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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)

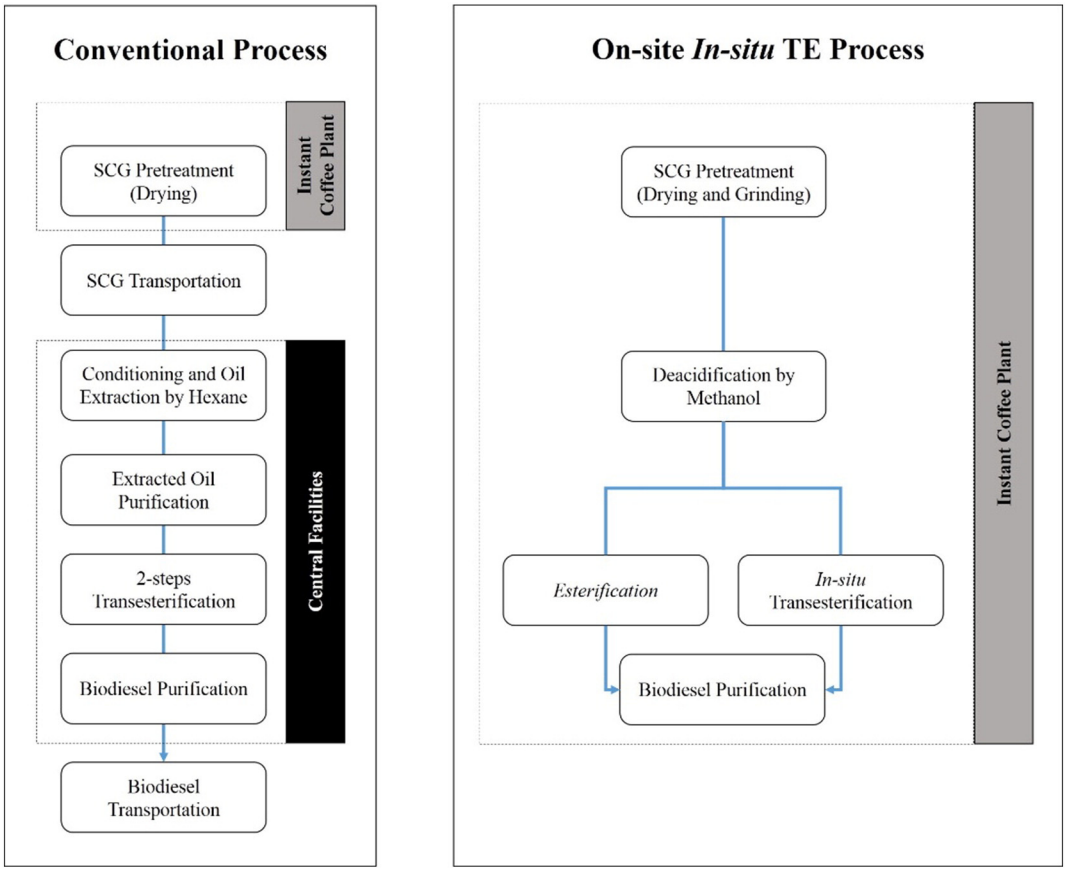

Fig. 1. A comparison of conventional and on-site *in-situ* TE SCG biodiesel process steps.

to remove the residual glycerol, methanol and catalyst (*12A* in Fig. 2). The process conditions and performance used followed those presented by Varanda et al. (2011).

Biodiesel and glycerol purification. In order to achieve high quality biodiesel (purity >99.6%) and glycerol (purity >93%), four-stage vacuum distillation with a reflux ratio of 2 (*R106A* and *R108A* in Fig. 2) was applied (Varanda et al., 2011).

Removal of the catalyst. The NaOH catalyst was neutralized by H_3PO_4, and formed Na_3PO_4 salt as a waste product.

On-site in-situ TE process (scenario II)

The SCG were used as the biodiesel feedstock in the on-site biodiesel production unit at an instant coffee plant. Thus, there was no transportation for raw material; SCG and the product; biodiesel. The conditions and performance of the processes used for analysis were obtained

