



Life cycle assessment of waste cooking oil for biodiesel production using waste chicken eggshell derived CaO as catalyst via transesterification



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ABSTRACT

There are plentiful experimental studies on biomass as heterogeneous catalyst and its reasonable cost, it can be a potential catalyst feedstock for biodiesel production. This study presents the life cycle assessment (LCA) of waste cooking oil biodiesel production catalyzed by waste chicken eggshell derived CaO catalyst to validate the suitability of waste chicken eggshell as a green catalyst in biodiesel field. To the best of our knowledge, LCA was first performed for the heterogeneous catalyst, CaO preparation as a subsystem in a biodiesel production. Comparative studies were performed to evaluate the difference of environmental impacts contributed by waste cooking oil, WCO biodiesel production catalyzed by waste chicken eggshell derived CaO with the two different production processes via *Jatropha* oil as the oil feedstock and potassium hydroxide, KOH as the homogeneous catalyst. Utilization of WCO as the oil feedstock for biodiesel production has lesser environment impact than the *Jatropha* oil as the WCO biodiesel production does not involve agriculture phase. Likewise, utilization of waste chicken eggshell derived CaO catalyst (heterogeneous catalyst) has less contribution on the overall impact categories than KOH (homogeneous alkali-based catalyst) as the production of KOH required addition of chemical and additives, plus complex purification and neutralization processes are required during the production phase. The overall impact results clearly indicated the best environmental performance of waste chicken eggshell derived CaO of 1.17 Pt was over the traditional KOH catalyst and implementation of *Jatropha* oil but also identified some bottlenecks that should be addressed for more sustainable solutions.

1. Introduction

Biodiesel is known as a favourable alternative energy source to replace conventional petroleum fuel, which currently is the most common fossil fuel for internal combustion engines. Utilization of biodiesel is an effective countermeasure to tackle the issues of depletion of fossil fuel and exploitation of conventional energy resources due to the rapid growth of global population and industrial development (Goli and Sahu, 2018). Biodiesel has several advantages over conventional fossil fuel such as low toxicity, high oxygen content (10–11%) that would give great combustion efficiency and most importantly, it is biodegradable (Tan et al., 2019). Likewise, conventional fossil fuel has some disadvantages such as it is non-renewable energy source and will lead to global warming as a result of carbon dioxide emission. United States Environmental Protection Agency has made a research on global

greenhouse gas emission by gas and it shows that fossil fuel and industrial processes has caused 65% of carbon dioxide emission and only 11% is contributed by forestry and other land use (US EPA, 2018). According to World Bank Group, CO₂ emission from liquid fuel consumption in Malaysia has increased dramatically for the past few decades which it had raised from 13,773 kilotons in 1970 to 89,628 kilotons in 2014 (CO₂ Emissions from Liquid Fuel Consumption, 2018). Therefore, adoption of renewable environment friendly and economically feasible biodiesel will change the course of the world towards a cleaner and greener environment for the future generations.

The current drawback for biodiesel production is it needs a relatively higher cost of production by comparing to conventional fossil fuel due to expensive raw feedstock and homogeneous catalyst system, which is mostly opted in biodiesel industry as homogeneous base-catalyzed reaction could employ low yield of free fatty acid (FFA) (Thokchom and

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Tikendra, 2019). Biodiesel obtained by transesterification process using heterogeneous catalyst has received a lot of interest lately as a sustainable and reliable source of biofuel. Apart from that, WCO has the economic potential to become the oil feedstock of biodiesel production. A recent study shows that price for biodiesel (B99–B100) is about \$3.46/gallon and biodiesel (B20) is \$2.87/gallon, meanwhile gasoline and diesel cost around \$2.67/gallon and \$3.03/gallon respectively (US Department of Energy, 2018). However, reduction of biodiesel production cost can be achieved by using a cheaper and easily obtained feedstock such as waste cooking oil, animal fats, palm fatty acid distillate (PFAD) and *Jatropha curcas* oil (Mansir et al., 2018). To overcome the high capital cost of material, studies suggested by using waste cooking oil (WCO) as an alternative feedstock can eventually reduce the cost of biodiesel since waste cooking oil, WCO has a lower price and high availability compared to palm oil, soybean and sunflower oil as pure refined vegetable oil needed extra purification cost (Gupta et al., 2016). WCO is oil that is used to cook, or fry food and it is very unhealthy to reuse. It could lead to environmental problem due to improper waste management and dispose of WCO from households and restaurants direct into the drainage. Such actions would lead to serious environmental issues such as water and soil pollution which consequently affecting the health of human, plants and most of the aquatic life, plus generating higher cost for wastewater treatment in order to remove WCO.

According to Gnanaprakasam et al. (2013), homogeneous base catalyst is not suitable to use in transesterification process if the amount of free fatty acids, FFA in the raw material exceeded 3%. Another disadvantage of using homogeneous catalyst is formation of soap will slowly consume the catalyst and revert backward of the reaction, subsequently decreasing the biodiesel production (Tan et al., 2017). In the meantime, formation of soaps and other intermediates generates wastewater during the purification and neutralization stages in order to remove the non-reusable homogeneous catalyst residues (Thoai et al., 2019). Nonetheless, using homogeneous catalyst for the production of biodiesel is considered as unsustainable process in terms of economic and environmental. The usage of heterogeneous catalyst to produce biodiesel plays a vital outlook when it comes to the economics that goes behind the commercial side of biodiesel production (Shan et al., 2015). The replacement of homogeneous catalysts will give various advantages such as the reduction of environment pollutants, easy product purification and also easy catalyst separation from the reaction mixture. It also has a high chance of reusability that aid the economical aspect of the process (Karabas, 2013). Nevertheless, the production of biodiesel can be elevated to a more economical and eco-friendly resource given that waste catalysts are used. Among the type of alkali earth oxides that available, CaO is widely used catalyst due to its availability in nature, low cost, long lifetime, highest activity under mild reaction conditions and high activity (Mazaheri et al., 2018). This being stated, waste chicken eggshell derived CaO catalyst can be effectively utilized for the transesterification.

Lack of environmental impact study via various environmental friendly waste catalysts. If these catalysts are implemented in biodiesel field, the environmental impact studies are required to measure potential environmental impacts of these systems, especially long-term impact. The Life Cycle Assessment (LCA) has been used in recent years for assessing various bioenergy systems. LCA is an internationally systematic tool that evaluates and analyzes the environmental impacts of a product, along its entire production stages which include the primary process or activity and final disposal after use (ISO, 2006). LCA tool can be complicated and generally limited by data availability and generalizations (Macombe et al., 2013). LCA will be serving as a methodology that evaluate the potential environmental impact that are attributed to the process and provide the understanding for decision-making towards sustainable options. The evaluation of the life cycle environmental impacts, consisting of a combination of catalyst preparation and transesterification. This may reduce the potential critical environmental impacts of biodiesel production using certain types of catalyst. The use

of CaO-based catalyst from waste chicken eggshell underwent an experimental study (Tan et al. 2015, 2017) to evaluate to the productive implementation process. Up to date, there is no report about the LCA of eggshell-catalyzed biodiesel synthesis from waste cooking oil.

