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Monte Carlo analysis of life cycle energy consumption and greenhouse gas (GHG) emission for biodiesel production from trap grease

Qingshi Tu [a,*], Bryant E. McDonnell [b]

[a] Department of Biomedical, Chemical and Environmental Engineering, University of Cincinnati, 2600 Clifton Avenue, Cincinnati, OH 45221, USA
[b] Water Resources Engineer, ARCADIS-U.S., Inc., 4335 Cornell Road, Cincinnati, OH 45241, USA

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ABSTRACT

Trap grease is an environmental burden and its management has been costly and ineffective. Utilizing trap grease as a feedstock for biodiesel has the potential to reduce the cost of waste removal and biofuel production. This study presents a life cycle analysis to evaluate the energy consumption and greenhouse gas (GHG) emission from the trap grease-to-biodiesel production process. It was shown that utilizing the solids in the trap grease for anaerobic digestion (AD) was crucial in reducing both energy consumption and GHG emissions. Monte Carlo simulation revealed significant variation in both the life cycle energy consumption and GHG emission, which was caused by the uncertainties within several key variables. The result of the sensitivity analysis indicated that trap grease has the potential to be a more energy efficient and low-GHG-emission feedstock under certain conditions, as compared with the current common feedstocks (e.g. soybean and algae).

1. Introduction

Trap grease is a mixture of water, solids, fats, oils, and greases (FOG) which accumulate in grease trap/interceptors of restaurants and food processing facilities (Tu et al., 2012). Once released to the sewer system, trap grease can clog and corrode sewer pipes, leading to overflows and infrastructure damage, causing severe environmental impacts such as the release of wastewater into ground and surface waterbody (US EPA, 2003). Restaurants and food processing facilities are required to have their grease traps cleaned on a regular basis by the registered grease haulers to prevent the release of trap grease into the sewer system (US EPA, 2007). Currently, the common practice is to send trap grease to a landfill for final disposal (Tu et al., 2012).

In recent years, efforts have been focused on the reuse of trap grease in order to reduce the burden on landfills. One way is to separate the FOG from the trap grease and use it as the industrial lubricant or "bio-crude" to prime and clean boilers (Ward, 2012). Another option is to feed the trap grease to an anaerobic digester (AD) to co-digest with other organic wastes. The FOG in the trap grease are digested by the microorganisms, generating biogas which can then be used to produce electricity and heat. However, it is found that the high free fatty acids (FFA) concentration of the FOG in the trap grease can inhibit the microbial process in the AD. Therefore, the addition of trap grease needs to be carefully controlled (Luostarinen et al., 2009; Pereira et al., 2005; Wang et al., 2013). Also, it is reported that biogas generation is a less efficient way of utilizing the energy content of the FOG when compared with biodiesel production (Chakrabarti et al., 2008; Turner et al., 2011). Another option is to use trap grease as a feedstock for biodiesel production. Biodiesel is a mixture of fatty acid methyl esters (FAME) made from oil sources, such as soybean oil, canola oil and waste cooking oil (Chai et al., 2014). Compared with using petroleum-based diesel, the air pollutant emissions (e.g. CO, PM, SO_2) from the combustion of biodiesel are significantly lower (EIA, 2004). Currently, the primary biodiesel feedstock in the US is soybean oil which can account for up to 80% of the total production cost (Haas and Foglia, 2005). As it is considered a waste, the cost of obtaining trap grease is expected to be much lower than that of soybean oil. For example, the estimated price of soybean oil is \$0.24/lb (Haas et al., 2006) while that of trap grease is approximately \$0.13/lb (Jolis and Martis, 2013). Wiltsee (1998) estimated that over 400 million gallons of biodiesel could be produced from trap grease yearly in the US which is equivalent to approximately 31.5% of the total biodiesel production in 2014 (EIA, 2015). Also,

* Corresponding author. Department of Biomedical, Chemical and Environmental Engineering, ERC 701, PO Box 210071, University of Cincinnati, 2600 Clifton Avenue, Cincinnati, OH, 45221-0012, USA. Tel.: +1 513 3646079.
E-mail address: tuqi@mail.uc.edu (Q. Tu).

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using trap grease instead of the dedicated oil crops avoids the resource consumptions (e.g. irrigation, land use) that otherwise would have occurred during feedstock growth. In addition, separating FOG from trap grease for biodiesel production instead of sending the entire mixture to an AD may help to maintain a stable AD performance (Lopez et al., 2014).

Characterization of life cycle energy consumption and GHG emission has been performed for biodiesel production from a variety of feedstocks (Tables 1 and 2), including soybean oil (Luque et al., 2010; Pradhan et al., 2011; Sheehan et al., 1998), palm oil (Cho et al., 2013; Luque et al., 2010), waste cooking oil (WCO) and animal fats (Dufour and Iribarren, 2012; Lopez et al., 2010; Talens Peiro et al., 2010) and algae (Azadi et al., 2014; Frank et al., 2012; Sander and Murthy, 2010; Shirvani et al., 2011; Sills et al., 2012; Stephenson et al., 2010). These studies provide insights for understanding and comparing the life cycle energy use and GHG emission of biodiesel production from different feedstocks. However, to the best of authors' knowledge, such a study has not yet been conducted for trap grease-to-biodiesel process. There are multiple occasions where the energy and material consumption of the trap grease-to-biodiesel process may be significantly different from that of biodiesel made from other feedstocks. For example, a three-phase separation process is typically applied to separate FOG, water and solids in trap grease (Turner et al., 2011), which involves energy consumption for pumping and heating. In addition, the FFA concentration is usually very high (e.g. over 90% by weight, wt%) in the FOG derived from trap grease (Chakrabarti et al., 2008; Ngo et al., 2011). FFA is detrimental to the biodiesel production process because it reacts with alkaline catalyst of the process, generating soap and reducing the yield of the biodiesel. The esterification reaction catalyzed by H_2SO_4 is typically used to convert FFA into esters in order to reduce the FFA concentration in the feedstock oil (Chai et al., 2014). Therefore, for the FOG derived from trap grease, a rigorous esterification step which involves energy–intensive processes such as methanol recovery is needed before it can be used for biodiesel production. Accordingly, the life cycle GHG emission associated with energy and material consumption is also expected to be different from that of other feedstock-to-biodiesel processes in the existing studies. Therefore, understanding the energy consumption and GHG emission involved in the trap grease biodiesel production life cycle is an indispensable step toward evaluating the cost-effectiveness and sustainability of this practice.

