Life Cycle Assessment Studies of Jatropha (*Jatropha curcas*) Biodiesel Production Processed by In-situ Transesterification Method

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Abstract

In situ transesterification is a biodiesel production method that utilizes the original lipid-bearing agricultural products instead of purified oil as the source of triglycerides for direct transesterification. This method will eliminate the costly extraction process and reduce the long production system associated with pre-extracted oil and maximize alkyl ester yield. In this paper the production of fatty acid methyl ester (FAME) by direct in situ alkaline-catalyzed transesterification of the triglycerides (TG) in jatropha seeds was investigated and its environmental performance was compared with the conventional alkali catalyzed transesterification process using LCA as a tool. In-situ transesterification process is technically offers the advantages of the production of non-toxic jatropha seed cakes. The seed cakes after in-situ transesterification is rich in protein and is a potential source of livestock feed. However, it still generates significantly higher environmental load since in-situ transestrification needs large amount of methanol and longer duration of process. A large amount of energy will be required in methanol recovery unit.

***Keywords**: Jatropha curcas, biodiesel, in-situ transesterification, LCA, environmental performance*

1 Introduction

Biodiesel is currently considered as a feasible alternative diesel fuel. It is made from renewable biological sources such as vegetable oils and animal fats, biodegradable, nontoxic, renewable, environmentally benign [1,2] and its use in diesel engines also shows a decrease in the emission of CO, SOx, unburned hydrocarbons and particulate matter during the combustion process [3,4]. However, high cost of biodiesel production is the major impediment to its large-scale commercialization. Therefore, methods to reduce the production cost of biodiesel must be developed [5].

One of biodiesel production method which eliminates the costly extraction process and works with virtually any lipid-bearing material, could reduce the long production system associated with pre-extracted oil and maximize alkyl ester yield is in situ transesterification [6-10].

There are quite a few non-edible oil seed species that could be used as source for oil production. *Jatropha curcas*, which mainly grows in tropical and sub-tropical climates across the developing world, is one of them. This multipurpose species with many attributes and potentials [11,12] can be grown in low- to high-rainfall areas, either on the farms as a commercial crop or on the boundaries as a hedge to protect the fields from grazing animals and to prevent erosion [13]. Its hardness, rapid growth, easy propagation and wide-ranging usefulness have resulted in its spread far beyond its original distribution [14].

In addition to being a source of oil for biodiesel production, *J. curcas* seed also provide highly nutritious and economic protein supplement for animal feed, but the toxic phorbol esters in the *J. curcas* seed must be removed before being fed to animals. Thus, it is necessary for *J. curcas* seed cake to be further processed to reduce phorbol esters to permissible levels as animal protein feed resources. Due to the presence of excess of polar methanol during in situ transesterification, the toxic polar phorbol esters which exists in *J. curcas* seed could be extracted. Therefore, a nontoxic seed cakes could be produced.

However, since the cost and efficiency of the selected process will be tied up with the production for a long time and affect the capital and operating costs and finally the environmental load of the product, selecting an appropriate process for the biodiesel production is a critical decision. The capital and operating costs issues are relatively straightforward, but the issue on environmental load of the product is quite complicated [15]. One of the tools that can be employed to help answer this last issue is life cycle assessment (LCA). LCA is used to evaluate the environmental impact and other potential factors that a product (or service) has on the environment over the entire period of its life – from the extraction of the raw materials from which it is made, through the manufacturing, packaging and marketing processes, and the use, re-use and maintenance of the product, on to its eventual recycling or disposal as waste at the end of its useful life [15, 16].

This paper aims to study the environmental performance of two different biodiesel production processes: the conventional widely used alkali-catalyzed method and the in situ transesterification process, using jatropha oil which has low free fatty acid content as a raw material. The environmental load produced from each process was estimated by using the information obtained from a process simulator, *HysysPlant* Version 3.2 [17]. *HysysPlant* was used to estimate the materials and energy used during biodiesel production and the results from this process simulation were used as inputs for the LCA analyses using the Simapro 7 [18] program for the LCA analysis.