While many eggshells catalyst in synthesizing biodiesel via various experimental methods had been vastly reported in literature, while in this context, the primordial purpose of this paper is to study the life cycle assessment of waste cooking oil biodiesel production with the introduction of waste chicken eggshell derived calcium oxide, CaO to act as the heterogeneous catalyst. Utilization of waste chicken eggshell in the production of catalyst helps in minimizing disposal of waste chicken eggshell since it is known as hazardous agricultural waste by UE regulations. LCA study was carried out in this research report by using OpenLCA V1.8 developed by GreenDelta and the selected impact assessment methodologies were Eco-indicator 99 and CML 2 Baseline 2000.

2. Materials and methods

2.1. Life cycle assessment functional unit and assumptions

The goal of this LCA study is to determine the feasibility of WCO biodiesel production in terms of environmental and human health perspectives by referring to the methodological framework in EN ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework (International Standards Organization, 2006). The functional unit in this study is 1000 kg of biodiesel produced per day from the transesterification process after purification using WCO (Mohammadi et al., 2013). LCA assumptions listed in this study are stated below in Table 1:

- The conversion rate of the WCO biodiesel production was 70% for industrial scale production, which includes the consideration of uncertainties.
- Water content was neglected for the WCO.
- Distance travelled for the transportation of collected waste cooking oil from distribution center to the pretreatment plant was 200 km.
- Location of pretreatment plant was in close proximity with biodiesel production plant, therefore, transportation distance between pretreatment plant to biodiesel production plant will not be considered in the LCA.
- Oil filtration and oil decantation were completed at the distribution center of WCO and will not be considered as part of LCA.
- The whole production process was considered as batch process.
- Electricity was referred to the electricity consumption of jacketed batch reactor.
- Efficiency for the separation was assumed to be 100%.
- Water required to purify the biodiesel is 1 m³ (Mohammadi et al., 2013).

2.2. System boundaries

In this study, system boundaries of biodiesel production were defined as the raw material collection, raw material transportation, pretreatment of WCO and transesterification process. Moreover, preparation of catalyst was considered as part of transesterification process in the present study. The output of the study included waste gas emission, wastewater, heat, glycerol and biodiesel production. Fig. 1 shows all the system boundary for each process which each of them were categorized by using red dotted boxes and yellow dotted box represents the independent subsystem (catalyst preparation phase). Eco-indicator 99 does not include data and impact factor for methanol (emission to soil), sulfuric acid (emission to soil) and wastewater (emission to water) which the calculation is done without the impact factor from the components mentioned.

Table 1

Inventory of input and output flows of raw material collection, raw material transportation, pretreatment of WCO and transesterification.

Components	Unit	Input	Output	Reference
Raw material collection				
Waste cooking oil	kg	1500	–	–
Raw material transportation				
Diesel ^b	kg	25.52	–	Mohammadi et al. (2013)
Transportation (lorry >32t) ^c	t*km	–	196.5	–
Catalyst Preparation				
Electricity, production mix	kWh	12	–	Alibaba (2019)a,b
Eggshells	kg	26.71	–	Tan et al. (2015)
Water	m ^c	1	1	Mohammadi et al. (2013)
Carbon Dioxide	kg	–	11.74	–
Waste Chicken Eggshell derived CaO	kg	–	14.96	–
Natural gas, burned in furnace > 100 kW of greenhouse	MJ	20.73	–	–
Industrial furnace, natural gas	item	1	–	–
Pretreatment of WCO				
Sulfuric acid	kg	9.83	9.83	Chai et al. (2014)
Methanol	kg	155.65	140.092	(Chai et al., 2014), (Photaworn et al., 2017)
Electricity, production mix ^a	kWh	11	–	Alibaba (2019)a,b
Water	m ^c	–	1	Photaworn et al. (2017)
Transesterification of WCO				
Hot water	m ^c	1	–	Mohammadi et al. (2013)
Electricity, production mix, separation	kWh	32	–	Mohammadi et al. (2013)
Methanol	kg	449	–	–
Glycerol	kg	–	428.57	–
Biodiesel	kg	–	1000	–
Used Waste Chicken Eggshell derived CaO	kg	14.96	14.96	–
Wastewater	m ^c	–	0.9	–

^a Electricity used is reference to the electricity from UCTE (Union for the Coordination of the Transmission of Electricity) which it provides electricity across countries in continental Europe, as database for electricity production in Malaysia is not available.

^b Diesel is an input for the transportation operation of lorry >32t.

^c Transportation data is referred to average transport conditions in Europe (EU 15 Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland and Italy).

2.3. Life cycle inventory analysis (LCI)

All the important information required for the LCA simulation were obtained from various sources. Brief explanation on each phase was made. Life cycle assessment simulation data acquired was tabulated in Table 1.

2.3.1. Raw material collection and transportation

Amount of WCO and methanol were calculated with respect to 1000 kg of biodiesel production. A 12:1 molar ratio of methanol to oil was chosen for the transesterification process based on experiment conducted by using chicken eggshell derived CaO as catalyst to produce biodiesel (Tan et al., 2015). As above mentioned, transportation only covered the distance travelled from the WCO collection distribution center to WCO biodiesel production plant (pretreatment was included). Due to lack of specific information in Malaysia and South East Asia, transport operation was referred to operation process, transport lorry >32t in the database. Amount of diesel fuel for the transportation was referred to the diesel consumption for raw material transportation in palm oil mills in Malaysia within 200 km (Mohammadi et al., 2013).

2.3.2. Pretreatment of WCO

Pretreatment of waste cooking oil was required for the production of WCO biodiesel due to high amount of FFA content in the WCO. Here, electricity was referred to the electricity consumption of jacketed batch reactor. During the pretreatment process, sulfuric acid and methanol were added to used oil feedstock to reduce its FFA content lower than 3%. Practically, methanol is often added excessively into WCO as the esterification reaction is reversible, methanol in excess helps to drive the forward reaction to favor the reduction of FFA content in WCO. According to Chai et al. (2014), a 20:1 methanol – to – FFA molar ratio is suggested to use with FFA in range of 15–25% and 5% acid amount with FFA range within 15–35%. In this study, average FFA amount is assumed to be 20 wt% of oil used, nevertheless WCO input as the functional input to the transesterification reaction was 1500 kg. Through calculation and referring to Chai et al. (2014), amount of methanol needed for acid esterification was 155.65 kg, whereas 9.83 kg of sulfuric acid was required. Photaworn, Tongurai and Kungsanunt (2017) stated that during the separation process of methanol and sulfuric acid, sulfuric acid was completely removed from the process and only 90.67% of methanol was removed. There was no water content in the raw WCO because the WCO had undergone oil decantation and oil filtration in the first place before esterification process. These processes have applied thermal treatment to remove the water content in the collection center. From the experiment conducted by Photaworn et al. (2017), the conversion of FFA to ester was approximately 80% and 0.78 wt% of water were generated.