In addition, existing life cycle studies typically report the life cycle analysis result in a single value. However, it is rational to expect that uncertainties exist in the assumptions, data sources, and unit processes for the studies, which may render a single value not sufficiently representative of all possible circumstances. The influence of these uncertainties on the results should be addressed. Therefore, it has been recommended that the result of life cycle studies should be reported as a range of values instead of a single value when variations and uncertainties are involved (Sills et al., 2012). Monte Carlo simulation is a widely used approach to evaluate the influence that rises from the uncertainty within a specific variable/set of variables on the outcome of the model (Maurice et al., 2000; Sonnemann et al., 2003; Clarens et al., 2011). For this study, applying Monte Carlo simulation to the life cycle model will generate a range of results based on different input values of the variables, which helps to understand the impact from uncertainties in those key variables, such as raw trap grease properties and the performance of the anaerobic digester, on the life cycle energy consumption and GHG emission of trap grease biodiesel production.

Table 1
Values of life cycle energy consumption for biodiesel production from different feedstocks.

Feedstock	Life cycle energy consumption			Reference
	Original value	Original unit	MJ/gal	
Sunflower	3.2	MJ BioD/MJ non-renewable energy	39.01	Luque et al., 2010
Rapeseed	2.7		46.24	
Soybean	3		41.61	
Palm	9		13.87	
Palm fatty acid distillate	3.23	Net energy ratio (NER)	38.65	Cho et al., 2013
Soybean	5.60	MJ/L BioD	21.17	Pradhan et al., 2011
WCO	1054.62	MJ/tonne BioD	6.17	Talens Peiro et al., 2010
WCO	13.80	MJ/kg BioD	46.36	Lopez et al., 2010
Tallow	16.80		56.44	
Poultry fat	19.10		64.17	
WCO	4325.56	MJ/tonne BioD	14.53	Dufour and Iribarren, 2012
Tallow	2718.86		9.13	
Poultry fat	3171.88		10.66	
Sewage sludge	2343.07		7.87	
Algae (OP)	1.70	Energy balance ratio (EBR)	212.22	Shirvani et al., 2011
Algae (OP)	HG: 0.50	Energy balance ratio (EBR)	62.42	Azadi et al., 2014
	AD: 0.96		119.84	
	G-CHP: 1.48		184.76	
	G-FT: 1.81		225.96	
Algae (OP)	−6670.34	MJ/kMJ BioD	−832.71	Sander and Murthy, 2010
	−3768.34		−470.43	
Algae (OP)	548,329	Btu/MMBtu of BioD	60.57	Frank et al., 2012
Algae (OP)	6.50	GJ/ton BioD	21.84	Stephenson et al., 2010
Algae (PBR)	199.50		670.24	
Petroleum diesel	1.19	MJ/MJ Diesel	162.08	Sheehan et al., 1998

*Results were based on mass-based partition between biodiesel (88.5%) and glycerin (11.5%) (Lopez et al., 2010), unless specified in the literature; OP: open pond; PBR: photobioreactor.
**Sander and Murthy (2010): algae biomass was assumed to replace corn for ethanol production, generating significant amount of energy credit by avoiding corn growth; lower energy consumption (−6670.34 MJ/kMJ BioD) by using filter pressing for dewatering.
***EBR: the ratio of non-renewable energy consumed to energy from biodiesel; HG = hydrothermal gasification; AD = anaerobic digestion; G-CHP = gasification-power generation; G-FT = gasification-Fischer-Tropsch.
****NER: ratio between total energy outputs and total energy inputs.

Table 2
Values of life cycle GHG emission for biodiesel production from different feedstocks.

Feedstock	Life cycle GHG emission			Reference
	Original value	Original unit	g CO_2 eq/gal	
Soybean	2.6	tonne CO_2 eq/tonne BioD	8734.96	Luque et al., 2010
Rapeseed	1.79		6013.68	
Palm	1.73		5812.11	
Wood	0.27		907.09	
Palm fatty acid distillate	53.12	g CO_2 eq/MJ BioD	6631.39	Cho et al., 2013
WCO	299.60	kg CO_2 eq/tonne BioD	890.78	Talens Peiro et al., 2010
WCO	576.02	kg CO_2 eq/tonne BioD	1734.60	Dufour and Iribarren, 2012
Tallow	820.41		2470.54	
Poultry fat	829.46		2786.66	
Sewage sludge	725.07		2435.95	
Algae (OP)	26	g CO_2 eq/MJ BioD	3245.79	Shirvani et al., 2011
Algae (OP)	HG: 10	g CO_2 eq/MJ BioD	1248.38	Azadi et al., 2014
	AD: 55		6866.09	
	G-CHP: 78		9737.36	
	G-FT: 93		11,609.93	
Algae (OP)	−21.56	kg CO_2 eq/kMJ BioD	−2691.51	Sander and Murthy, 2010
	135.05		16,589.37	
Algae (OP)	−25,441	g CO_2 eq/MMBtu of BioD	−2663.47	Frank et al., 2012
Algae (OP)	713	kg CO_2 eq/tonne BioD	2395.39	Stephenson et al., 2010
Algae (PBR)	11,919		40,043.07	
Petroleum diesel	638.35	g CO_2 eq/bhp-h	11,643.86	Sheehan et al., 1998

*Results were based on mass-based partition between biodiesel (88.5%) and glycerin (11.5%) (Lopez et al., 2010), unless specified in the literature; OP: open pond; PBR: photobioreactor; fuel use stage was excluded during the conversion of the data for all cases.
**Sander and Murthy (2010): algae biomass was assumed to replace corn for ethanol production, generating significant amount of energy credit by avoiding corn growth; negative GHG emission (−21.56 kg CO_2/kMJ BioD) by using filter pressing for dewatering.
***Sheehan et al. (1998): including the tailpipe CO_2 emission.
****EBR: the ratio of non-renewable energy consumed to energy from biodiesel; HG = hydrothermal gasification; AD = anaerobic digestion; G-CHP = gasification-power generation; G-FT = gasification-Fischer-Tropsch.

1.1. Goal and scope definition

The goal of the current study is to analyze the life cycle energy consumption and GHG emission for biodiesel production from trap grease on a "gate-to-gate" scope and to present the result in ranges by using Monte Carlo simulation. The concept of life cycle energy was applied to account for both the direct energy consumption (e.g. the embedded energies of electricity and natural gas) and indirect energy consumption (e.g. the energy consumption associated with the production of materials). This concept is similar to the definition of direct and indirect CO_2 emission by Zhang et al. (2014). The current study also evaluated the impact on life cycle energy consumption and GHG emission from utilizing solids separated from the raw trap grease for energy co-generation via anaerobic digestion. The system boundary of the study is shown in Fig. 1. The biodiesel production facility was assumed to be co-located within a wastewater treatment plant (WWTP), as suggested by most existing feasibility studies (Chakrabarti et al., 2008; Turner et al., 2011).