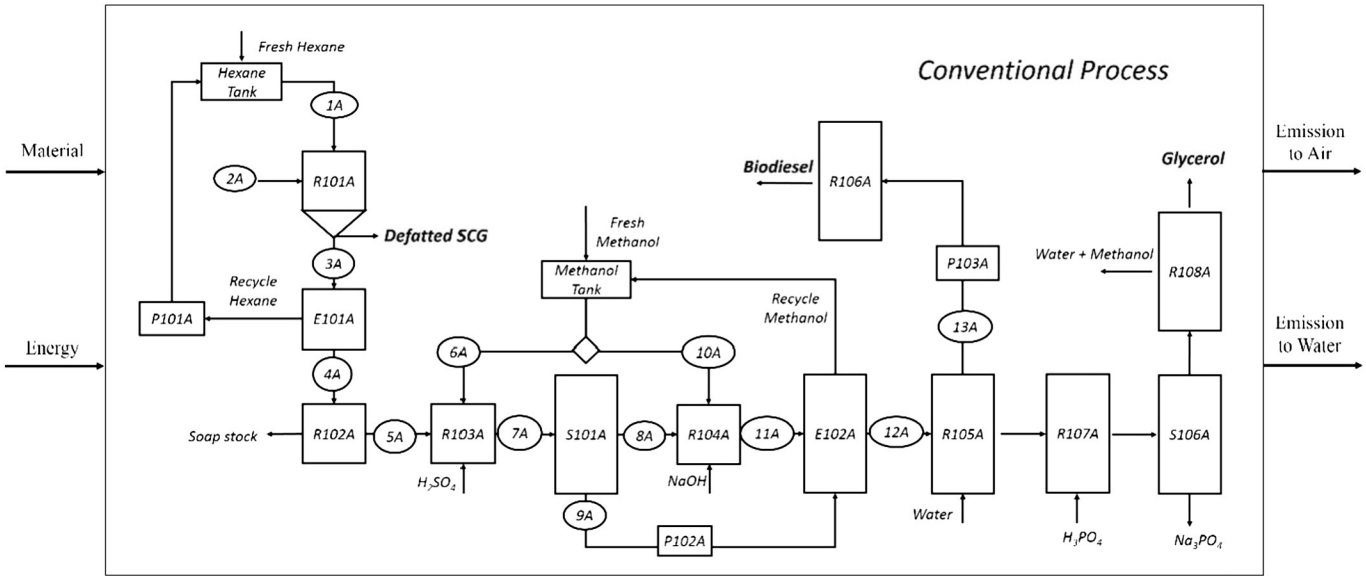

Fig. 2. System boundary of conventional SCG biodiesel production at a central facility.

Table 1
Inventory process of the conventional process for producing 1 kg of SCG biodiesel.

Feed		Product (kg)		Waste (kg)		Note
Drying & transportation						
30% MC SCG (kg)	7.81	15% MC SCG	6.43	Water	1.38	–Dryer performance 60%
Heat (MJ)	5.86					–Truck 28 t ETH model (50% load)
Diesel (MJ)	1.25					
Oil crushing						
15% MC SCG (kg)	6.43	Defatted SCG	4.48	Water	Not reported	Pradhan et al. (2011)
Heat (MJ)	3.94	SCG oil	0.99	Hexane	1.11E−02	
Electricity (kWh)	0.21					
2-Step transesterification						
SCG oil (kg)	0.99	Biodiesel	1.00	Na_3PO_4	4.46E−03	Varanda et al. (2011)
Methanol (kg)	0.21	Glycerol	0.09	H_2SO_4 + Glycerol + Methanol	8.59E−02	
H_2SO_4 (kg)	9.13E−03			Water + Methanol	3.83E−02	
NaOH (kg)	3.26E−03					
H_3PO_4 (kg)	2.67E−03					
Heat (MJ)	3.55					
Electricity (kWh)	2.66E−03					
Transportation (biodiesel)						
Diesel (MJ)	1.25					–Truck 28 t ETH model (50% load)

from our pilot scale operation (4 kg SCG/batch). An overview of the biodiesel production process is illustrated in Fig. 3. For the industrial instruments, we applied the specifications and energy usage data from Kaewcharoensombat et al. (2011). An inventory analysis of this process is provided in Table 2.

Drying and grinding. The sundried SCG with 30% MC was reduced to <1% MC using the same dryer mentioned in the conventional process. Approximately 2.76 kg of water had to be removed from the SCG. The dried SCG (6.44 kg) was then ground by a Micro-Max air swept fine grinder, model MM1600 (http://www.stedman-machine.com/micro-max-fine-grinders.html).

Deacidification. To reduce the high acid value from FFA in SCG, a pretreatment is required. In this study, the solid-liquid extraction technique using methanol was applied. Methanol is a very selective solvent; it can extract the FFA but still preserve the quantity of the oil (triglyceride) in SCG due to its hydrophilic property. A methanol-to-SCG ratio of 3 mL/g was applied with a 300 rpm mixing speed at 45 °C for 1 h (*R101B* in Fig. 3). Then, the slurry was filtrated through a metal sieve to separate the deacidified SCG (DSCG; *4B* in Fig. 3) from the liquid fraction (methanol extracted; *3B* in Fig. 3). The oil content in the DSCG was 18.34% mass with an acid value of <0.5 mg KOH/g oil. The titration result of the extracted methanol and molecular weight of triglyceride in the SCG (858 g/mol) showed that approximately 0.16 kg of FFA was found in the methanol.

Esterification. H_2SO_4 (*Acid (2)* in Fig. 3) was directly added to the methanol that was extracted (*3B* in Fig. 3) at a 1% *w/w* concentration, as the acidic catalyst, to convert all FFA to biodiesel. The process temperature was set at 50 °C for 0.5 h (*R103B* in Fig. 3).