2.3.3. Catalyst preparation

Waste chicken eggshell derived CaO was selected as the heterogeneous catalyst for the transesterification as per conducted by Tan et al. (2015), which synthesized from the high temperature thermal treatment of waste chicken eggshell. According to experiment conducted by Tan et al. (2015), proposed optimum catalyst loading of 1.5 wt% chicken eggshells were selected for the transesterification process. The required weight of chicken eggshells was calculated based on the weight percentage of chicken eggshells and required amount of WCO used in the process, that is 14.96 kg as per stated in Table 1. The needed electricity was referred to the electricity demand for eggshells milling machine. Natural gas fired furnace was chosen for the calcination process and 20.73 MJ of natural gas was required to fully calcinate the 26.71 kg of chicken eggshells at the selected optimum calcination temperature, 900 °C based on the specification of the chosen furnace. Experiments conducted by Denys et al. (2004) have proven that chicken eggshell has an average specific heat capacity of 888 J/kg °C. thus, 20.59 MJ of heat was required to fully convert the eggshells to calcium oxide powder at their selected optimum calcination temperature, 900 °C. Furthermore, clean tap water was used to wash the chicken eggshells and water consumption was assumed to be 1 m³. To the best of our knowledge, LCA was first performed for the catalyst preparation as a subsystem in a biodiesel production and the boundary was highlighted with yellow dotted lines.

2.3.4. Biodiesel production

In the overall stage of biodiesel production, there are processes such as transesterification, separation, purification and drying. WCO biodiesel and glycerol are the final products. Glycerol was not treated as a waste from the final production due to its economic value as glycerol can be used to produce soap. In the initial stage of transesterification process, waste chicken eggshell derived CaO and methanol were firstly activated before adding into to the mixture of pre-treated feedstock. The mixture was then heated up to 65 °C for 2 h in a reactor. The reaction needs methanol (449 kg) and eggshell catalyst (14.96 kg). Removal of catalyst was done by a centrifuge and the amount of catalyst was assumed to remain the same as the input since it was not consumed during the transesterification process. In addition, amount of glycerol generated was calculated based on the conversion rate of 70% based on

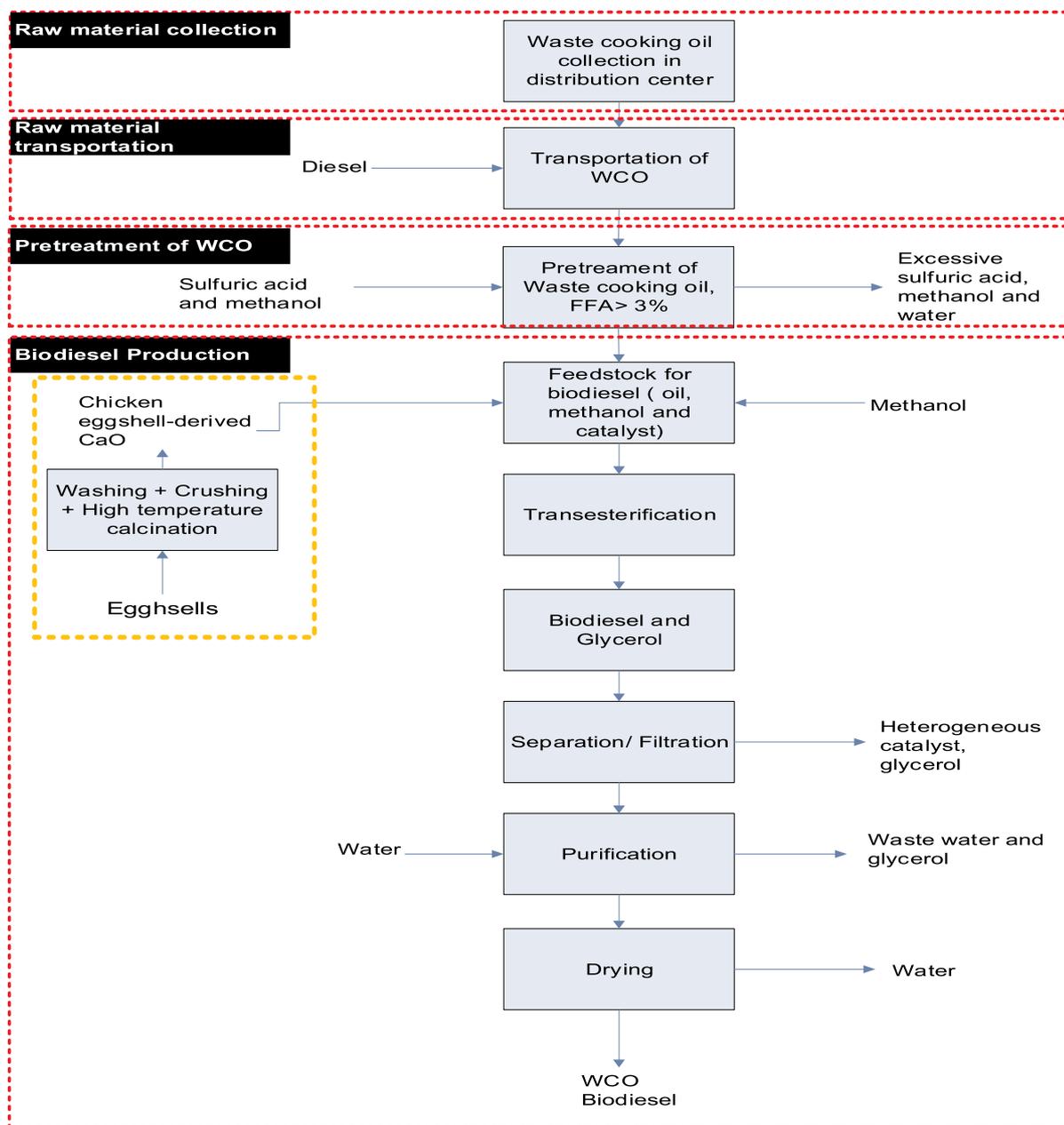


Fig. 1. Overall system boundaries.

the assumptions given earlier. A 1 m^3 of 100°C hot water was assumed to use to purify the biodiesel mixture. The output of the wastewater generated during the process was assumed at 10% loss due to the water evaporation during the separation process. Wastewater generated during the process of drying can be neglected as the amount of water removed from the biodiesel was insignificant. Moreover, 10% loss of biodiesel mixture has included in the calculation as well during the purification stage. Since the required information of the electricity required for the transesterification of WCO biodiesel could not be found, it was assumed to be similar as the electricity consumption in transesterification process of the palm oil biodiesel in Malaysia conducted by Mohammadi et al. (2013).