There are five common stages in the life cycle: (1) raw trap grease transportation, (2) FOG separation, (3) FOG pretreatment (acid esterification), (4) biodiesel production (alkaline transesterification) and (5) transportation of waste solids to a landfill. One additional stage was included in the life cycle if the solids were utilized for anaerobic digestion. The biodiesel production life cycle started with raw trap grease acquisition, where grease haulers collected raw trap greases from restaurants and transported them to the WWTP (raw trap grease transportation stage). Upon arrival at the WWTP, raw trap greases underwent a process to separate FOG, solids and water through the three-phase separation technology (FOG separation stage). The FOG portion was sent to a treatment process for further refining (FOG pretreatment stage), while the solids were sent to an anaerobic digester for biogas generation (AD stage) or directly to a landfill in the alternative scenario (transportation of waste solids stage). The separated water portion was discharged for wastewater treatment and the waste from the anaerobic digester was sent to a landfill. After refining, the FOG was converted into biodiesel in the biodiesel production process (biodiesel production stage). This life cycle model was constructed using Python 2.7 programming language (www.python.org) and a Monte Carlo simulation was performed to account for the uncertainties within the variables used in current study (e.g. the variation of FOG concentration in raw trap grease) and to report the life cycle energy consumption and GHG emission with a range of values. A sensitivity analysis was also conducted to identify the variables of high impact on life cycle energy consumption and GHG emission of making biodiesel from trap grease.

1.2. Functional unit and assumptions

The functional unit of current study is one gallon of biodiesel from trap grease (1gal). Accordingly, the results of life cycle energy consumption and GHG emission were normalized to the functional unit, as "MJ/gal" or "g CO_2 eq/gal". It was assumed that differences in the energy content of biodiesel made from different feedstocks (e.g. trap grease, soy oil) were negligible. The energy consumption and GHG emission associated with capital investments, such as the construction and manufacturing of facilities, instruments and vehicles, were excluded from the scope of the study.

2. Methodology

2.1. Data sources

The data source for each stage of the trap grease-to biodiesel life cycle is summarized as follows: transportation distances and fuel consumption for transferring raw trap grease from restaurants to the wastewater treatment plant were estimated based on information collected from the grease haulers registered with the Metropolitan Sewer District of Greater Cincinnati (MSDGC). The distance between the wastewater treatment plant and the landfill

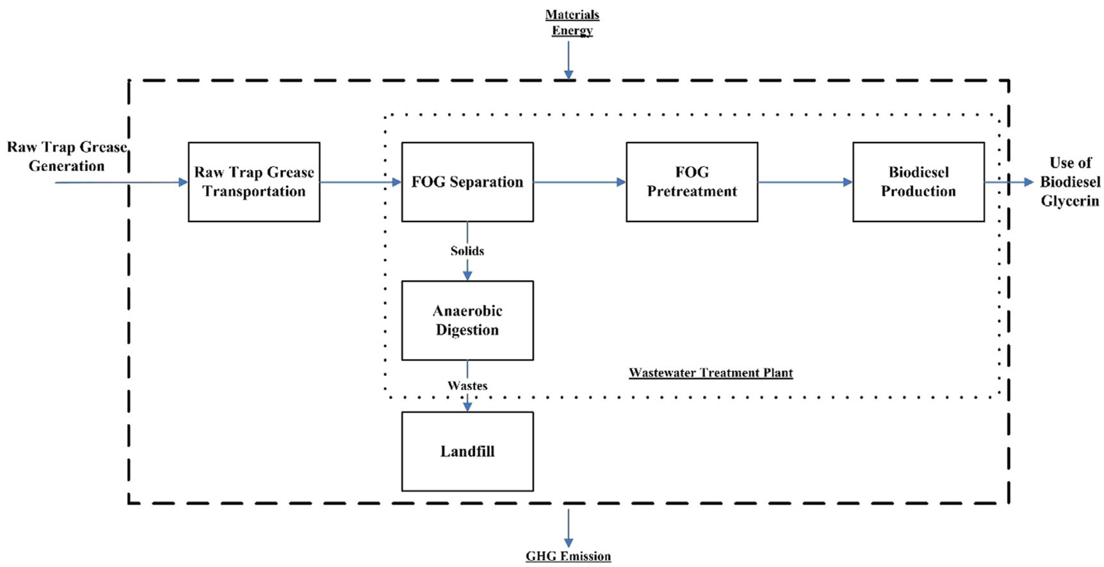

Fig. 1. System boundary of current study.

site was estimated based on the literature search (Sills et al., 2012). For FOG separation stage, a comprehensive data collection was performed in order to characterize the composition of raw trap grease, *i.e*., the percentages of FOG, water and solids. A survey was conducted among professionals in wastewater treatment, biodiesel production, trap grease hauling, fundamental research, federal regulation, and non-governmental organizations (NGOs). In addition to the survey, a comprehensive literature review of existing peer-reviewed journal articles, technical reports, presentations and online resources was performed to enrich the data pool of the raw trap grease composition (Table S12 in the supporting information). Likewise, the data of initial FFA concentration in the FOG and the dose of chemicals for FOG treatment (acid esterification) were obtained from a literature review as well as personal communications with industrial experts (Tables S13 & S14 in the supporting information). For the biodiesel production (alkaline transesterification) and anaerobic digestion stages, process input data, *i.e*., material and energy inputs, was retrieved from the peer-reviewed journal articles.

2.2. Unit processes

2.2.1. Transportation

In this study, there are three major transportation activities of interest: (1) the transportation of collected raw trap grease from restaurants to the hauler's facility, (2) transferring raw trap grease from hauler's facility to the WWTP and, (3) sending waste solids from the FOG separation stage or from the AD stage to a landfill, depending on whether the solids were utilized or not. The details about transportation distances and vehicle information can be found in Appendix S-5 in the supporting information.

2.2.2. Trap grease pretreatment (FOG separation)

A common method to separate FOG from raw trap grease is to apply moderate heating and gravity settling (Chakrabarti et al., 2008; Turner et al., 2011). A flow chart of the pretreatment process used in current study is provided in Fig. 2. This chart is a replica of a commercial process designed for Eastern Municipal Water District (EMWD) to convert the trap grease into biodiesel (van Keppel, 2011). The process does not involve energy-intensive equipment, such as centrifuges or distillation towers. Details of the FOG separation process can be found in Appendix S-1 in the supporting material.

