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Process simulation and life cycle analysis of biodiesel production

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ABSTRACT

Biodiesel is a renewable and sustainable biofuel. There are various production processes to produce biodiesel from different kinds of raw materials. In this study, the environmental impacts of biodiesel production from non-edible Jatropha oil and waste cooking oil (WCO) were investigated and compared using systematic life cycle assessment. The results show that crops growing and cultivation of non-edible Jatropha curcas lead to higher environmental impacts compared to WCO process. However, biodiesel production process from Jatropha oil has better performance because the WCO process needs to consume variety of chemicals and requires a large amount of energy for the pretreatment of raw WCO and further chemical conversion to biodiesel. Results also indicate that the collection mechanism of WCO has significant contributions towards environmental impacts. In general, biodiesel production from Jatropha oil shows higher impacts for damage categories of climate change, human health and ecosystem quality whereas biodiesel production from WCO has more severe environmental impacts for resource category. The total environmental impact is 74% less in case of using WCO as raw material compared to non-edible Jatropha oil.

1. Introduction

In 2012, United States has been the major consumer of crude oil in the world [1]. This consumption is linked with increased demand of crude oil as transport fuel and is continuously depleting natural resources of fossil fuel. Besides these facts, the consumption of conventional crude oil is contributing to severe environmental impacts. One of those impacts is the global warming [2]. As an alternate fuel to conventional crude oil, biodiesel has the potential to reduce the dependency on natural resources and greenhouse gas emissions [3].

The production of biofuel from biomass depends on two major factors. First, the availability of raw material for biofuel and second, the process adopted to produce biofuel. Abbaszaadeh et al. [4] summarized different biodiesel production technologies. The most widely used process to produce biodiesel is the transesterification, a chemical reaction between biomass feedstock and an alcohol in the presence of a catalyst. The reaction bi-products are biodiesel, chemically known as ethyl or methyl esters, and glycerol. The biomass feedstock could be vegetable oil or animal fat. In edible oils, typically, soybean oil, sunflower oil, rapeseed oil, and palm oil are used as raw materials. Since these raw materials are also used as food, their abundant use to produce biofuel (energy) can lead to food shortage.

In order to avoid this conflict between energy and food demand, in recent years, the research has been shifted to produce biodiesel from non-edible resources [5–9]. Though the use of non-edible resources as biomass feedstock eliminates the debate of food and energy scarcity, the non-edible biomass feedstock still requires the use of land to grow crops. But the requirement of land is much less demanding as compared to those for edible biomass feedstocks preparations [10]. The non-edible biomass feedstocks include mainly the oils from non-edible vegetables, such as *Jatropha curcas* (Jatropha) [11,12], *Linum usitatissimum* (Linseed) [13], *Simmondsia chinesnsis* (Jojoba) [14], *Hevea brasiliensis* (rubber seed) [15], *Azadirachta indica* (Neem) [16], Cotton seed [17], *Calophyllum inophyllum* (Polanga) [11], *Nicotianna tabacum* (tobacco) [18], *Pongamia pinnata* (karanja) [19] and *Maduca indica* (mahua) [20].

Studies have been carried out to scrutinize the physicochemical properties of biodiesel produced from these non-edible biomass feedstocks [9,21]. Other than non-edible vegetable oils, research is underway to use waste cooking oil (WCO) as potential biomass feedstock to produce biodiesel [22,23]. The availability of WCO comes from different resources, including commercial, industrial, and domestic sources.

The advantages of using WCO to produce biodiesel are threefold. First, it can significantly decrease the amount of farmland, which is necessary for biodiesel producing corps. Second, the usage of WCO

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also helps to reduce biodiesel production costs [24–27]. Third, the waste management of WCO is a problematic step and its use as biofuel raw material reduces the cost of waste product removal and treatment. In the light of above facts, research has recently been focused on the use of WCO as raw material to produce biodiesel [28–31]. However, there are also few disadvantages associated with the use of WCO as biodiesel raw material, during the frying of cooking oil, free fatty acid and other products namely polymerized triglycerides are formed in oil. These products effect the transesterification reaction for biodiesel production [26]. The collection and supply chain mechanism of WCO in some countries has not been sufficiently develop [32,33]; and research is being conducted to develop an effective WCO collection mechanism [34].

From the production point of view, either of these raw materials can be used to produce biofuel by transesterification. However, from environmental perspective, the choice between these raw materials is not straight forward as the use of both raw materials has their respective advantages and disadvantages. The transesterification of non-edible oil seems to be simple and the raw material requires no special treatment, which helps to reduce the chemical consumptions in the production process. However, the preparation of non-edible biomass requires crop cultivation, which consumes fertilizers, chemicals, conventional fuels, water, pesticides, and energy – thus generating high environmental impacts. On the other hand, a pre-treatment of WCO is essential before it is converted to biodiesel through transesterification. This pretreatment requires different kinds of chemicals and have different energy requirements, which also engender significant environmental impacts. Although biodiesel production from WCO does not need to use fertilizers, land and water for biomass culture, a collection system has to be developed to collect the WCO from different resources. Clearly, no apparent solution is available to evaluate which raw material provides less environmental damages unless a complete systematic study is conducted. One of the tools employed for quantitative assessment of the environmental impacts (greenhouse gas emissions (GHG), resource consumption and depletion, and human health impacts, etc.) of biodiesel production is the life cycle assessment (LCA). LCA helps to evaluate the environmental impacts of a product over its entire life – from the preparation of raw material, through the manufacturing of product and its use, reuse and disposal at the end of its useful life [35].