2.4. Life cycle impact assessment

To assess the environmental impact of the whole processes, the consistency, accuracy and geographical specification of data collection is in accordance with EN ISO 14040: 2006 (International Standards

Organization, 2006). The software used in this research study was Open LCA v1.8 by Green Delta. Two impact assessments were used in this study which they are CML 2001 (all categories) and Eco-indicator 99. The main databases used in the simulation were Agribalyse and NEEDS database. 11 midpoint impact categories of Eco-indicator 99 were evaluated which included land conversion, acidification, eutrophication, ecotoxicity, carcinogenic, climate change, ionizing radiation, ozone layer depletion, respiratory effects caused by inorganic and organic substances, fossil fuels and minerals. Whereas, the intermediate endpoint categories are divided into three damage groups: human health, resources and ecosystems. To avoid subjectivity of the analysis, normalization and weighting were neglected in this methodology. For the alternative assessment method (CML 2 Baseline, 2000), 10 following categories were assessed in the simulation: abiotic depletion (kg Sb eq), acidification (kg SO_2 eq), eutrophication (kg PO_4 eq), fresh water aquatic ecotoxicity (kg 1,4-DB eq), global warming potential (kg CO_2 eq), human toxicity (kg 1,4-DB eq), marine aquatic ecotoxicity (kg 1,4-DB eq), ozone layer depletion (kg CFC-11 eq), photochemical

oxidation (kgC₂H₄ eq) and terrestrial ecotoxicity (kg 1,4-DB eq). Normalization factors West Europe 1995 was applied during the analysis. In this study, impact analysis of catalyst preparation phase was done separately in order to observe and evaluate the environmental impact due to the use of heterogeneous catalyst (waste chicken eggshell derived CaO).

3. Results and discussion

3.1. Life cycle impact analysis results

In this study, midpoint assessment was conducted based on two impact methodologies which they are Eco-indicator 99 and CML 2 baseline 2000 in order to have a better understanding and comparison on the impact categories. While, Eco-indicator 99 was used to conduct both midpoint analysis and endpoint analysis. CML 2 baseline 2000 was used for comparison with results obtained from other literature that used the same transesterification catalyze by KOH. All processes were assessed with impact indicators that are available to evaluate the contribution of impact categories for each process. In this study, LCA of biodiesel production was conducted based on four stages in the inventory analysis: raw material transportation, catalyst preparation, pretreatment of WCO and transesterification of WCO. First stage of the WCO biodiesel production, raw material collection, was not included in the impact assessment since raw material collection phase did not involve any energy input or emission during the process. Scope of the study was defined under Fig. 1.

3.2. Midpoint indicator assessment

This research study covers the simulation of life cycle assessment of biodiesel production from waste cooking oil feedstock and agricultural waste via transesterification with Open LCA V1.8 simulation software. The chosen oil feedstock for the biodiesel production was waste cooking oil, whereas the catalyst used was chicken eggshell-derived CaO. This study is only focused on the LCA performed using OpenLCA V1.8 with two impact assessment methods: Eco-indicator 99 and CML 2 Baseline 2000, along with comparative study with other literature.

Midpoint analysis results obtained from Eco-indicator 99 was tabulated in Table 2 below. It was observed that raw material transportation phase has the least impact on the system compared to all other phases, which all of the value obtained from the impact categories are closed to zero. The result is in line with the outcome obtained by Kaewcharoensombat et al. (2011) which low damage from transportation phase was mainly due to the unit opted in the database to compile emissions of the model of transportation, which is load-length in tonnes-kilometer (t × km), plus the assumed distance travelled for the transportation is considered as short.

For catalyst preparation phase, the damages were found in fossil fuels consumption (3.77 MJ surplus), climate change (3.36E-06 DALY), ecotoxicity (1.26E-01 PAF × m²yr) and land use (4.72E-01 PDF × m²yr).

Radiation impact from catalyst preparation is mainly due to the emission of radiation from Radon-222 and Carbon-14 from the electricity production obtained from the database. Radiation impact contributed in this process (7.29E-08 DALY) can be neglected since the power plant in Malaysia does not utilize the use of nuclear energy to generate electricity, whereas the database is widely used in Europe countries. The result of climate change is largely due to the carbon dioxide emission released during the calcination of waste chicken eggshells. During the high temperature calcination, calcium oxide (catalyst) transformed from calcium carbonate tend to release certain amount of carbon dioxide gas to the surrounding. On the other hand, climate change impact contributed by the carbon dioxide emission from the production of natural gas is insignificant as indicated in the simulation. For land wise, which relates to the ground used is the second largest impact in this phase due to the land transformation. This land transformation has direct link with electricity production in the database. Fossil fuel is the largest contribution of damage in this system due to the close relationship to the amount of coal used for the electricity production in the database. Electricity consumption in this process shows the highest value due to electricity requirement for the usage of equipment and natural gas production in the database.

Impact categories of pretreatment phase are mostly due to the damage inflicted by electricity production in the database used. Eco-indicator 99 does not include data and impact factor for methanol (emission to soil), sulfuric acid (emission to soil) and wastewater (emission to water) thus these impacts are not evaluated. Also, database for the source of sulfuric acid and methanol used for the pretreatment of WCO are not provided in OpenLCA. Among all processes, transesterification of WCO shows a greater level of damage, which contributed to the highest impact categories in life cycle of WCO biodiesel. This is due to the transesterification of WCO involved larger electric energy consumption than other phases. This is mainly depending on the equipment use and purification/centrifugation process is consequently generated a larger amount of emission from the electricity production. Top three contribution on the impact categories from this process included fossil fuels consumption (1.01E+01 MJ surplus), land use (1.26E+00 PDF × m²yr) and ecotoxicity (3.37E-01 PAF × m²yr). Likewise, it is found that more carcinogen substances such as cadmium and arsenic were emitted from the electricity supply during the transesterification process. Some toxic gases such as nitrogen oxides, sulfur dioxide and other particulates (<2.5 μm) were released more often in transesterification process than other processes (Photaworn et al., 2017). Subsequently, these inorganic gases result in human respiratory disease, as well as causing climate change and soil acidification or eutrophication.

Relative results were generated from the simulation which indicator results maximum is set 100%. Fig. 2 below shows that transesterification process is mostly above of all other processes in terms of impact categories, except for the climate change. This is due to the larger amount of carbon dioxide being produced during the catalyst preparation stage, calcination process to fully converting the calcium carbonate

Table 2
Midpoint results from Eco-indicator 99 (E) for different system boundaries.

Impact category	Unit	Raw Material Transportation	Catalyst Preparation	Pretreatment of WCO	Transesterification of WCO
Acidification/Eutrophication	PDF × m ² yr	7.87E-03	2.67E-02	2.20E-02	6.39E-02
Carcinogens	DALY	8.22E-09	5.28E-08	4.83E-08	1.41E-07
Climate change	DALY	3.46E-08	3.36E-06	5.92E-07	1.72E-06
Ecotoxicity	PAF × m ² yr	6.79E-02	1.26E-01	1.16E-01	3.37E-01
Fossil fuels	MJ surplus	2.06E-01	3.77E+00	3.46E+00	1.01E+01
Land use	PDF × m ² yr	4.24E-03	4.72E-01	4.33E-01	1.26E+00
Minerals	MJ surplus	2.49E-03	2.31E-02	2.12E-02	6.17E-02
Ozone layer	DALY	2.42E-11	3.20E-10	2.94E-10	8.54E-10
Radiation	DALY	2.82E-10	7.29E-08	6.68E-08	1.94E-07
Respiratory inorganics	DALY	2.08E-07	6.23E-07	5.30E-07	1.54E-06
Respiratory organics	DALY	3.68E-10	1.38E-09	1.23E-09	3.56E-09