2.2.3. FOG pretreatment (acid esterification)

FOG was collected and sent to the esterification unit for further treatment after separation process. The function of esterification unit was to convert the FFA content in the FOG into esters. In this study, FOG was defined to be composed of FFA and "oil". The term "oil" was a collective description of the part of FOG that was not in the form of FFA. The concentration of FFA varied among the FOG samples, as indicated from the collected data (Table S13). During the esterification reaction, FFA reacted with methanol with H_2SO_4 as the catalyst at atmospheric pressure and a temperature close to 65 °C. The dosages of methanol and catalyst were related to the concentration FFA in the FOG (Canakci and van Gerpen, 2003) and therefore varied from case to case. In most cases, extra methanol was needed to quench the reverse reaction during the esterification process (Chai et al., 2014). After the reaction was complete, NaOH was added to neutralize the catalyst before the treated FOG (containing esters and remaining oil) was sent to the next stage. Depending on the quality of the FOG, the esterification process might be conducted twice to ensure that FFA was reduced to the acceptable level (Canakci and van Gerpen, 2001). After the esterification stage, a 100% conversion of FFA into esters was assumed for this study.

2.2.4. Biodiesel production (alkaline transesterification)

After the esterification process, the mixture of esters and oil was sent to the transesterification unit for the production of biodiesel. The unit used in current study was composed of two sequential transesterification reactors, each having a conversion efficiency of 90% (Sheehan et al., 1998). During the transesterification process, oil was converted into esters by reaction with methanol under the catalysis of $NaOCH_3$. It was assumed that after esterification stage, the resulting oil can be treated with the same operational conditions as those for soybean oil (Huo et al., 2008). The composition of the ester and oil mixture was determined from the precedent esterification process. After production, the crude biodiesel and glycerin were separated and weakly acidic water (by adding HCl) was added to remove impurities from crude biodiesel in the washing tank.

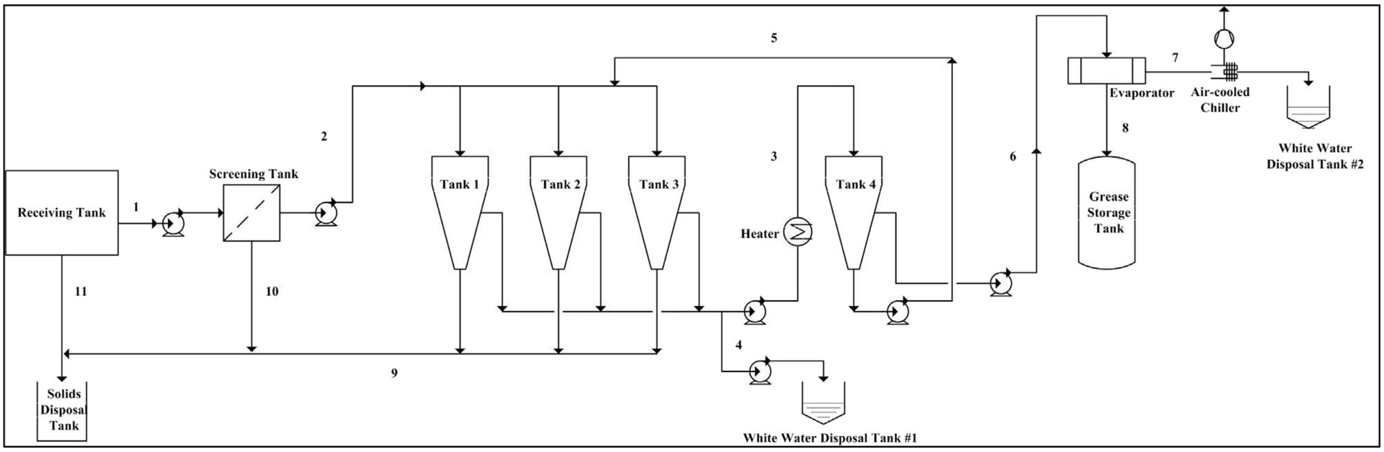

Fig. 2. Flowchart for the FOG separation stage (EMWD case study).

2.2.5. *Anaerobic digestion*

The solids separated from raw trap grease in the pretreatment step can be fed to an anaerobic digester (AD) for biogas generation, which can be captured and utilized for electricity and heat generation. The performance of a digester is measured based on the destruction of the volatile solids (VS) in the feed. The operational conditions of the anaerobic digester proposed in current study were cited from Sills et al. (2012): a completely mixed reactor at operated at 35 °C with a hydraulic retention time (HRT) of 15 days. After the digestion process, biogas was sent to a scrubbing unit to remove H_2S before combustion in a combined heat and power generation unit (CHP). The destruction rate of VS for a 15-day digestion time was 56% (Tchobanoglous et al., 2003). The remaining solids from the digester were collected and sent to a landfill.

2.3. *Monte Carlo simulation*

As described earlier, a Monte Carlo simulation procedure was used as the supportive framework to demonstrate the probable variability of the life cycle energy consumption and GHG emission for the trap grease feedstock. Process performance, as well as process inputs, are variable to some degree and the randomization Monte Carlo simulation inherently considers the probable system performance. Fig. 3 illustrates the simplified Monte Carlo simulation assuming a single parameter variant. The number of iterations (n) for each Monte-Carlo process was set to 100,000. As illustrated in Fig. 3, the first step was to choose the parameter to vary. Next, a random value was chosen using Python 2.7 parametric random functions (Table S15 in the supporting material). With the parameter value now specified, the simulation was executed. Current iteration step (i) was compared to the max number of iterations (n); if $i = n$, the process was ended; else, the process was sent back to the random value block. Results were then gathered for final analysis.

3. Results

3.1. *Sample calculation*

A sample calculation (or nominal case) was performed to demonstrate the procedure of quantifying the life cycle energy consumption and GHG emission for producing biodiesel from trap grease. The mass of the raw trap grease was assumed to be 100,000 lbs. The data for raw trap grease composition and FFA concentration in the FOG was cited from an industry professional (van Keppel, 2011) and the operational conditions of the AD were cited from Sills et al. (2012). The parameter values are summarized in Table 3. When more than one product was generated at the end of a stage, allocation of energy consumption and GHG emission was performed based on the mass portion of the co-products obtained at the end of the stage, as indicated from many of the existing LCA studies (Dufour and Iribarren, 2012; Lopez et al., 2010; Pradhan et al., 2011; Talens Peiro et al., 2010). The detailed procedure for the sample calculation can be found in Appendix S1 to S6 in the supporting information.