In-situ transesterification. The DSCG was treated with 0.9% *w/v* sodium methoxide solution, prepared by dissolving NaOH in methanol. This

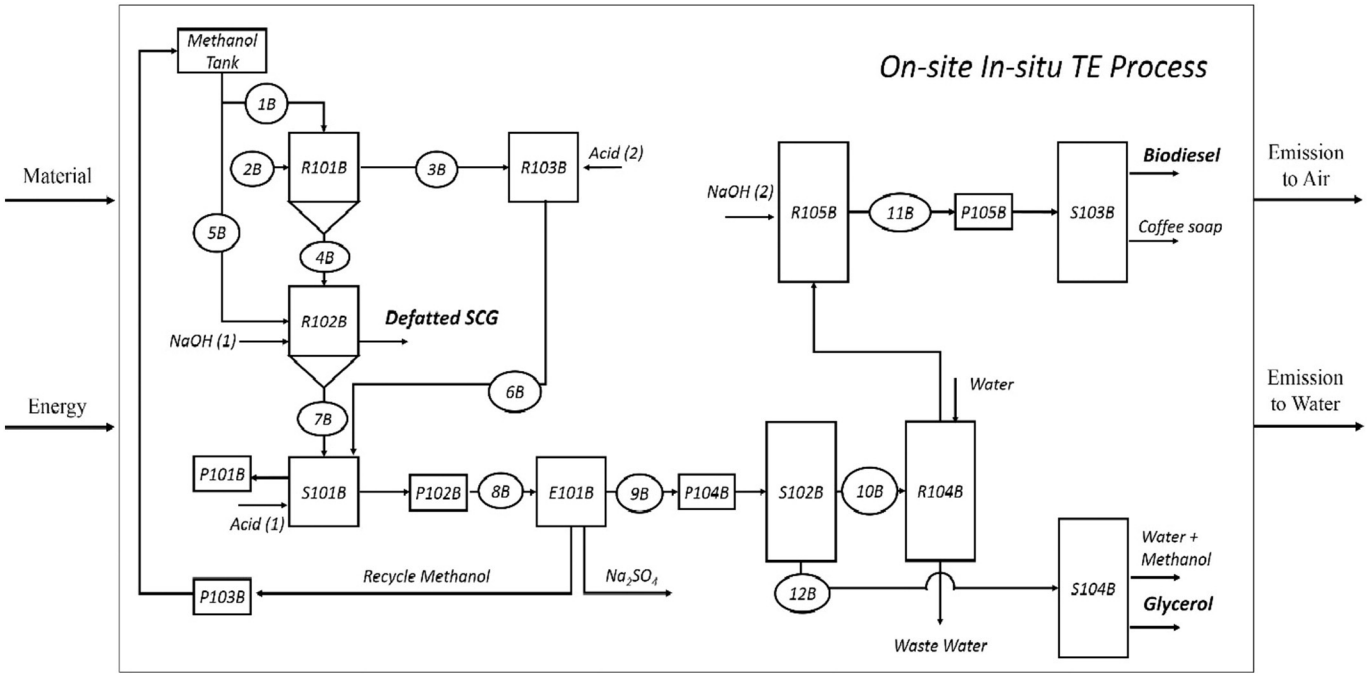

Fig. 3. System boundary of the on-site SCG biodiesel production process.

Table 2
Inventory process of the on-site *in-situ* TE process for producing 1 kg SCG biodiesel.

Feed		Product (kg)		Waste (kg)		Note
Drying and grinding						
30% MC SCG (kg)	9.20	Dried SCG	6.44	Water	2.76	–Dryer performance 60%
Heat (MJ)	11.73					–Grinder Micro-Max, model MM1600
Electricity (kWh)	5.60E−04					
In-situ TE process						
Dried SCG (kg)	6.44	Defatted SCG	5.46	Water + Glycerol	0.14	Process conditions and performances.
Methanol (kg)	30.55	Biodiesel	1.00	Methanol	6.37E−03	–Extrapolated from previous study
NaOH (kg)	0.20	Glycerol	9.14E−02	Coffee soap	2.04E−02	
H_2SO_4 (kg)	0.23	Na_2SO_4	0.35	Methanol extracted	3.54E−02	Energy usage of each instrument.
Water (kg)	2.72E−02					–US centrifuge systems, model MAC 250
Heat (MJ)	62.06					–Others: Kaewcharoensombat et al. (2011)
Electricity (kWh)	5.77E−02					

solution directly converts the triglyceride in DSCG to biodiesel and glycerol, which can be extracted by a sodium methoxide solution. The sodium methoxide solution-to-DSCG was 3.5 mL/g at 50 °C and mixed at 300 rpm for 3 h (*R102B* in Fig. 3). Then, the solid fraction (defatted SCG) was separated from the liquid fraction (diluted biodiesel and glycerol in a sodium methoxide solution; *7B* in Fig. 3) by a metal sieve with a vacuum pump (*P101B* in Fig. 3).