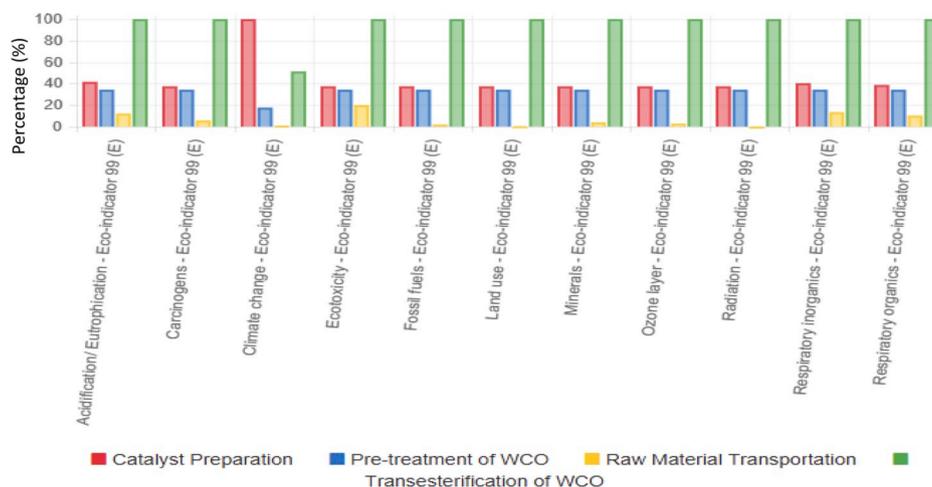


Fig. 2. Eco-indicator 99 midpoint indicators for different processes in WCO biodiesel production catalyzed by chicken eggshells derived CaO.

components to the desired product, calcium oxide. It can be observed that the transportation phase has the least contribution in all impact categories. However, the transportation phase has a slightly higher percentage (20%) on ecotoxicity when compared to other processes. It is mainly due to the greater emission of heavy metals such as zinc, nickel, and chromium, which were displayed in the simulation result. During the raw material transportation, these heavy metal elements can be found as well in the diesel fuel used for heavy trucks (Mohammadi et al., 2013). Moreover, the catalyst preparation phase attributed to a higher contribution of damage to the impact categories compared to the pretreatment of WCO. This is due to the greater electricity consumption, as well as the utilization of natural gas for the furnace. Pretreatment of WCO has contributed an average value of 20–40% in overall impact categories. In summary, the transesterification process has denoted as most of the damage component on the impact categories since it required more electricity consumption during the biodiesel production stage compared to all other processes due to the inclusion of purification, separation, and drying processes of biodiesel.

3.3. Endpoint assessment analysis

Eco-indicator 99 (E/E) can be used to evaluate the endpoint results from the processes. Furthermore, all the damages can be defined into three broad categories, which consist of human health, ecosystem quality, and resources. Even though there are three different damage categories, all processes are assigned with a single score that will be calculated based on the relative environmental impact contributed by each process to ease for comparison.

Ecosystem quality is referred to the impact contributed on acidification, ecotoxicity, eutrophication, and land use. For the human health category, it is related to the impacts caused by environmental degradation, which involves the number and duration of diseases, as well as the loss of life-years owing to deaths. While, for resources, the result obtained from this category is closely related to the depletion rate of raw materials and energy sources. The result is evaluated based on the surplus energy required in the future to produce lower-quality energy and minerals. It is important to know that agricultural resource depletion is not considered in this impact category since WCO collection does not require plantation (Singh et al., 2018).

The impact contributed by all phases in the endpoint indicator assessment are in accordance with the results generated from the midpoint indicator assessment above. The obtained endpoint results were defined in points and categorized under the three main damage categories to evaluate the damage contributed in the endpoint indicator assessment. By referring to the results tabulated in Table 3 and Fig. 3 below, it is observed that the transesterification process has the highest impact among all

other processes. It shows that transesterification of WCO has contributed a total of 0.853 Pt with the accumulation impacts on resources, human health, and ecosystem quality, which are the results tally with the midpoint indicator assessment as per discussed in the section above. It has been proven that the transesterification process obtained the highest impact score on resources by showing that the process reduces the world's resource by about 0.683 Pt at present time. The overall analysis has indicated that this process required a lot of resources, such as fuel and electricity. The utilization of multiple units such as distillation column and reactor, which requires a massive amount of electricity to operate, may possibly be attributed to this result (Kaewcharoensombat et al., 2011). Additionally, transesterification contributed a 0.138 Pt damage on human health as a result of the emission of toxic gases, such as CO and SO_x during the use of electricity. However, the transesterification process contributed the least impact on ecosystem quality, which means the process does not contribute much damage to the environment. Nevertheless, there may be other sources that contribute to human health from the emission of volatile compounds during transesterification, thus a total score of 0.032 Pt was given.

The second highest contribution on the impact categories is the catalyst preparation phase with a total score of 0.331 Pt. It is only slightly higher than the pretreatment of WCO, which has a score of 0.293 Pt in total. Both stages contributed similar damage on resources as there was only a slight difference in electric consumption for both processes. Catalyst preparation is defined as the most significant impact, mainly due to the usage of natural gas for the furnace and carbon dioxide emission during the calcination of waste chicken eggshells. Out of all processes, raw material transportation has the least contribution on all impact categories with a slightly lower total impact of 0.027 Pt. It can be noticed that all phases have similar trending, i.e. lower impact on ecosystem quality and higher impact on resource depletion and damage category due to greater electricity usage for electricity generation (Singh et al., 2018). Fig. 4 below displays the overall total single scores of all processes. Observation showed that transesterification of WCO is differed from the raw material transportation about 31 times. Hence, it can be concluded that the contribution of damage on ecosystem quality, human health, and resources are contributed from the main component of biodiesel production, the transesterification.

3.4. Comparison of LCA with *Jatropha* oil biodiesel production

A comparison was made between WCO biodiesel and *Jatropha* oil biodiesel in order to investigate the sustainability of both biodiesels. The results used for comparison were extracted from the simulation conducted by Kaewcharoensombat (2011) which the results were generated from SimaPro 7 by using Eco-indicator 99 as the impact assessment method.

Table 3
Endpoint results from Eco-indicator 99 (E/E) for different system boundaries.