3.1.1. *Life cycle energy consumption*

The esterification stage consumed 36.18 MJ of energy per gallon biodiesel produced, which was mainly due to the natural gas consumption for recovery of excessive methanol during the two consecutive esterification steps. Transesterification, on the other hand, accounted for about 4.62 MJ/gal, which was approximately 13% of the consumption by esterification. Also, transportation consumed a large amount of energy because of the low fuel economy of the truck (6.5 mpg) and long travel distances. The energy input for transportation stage differed based on whether AD was included in calculation. Energy consumption was 33.25 MJ/gal for the scenario w/AD and 33.79 MJ/gal for the scenario w/o AD, which was due to the difference in the amount of solids landfilled at the end of the life cycle. The energy

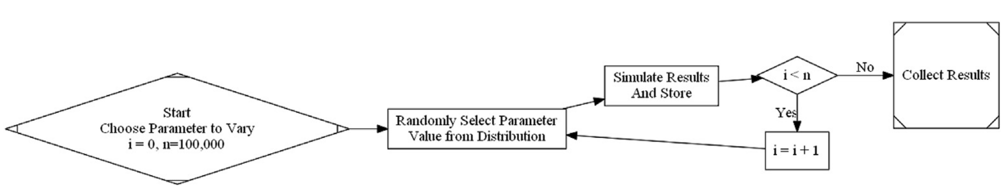

Fig. 3. Monte Carlo simulation flow diagram.

Table 3
Summary of key parameters for the sample calculation (100,000 lbs raw trap grease).

Parameter	Value	Reference
FOG concentration in raw trap grease	4.23 wt%	van Keppel, 2011
Water concentration in raw trap grease	86.35 wt%	
Solids concentration in raw trap grease	9.42 wt%	
Volatile solid (VC) concentration in solids	94%	Wang et al., 2013
CH_4 generation rate	0.3 L/g VS	Sills et al., 2012
CHP electricity generation efficiency	33%	
CHP heat generation efficiency	43%	

consumption involved in the FOG separation stage was 12.70 MJ/gal, since no energy-intensive equipment was used in the stage. It is noteworthy that although the energy input for operating the AD was high (46.31 MJ/gal), the energy output was considerable (67.80 MJ/gal, 22.37 MJ in the form of electricity and 45.43 MJ in the form of heating by natural gas). It is noteworthy that the ***avoided*** life cycle energy consumption associated with using the energy output from AD was 101.68 MJ/gal, instead of the "apparent" energy output of 67.80 MJ/gal. This is due to the fact that to quantify the effect of displacing electricity and natural gas inputs, the life cycle energy, not the embedded energy, of these utilities should be used in the calculation. As a result, the life cycle energy consumption for the sample calculation was 31.39 MJ/gal for AD-included (w/AD) and 87.29 MJ/gal for AD-excluded (w/o AD) scenarios. It is evident that incorporating an AD into the biodiesel production process has the potential to significantly reduce the energy consumption for biodiesel production from trap grease. Figure S5 in the supporting information shows energy inputs (consumption) and outputs of the sample calculation. Figure S6 in the supporting information categorizes the life cycle energy consumption by utility and materials uses. It is obvious that by using the energy generated from AD, the consumption of electricity could be completely avoided and the use of natural gas can be reduced by 51.82%. This again indicates the necessity to integrate an AD into the trap grease biodiesel production system. Energy consumption associated with the use of chemicals was the same for both scenarios and the fuel consumption was slightly lower in the scenario w/AD because fewer solids were sent to the landfill.

3.1.2. Life cycle GHG emission

Similar to life cycle energy consumption, esterification (2179.03 g CO_2 eq/gal) and transportation (2410.11 g CO_2 eq/gal when AD is included in the system) were the two major contributors to the total GHG emission, followed by FOG separation (873.35 g CO_2 eq/gal) and transesterification (234.06 g CO_2 eq/gal). It is shown that utilizing solids for anaerobic digestion generated a significant GHG reduction which eventually rendered the life cycle GHG emission negative (−55.49 g CO_2 eq/gal). In comparison, when solids were treated as waste, the life cycle GHG emission was 5735.22 g CO_2 eq/gal.

3.2. Monte Carlo simulation

3.2.1. Life cycle energy consumption

The variables for Monte Carlo simulation were: FOG concentration in raw trap grease (wt%), FFA concentration in separated FOG (wt%), VS concentration in solids (wt%), electricity for mixing in AD (kWh/kg VS), heating energy consumption for AD (MJ/kg VS), CH_4 generation rate (L/g VS), and CHP electric efficiency (%). The distributions of each variable are summarized in Table S15 in the supporting information. 100,000 runs of the Monte Carlo simulation were performed and the results are shown in Figs. 4 and 5. The potential biodiesel production ranged from approximately 14 to 4400 gallons. As is expected, the distribution of the volumes of biodiesel was consistent with the distribution of FOG concentration in raw trap grease. The extremely low volume (e.g. 14 gallons) represents the situation where the concentration of FOG in the raw trap grease was extremely low (e.g. lower than 1%). Fig. 4a shows the empirical cumulative density of the life cycle energy consumption result when AD was included in calculation. The range was approximately between 20 and 760 MJ/gal. The high values (e.g. 760 MJ/gal) occur when the volume of biodiesel produced was close to the lower end of the range (e.g. 14 gallons). It is indicated from the figure that the probability that the life cycle energy consumption would be less or equal to 100 MJ/gal was around 80%. Fig. 4b shows the result when AD was excluded. The range was approximately between 40 and 1700 MJ/gal and the probability that the result would be equal or less than 100 MJ/gal was approximately 60%. In addition, the results were compared in pair for each of the 100,000 runs to see if there would be a situation where life cycle energy consumption would be lower when solids were treated as waste instead being utilized for anaerobic digestion. It was observed that the energy consumption for making one gallon of biodiesel from trap grease was almost always lower when AD was included in the production life cycle (>99.9% of the simulation results). However, it is interesting that there would be some outliers when the ***avoided*** life cycle energy