Catalyst neutralization. The liquid fractions from the esterification (*6B* in Fig. 3) and *in-situ* TE (*7B* in Fig. 3) processes were pooled together. Then, H_2SO_4 (*Acid (1)* in Fig. 3) was added to neutralize the alkaline catalyst and Na_2SO_4 salt formed as a by-product.

Methanol recovery. The methanol in the neutralized liquid fraction (*8B* in Fig. 3) was evaporated by a vacuum distillation column with 7 stages (*E101B* in Fig. 3) as described by Kaewcharoensombat et al. (2011). The recycled methanol was send back to be used in *in-situ* TE process.

Biodiesel purification. The crude biodiesel and glycerol were separated by a gravity tank (*S102B* in Fig. 3). At the bottom of the tank, crude glycerol (*12B* in Fig. 3) was sent to the glycerol purification process; then the upper crude biodiesel was washed by deionized (DI) water using the same process described by Kaewcharoensombat et al. (2011). After washing the biodiesel, the 0.68% *w/v* aqueous NaOH solution (*NaOH(2)* in Fig. 3) was added to the biodiesel to reduce its acid value, and then it was centrifuged to separate the soap from the biodiesel using a US centrifuge system, model MAC 250 (*S103B*, Fig. 3) (http://www.uscentrifuge.com/mac-250.php).

Glycerol purification. The bottom crude glycerol was purified to 93% using a multi-distillation column (*S104 B*, Fig. 3), as described by Kaewcharoensombat et al. (2011).

Allocation procedure

In addition to biodiesel, several valuable by-products were obtained during the process: glycerol and defatted SCG, for example. Therefore, the energy usage and environmental impacts of these by-products have to be acknowledged. In this work, the mass-based allocation method was applied to determine how the energy usage and environmental impacts were attributed among these products at different stages of the studied biodiesel production processes, as shown in Fig. 4A and B.

Life cycle impact assessment

In this study, SimaPro 8.0.5.13 software package (PRe, 2015) was used to calculate the impact of these processes on the environment. The IMPACT 2002 + method (Jolliet et al., 2003) was used in this study to quantify the impacts in the LCA into three parts: midpoint, endpoint and single score. It should be noted that plant construction and waste treatment were not included in this study. Also, the environmental impacts from producing SCG were not included in this assessment since they were considered waste of the instant coffee industry.

Sensitivity analysis

The sub-objective of this study is to determine whether a conventional or on-site *in-situ* TE situation would be better suited to produce SCG biodiesel. In this part, the energy usage was used as the selecting criterion. In a real situation, the SCG source might be far removed and thus have a significant effect on energy usage in the transportation section. Therefore, the transportation distance between the SCG source and a central facility for biodiesel production was considered when setting up the sensitivity factor (60–240 km). In addition, the different diesel consumption of vehicles was also considered in the study (4–18 km/L). The results can thus provide useful information on which vehicle type (*i.e.*, trucks or trains) should be used according to fuel consumption and distance requirements.

Results and discussion

Energy usage

The energy usage of the conventional process was dramatically lower than that of the on-site *in-situ* TE one, as shown in Fig. 5. To improve energy usage, the hotspots of the process had to be identified. For the conventional process, the hot spots were biodiesel synthesis and purification, which contributed to more than 50% of its total energy usage or 3.27 MJ/kg biodiesel, followed by biodiesel transportation (19.3%), SCG drying (14.9%), oil crushing (12.0%), and SCG transportation (3.4%), as shown in Fig. 5A. Unlike edible biodiesel feedstock (soybean, palm and canola), the defatted SCG could be used as an energy source, and considered as a form of renewable energy due to its high heating value.

The heating value of defatted SCG was 20.3 MJ/kg; therefore, an estimated 90 MJ of heat energy could be obtained from defatted SCG for every 1 kg of biodiesel product (Fig. 4A). This energy alone would be sufficient for supporting for the whole SCG biodiesel production process of a conventional and on-site *in-situ* TE system. In the case of the on-site *in-situ* TE system, moreover, the excess energy could be used in the instant coffee production process. This could increase interest in installing an on-site SCG biodiesel production unit.

Furthermore, the majority of energy usage in the on-site *in-situ* TE system (Fig. 5B) came from the methanol recovery step, which was responsible for 73.1% of the total energy usage or 8.33 MJ/kg biodiesel, followed by drying and grinding (14.8%), esterification (7.6%), *in-situ* TE (2.7%), deacidification (1.7%), and biodiesel purification (0.1%).This