2 Biodiesel Production

Biodiesel (fatty acid alkyl ester) is usually produced by the transesterification of a lipid feedstock. Transesterification is the reversible reaction of a fat or oil (which is composed of tri-glycerides) with an alcohol to form fatty acid alkyl esters (FAME) and glycerol. Stoichiometrically, the reaction requires a 3:1 molar alcohol-to-oil ratio, but excess alcohol is usually added to drive the equilibrium toward the products side [19,20]. The reaction is shown in Figure 1.

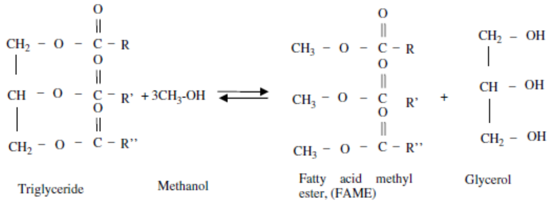

Figure 1: The transesterification of triglycerides with methanol to produce fatty acid methyl ester (FAME biodiesel) and glycerol

Transesterification reactions can be performed with or without catalysts, and those involving catalysts can be catalyzed by alkali, acid or enzymes. Among these three catalyst-based approaches, the conventional or widely used method in industry is alkali-catalyzed reactions mediated typically by sodium or potassium hydroxide (but also sodium methoxide and ethoxide) because of the reaction rate is fast [15].

2.1 *In-situ Transesterification Process*

Low FFA (<2%) of milled jatropha seeds were mixed with methanol in which sodium hydroxide had been dissolved (alkaline alcohol) and the mixture was heated for several hours. The experimental results showed that the amount of *Jatropha curcas* seed oil dissolved in methanol was approximately 83% of the total oil and the conversion of this oil could achieve 98% under the following conditions: less than 2% moisture content in *Jatropha curcas* seed flours, 0.3–0.335 mm particle size, 0.08 mol/L NaOH concentration in methanol, 171:1 methanol/oil mole ratio, 45°C reaction temperature and 3 h reaction time [10].

2.2 *Homogeneous Alkali-catalyzed Process*

Low FFA (<2%) of jatropha oils were mixed with methanol in which sodium hydroxide had been dissolved (alkaline alcohol) and the mixture was heated for several minutes. It was found that the maximum methyl ester yield of 98 % was obtained using 20 % methanol and 1.0 % NaOH at $60^{o}C$ reaction temperature. The minimum reaction time required for maximum ester yield was found to be 90 min [21].

2.3 *Comparison of Biodiesel Process*

Table 1 summarizes biodiesel production processed by in-situ transesterification and conventional process (homogeneous catalyzed process). It can be observed that the conventional process has a number of strong points, the reaction rate is fast and so requires a small reactor size for the same production output, but the process requires more energy for oil extraction and only produce 2 products (methyl ester and glycerol). In contrast, the in-situ transesterification seems to be simpler, eliminate the costly extraction process and reduce the long production system associated with pre-extracted oil, produduce 3 products (methyl ester, glycerol and jatropha seedcakes). Since both the processes have advantages and disadvantages, it is interesting to evaluate them in the environmental load aspect as well.

Table 1: Comparison of biodiesel production processed by in-situ transesterification and conventional process

Inventory	Conventional	In-situ Transesterification
Raw material for feed stock	Jatropha oil	Milled jatropha kernel
Reaction condition	1 atm, $60^{o}C$	1 atm, $45^{o}C$
Reaction time	90 minutes	3 hours
Products	Methyl ester and glycerol	Methyl ester, glycerol and non-toxic seedcakes

3 LCA Methodology

LCA methodology used in this study was based on ISO 14040 framework [22,23], which consists of four steps; goal and scope definition, inventory analysis, impact assessment, and interpretation.

3.1 *Goal and scope definition*

The goal of this study is to assess the environmental performance of jatropha biodiesel production processed by in-situ transesterification and conventional process using homogeneous catalyst on a life-cycle approach. The jatropha seed was passed through the same treatment for both processes, the environmental impact from jatropha seed production will be the same. The system boundary was drawn from jatropha seed being fed to oil extraction. The functional unit (FU) of this study is 1 kg of jatropha biodiesel production. The system boundary is shown in Figure 1 and Figure 2.