Damage Category	Unit	Raw Material of Transportation	Catalyst Preparation	Pretreatment of WCO	Transesterification of WCO
Ecosystem Quality	Pt	0.003	0.012	0.011	0.032
Human Health	Pt	0.01	0.063	0.047	0.138
Resources	Pt	0.014	0.256	0.235	0.683
Total	Pt	0.027	0.331	0.293	0.853

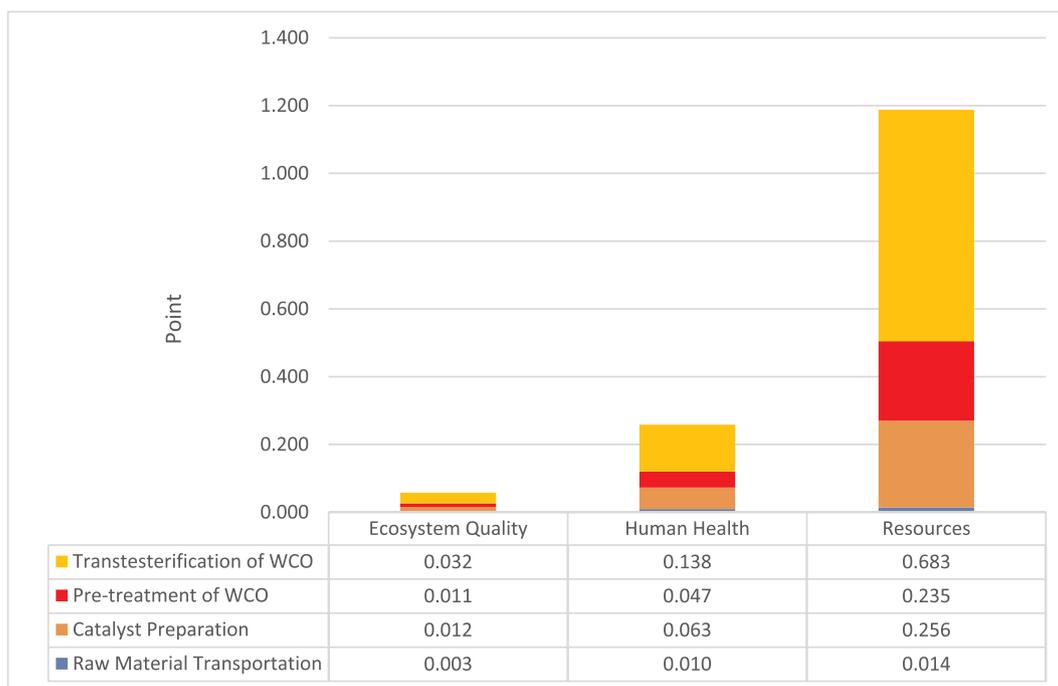


Fig. 3. Weighting of the biodiesel life cycle for different categories.

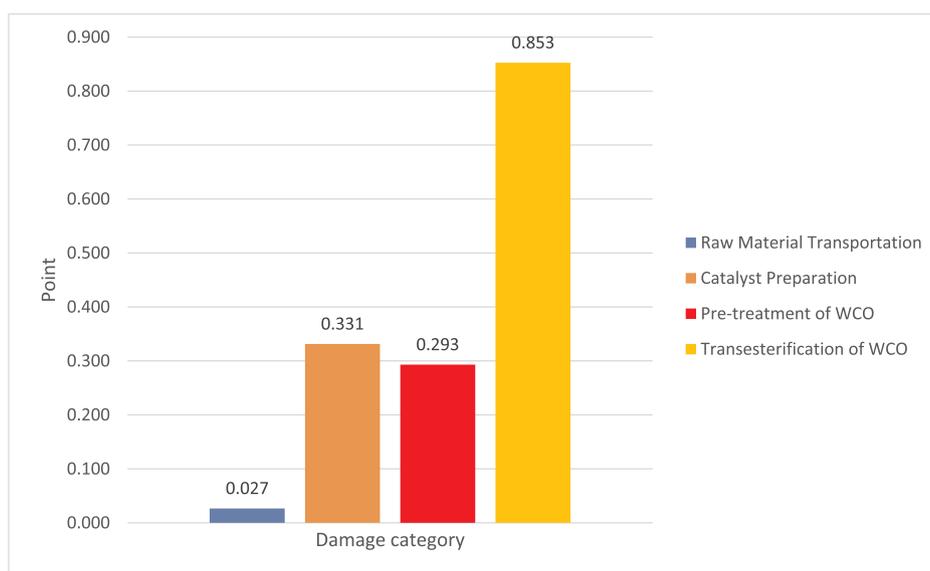


Fig. 4. Total single scores for all processes of WCO biodiesel production catalyzed by chicken eggshells derived CaO.

Similar to this study, the functional unit was set as 1000 kg of biodiesel production and all inputs and outputs were referred to the specified functional unit. In their studies, the oil conversion was set at 99% and the wash water was assumed to be 0.3 kg/kg oil. In order to ease the

comparison process, use phase, which involved the combustion of biodiesel, was excluded from the results since use phase was not included in the system boundary in this study. Note that both studies used electricity production database that was set to Europe context.

Jatropha oil biodiesel production included the agriculture phase in the system boundary which it involved the plantation of Jatropha seed and harvesting. Meanwhile WCO biodiesel production does not include the agriculture since it can be collected directly from the WCO distribution center, which makes it to be less harmful to the environment. [Kaewcharoensombat et al. \(2011\)](#) stated that agriculture phase of Jatropha seed required a higher amount of resources as it involved the use of agro-vehicles that utilize diesel fuel to operate. In [Table 4](#) below, agriculture phase shows second greatest contribution on ozone layer depletion among other stages with an impact of 1.53E-08 DAILY. The plantation process used refrigerants in the fertilizer process which it releases CFCs and HFCs that resulted in ozone layer depletion. As for the catalyst preparation phase in WCO biodiesel production, greater damage on human health is found as the calcination of eggshells eliminates certain amount CO₂ into the atmosphere, which indirectly contributed impact on climate change. However, CO₂ is less harmful than other emissions such as nitrogen oxide and sulfur oxide, which they are detrimental to human health. Catalyst preparation phase in this study did not involve any use of refrigerant fertilizer during the process, thus, the ozone layer depletion is rather low and it is mostly due to the emission of methane gas during the electricity production.

In Jatropha oil biodiesel context, [Kaewcharoensombat et al. \(2011\)](#) had define the system boundaries to include the process of Jatropha oil extraction and transesterification process to produce biodiesel. Jatropha oil biodiesel exerted a higher impact in terms of all impact categories compared to WCO biodiesel production as shown in [Table 4](#) below. It can be observed that fossil fuels consumption (3.43E+02 MJ surplus), ecotoxicity (8.72E+00 PAF × m²yr) and acidification/eutrophication (5.14E-02 PDF × m²yr) in Jatropha oil biodiesel production phase are higher than WCO biodiesel production phase. This is due to large amount of resources consumption during the process of extraction and transesterification and these processes utilize many equipment that consumed the earth resources directly ([Kaewcharoensombat et al., 2011](#)). Both carcinogen and respiratory inorganic impact categories obtained a value of 5.94E-06 DALY and 1.35E-04 DALY, respectively in Jatropha oil biodiesel production. It has indicated that the amount of carcinogen and respiratory inorganic substances emitted from the biodiesel production phase of Jatropha biodiesel is significant compared to other stages. This process may emit toxic gases such as CO, NH₃ and SO_x into the atmosphere during the use of resources. Meanwhile, transesterification process in WCO biodiesel production only discharged carcinogen and respiratory inorganic substances with the values of 1.41E-07 DAILY and 1.54E-06 DAILY. The required electricity in this process is lower than Jatropha oil biodiesel production due to exception of extraction phase for oil feedstock.