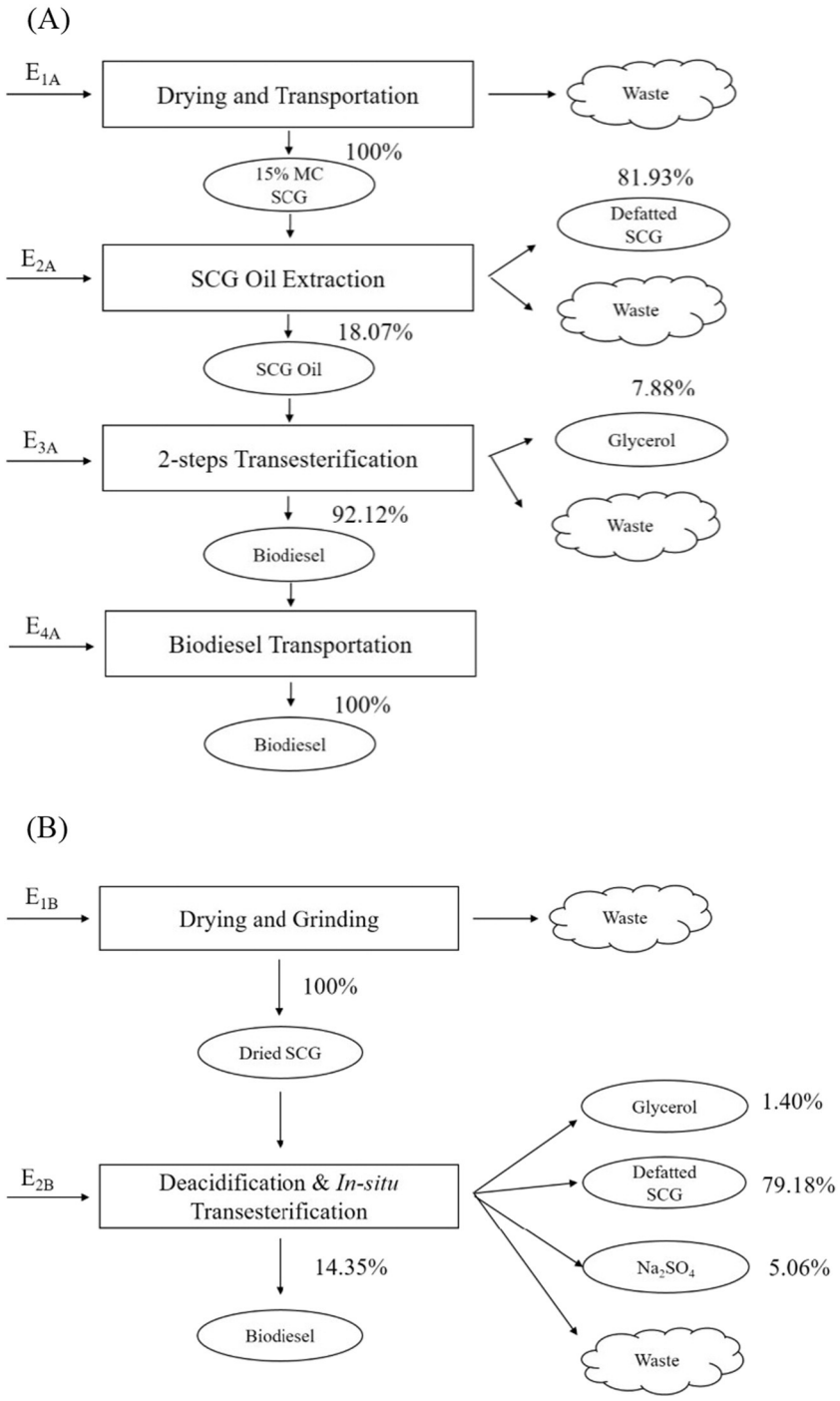

Fig. 4. Mass-based allocation of biodiesel and its by-products from the conventional (A) and on-site *in-situ* TE processes (B).

was due to the large amount of methanol used in this process, with 30.94 kg methanol needed to produce only 1 kg of SCG biodiesel.

A tremendous amount of energy (*i.e.*, process steam from natural gas) was required to separate the large amount of methanol from the biodiesel. In order to solve this problem, we had to reduce the amount of methanol loading by reusing methanol in the deacidification and *in-situ* TE steps, for instance. Reusing methanol increased the concentration of biodiesel before methanol evaporation, therefore, greatly decreasing the energy usage per kg of biodiesel product in the methanol recovery step. Another solution was applying the countercurrent extraction technique in place of a simple batch extraction reactor. This option accumulated the extracted biodiesel during the process and enhanced the extraction performance by improving the concentration driving force (Beckel et al., 1946). A future study on reusing methanol and/or countercurrent extraction for the deacidification and *in-situ* TE steps may provide worthwhile information.