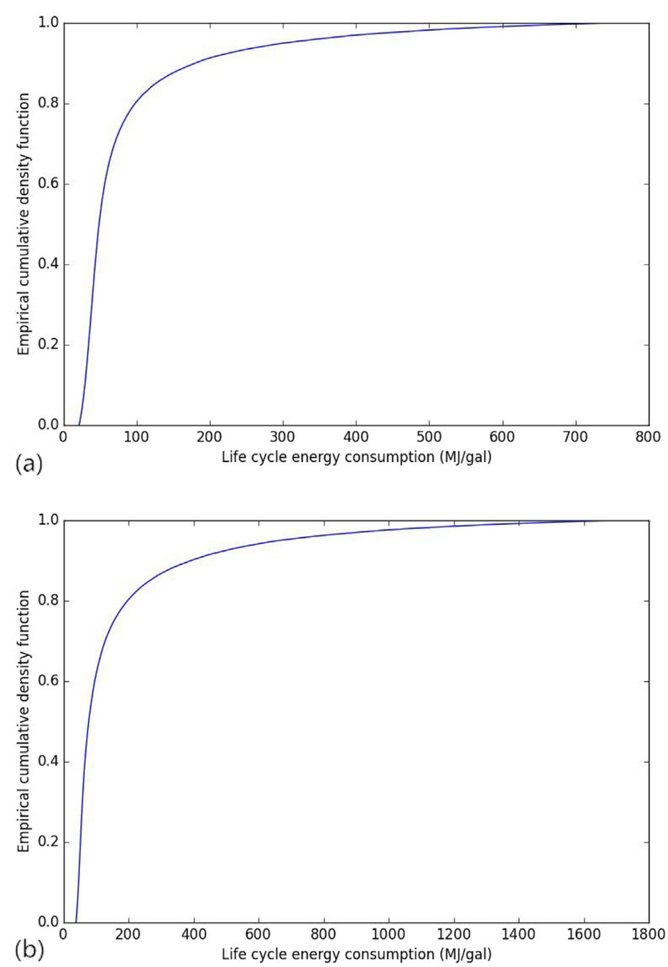

Fig. 4. Empirical cumulative density plot of life cycle energy consumption (a: w/AD; b: w/o AD).

consumption associated with the energy output from AD was less than the energy consumption to operate the AD (<0.01% of the simulation results). This represents the situation where the AD is poorly operated (e.g. the CH_4 generation rate is low).

3.2.2. Life cycle GHG emission

Fig. 5 shows the empirical cumulative density plot of the life cycle GHG emission for the trap grease-to-biodiesel process. When AD was included in the system (Fig. 5a), the result ranged approximately from −2700 to 25,000 g CO_2 eq/gal. The negative values of the GHG emission indicate that in certain circumstances the GHG reduction from the energy credit generated through the AD could outweigh the GHG emission associated with energy and materials consumption. In comparison, when AD was excluded from the system boundary, the range was from approximately 2400 to 121,000 g CO_2 eq/gal. Similar to life cycle energy consumption, the extremely high values of GHG emission were due to the very low volume of biodiesel produced. Also, the life cycle GHG emission was almost always lower when AD was included in the system boundary (>99.9% of the simulation results). As indicated from Fig. 5a, the probability was over 90% that the life cycle GHG emission for the trap grease biodiesel would be less than or equal to 10,000 g CO_2 eq/gal. On the other hand, the probability decreased to about 70% when AD was excluded from the system boundary (Fig. 5b). This again indicates the necessity to utilize the solids for AD.

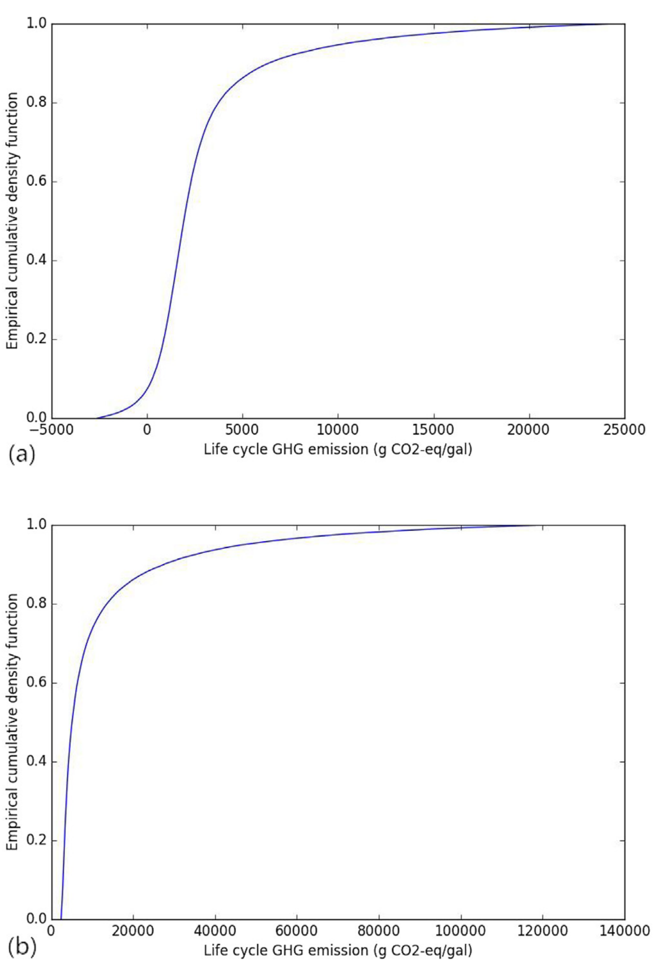

Fig. 5. Empirical cumulative density plot of life cycle GHG emission (a: w/AD; b: w/o AD).

3.3. Sensitivity analysis

3.3.1. Life cycle energy consumption

A sensitivity analysis was performed to evaluate the impact on life cycle energy consumption caused by the uncertainty within individual variables. To conduct the sensitivity analysis, 100,000 runs of Monte Carlo simulation were executed for a single variable (e.g. FOG concentration in raw trap grease) while holding the other variables constant. The results of the sensitivity analysis are presented in the form of box–whisker plot. The lower and upper "whiskers" indicate the data points at the 5th and 95th percentiles of the entire data set, respectively. Similarly, the lower, middle, and the upper lines of the "box" indicate the 25th, 50th and 75th percentiles of the entire data set, respectively. The result of the sensitivity analysis for life cycle energy consumption is shown in Fig. 6. For the scenario w/AD (Fig. 6a), the uncertainty within the FOG concentration had a higher impact than any other variable, because it directly affects the volume of biodiesel that could be generated. This indicates the importance of the quality of the raw trap grease. CH_4 generation rate had the second largest influence due to the fact that it had the most impact on the energy generation from the AD. FFA concentration (%) had the third largest impact because it directly affected the methanol input and accordingly the energy consumption for recovering the methanol during the esterification stage. On the other hand, VS concentration, electricity