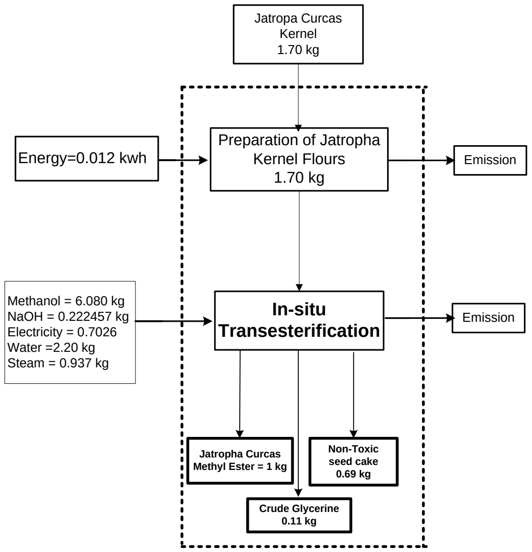

Figure 1: Product system boundary of in-situ transesterification process

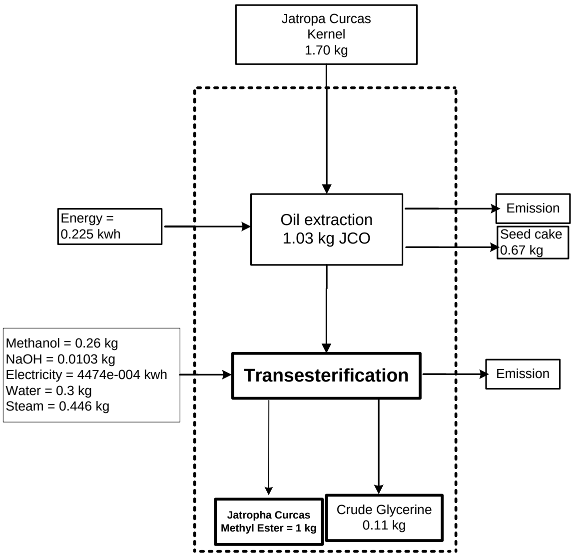

Figure 2: Product system boundary of conventional process

3.2 *Life-cycle inventory analysis*

The life-cycle inventory analysis was performed on the material and energy inputs, air emission, waterborne emission, and solid wastes involved in the life cycle of biodiesel production based on 1 kg biodiesel. In this study, most of input–output data were collected as primary data from laboratory experiment [10, 21]. The data on energy consumption, utilities, and wastes generated within the system boundary mostly obtained by estimating their value with the commercial process simulator, *Hysys Version 3.2*. Other secondary data were used in this study as necessary collected from literatures, calculation, and ecoinvent database. Table 2 shows the information related to materials and energy uses as well as waste generation for producing 2 million litres biodiesel per year from both the processes.

3.3 *Life cycle impact assessment*

In order to evaluate the environmental impact, the impacts caused by the use of resources and the emissions of the wastes from the production processes are required. This information can be obtained from LCA software, such as *Simapro, Gabi, Umberto*, etc. In this work, *Simapro* version 7 and ECO indicator 99 were used for the evaluation. Eleven categories of environmental impacts were of interest: climate change, carcinogen, respiratory organics and inorganics, ozone layer depletion, ecotoxicity, acidification/ eutrophication, minerals, radiation, land use and fossil fuels.

3.4 *Valuation and interpretation*

The results from the analysis would be used to evaluate each process to help make any decision as to which process to use.

4 Results and Discussion

4.1 *Environmental impact generated by different processes*

In this study, 11 categories of environmental impacts were considered: climate change, carcinogen, respiratory organics and inorganics, ozone layer depletion, ecotoxicity, acidification/eutrophication, mineral use, radiation, land use and fossil fuels. After obtaining the materials and energy uses from the process simulation, these results were used as inputs for the inventory analysis in LCA software as the preceding step of the impact assessment to obtain the environmental damage from the use of the resources in each unit process. Relative comparisons between the conventional alkali-catalyzed and in-situ transesterification processes were made for each environmental impact, with the larger of the two figures for each category set as 100% and the other displayed as the level relative to the former (Figure 3).

