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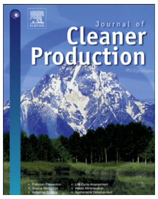

Evaluating the environmental impacts of bio-hydrogenated diesel production from palm oil and fatty acid methyl ester through life cycle assessment

Bulin Boonrod [a], Chaiwat Prapainainar [b, c], Phavanee Narataruksa [b, c], Angsana Kantama [b], Worayut Saibautrong [a], Kandis Sudsakorn [a], Thumrongrut Mungcharoen [a], Paweena Prapainainar [a, d, e, *]

[a] *Department of Chemical Engineering, Faculty of Engineering, Kasetsart University, Bangkok, 10900, Thailand*
[b] *Department of Chemical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, 10800, Thailand*
[c] *Research and Development Centre for Chemical Engineering Unit Operation and Catalyst Design, King Mongkut's University of Technology North Bangkok, Bangkok, 10800, Thailand*
[d] *Center for Advanced Studies in Nanotechnology and Its Applications in Chemical Food and Agricultural Industries, Kasetsart University, Bangkok, 10900, Thailand*
[e] *NANOTEC-KU-Center of Excellence on Nanoscale Materials Design for Green Nanotechnology, Kasetsart University, Bangkok, 10900, Thailand*

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ABSTRACT

Bio-hydrogenated diesel (BHD) produced from two different raw materials—palm oil fatty acid distillate and fatty acid methyl ester—was compared in terms of environmental impacts using the life cycle assessment (LCA) technique with the SimaPro 7.3 software. The energy consumption, greenhouse gas emission, and environmental impacts reported in unit points (Pt.) were assessed using the Eco-indicator 95, IPCC 2007, and CML 2 Baseline 2000 methodologies, respectively. The functional unit was 1 kg of biofuel product. The system boundary defined included three main processes in the bio-hydrogenated diesel production phase—catalytic hydroprocessing, separation, and upgrading. The results indicated that the energy consumption of bio-hydrogenated diesel production from palm oil fatty acid distillate was 1.26 times (or 9.69×10^{-3} MJ higher) that of the bio-hydrogenated diesel production from fatty acid methyl ester. On the other hand, the greenhouse gas emission from bio-hydrogenated diesel production from palm oil fatty acid distillate was 2.29 times lower than that from fatty acid methyl ester due to the palm trees absorption of CO_2 for photosynthesis being greater than the amount released into the atmosphere during the oil palm cultivation stage. The major contributor was crude palm oil as a feedstock to produce either palm oil fatty acid distillate (physical refining) or fatty acid methyl ester (trans-esterification), which were about 93% and 84% of the total energy consumption and greenhouse gas emission, respectively. The results of environmental impacts showed that the bio-hydrogenated diesel production from palm oil fatty acid distillate was 1.37 times (2.05×10^{-12} Pt) greater than that from fatty acid methyl ester. Consumption of palm oil fatty acid distillate and fatty acid methyl ester in both processes made the largest contribution to most environmental impacts (99% of the total impact score was from both processes). The main impacts of both bio-hydrogenated diesel production from palm oil fatty acid distillate and fatty acid methyl ester were the terrestrial ecotoxicity potential, fresh water aquatic ecotoxicity potential, and marine aquatic ecotoxicity potential. An essential factor which caused these impacts was the use of crude palm oil during the production of palm oil fatty acid distillate and fatty acid methyl ester. Therefore, fatty acid methyl ester was found to be a suitable raw material for bio-hydrogenated diesel production based on the economic evaluation and the lower environmental impacts during the production stage. This present work highlights the benefit of by-products as feedstock for alternative fuel production in order to increase the by-product marketing value.

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[*] Corresponding author. Department of Chemical Engineering, Faculty of Engineering, Kasetsart University, Bangkok, 10900, Thailand.
E-mail address: fengpwn@ku.ac.th (P. Prapainainar).

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1. Introduction

Currently, the demand especially for 80% of refined liquid fuels derived from petroleum is in the transport sector (Neamhom et al., in press). In addition, conventional diesel has long been identified as a contributor to environmental impacts such as global warming from the emission of greenhouse gases (GHG) (Dayaratne and Gunawardana, 2015). Nowadays, Thailand's industrial sector contributes more than 70% of total energy consumption and is also the second largest energy consumer and CO_2 emitter among ASEAN countries (Silalertruksa et al., 2012; Waewsak et al., 2015). Therefore, intensive studies and the development of alternative energy or renewable energy have been undertaken recently.

Alternative energy sources such as solar power, wind power, water, and energy from biomass are environmentally friendly. In transportation, alternative energy fuels are generally known as gasohol or gasoline mixed with alcohol, bio-oil from biomass through Fisher Tropsch synthesis, and biodiesel that can be used in diesel engines (de Sousa et al., 2016; Kittithammavong et al., 2014). Biofuel is another option. The Renewable and Alternative Energy Development Plan (AEDP: 2012–2021) promoted by the Thai government in 2013 is a strategy to develop new fuels that can be substituted for conventional diesel as the first generation of biodiesel products. The target amount of 25 ML/day includes various advanced biofuels, for example biodiesel from microalgae, biomass to liquid, and bio-hydrogenated diesel (Lecksiwilai et al., in press). Green diesel is also known as BHD (bio-hydrogenated diesel), HRD (hydrogenated renewable diesel), HBD (hydrogenated biodiesel), HVO (hydrotreating of vegetable oils), HDRD (hydrogenation derived renewable diesel), and RD (renewable diesel) (Yano et al., 2015). Green diesel is a fuel of the second generation type of biodiesel that is produced from oil field crops (both consumable and nonconsumable) such as palm oil, soybean oil, sunflower oil, rapeseed oil, and jatropha oil using a hydrogenation process (Hilbers et al., 2015; Mohammad et al., 2013; Uusitalo et al., 2014). At present, there are technologies available to produce BHD commercially that are used by various companies such as ConocoPhillips, Neste Oil, Petrobras, Syntroleum, UOP, Dynamic Fuels, Darling International Inc, Terviva, Nippon Oil, and AltAir Fuels (Arvidsson et al., 2011; Gärtner et al., 2006; Hilbers et al., 2015). These companies use a technology known as ecofining that consists of two main processes—hydrotreating and hydroprocessing.

