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The energy usage and environmental impact assessment of spent coffee grounds biodiesel production by an *in-situ* transesterification process

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ABSTRACT

Spent coffee grounds (SCG) waste has been drawing attentions in the biodiesel industry due to the promising of oil content. However, SCG sources is very disperse and requires a transportation system. Moreover, a complexity of oil extraction steps using hazardous n-hexane can hinder the SCG biodiesel promotion. Therefore, an alternative approach using *in-situ* transesterification (*in-situ* TE), an n-hexane free process, was introduced for producing biodiesel at an on-site SCG source. Life cycle assessment was performed to compare the energy usage and environmental impacts between a conventional process, which requires transportation and n-hexane, and an on-site *in-situ* TE process. Producing SCG biodiesel using conventional process required 43% less energy and produced fewer environmental impacts than those of the on-site *in-situ* TE. Much of the difference was attributable to 73% of the energy in the *in-situ* TE being consumed in methanol recovery. Nevertheless, the *in-situ* TE process gained better scores in terms of respiratory organs and land occupation. A sensitivity analysis of energy usage on transportation distances and fuel consumption rates suggested that an on-site *in-situ* TE process could be viewed as more favorable once the transportation distance is greater than 180 km with 7 km/L of fuel consumption rate.

Introduction

Spent coffee grounds (SCG) have been drawing great attention in the biodiesel industry because they have a promising oil content between 15 and 28% (Caetano et al., 2012; Kondamudi et al., 2008; Kwon et al., 2013; Vardon et al., 2013) depending on the coffee species, coffee roasting and brewing processes; and are considered a waste product of the coffee production industry. Thus, the use of SCG as biodiesel feedstock does not divert edible oil from the food supply chain. Global coffee consumption has been increasing annually and in 2014 more than 9 billion tons was consumed (International Coffee Organization, 2016), half of which was produced by the instant coffee industry (Ramalakshmi et al., 2009). This can guarantee a stable, long-term SCG supply to the biodiesel industry. Several studies have reported the succession in producing SCG biodiesel *via* alkaline transesterification (TE) with the assistance of an oil pretreatment step (Al-Hamamre et al., 2012; Caetano et al., 2012; Vardon et al., 2013). However, the SCG biodiesel had a low oxidative stability index and high cloud point; thus it has to be blended with petroleum diesel to meet the blend diesel standards of ASTM D975 and ASTM D7467 (Vardon et al., 2013).

Like other biodiesel feedstocks (*e.g.*, soybeans, palm kernels, and canola), an oil extraction step is needed, and n-hexane, known for being hazardous, is often used. This step is a major barrier in the biodiesel industry because such a process can only be economically feasible at a production scale of 2400 tons of dried oilseed per day or more (Haas et al., 2004). Globally, the supply of SCG is sufficient for this kind of process; however, SCG sources can be spread out. Even though it is possible to collect the SCG and transport them to a central facility for oil extraction and biodiesel production, the question of transportation cost remains.

Recently, the application of *in-situ* transesterification (*in-situ* TE), an n-hexane free process, has been gaining interest in small-scale biodiesel production. It is a reactive extraction process using a sodium methoxide solution as the reactant and simultaneously as the oil extraction solvent, which thus reduces the size and complexity of the biodiesel production system (Haagenson and Wiesenborn, 2011; Tuntiwiwattanapun et al., 2016). Such a process can be set up within an instant coffee plant as an on-site biodiesel production unit. Moreover, several co-benefits could be obtained, such as: (1) it will add value to the SCG and reduce the waste management cost of the instant coffee plant; (2) the heat

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waste from the brewing and drying processes during instant coffee production could be utilized for on-site SCG biodiesel production; and (3) the post defatted SCG contains a high energy content, which could be used for heat and steam generation.

Although producing biodiesel at an instant coffee plant reduces transportation needs and has several additional co-benefits, there is still a lack of information regarding the application of the *in-situ* TE process as an on-site SCG biodiesel production in terms of its industrial-scale energy usage and environmental impacts. It is thus very important to investigate this to identify the hotspots of the process requiring further improvement.

A life cycle assessment (LCA) is a tool to quantify and compare the energy and environmental flows of a product over a designated boundary. LCA has become an important decision-making tool for promoting alternatives to petroleum fuel since it can reveal valuable information on the energy efficiency, environmental impacts and cost benefits of products.

Therefore, the objectives of this work are to evaluate the energy usage and environmental impacts of an on-site *in-situ* TE as SCG biodiesel production process, and compare the results to those of the conventional process using LCA.The inventory analysis of the on-site *in-situ* TE process was estimated by extrapolating the process conditions and performances of our pilot-scale *in-situ* TE process at an SCG load of 4 kg per batch; in the meantime, that of the conventional process was obtained from the literature.