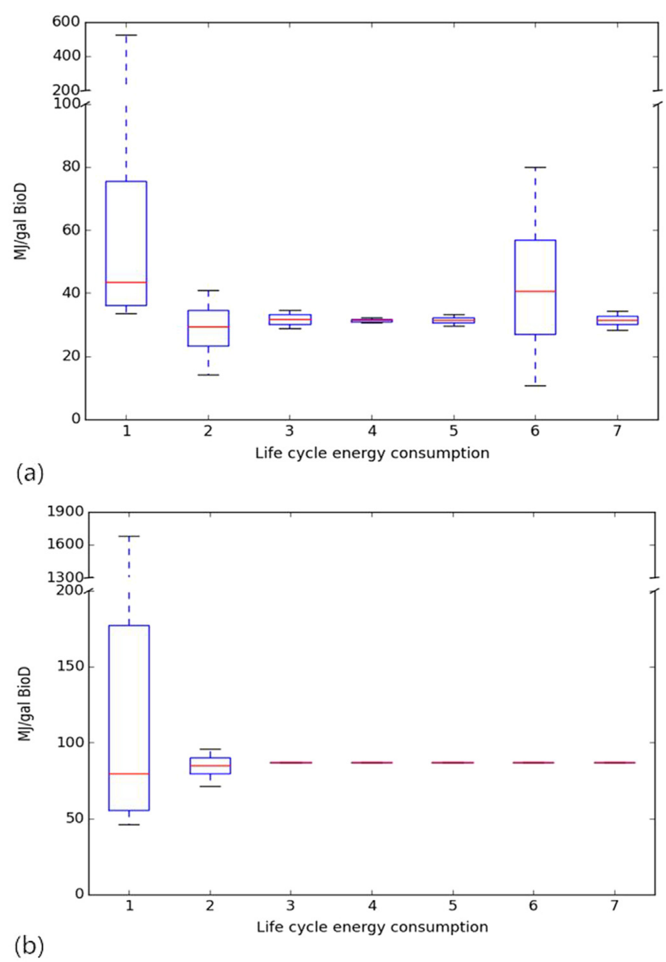

Fig. 6. Sensitivity analysis for life cycle energy consumption (a: w/AD; b: w/o AD) 1-FOG concentration; 2-FFA concentration; 3-VS concentration; 4-electricity consumption for mixing in the AD; 5-heating energy consumption for the AD; 6-CH_4 generation rate; 7-electricity generation efficiency of the CHP.

consumption for mixing in the AD, heating energy for AD and electricity generation efficiency of the CHP had minimal influence on the life cycle energy consumption. For the scenario w/o AD, FOG and FFA concentrations were the only two variables that would affect the life cycle energy consumption (Fig. 6b). Likewise, the uncertainty caused by variation in the FOG concentration was more than one order of magnitude higher than that of FFA concentration.

3.3.2. Life cycle GHG emission

Fig. 7 shows the results of the sensitivity analysis for life cycle GHG emission. When the AD was included in the system boundary (Fig. 7a), it was found that FOG concentration was no longer the most dominant variable that impacts the sensitivity of the result. Instead, CH_4 generation rate had the highest impact. This indicates the importance of maintaining high AD performance. The impact of the FFA concentration ranked second, mainly due to the large range of variation in energy and material consumption associated with the change in FFA concentration. The changes in the life cycle GHG emission caused by the variation in FOG concentration and electricity generation efficiency of the CHP were close to each other, followed by the variation in VS concentration. The two operational variables, electricity consumption for mixing and heating energy for the AD had the lowest impact on the sensitivity of the results. On the other hand, the situation was similar to the sensitivity analysis for life cycle energy consumption when AD was excluded from the system boundary of the study (Fig. 7b). Also, no negative value of GHG emission was observed when solids were treated as waste.

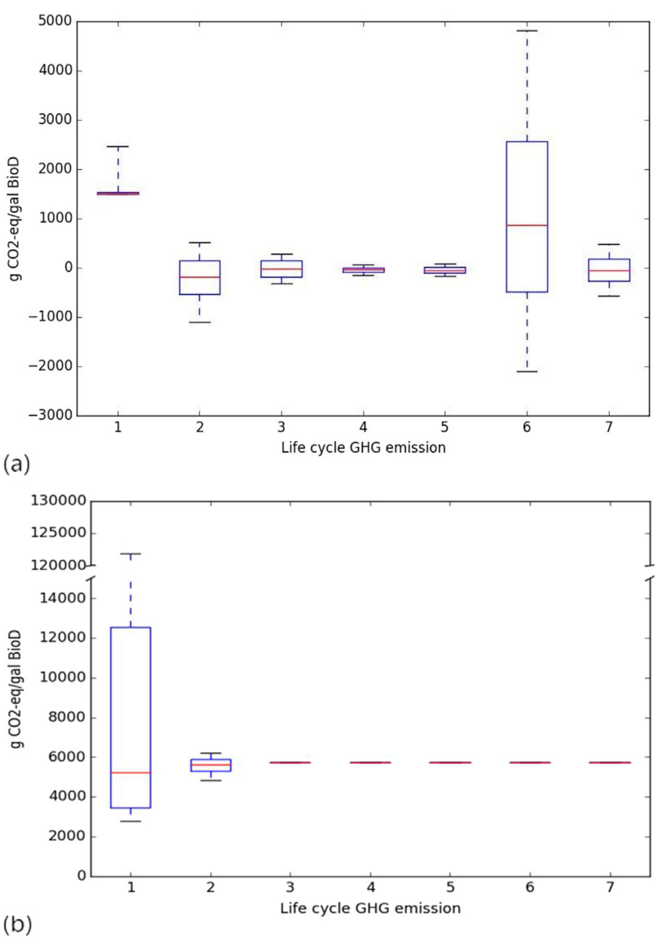

Fig. 7. Sensitivity analysis for life cycle GHG emission (a: w/AD; b: w/o AD) 1-FOG concentration; 2-FFA concentration; 3-VS concentration; 4-electricity consumption for mixing in the AD; 5-heating energy consumption for the AD; 6-CH_4 generation rate; 7-electricity generation efficiency of the CHP.

4. Discussion

4.1. Comparison with existing literature

4.1.1. Life cycle energy consumption

Studies on the life cycle assessment (LCA) of biodiesel production have been conducted for a variety of other feedstocks. The values of energy consumption from the literature are summarized in Table 1. The values are shown in original units and also converted into the normalized unit of current study for comparison. Details for the conversion can be found in Appendix S8 of the supporting information.