The hydrogenation process removes oxygen molecules from triglyceride molecules and fatty acids by reacting with hydrogen gas (H_2) to form water, carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons similar to petroleum diesel (Bezergianni and Dimitriadis, 2013; Kiatkittipong et al., 2013). Table 1 shows the properties of BHD compared to other renewable fuels and diesel used in the transport sector. The cetane number of BHD is very high, resulting in a high engine efficiency and low emissions to the environment due to its low sulfur content. BHD also has better properties than biodiesel such as reduced emissions of NO_X, oxidative stability, reducing acidity, viscosity of the composition of oxygen in the fuel, and improved flow properties at low temperatures (cold flow property) (Bezergianni and Dimitriadis, 2013). This latter property benefits the combustion process as well as the catalytic after-treatment process (Arvidsson et al., 2011). Therefore, BHD is suitable to be mixed effectively with diesel from petroleum. On the other hand, by-products from the production of BHD such as propane have a higher marketing price than glycerol produced from the biodiesel production process.

Table 1
Bio-hydrogenated diesel properties versus mineral ultra low sulfur diesel (ULSD) and biodiesel (Bezergianni and Dimitriadis, 2013; Rotwiroon et al., 2012).

Property	Mineral ULSD	Biodiesel, (FAME)	BHD
Oxygen content, %	0	11	0
Specific gravity	0.84	0.88	0.78
Sulfur content, ppm	<10	<1	<1
Heating value, MJ/kg	43	38	44
Cloud point, °C	0	−5 to +15	−20 to +20
Distillation range, °C	200 to 360	340 to 370	200 to 320
Polyaromatics, wt%	11	0	0
NO_x emission, wt%	Baseline	+10%	−10%
Cetane number	51	50 to 65	70 to 90
Stability	Baseline	Poor	Baseline

Palm has potential as a feedstock for BHD production because it is a perennial crop so its outputs are produced all year. In addition, palm is a vegetable oil tree that is grown predominantly in Southeast Asian countries. During 1987 to 2011, the status of the palm oil industry has decreased and increased every 5 years, respectively (Mohammad, 2015; Valipour et al., 2015). In 2012, palm oil was the greatest contributor (almost 50 Mt) to the global vegetable oil trade (Schmidt, 2015). Thailand is the world's third largest producer of palm oil from fresh fruit bunches (FFB) with 11.32 Mt/M ha of palm under cultivation (Lecksiwilai et al., in press). This reflects the promotion of the biodiesel policy and the increasing world oil price. With a global production of almost 60 Mt and a global vegetable oil market share of more than 35% by weight, palm oil is the most produced vegetable oil in the world (Hansen et al., 2015).

A number of research laboratories and pilot plants have studied the production of raw materials for BHD. BHD production depends on the operating parameters and catalyst types of each feedstock. For example, Schmidt (2015) promoted catalytic hydrocracking of palm oil mill effluent (POME) using an Ni/MO-PM catalyst. This catalyst produced gasoline with diesel ranging from 5% to 10%. Guzman et al. (2010) used crude palm oil (CPO) as a feedstock with a Pd/C catalyst at 400 °C under 40 bar pressure, and a reaction time of 3 h. It provided a range of diesel at 50% and 90% conversion. Kiatkittipong et al. (2013) reported the operating conditions using degummed palm oil (DPO) feedstock with an $NiMo/\gamma\text{-}Al_2O_3$ catalyst at a temperature and pressure of 400 °C and 40 bar, respectively. This resulted in 70% conversion of diesel with a reaction time of 1 h. In addition, Kiatkittipong et al. (2013) produced palm fatty acid distillate (PFAD) using a with Pd/C catalyst at 375 °C with 40 bar pressure and achieved 81% diesel conversion with a reaction time of 0.5 h Srifa et al. (2015) recommended the optimum conditions of operating refined palm oleine (RPO) using an $NiMoS_2/\gamma\text{-}Al_2O_3$ catalyst at temperature and pressure of 300 °C and 30–50 bar, respectively, while LHSV (liquid hourly space velocity) and H_2/oil ratio at 1–2 per hour and 750–1000 N (cm^3/cm^3), respectively. This resulted in a product yield of 90% and an n-alkane content of more than 95.5%. Moreover, BHD was also produced from methylester which was the main component in biodiesel (Zuo et al., 2012).

The current research investigated the production process of BHD from two feedstocks—PFAD and biodiesel. PFAD is a by-product from the palm oil refining process. Typically, it can be used as material in many industries such as soaps, animal foods, biodiesel, and chemical production. It is a promising feedstock for biodiesel production as it is cheaper compared to refined oils by about 0.06 USD/kg in 2015 (Cheryl-Low et al., 2015; Kantama et al., 2015; Lokman et al., 2015). FAME (fatty acid methyl ester)-derived biodiesel is produced from the transesterification of refined palm stearin (RPOs) which is a by-product separated from RPO or palm oil for consumption. Silalertruksa et al. (2012) found that FAME from palm was more environmentally friendly than diesel in terms of CO_2 and SO_2 emissions. However, as palm oil is a raw material for the production of FAME, there is a limitation of 7% on the blending

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