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Life cycle assessment of hydrogenated biodiesel production from waste cooking oil using the catalytic cracking and hydrogenation method

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ABSTRACT

There is a worldwide trend towards stricter control of diesel exhaust emissions, however presently, there are technical impediments to the use of FAME (fatty acid methyl esters)-type biodiesel fuel (BDF). Although hydrogenated biodiesel (HBD) is anticipated as a new diesel fuel, the environmental performance of HBD and its utilization system have not been adequately clarified. Especially when waste cooking oil is used as feedstock, not only biofuel production but also the treatment of waste cooking oil is an important function for society. A life cycle assessment (LCA), including uncertainty analysis, was conducted to determine the environmental benefits (global warming, fossil fuel consumption, urban air pollution, and acidification) of HBD produced from waste cooking oil via catalytic cracking and hydrogenation, compared with fossil-derived diesel fuel or FAME-type BDF. Combined functional unit including "treatment of waste cooking oil" and "running diesel vehicle for household waste collection" was established in the context of Kyoto city, Japan. The calculation utilized characterization, damage, and integration factors identified by LIME2, which was based on an endpoint modeling method. The results show that if diesel vehicles that comply with the new Japanese long-term emissions gas standard are commonly used in the future, the benefit of FAME-type BDF will be relatively limited. Furthermore, the scenario that introduced HBD was most effective in reducing total environmental impact, meaning that a shift from FAME-type BDF to HBD would be more beneficial.

1. Introduction

To develop a low-carbon society, it is important to promote the production of biofuels such as biodiesel fuel (BDF). Biofuels are produced worldwide: Biofuel consumption in road transport accounted for 1.3 Mboe/day (million barrels of oil equivalent per day) as of 2011, and is expected to increase to 4.1 Mboe/day in 2035, an increase from 3% of road transport fuel demand in 2011 to 8% in 2035. Of this, biodiesel consumption accounted for 0.4 Mboe/day and is estimated to be 1.1 Mboe in 2035 (IEA, 2013). The fuels that are currently under development utilize non-food feedstock, including waste (Naik et al., 2010; Sims et al., 2010; Takamizawa et al., 2013). Such fuels are thought to be more environmentally desirable, because biofuels derived from food crops such as soybeans are associated with a number of problems: competition with food agriculture for land and water use, and widely varying assessments of net greenhouse gas (GHG) reductions once land-use change is taken into account (Fargione et al., 2008; Searchinger et al., 2008).

In Kyoto city, Japan, waste cooking oil has been collected from households since 1998, and used to produce BDF since 2004. The BDF production facility operated by Kyoto city has a capacity of 5 kL/day (1500 kL/yr), and is the largest facility managed by a local government in Japan. The alkali catalysis method is commonly used to convert waste cooking oil to BDF, which consists of fatty acid methyl esters (FAME) (Meher et al., 2006; Salvo and Panwar, 2012). As of fiscal year (FY) 2012, approximately 1300 kL of FAME-type BDF has been produced annually from waste cooking oil (approximately 196 kL from households and 1110 kL from

Abbreviations: BDF, biodiesel fuel; DALY, disability-adjusted life year; DAP, deposition-oriented acidification potential; EINES, expected increase in number of extinct species; FAME, fatty acid methyl esters; FY, fiscal year; GHG, greenhouse gas; GWP, global warming potential; HBD, hydrogenated biodiesel; HDRD, hydrogenation derived renewable diesel; HVO, hydrotreating of vegetable oils; LCA, life cycle assessment; NPP, net primary productivity; PM, particulate matter; UAF, urban air pollution characterization factor.

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businesses). Considering that the generation of waste cooking oil from households was estimated to be approximately 1140 kL within Kyoto city, this represents a collection rate of 17% waste cooking oil from households for BDF production. The produced BDF has been used as fuel for city buses (B20) and household waste collection vehicles (B100) within Kyoto city.

From the standpoint of air pollution, there has been an increasing focus globally on the control of gas emissions from diesel vehicles (EC, 2007). As shown in Table 1, Japan has also established and enforced gas emission standards that regulate pollutants such as NO_x and particulate matter (PM) emissions in a number of stages (DELPHI, 2014). For instance, in the case of NO_x emissions, the standard value for vehicles of gross weight more than 3.5 tons is 3.38 g-NO_x/kW h for the new short-term emissions gas standard (2002–2004), 2.00 g-NO_x/kW h for the new long-term standard (2005–2008), and 0.700 g-NO_x/kW h for the post new long-term standard (2009 onward). However, FAME-type BDF is occasionally problematic when used in diesel vehicles (Fukuda et al., 2008; WFCC, 2013). In particular, some technical problems have arisen in terms of the suitability of BDF for new-model diesel vehicles equipped with diesel particulate filters and NO_x reduction devices after implementation of the new long-term emissions standard.