Table 2: Materials and energy used to produce biodiesel in each process based on 2 million liters of annual production capacity

Inventory	Conventional	In-situ Transesterification
Materials (kg/h)		
Kernel		379.31
Oil	220.00	
NaOH	2.16	49.08
Methanol	44.00	1340.98
H_2O	6.60	6.60
H_3PO_4	2.20	41.72
Energy (electricity, kWh)		
Feedstock Preparation	49.43	2.73
Transesterification	5.234e-002	104.68e-02
Methanol recovery	4.352e-004	95.86e-002
Glycerol-Methanol separation	5.567e-003	8.96e-003
FAME purification	3.719e-002	3.719e-003
Alkali removal for glycerol purification	9.153e-003	9.153e-003
Energy (heat, kcal/h)		
Feedstock Preparation		
Transesterification	19023.96	17652.535
Methanol recovery	3075.24	56356,03
Glycerol-Methanol separation		
FAME purification	29396.35	30360.57
Alkali removal for glycerol purification	1344.66	1344.66
Utilities (*Cooling Water/kg/h*)		
Feedstock Preparation		
Transesterification	17243	16854.72
Methanol recovery	384.78	807.84
Glycerol-Methanol separation		602.77
FAME purification	543.99	583.79
Alkali removal for glycerol purification	14.96	14.96
Products		
Biodiesel (kg/h)	212.37	212.37
Glycerol (kg/h)	21.97	21.97
Non-toxic seed cakes		159.31
Waste (kg/h)		
Waste water	7.04	479.53
Na_3PO_4	8.84	201.15

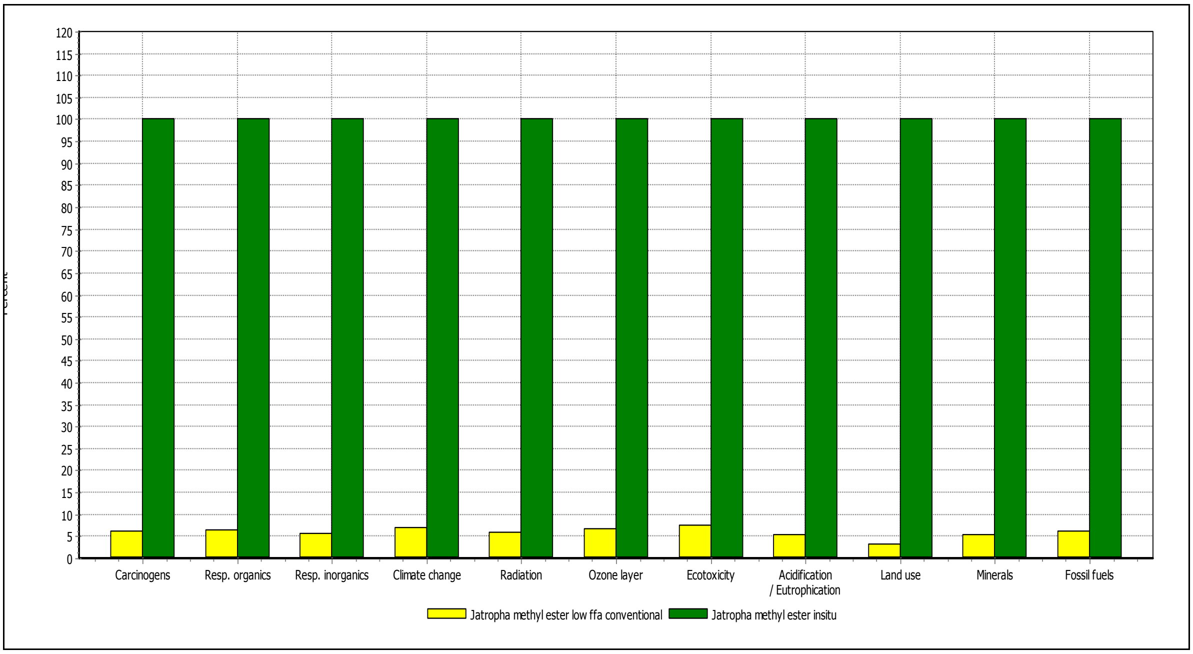

Figure 3: Comparison of the environmental impacts due to the conventional and in-situ transesterification processes on each of the 11 environmental categories.