In recent years, a number of studies have been undertaken to estimate the environmental impacts of biodiesel production from various biomass feedstock. Farrell & Cavanagh [36] studied the environmental impacts of biodiesel from waste vegetable oil and fresh vegetable oil and made a comparison of the results with those of petroleum diesel. Kaewcharoensombat et al. [37] studied LCA of biodiesel production from Jatropha oil using two different catalysts, i.e., sodium hydroxide and potassium hydroxide. They studied eleven environmental categories except global warming, which is an important environmental impact category. Morais et al. [38] performed simulation and an LCA of three process design alternatives for biodiesel production using waste cooking oil as raw material. Their simulation for alkali-catalyzed process with free fatty acid (FFA) pre-treatment did not include any treatment of unconverted oil stream neither it was considered as a waste in their LCA studies.

Previous LCA studies of biodiesel focus on few environmental impacts and do not present the complete picture of environmental damages. As shown in the literature review, some of LCA studies, even, do not include complete production process in their analysis. The production stage of biodiesel has high requirements of material and energy and emits high wastes, therefore any waste or stream in production stage cannot be neglected without proper justification. Neglecting such streams might have huge environmental impacts, which could mislead the results of LCA. Moreover, previous studies do not provide an LCA on a comparative base. A unique system boundary and functional unit is required to compare two cases, as the LCA studies are highly dependent on these two factors.

This paper aims to study biodiesel produced from two different raw materials: the Jatropha oil and WCO using alkali-catalyzed transesterification method. The LCA was performed on the preparation of respective raw materials, their production, industrial conversion of raw materials into biodiesel and biodiesel end use. Moreover, in case of Jatropha oil, the environmental damage due to crops growing, their harvesting, raw material transportation and seed-oil extraction was included. The environmental impacts of biodiesel production from WCO was also studied using its supply chain, collection technologies, the energy required in pretreatment of WCO and quality of biomass. The production environmental load from each case was estimated by using a process simulator, Aspen HYSYS v7.3, for assessing the material and energy requirements. The results of the process simulation were used as input for LCA study. A detailed life cycle assessment on an equal comparison bases was also carried out.

2. Methodology

2.1. Process simulation

The production of biodiesel from biomass feedstock is a well-understood process. In the current study, alkali-catalyzed transesterification process is studied to produce biodiesel. This process requires low reaction temperatures (66 °C) and low-pressure (20psi). Moreover, the reaction completes in a short time while provides high conversion factor (98%). The catalyst used in the current study is sodium hydroxide. In order to study the LCA of biodiesel production from Jatropha oil and WCO, the material and energy requirements, based on process flow sheeting, were required. In earlier publication, a biodiesel plant producing 45,000 t/yr biodiesel was simulated in HYSYS [39]. The plant utilises Jatropha oil as raw material to produce biodiesel. The results of material and energy balances were referred in this paper. In case of WCO, a biodiesel plant using WCO as raw material was simulated in HYSYS for the same production rate. Due to ease of availability, WCO provide a viable alternative to conventional diesel. The production of biodiesel from WCO is an energy efficient process [40]. WCO collected from different resources contains approximately 6% free fatty acids. Such high free fatty acid contents make the raw WCO difficult to be directly reacted with methanol, in the presence of sodium hydroxide to produce biodiesel. Hence, a pre-treatment of raw WCO is prerequisite. The steps for pretreatment of raw WCO and chemical conversion of WCO to biodiesel (alkyl ester) are as follows,

1) Filtration – removes any suspended solids in raw WCO
2) Reaction of methanol, sulphuric acid (5%) and filtered WCO – it produces methyl esters and stream contains sulphuric acid.
3) Glycerol washing, the stream from step two is washed with glycerol – it removes sulphuric acid in the stream and WCO produced has 0.3% free fatty acid contents. WCO is reacted with methanol in the presence of sodium hydroxide to produce biodiesel [39].
4) Bottom stream of glycerol washer is distilled to recover methanol – methanol is obtained at the top of distillation column, which is recycled into the system, and bottom stream contains glycerol and sulphuric acid.
5) Distilled bottom stream is reacted with calcium oxide followed by the gravity separator – the step converted sulphuric acid into calcium sulphate.
6) An evaporator is used to separate methanol and glycerol – glycerol is recycled into the process.