It can be observed from [Table 5](#), the transportation phase for Jatropha oil biodiesel production has lesser environmental impact than the one in WCO biodiesel production. The total single score for

transportation of raw material of Jatropha oil is 0.00537 Pt, whereas for WCO is 0.027 Pt. This can be explained by the distance travelled for the raw material of Jatropha to biodiesel plant was shorter (0.16 t × km) and the selected transportation data for raw material of WCO was referred to transport operation of lorry >32t in Europe countries, whereas the transportation data for Jatropha oil biodiesel was referred to transport operation in Thailand. Different transportation data have different emission and impact factor for each component. The total impact generated by agriculture phase in Jatropha oil biodiesel production is 0.429 Pt, which it is greater than the total impact from catalyst preparation (0.331 Pt), as shown in [Table 5](#) below. By referring to the total single scores of the both biodiesel life cycle in [Table 5](#), the results clearly show that biodiesel production from Jatropha oil contributed a larger impact (15.7Pt) than the summation of single scores of pretreatment and transesterification process of WCO (1.146 Pt). This has indicated that Jatropha oil biodiesel has included agriculture phase in [Kaewcharoensombat et al. \(2011\)](#) simulation and this required higher electricity usage. However, both WCO biodiesel and Jatropha oil biodiesel production have revealed higher effect on the human health than ecosystem quality. It has designated that both biodiesel productions would discharge harmful emissions during electricity production and lead to human health issue ([Mohammadi et al., 2013](#)). It has proven that the biodiesel production from WCO is one of the most reliable methods to mitigate the environment impacts in the production of green fuel, biodiesel. Biodiesel production from Jatropha oil generated higher impact on ecosystem quality, human health and resources due to the additional the extraction process of Jatropha oil. Another tendency would be the differ technology used for the transesterification of Jatropha oil, which varies from transesterification of WCO in this study. Thus, it can be determined that WCO biodiesel production using waste chicken eggshell derived CaO as catalyst is more environment friendly compared to Jatropha oil biodiesel production.

3.5. Comparison of LCA on WCO biodiesel production with homogeneous catalyst (KOH)

[Tables 6 and 7](#) below show the comparison of results obtained from CML 2 baseline 2000 impact assessment method between WCO biodiesel using waste chicken eggshell derived CaO and WCO biodiesel production using potassium hydroxide (KOH) as catalyst. In this comparative study, CML 2 Baseline 2000 was chosen as the impact assessment method to ensure the results obtained from WCO biodiesel production using waste chicken eggshell derived CaO is in accordance to WCO biodiesel production using KOH as catalyst. Results of WCO biodiesel production using waste chicken eggshell derived CaO generated by CML 2 Baseline 2000 was shown in [Table 6](#) below and these results of WCO biodiesel production using KOH were obtained from the simulation conducted by [Talens Peiró et al. \(2010\)](#). Electricity production and

Table 4
Midpoint results of Jatropha oil-based biodiesel and WCO biodiesel from Eco-Indicator 99.

Impact Category	Unit	Jatropha Biodiesel (Kaewcharoensombat et al., 2011)			WCO Biodiesel			
		Agriculture	Biodiesel Production	Transport	Transportation	Catalyst Preparation	Pretreatment of WCO	Biodiesel Production
Acidification/ Eutrophication	PDF × m ² yr	5.14E-02	4.53E+00	5.86E-03	7.87E-03	2.67E-02	2.20E-02	6.39E-02
Carcinogens	DALY	1.82E-07	5.94E-06	1.04E-09	8.22E-09	5.28E-08	4.83E-08	1.41E-07
Climate change	DALY	3.52E-07	4.65E-05	1.21E-08	3.46E-08	3.36E-06	5.92E-07	1.72E-06
Ecotoxicity	PAF × m ² yr	5.98E-01	8.72E+00	6.77E-02	6.79E-02	1.26E-01	1.16E-01	3.37E-01
Fossil fuels	MJ surplus	1.12E+01	3.43E+02	5.80E-02	2.06E-01	3.77E+00	3.46E+00	1.01E+01
Land use	PDF × m ² yr	3.82E-02	2.30E-01	1.98E-04	4.24E-03	4.72E-01	4.33E-01	1.26E+00
Minerals	MJ surplus	1.10E-02	1.01E-02	5.17E-05	2.49E-03	2.31E-02	2.12E-02	6.17E-02
Ozone layer	DALY	1.53E-08	1.04E-07	7.93E-11	2.42E-11	3.20E-10	2.94E-10	8.54E-10
Radiation	DALY	5.63E-09	0	2.92E-11	2.82E-10	7.29E-08	6.68E-08	1.94E-07
Respiratory inorganics	DALY	1.37E-06	1.35E-04	9.81E-08	2.08E-07	6.23E-07	5.30E-07	1.54E-06
Respiratory organics	DALY	3.17E-08	2.19E-06	3.59E-10	3.68E-10	1.38E-09	1.23E-09	3.56E-09

Table 5Scores for all damage categories of the biodiesel life cycle for *Jatropha* oil-based biodiesel and WCO biodiesel.

Jatropha Biodiesel (Kaewcharoensombat et al., 2011)				WCO Biodiesel				
Damage Category	Unit	Agriculture	Biodiesel Production	Transport	Transportation	Catalyst Preparation	Pretreatment of WCO	Transesterification of WCO
Ecosystem Quality	Pt	0.0145	0.549	0.00125	0.003	0.012	0.011	0.032
Human Health	Pt	0.038	3.67	0.00217	0.01	0.063	0.047	0.138
Resources	Pt	0.377	11.5	0.00195	0.014	0.256	0.235	0.683
Total	Pt	0.429	15.7	0.00537	0.027	0.331	0.293	0.853

Table 6

Environmental impact of all processes in WCO biodiesel production catalyzed by chicken eggshells derived CaO using evaluated using CML 2 Baseline 2000 from OpenLCA.

Impact category	Unit	Raw Material Transportation	Catalyst Preparation	Pretreatment of WCO	Transesterification of WCO
Abiotic depletion	kg Sb eq	1.20E-03	2.60E-02	2.38E-02	6.93E-02
Acidification	kg SO ₂ eq	9.63E-04	4.67E-03	4.05E-03	1.18E-02
Eutrophication	kg PO ₄ eq	1.92E-04	6.16E-04	5.08E-04	1.48E-03
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	7.10E-03	6.08E-02	5.57E-02	1.62E-01
Global warming potential	kg CO ₂ eq	1.65E-01	1.60E+01	2.83E+00	8.23E+00
Human toxicity	kg 1,4-DB eq	3.77E-02	5.48E-01	3.79E-01	1.10E+00
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.59E+01	2.29E+02	2.10E+02	6.10E+02
Ozone layer depletion	kg CFC-11 eq	2.31E-08	3.03E-07	2.78E-07	8.09E-07
Photochemical oxidation	kg C ₂ H ₄ eq	3.14E-05	3.21E-04	2.66E-04	7.75E-04
Terrestrial ecotoxicity	kg 1,4-DB eq	3.26E-04	3.77E-03	3.44E-03	1.00E-02

Table 7

Comparison of results between WCO biodiesel production catalyzed by chicken eggshells derived CaO and KOH.