The great advantage of an on-site *in-situ* TE system is the absence of feedstock and biodiesel transportation requirements, which can consume a minimum of 20% of the energy in a conventional process (Fig. 5). In addition, this energy usage can increase based on the distance of the transportation route and also the fuel consumption rate of the vehicle, as shown in Fig. 6. This suggests that an on-site *in-situ* TE process is more desirable when the transportation distance is more than 180 km and the fuel consumption rate is 6.38 km/L. If, therefore, the transportation distance is greater than180 km, a combination of vehicles (*e.g.*, trucks, barges and trains) should be considered. The results in Fig. 6

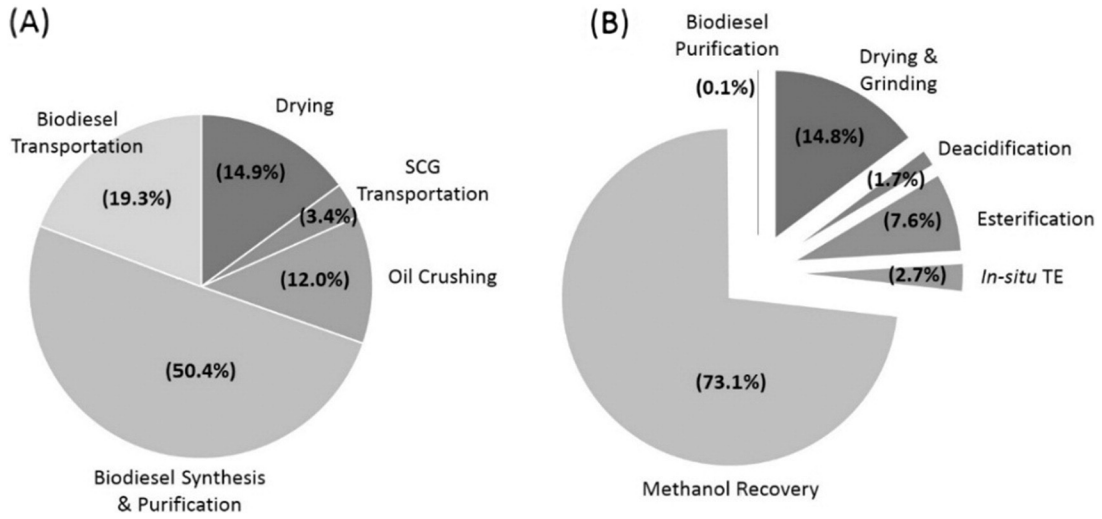

Fig. 5. Percentage of energy usage of each sub-process in the conventional (A) and on-site *in-situ* TE processes (B). The energy usages of the conventional and on-site *in-situ* TE processes were 6.49 and 11.38 MJ/kg biodiesel, respectively.

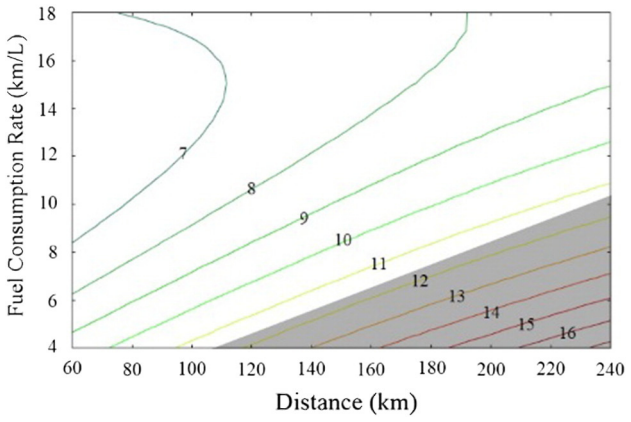

Fig. 6. Energy usage (MJ/kg biodiesel) of conventional processing at various transportation distances and vehicle fuel consumption rates; the shade area indicates the conditions that have energy usage that exceeds that of an on-site *in-situ* TE processing (11.38 MJ/kg biodiesel).

may be used to select a suitable combination of vehicles for feedstock and biodiesel transportation or they may be used to opt for a non-site *in-situ* TE process.

Environmental impacts

The midpoint results suggest that producing SCG biodiesel *via* a conventional process showed better environmental impacts than those of the on-site *in-situ* TE process because of the tremendous energy used in the methanol recovery step of the on-site *in-situ* TE process (Fig. 7). However, the on-site *in-situ* TE process provided lower environmental impacts to respiratory organs and land occupation.

The extremely high impact to respiratory organs in the conventional process mainly comes from the leaking of n-hexane during the process.The Clean Air Act (1990) categorized n-hexane as a hazardous air pollutant. The amount of n-hexane leaking from the process in this work came from the average produced by soybean oil extraction plants in the USA at a crushing capacity of >2400 tons of soybean daily (Pradhan et al., 2011). Smaller oil extraction plants might release more n-hexane than the amount we used in this work. Therefore,