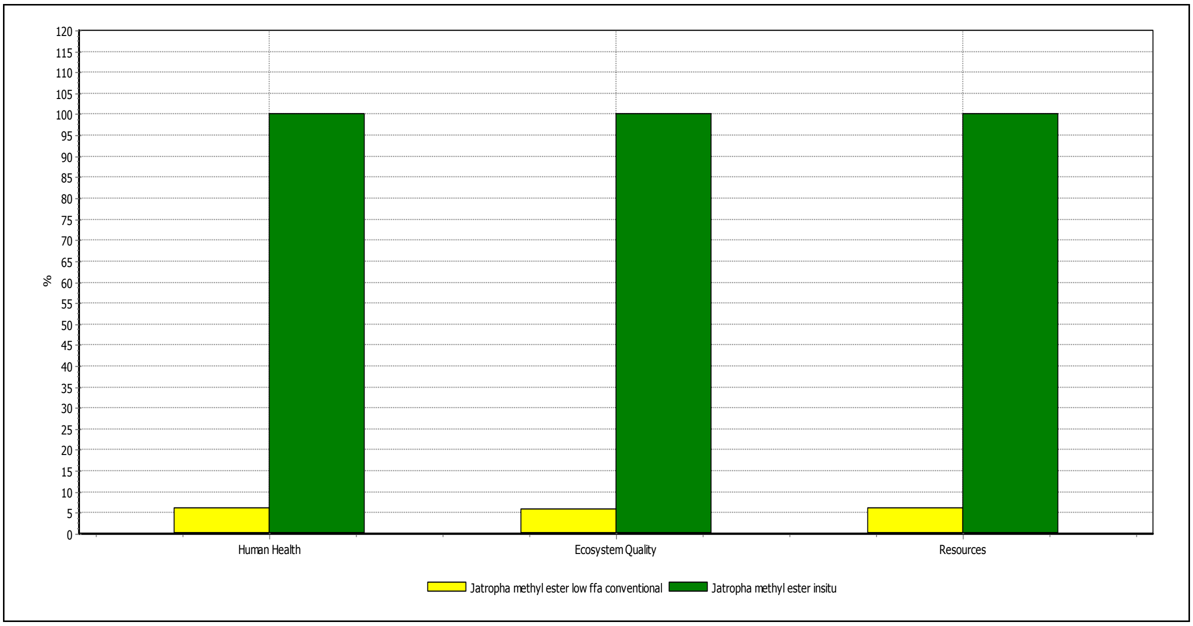

Figure 4: Comparison of the environmental impacts due to the conventional and in-situ transesterification processes on the three main environmental impacts: humanhealth, ecosystem and resources.

Of the 11 impact categories, the conventional alkali-catalyzed process caused a lower environmental impact, with all of these being more than 90% lower.

When focused on damage assessment categories (Figure 4) the in-situ process generates 95% larger damages on human health, ecosystem quality and resources, respectively, than the conventional process (which contributes around 6% of the damages generated by the in-situ process). The reason that the in-situ process used large amount of methanol and an energy-intensive process, especially the process of recovering the methanol, and this reflects the environmental cost of energy production and use from fossil fuels.

After normalization, it was found that only 3 of the 11 factors: respiration inorganics, climate change, and, most dramatically, fossil fuels remained as important environmental impacts (Figure 5).