Impact category	Reference unit	Our study	WCO biodiesel production using KOH (Talens Peiró et al., 2010)	Discrepancy
Abiotic depletion	kg Sb eq	1.20E-01	5.51E+00	5.39E+00
Acidification	kg SO ₂ eq	2.15E-02	1.39E+00	1.37E+00
Eutrophication	kg PO ₄ eq	2.79E-03	1.00E-01	9.72E-02
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	2.86E-01	1.92E+01	1.89E+01
Global warming potential	kg CO ₂ eq	2.72E+01	3.00E+02	2.72E+02
Human toxicity	kg 1,4-DB eq	2.07E+00	1.07E+02	1.05E+02
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.06E+03	1.39E+05	1.38E+05
Ozone layer depletion	kg CFC 11 eq	1.41E-06	5.80E-05	5.66E-05
Photochemical oxidation	kg C ₂ H ₄ eq	1.39E-03	8.00E-02	7.86E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	1.75E-02	5.20E-01	5.02E-01

transport operation were mainly referred to Spain context for the WCO biodiesel production using KOH as catalyst. Selected data in the literature was extracted from the database available in Ecoinvent V1.2. Both studies used the same functional unit which it was 1000 kg of biodiesel production. Although the software used for the literature was SimaPro7.02, the gotten results were comparable using OpenLCA because they both opted for the same impact assessment method and both results have included the pretreatment stage. Note that the life cycle inventory used for both processes were different due to different location and technology used.

Similarly, the result has illustrated that both WCO biodiesel productions generated the greatest impact on marine aquatic ecotoxicity with a value of 1.60E+03 and 1.39E+05 kg 1,4-DB eq, respectively. A significant discrepancy value between both processes, 1.38E+05 kg 1,4-DB eq is observed. Electricity production used in WCO biodiesel production using waste chicken eggshell derived CaO discharged heavy metals such as barite and nickel into the freshwater or ocean that would

affect the marine ecosystem (Talens Peiró et al., 2010). The simulation results in this study also have displayed that transportation is insignificant in the marine aquatic ecosystem because the generated gaseous is low. Whereas, for WCO biodiesel production using KOH as catalyst, pretreatment of WCO stage contributed a larger marine aquatic toxicity impact with a value of 60% on the overall impacts. Talens Peiró et al. (2010) stated that ~85% electricity production is the major contributor on marine aquatic ecotoxicity impact category due to the involvement of the burning of hard coal and fuel oil. Electricity supply in their study was a combination production stages, which it involved several types of resources, such as coal and nuclear energy to produce electricity as shown in the database, whereas our study was mainly using electricity supply from hydropower.

Table 6 shows the catalyst preparation phase of waste chicken eggshell derived CaO generated a smaller impact on human toxicity and terrestrial ecotoxicity with the amount of 5.48E-01 kg 1,4-DB eq and 3.77E-03 kg 1,4-DB eq, respectively. According to Talens Peiró et al. (2010) study, biodiesel production via KOH catalyst have contributed to human toxicity (14%) and terrestrial ecotoxicity (24%). The difference between WCO biodiesel using waste chicken eggshell derived CaO and KOH on human toxicity and terrestrial ecotoxicity are 1.05E+02 kg 1,4-DB eq and 5.02E-01 kg 1,4-DB eq. The impact associated to KOH production is more significant as the synthesis of pure KOH chemical required larger electricity supply than the high temperature calcination process of chicken eggshells. Besides, the production of KOH involved various type of chemicals and additives as the raw materials, along with multiple complex processes. While, waste chicken eggshell is generally collected from restaurants or bakeries and the catalyst generation only required high temperature thermal treatment, which releases handful carbon dioxide gas and this process does not consume much electricity. Therefore, the impact contributed on the environment is lesser compared to the production of KOH.

Nonetheless, the overall WCO biodiesel production for both catalysts also show a significant discrepancy, especially on the global warming potential, human toxicity, freshwater aquatic ecotoxicity and acidification, which can be obtained in Table 7 below. Both biodiesel production processes possessed high damage on the global warming potential. Nevertheless, the transesterification catalyzed by KOH shows a greater impact on global warming with a value of 3.00E+02 kg CO₂ eq. The difference of impact on global warming potential between both processes is 2.72E+02 kg CO₂ eq. Transesterification catalyzed by KOH

emitted more carbon dioxide to the surrounding in comparison, which it is mainly due to larger amount of resource (electricity, etc.) was selected in the simulation (Talens Peiró et al., 2010). Whereas, WCO production using chicken eggshells derived CaO demonstrated lesser impact on all damage categories than KOH as catalyst. One of the reasons for WCO biodiesel production using KOH displayed a greater significant environment impact is its non-reusable properties, which lead to higher soap formation and other residues, such as potassium sulfate during the process of purification and neutralization of WCO. Consequently, this has resulted in generation of large amount of wastewater and this wastewater will lead to pH alteration of the water sources (river, streams, etc.), deteriorating the aquatic life, as well as human health. Purification and neutralization process of the biodiesel mixture required huge amount of electricity and chemical additives (Renato et al., 2017). Unlike KOH catalyst, waste chicken eggshell is undergone one process step, high temperature calcination to form chicken eggshell derived CaO to be used as the solid catalyst. The derived CaO from chicken eggshell can be reused up to 5 cycles and it eliminates the complex purification or neutralization process, which has further reduced the electricity consumption than any homogeneous catalyst (Martínez et al., 2019). Separation of waste chicken eggshell derived CaO is easier via filtration and decantation process without requirement of high electricity supply. Implication of waste chicken eggshell derived CaO as solid catalyst can reduce the natural resource depletion and at the same time, it could generate a higher yield of biodiesel. Likewise, utilization of waste chicken eggshell to derive the CaO catalyst can reduce the production cost by reusing the waste material, indirectly decrease the landfill size and the reusability feature of this catalyst is worth to invest.

4. Conclusion

This research studied the LCA of WCO biodiesel production with the waste chicken eggshell-derived CaO as solid catalyst. Midpoint of LCA result shows that transportation phase has the least contribution, while transesterification process alone has contributed 1.01 + 01 MJ surplus on fuel consumption, 1.26 PDF \times m²yr on land use and 3.37E-01 PAF \times m²yr of ecotoxicity due to high demand of electricity supply. Endpoint indicator assessment shows resources depletion has the highest scores for all stages during production. It is found that Jatropha oil biodiesel production contributes to higher environment impact than WCO biodiesel production as it involves plantation and fertilizing. The summation of single scores of pretreatment and transesterification process of WCO is 1.14 Pt, whereas biodiesel production phase of Jatropha oil is 15.7 Pt. Second comparative study shows that both transesterifications catalyzed by waste chicken eggshell-derived CaO and KOH have large impact contribution on marine aquatic ecotoxicity which it is due to the release of heavy metal into the ocean/freshwater during electricity production. Utilization of waste chicken eggshell-derived CaO has lesser impact compared to KOH because calcination process does not involve complex process and huge usage of electricity. Moreover, biodiesel production using KOH contributed impact on climate change with 2.72E+02 kg CO₂ eq greater than that using waste chicken eggshell-derived CaO due to higher electricity demand.

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