 - Normalized midpoint results for processes 7, 9, 11 and diesel

In order to allow a more detailed analysis, the results of the midpoint impact analysis for the processes 7, 9, 11 and diesel are shown without the categories natural land transformation and the fossil depletion in figure 13. In the four most relevant categories, process 11 is the one with the greatest impacts, followed by diesel, process 9 and process 7, in this order. In the marine ecotoxicity category the impacts are relatively balanced, with only process 11 having a somewhat more pronounced impact. In the freshwater ecotoxicity category the processes 11 and diesel show impacts with considerable differences in relation to processes 7 and 9. With similar proportions but with less than half of the impacts of the previous category is the category human toxicity. In the category freshwater eutrophication is where the greatest contrast is verified, with process 11 having a much higher impact than the others. Less relevant but still interesting to analyze are the categories marine eutrophication and urban land occupation, in which diesel has the smallest impacts. In all other categories diesel has a clearly superior impact in relation to the other processes.

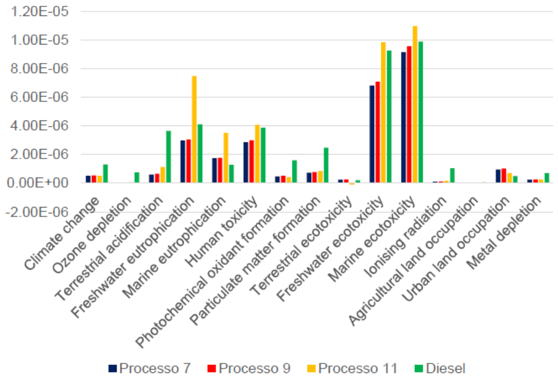

Figure 13 - Normalized midpoint results for processes 7, 9, 11 and diesel without the categories natural land transformation and fossil depletion

6.2 Comparison with gasoline

The results of the midpoint impact analysis for the processes 8, 10 and gasoline are represented in figure 14. The impact of gasoline in the natural land transformation category is so great that it makes it difficult to see the impacts of the other processes in the other categories, making it difficult to compare them.

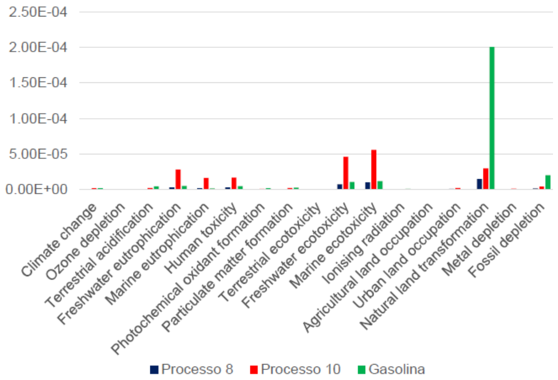

Figure 14 - Normalized midpoint results for processes 8, 10 and gasoline

In order to overcome the scale problems in the previous figure, the results of the midpoint impact analysis for the processes 8, 10 and gasoline are represented in figure 15 without the natural land transformation category. With the exception of the fossil depletion category, in which gasoline has the greatest impact, it can be observed that in all relevant categories process 10 has impacts much higher than process 8 and gasoline. This is most noticeable in the marine ecotoxicity category, closely followed by the category of freshwater ecotoxicity. The same trend is also found in the categories freshwater eutrophication, marine eutrophication and human toxicity but less relevant in the overall picture. It should be noted that in all categories, process 8 has the lowest impacts.