Fossil fuels was the category of most concern for both the processes followed by respiration inorganics, although this was some threefold lower in magnitude than fossil fuels. Again, if the program was changed to allow evaluation based upon biofuels rather than fossil fuels, it would be interesting to see how much these environmental impact categories changed both together (normalized) as well as between the two processes. Likewise, reanalysis of the main damage assessment categories after normalization (Figure 6) revealed that the main concern was resource depletion followed by human health but that ecosystem quality was not affected that much, consistent with these being principally energy demanding processes with little waste production.

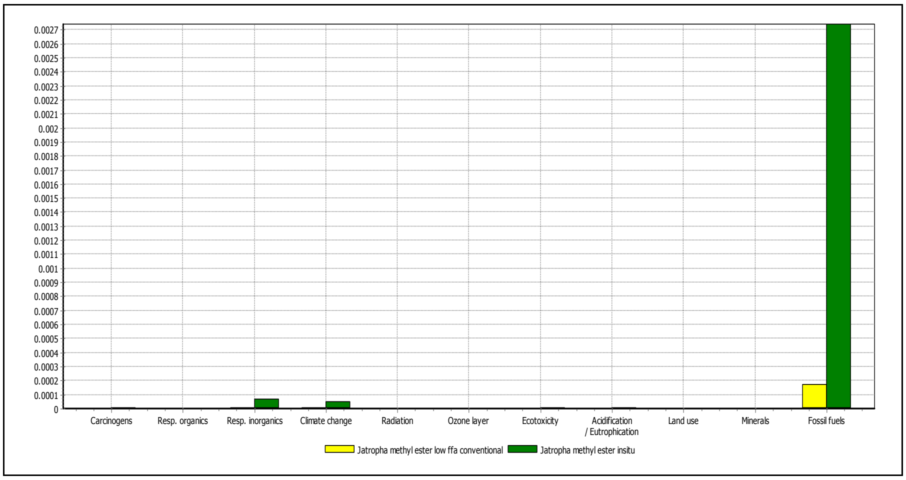

Figure 5: Comparison of the environmental impacts due to the conventional and in-situ transesterification processes on each of the 11 environmental categories after performing normalization.

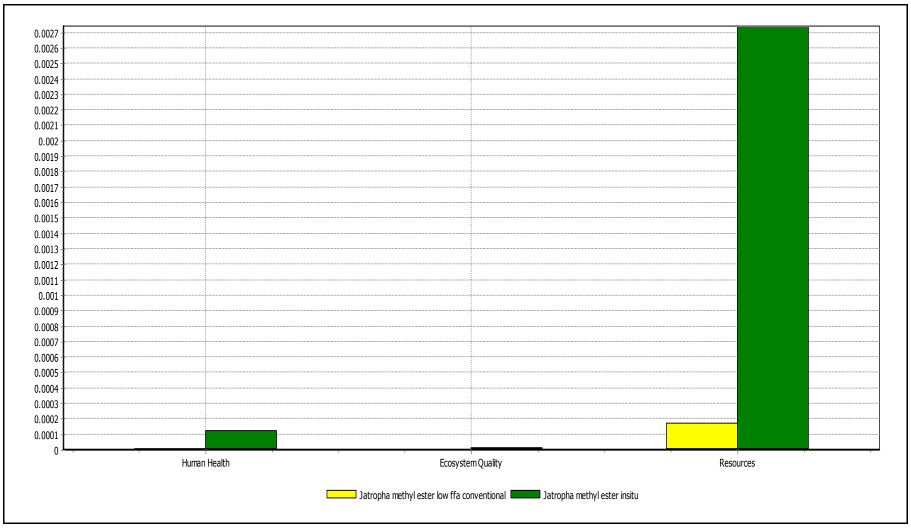

Figure 6: Comparison of the environmental impacts due to the conventional and in-situ transesterification processes on the three main environmental impacts after performing normalization