Materials and methods

Characterization of SCG waste from the instant coffee industry

The SCG used in this study was obtained from Jacobs Douwe Egberts (JDE) an instant coffee producer. The SCG had an initial moisture content (MC) of 75% by mass and was sun dried for three days to a MC of 30%. JDE's instant coffee process generates approximately 1725 kg of SCG per day (dried weight) (P. Senawong, personal communication). The total oil content was 18.07% by mass, which was quantified by Soxhlet n-hexane extraction. The acid value of the extracted oil was 5.93 mg KOH/g oil.

Goal and scope

This study was accomplished through four steps according to International Standardization Organization (ISO) standards (ISO 14040, 2006; ISO 14044, 2006). The study compares the energy usage and environmental impacts of biodiesel production using SCG waste from an instant coffee plant. Two different scenarios of biodiesel production were studied:

- A conventional process: a process in which the SCG had to be transported from an instant coffee plant to a central facility where the SCG oil was extracted by n-hexane extraction before being converted into biodiesel using a 2-step transesterification process. Then, the produced biodiesel was transported back and used in the instant coffee plant.
- An on-site *in-situ* TE process: an on-site reactive extraction process using *in-situ* TE, which is a combined process of oil extraction and biodiesel synthesis, using sodium methoxide solution as the biodiesel reagent and solvent. There was no SCG and biodiesel transportation since this process was set up at the instant coffee plant.

The system boundary, “gate-to-gate,” started from the SCG pretreatment process at the instant coffee plant and ended at SCG biodiesel product. Thus, the cultivation of the coffee beans, coffee roasting, and the brewing process were not included in this study as well as the use of SCG biodiesel as a biofuel. One kilogram of SCG biodiesel was used as the functional unit.

Life cycle inventory

Data for the inventory analysis were collected from several studies in the literature. Relevant background data (*i.e.* raw material acquisition) were used from the ecoinvent 3 database (Wernet et al., 2016). An overview of the two different approaches for SCG biodiesel production is exhibited in Fig. 1. The sub-processes of each approach are described under the topics of “Conventional process (scenario I)” and “On-site in-situ TE process (scenario II)”, respectively.

Conventional process (scenario I)

The SCG was transported to a central biodiesel production facility for oil extraction (using n-hexane), biodiesel synthesis, and purification. After that, the SCG biodiesel was transported back and used at the instant coffee production plant. It should be noted that secondary data from the literature (*e.g.*, process conditions, process performance, and the energy usage of the instruments such as the pump, distiller, and mixer motor) were used in this section. The details of each step are presented below. The overall process of SCG oil extraction and biodiesel synthesis is illustrated in Fig. 2. The inventory analysis results of this approach are provided in Table 1.

Drying and SCG transportation. To reduce the MC of the SCG from 30% to 15% mass, 1.38 kg of water had to be removed by a dryer using natural gas as the energy source before being transported. The 15% MC of the SCG (6.43 kg) was then transported to the central facility for SCG oil extraction and biodiesel production using a 28 t ETH model truck (50% load) as the carrier. The distance between the instant coffee processing plant and the central facility was fixed at 35 km, making the roundtrip 70 km.

SCG oil extraction. There has not been a report on SCG oil extraction by n-hexane on an industrial scale. Since n-hexane produced soybean oil has a similar oil content of 18.9%, the information from the process conditions of n-hexane soybean oil extraction were applied in this section. The conditions and performance of oilseed pretreatment (additional drying and grinding), oil extraction using n-hexane (*R101A* in Fig. 2) and oil purification (*R102A* in Fig. 2) in this section follow the method described by Pradhan et al. (2011). Then, the SCG oil was used in a 2-step transesterification process for biodiesel production. There was an assumption that for every ton of inputted oilseed, approximately 11.1 cm^3 of n-hexane was lost during the oil extraction process (Haas et al., 2004).

2-Step transesterification. Due to the high acid value from the free fatty acids (FFA) in SCG oil (*5A* in Fig. 2), a pre-treatment step comprising esterification using H_2SO_4 as the catalyst was required before the TE step using NaOH as the catalyst. The process conditions and performance of esterification and TE using waste cooking oil as the biodiesel feedstock proposed by Varanda et al. (2011) were applied in this section because of its similar acidic value. In the esterification process (*R103A* in Fig. 2), a methanol-to-oil molar ratio of 6 with 0.9% of H_2SO_4 at 70 °C and 400 kPa was applied. All FFA in the SCG oil were converted to biodiesel. Then, the pretreated SCG oil (*8A* in Fig. 2) was converted to biodiesel using a methanol-to-oil molar ratio of 6 and 1% *w*/*v* of NaOH catalyst at 60 °C and 400 kPa.

Methanol recovery. The crude biodiesel with glycerol (*9A* and *11A* in Fig. 2) was sent to a multi-stage vacuum distillation for methanol recovery (*E102A* in Fig. 2). The conditions and performance of the process used followed those described by Varanda et al. (2011). The four stages and a reflux ratio of 2 were applied to ensure the high quality of the product. The methanol was then recycled back into the process.

Biodiesel water washing. After gravimetrical separation of biodiesel and glycerol, the biodiesel was washed by water at 21 °C (*R105A* in Fig. 2)