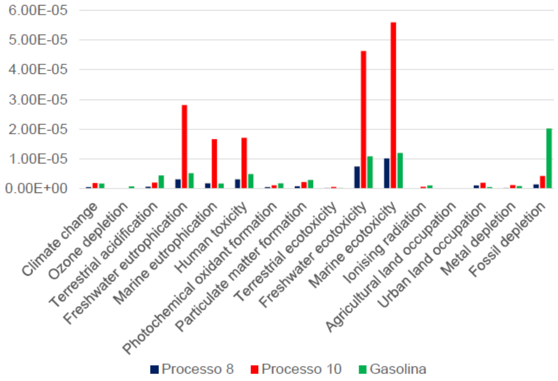

Figure 15 - Normalized midpoint results for processes 8, 10 and gasoline without the category natural land transformation

7. Conclusions

Of all the processes studied in this study, the three processes that are produced through the black liquor gasification and that use residual wood as the raw material were the ones that had the lowest impacts in all three methods of analysis (midpoint, endpoint and final score only). Of these processes, the one for syndiesel production has the smallest impacts, followed by the process of DME and with greater impacts was the methanol process. However, the differences in impacts between these processes are not substantial and all appear to be environmentally viable. It has been found that wood gasification processes account for about twice the impacts of those using black liquor gasification and also that processes using wood grown for feedstock have slightly higher impacts than those using wood waste. In all these processes the most significant part of the impacts was caused by the raw material used, and the distribution of biofuels was less relevant. In the comparison of single final scores, all these processes had a much lower impact than diesel and gasoline, and the same occurred in almost all relevant categories of the midpoint method. However, due to a simplification in gasification modeling, all these processes showed results lower than the real impacts. However, this is unlikely to have significantly influenced the results.

Of all the studied processes, the process for ethanol production showed the greatest impacts, taking into account the three methods of analysis used. The most significant portion of the impacts caused is due to the raw material used, in this case the straw. In the comparison with gasoline, in the midpoint analysis it presented much higher impacts in almost all the relevant categories. In short, the ethanol produced using straw as the raw material has not proved to be a particularly viable alternative in environmental terms.

The FAME production processes presented quite different results. The use of used oil as a raw material was one of the processes that presented smaller impacts, after the processes that use wood and gasification. However, in the midpoint analysis this one presented slightly higher impacts to diesel in several categories, and for this reason its viability as an alternative to diesel is not clear. The process that uses animal fat as the raw material was, in general, the one that presented the second biggest impacts of all the processes studied. According to the results obtained, the FAME production through this process does not appear to be viable, even more so because FAME production from used oil is a much better alternative.

The processes for biodiesel production from algae presented totally unreasonable impacts. This was already expected, given the very reduced scale at which these processes were modeled. The objective in analyzing them in this work was not to make a comparison with other fuels, but rather to compare them with each other. The conclusion to be drawn is that the production of biodiesel using Soxhlet extraction has fewer impacts than using supercritical extraction.

References

[1] IPCC, “Climate Change 2013: The Physical Science Basis. Summary for Policymakers,” *IPCC Fifth Assess. Rep.*, pp. 1–29, 2013.

[2] G. S. Lakshmi, G. S. Rathore, R. Sharma, A. Anand, S. Sharma, and A. S. Hada, “Energy Statistics,” p. 121, 2017.

[3] weo, “World Energy Outlook 2017 presentation,” no. November, 2017.

[4] Eurostat, Energy statistics - an overview, Web: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Primary_energy_production.

[5] S. Phillips, B. Flach, S. Lieberz, and A. Rossetti, “Biofuels Annual European Union (2017),” 2018.

[6] ISO14040, “International Standard 14040:2006,” *Int. Organ.*, vol. 2006, pp. 1–11, 2006.

[7] ISO, “International Standard 14044:2006,” *Environ. Manag. - Life cycle assessement - Requir. Guidel. ISO 14044, Int. Organ. Stand.*, vol. 2006, no. 7, pp. 652–668, 2006.

[8] R. Edwards *et al.*, *JRC Science for Policy Report - Definition of input data to assess GHG default emissions from biofuels in EU legislation*. 2017.

[9] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, “ReCiPe 2008 version 1.08,” 2013.

[10] A. F. Ferreira *et al.*, “A biorefinery from Nannochloropsis sp. microalga - Energy and CO 2 emission and economic analyses,” *Bioresour. Technol.*, vol. 138, pp. 235–244, 2013.

[11] S. Ermolaeva, G. Castro, V. Kandachar Materials selection for an automotive structure by integrating structural optimization with environmental impact assessment Materials and Design, 25 (8) (2004), pp. 689-698.