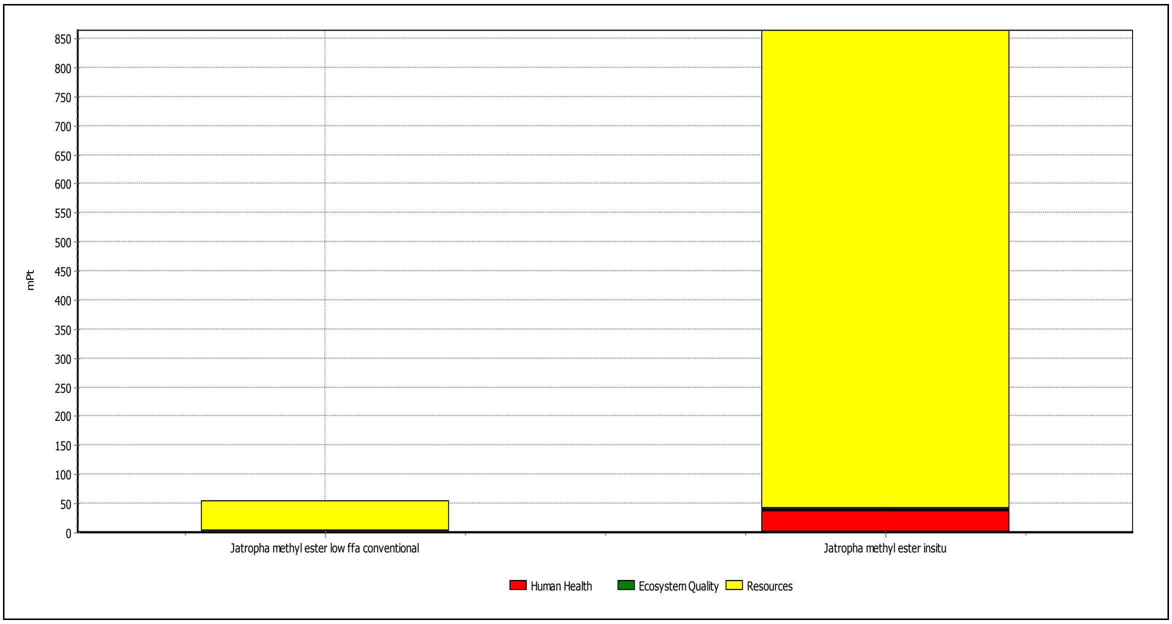

Figure 7: Comparison of the environmental impacts due to the conventional and in-situ transesterification processes on each environmental category based on a single cumulative score

Finally, combining the effects on all impact categories as a single score (Figure 7) supports the notion that the in-situ process (852 pt) generates 94% higher environmental load than the conventional process (51 pt), based upon fossil fuel usage.

4.2 *Global warming potential of JME produced by different process*

The proportion of greenhouse gas (CHG) emissions from each materials and energy used shown in Figure 8. The main contributions came from methanol used in transesterification and electricity.

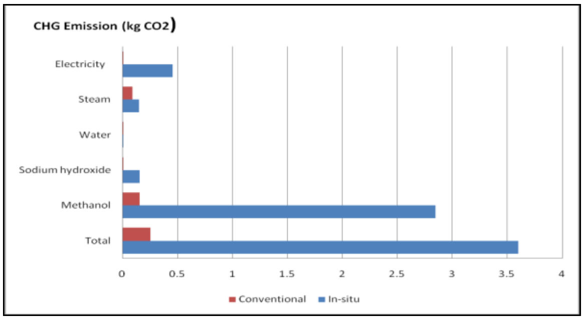

Figure 8: Comparison of life cycle GHG emissions of biodiesel production of conventional and in-situ transesterification (in-situ) process

5 Conclusions

Two biodiesel production processes, the conventional alkali catalyzed and the in-situ transesterification processes, were investigated for their impact on the environment. Life cycle assessment was used as a tool to determine the environmental impact generated by each process. It was found that the in-situ transesterification process always generated a higher impact on the environment, because of its requirement for large amounts of methanol during the reaction and consequently the energy expenditure in methanol recirculation in the recycle loop. This equated to a methanol flow of 1340.98 kg/h compared to only 44.00 kg/h in the conventional process. The proportion of greenhouse gas (CHG) emissions from each materials and energy used showed that the main contributions of CHG emissions also came from methanol used in transesterification and electricity

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