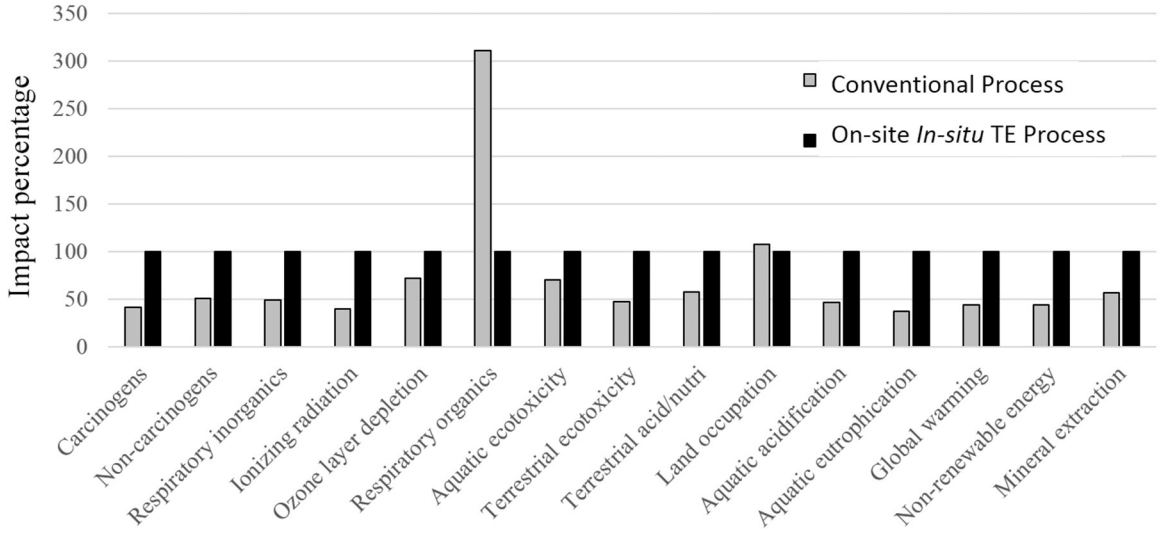

Fig. 7. Relative midpoint environmental impacts of SCG biodiesel produced by conventional and on-site *in-situ* TE processes according to IMPACT 2002+.

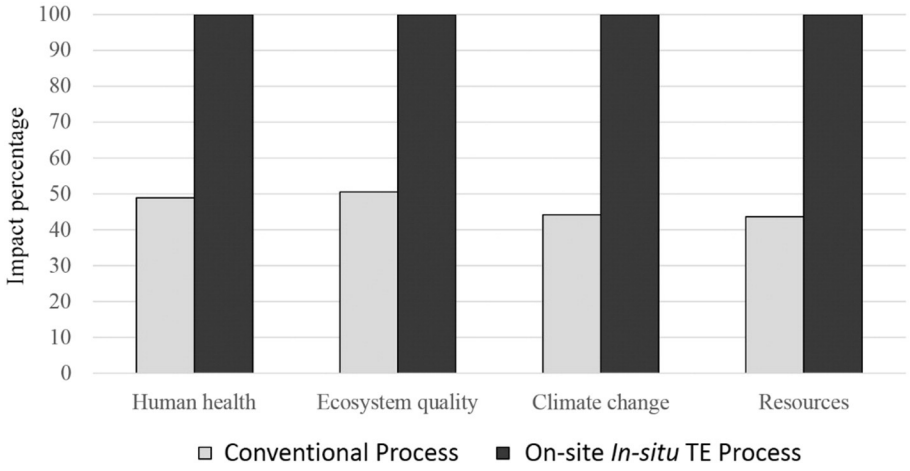

Fig. 8. Relative endpoint environmental impacts of SCG biodiesel produced by conventional and on-site *in-situ* TE processes according to IMPACT 2002+.

this should emphasize the advantage of the process used in our study, *in-situ* TE, which is an n-hexane free process.

The on-site *in-situ* TE process had a slightly lower land occupation impact due to the absence of transportation needs (Fig. 7). In the IMPACT 2002+ analysis, road construction accounted for, so it included the impact of land use changes due to road construction.This impact could increase based on the transportation distance between the SCG sources and central facility.

The fifteen midpoint environmental impact categories in Fig. 7 were then grouped up into four main types of endpoint impacts according to IMPACT 2002+ (Fig. 8). The results show that producing SCG biodiesel using an on-site *in-situ* TE process had higher environmental impacts than those of a conventional process in terms of human health, ecosystem quality, climate change and resources. Similar results were also reported by Nazir et al. (2012), who evaluated the environmental impacts of producing jatropha biodiesel *via in-situ* TE and the conventional process. However, the results from the present study provide far better environmental impacts compared to those of Nazir et al. (2012) since they did not allocate the environmental impacts to co-products (*i.e.*, jatropha meal and glycerol).Also, their study boundary did not include feedstock and biodiesel transportation, which was an advantage of the on-site *in-situ* TE process.

The hotspot of each endpoint impact was identified based on the form of energy and leaking of the solvent (Fig. 9). The results show that steam was the major source for concern in both types of processes. In the on-site *in-situ* TE process in particular, using steam contributed to more than 90% of the total environmental impact. In this study, the steam was produced from natural gas. To reduce the environmental impacts of steam, an alternative energy source (*i.e.* defatted SCG) should be considered.