These problems, which include the mixing of fuel with engine oil and the poor performance of NO_x reduction devices, have become major impediments to BDF use. Therefore, there are some challenges involved in producing new diesel fuels. HVO (hydrotreating of vegetable oils) has been developed and commercially supplied to mainly EU regions. HVO is also known as renewable diesel or HDRD (hydrogenation derived renewable diesel) in the USA, and as HBD (hydrogenated biodiesel) in the Far East including Japan (Neste Oil, 2014). HVO consists mainly of paraffins and is free of aromatics, oxygen, and sulfur. HVO generally shows higher cetane index and higher oxidation stabilities compared to FAME-type BDF (Bezergianni and Dimitriadis, 2013). HVO can be applied not only to vegetable oil but also to animal fats. Therefore, the HVO production method is expected to contribute to the expanding feedstock of BDF and resulting increases in fuel supplies. Neste Oil is the world's largest producer of HVO, which it supplies under the brand name "NExBTL." Its production capacity is approximately 2 million ton/yr from four facilities. HVO is made by hydrotreatment of vegetable oils and animal fats, but additionally, waste and residues such as waste animal fat accounted for over half of feedstocks (Neste Oil, 2013). The OPTIBIO project operated for 3.5 years, between autumn 2007 and December 2010, to demonstrate the use of NExBTL for city buses in Helsinki. The project confirmed that HVO can replace fossil-derived diesel without any modifications to the vehicles or refueling system (Nylund et al., 2011). The Worldwide Fuel Charter (WWFC) now evaluates HVO as being highly suited as a blendstock for diesel fuel (WWFC, 2013).

HVO has been also developed in Japan, where it is often called HBD. Attention has been given to the production method, namely catalytic cracking and hydrogenation (Tani et al., 2011a, 2011b), and a three-year demonstration project for this new method, involving Kyoto city, ASTEM, and other companies, was operational between April 2012 and March 2015 (ASTEM, 2013; Kakuta and Nakamura, 2014; Takasuga et al., 2014). Unlike the general methods, the catalytic cracking process promotes decarbonization, which has the notable benefit of reducing the consumption of energy and H_2. Hydrogenation after cracking requires normal pressure and temperature conditions (1.0 MPa G at 150 °C) and less H_2, whereas direct hydrogenation requires high pressure and temperature (4–6 MPa G at 300–350 °C) and consumes 10 times the amount of H_2. Therefore, hydrogenation after cracking is suitable for small- and mid-sized production facilities that utilize regional feedstocks such as waste cooking oil. The produced HBD has similar characteristics to those of diesel fuel, including calorific content and boiling point. The characteristics of some fuels, including HBD produced in the demonstration project at Kyoto city (ASTEM, 2013), are summarized in Electronic Supplementary Material.

A life cycle assessment (LCA) was performed to evaluate the effectiveness of BDF use in reducing negative environmental impacts. Liang et al. (2013) quantitatively showed that feedstocks had different environmental performances by comparing seven feedstocks including waste cooking oil. Dufour and Iribarren (2012) used LCA to evaluate six environmental impacts for four types of free fatty acid-rich wastes (used cooking oil, animal fats, sewage sludges), and concluded that biodiesel fuel from used cooking oil potentially achieved the most favorable environmental performance. On the other hand, when waste cooking oil was used for BDF production, the treatment (BDF production) method was also an important factor in environmental performance (Morais et al., 2010; Varanda et al., 2011). The environmental performance of HBD and its utilization system has not been adequately clarified. Garraín et al. (2014) showed that HBD blend diesel (13% blend) from soybean oil could reduce fossil fuel consumption by 2% and GHG emissions by 9% at well-to-tank stage compared with FAME blend diesel. Neste Oil (2014) estimated that the GHG reduction effects of NExBTL compared with fossil-derived diesel were 47%, 49%, and 91% for palm oil, rapeseed oil, and animal fat feedstocks, respectively; and, by conducting exhaust gas emission tests, showed that emissions of PM were reduced by approximately 30–40%. Evaluating exhaust gas emissions such as NO_x and PM from HBD production and its utilization system by means of a life cycle approach is also necessary to determine environmental performance compared with the FAME-type BDF that is generally used. Arvidsson et al. (2011) conducted an LCA of HBD production from rapeseed oil, palm oil, and Jatropha considering four environmental impacts: fossil fuel consumption, global warming, acidification, and eutrophication. The functional unit of the analysis focused on fuel supply (1 kW h of energy output). However, biofuel production and the treatment of waste cooking oil are important functions for society, especially when waste cooking oil is used as feedstock.

Table 1
Exhaust gas emission standards for heavy commercial vehicles in Japan.

Version of standard	Short-term	Long-term	New short-term	New long-term	Post new long-term
Implementation date	1994	1997	2003	2005	2009
Test mode	13 mode	13 mode	13 mode	JC08	JC08
Regulation value					
NO_x (g/kW h)	6.8	4.50	3.38	2.0	0.7
PM (g/kW h)	0.96	0.25	0.18	0.027	0.010
CO (g/kW h)	9.20	7.40	2.22	2.22	2.22
HC, NMHC (g/kW h)	3.80	2.90	0.87	0.17	0.17

The heavy commercial vehicle category has a gross vehicle weight >3.5 tons (>2.5 tons before 2005).
Implementation dates refer to new vehicle models.