According to the energy usage analysis (Fig. 5B) and endpoint results (Fig. 9B), the methanol recovery step, which used steam as its heat source, was the hotspot of the on-site *in-situ* TE process. The single score result was able to confirm this hotspot, which requires attention because climate change and resource depletion are main concerns in biodiesel production (Fig. 10). These two impacts were principally affected by the methanol recovery step, an energy demanding process, which consumed up to 73% of the total energy used. As mentioned previously, the defatted SCG could be used as an energy source to produce steam in the process, which could reduce the environmental impacts that lead to climate change and resource depletion. Moreover, reusing methanol and applying countercurrent extraction would greatly decrease the energy usage per kg of biodiesel in the methanol recovery step.

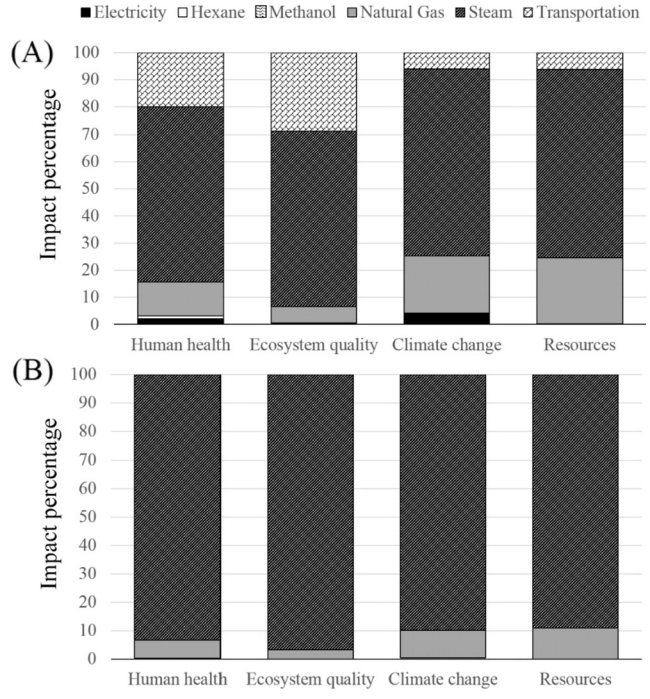

Fig. 9. Relative endpoint environmental impacts of conventional (A) and on-site *in-situ* TE (B) processes based on energy form and solvent leaking from the system, according to IMPACT 2002+.

Conclusion

Producing SCG biodiesel using the conventional process required 43% less energy usage and produced fewer environmental impacts than those of the on-site *in-situ* TE process. Nevertheless, the on-site *in-situ* TE process has lower effects on respiratory organs (due to the absence of hazardous n-hexane) and land occupation (due to the absence of transportation requirements). The methanol recovery step was identified as the hotspot of the on-site *in-situ* TE, because it consumed more than 73% of total energy used and used steam produced from natural gas as its heat source. Reusing methanol with a catalyst, applying countercurrent extraction, and utilizing the heat waste from the instant coffee industry are proposed to reduce the energy usage and environmental impacts of this on-site *in-situ* TE process. In addition, the defatted SCG by-product can be used as an energy source to generate heat and steam for the whole process, which can reduce negative impacts in the areas of climate change and resource depletion. Finally, the sensitivity analysis of the energy usage on various transportation

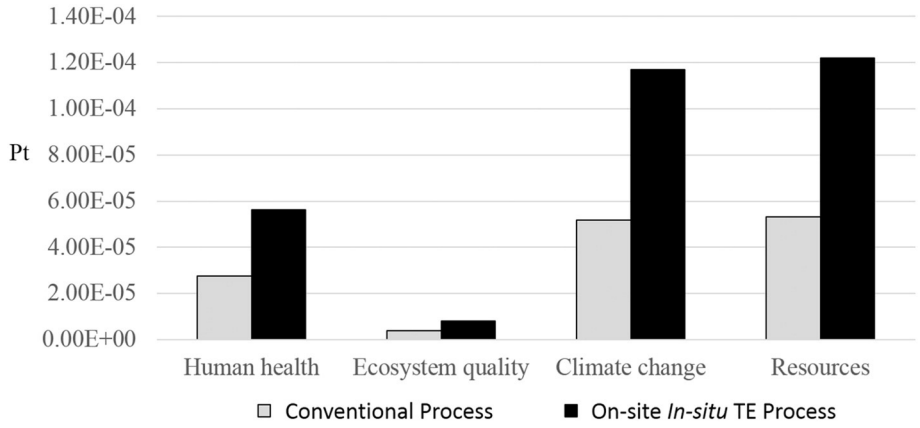

Fig. 10. Comparison of the single-score environmental impacts of producing SCG biodiesel *via* the conventional and on-site *in-situ* TE processes, according to IMPACT 2002+. Functional unit: 1 kg biodiesel. Units correspond to points (Pt).

distances and fuel consumption rates suggests that the on-site *in-situ* TE process can be viewed as more favorable once the transportation distance is greater than 180 km, assuming the fuel consumption rate of the transport vehicle is 7 km/L.

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