Overall, the selection of system boundary varies among existing studies. Generally, the system boundary starts with the feedstock collection for the biodiesel production from waste-derived feedstock, *i.e.* waste cooking oil, animal fats and sewage sludge. Rendering as a feedstock pretreatment stage is included in the system boundary by some authors (Dufour and Iribarren, 2012; Lopez et al., 2010). On the other hand, biodiesel production from oil crops and algae include crop growth and algae cultivation before the collection/harvesting stage. Oil extraction is typically a necessary stage before transesterification while it is usually not included as part of the system boundary when waste-derived feedstock is used. The end of the system boundary in the existing studies is either biodiesel production stage (transesterification) or biodiesel use stage (combustion in diesel engine). In addition to system boundary, allocation methods are not consistent among existing studies either. While most of the studies applied mass-based allocation (Dufour and Iribarren, 2012; Lopez et al., 2010; Pradhan et al., 2011; Talens Peiro et al., 2010), system expansion/displacement (Sander and Murthy, 2010; Shirvani et al., 2011) or a hybrid method was also used (Frank et al., 2012; Stephenson et al., 2010). In order to compare the result of current study with those reported in the literature, the system boundary of the existing studies were altered whenever possible and the accordingly, the values of energy consumption were adjusted and converted into the normalized unit of current study. As is shown in Table 1, the values vary significantly from case to case due to the differences in model scopes, allocation methods, data sources, and assumptions. Similar to the findings from current study, it is indicated in the literature that utilizing co-products for energy generation significantly reduces the life cycle energy consumption and the process can even be "self-sustaining" (negative value of energy consumption) under certain circumstances (Sander and Murthy, 2010). This, again, proves the importance of having energy generation facility on site to utilize the co-products. By grouping the feedstocks into oil crop (soybean, rapeseed, palm and sunflower), waste (waste cooking oil, animal fat and sewage sludge) and algae (open pond), the ranges of the grouped results from the existing studies were 13.87–46.24, 6.17–64.17, and −832.71 to 225.96 MJ/gal, respectively. The results of the Monte Carlo simulation were used to compare with the higher end of the ranges reported in the existing literature. By comparison with other waste feedstocks, the probability that the life cycle energy consumption of the trap grease-to-biodiesel life cycle was less than 64.17 MJ/gal was approximately 65% when AD was included in the system boundary and was about 39% otherwise. Compared to oil crops, the probability that the life cycle energy consumption of the trap grease-to-biodiesel life cycle was less than 46.24 MJ/gal was approximately 46% when AD was included in the system boundary and was about 13% otherwise. Compared to algae (with open pond system), the probability that the life cycle energy consumption of the trap grease-to-biodiesel life cycle was less than 225.96 MJ/gal was approximately 88% when AD was included in the system boundary and was about 79% otherwise. Compared to petroleum diesel, the probability that the life cycle energy consumption of the trap grease-to-biodiesel life cycle was less than 162.08 MJ/gal was approximately 85% when AD was included in the system boundary and was about 74% otherwise. It is indicated that the life cycle energy consumption of trap grease biodiesel production is highly likely to be lower than algae biodiesel, mainly due to the reason that harvesting and drying of wet algal biomass require significant amount of energy use. On the other hand, the advantage may not be as pronounced when trap grease is compared with waste oils or oil crops, which is primarily due to the high energy consumption during the treatment of high FFA content of the FOG derived from trap grease (e.g. energy consumption for methanol recovery during esterification). Therefore, if AD is not included in the system boundary, the probability dropped sharply, i.e. from 65% to 39% (compared with waste oils) and from 46% to 13% (compared with oil crops).

4.1.2. Life cycle GHG emission

Similarly, the results of the life cycle GHG emission from the existing literature were converted into "g CO_2 eq/gal" and are summarized in Table 2. Similar data grouping was performed for the GHG emission results and the ranges were 5812.11–8734.96, 890.78–2786.66, and −2663.47 to 16,589.37 g CO_2 eq/gal for oil crop (soybean, rapeseed, palm and sunflower), waste (waste cooking oil, animal fat and sewage sludge) and algae (open pond), respectively. Likewise, a comparison between the results of the current study and the higher end of the ranges reported by the existing literature was conducted. Compared to other waste feedstocks, the probability that the life cycle GHG emission of the trap grease-to-biodiesel life cycle was less than 2786.66 g CO_2 eq/gal was approximately 67% when AD was included in the system boundary and was about 11% otherwise. Compared to oil crops, the probability that the life cycle GHG emission of the trap grease-to-biodiesel life cycle was less than 8734.96 g CO_2 eq/gal was approximately 89% when AD was included in the system boundary and was about 68% otherwise. Compared to algae (with open pond system), the probability that the life cycle GHG emission of the trap grease-to-biodiesel life cycle was less than 16,589.37 g CO_2 eq/gal was approximately 93% when AD was included in the system boundary and was about 80% otherwise. Finally, compared to petroleum diesel, the probability that the life cycle GHG emission of the trap grease-to-biodiesel life cycle was less than 11,643.86 g CO_2 eq/gal was approximately 91% when AD was included in the system boundary and was about 74% otherwise. Similar to life cycle energy consumption, trap grease has a clear advantage over algae but the advantage is less pronounced when compared with waste oils and oil crops.

4.2. Limitations regarding the implementation of the trap grease-to-biodiesel production

Although the trap grease-to-biodiesel production shows the potential to become a promising waste-to-energy option, there are two major bottlenecks that may limit the implementation of this practice in certain regions. One is the highly heterogeneous nature of the raw trap grease. As shown in this study, the composition of raw trap grease varies substantially from case to case, which may add a significant uncertainty in both the production cost of the biodiesel and the operation of the plant. Secondly, as current study assumes a centralized production mode, i.e. trap grease is collected and transported by truck to the WWTP, the logistics (e.g. transportation cost) can be another issue if the sources of collection (e.g. restaurants, food processing plants) are scattered over a large area. Therefore, careful planning is needed before decision can be made on whether trap grease-to-biodiesel production can be implemented in a specific region. The life cycle model presented in this study can be a useful tool for that purpose.

5. Conclusion

Through the comparison with the results for biodiesel made from other feedstocks reported in the existing literature, it is indicated that trap grease could be a low energy consumption and low GHG emitting feedstock for biodiesel production under ideal conditions (e.g. high FOG concentration, low FFA concentration, high AD performance). This is an encouraging finding for promoting trap grease-to-biodiesel production. This analysis illustrated both a positive impact and ideal solution for both waste management and biodiesel production. The life cycle model presented in this study could be used by WWTPs to evaluate the prospects of utilizing trap grease for biodiesel production by using site-specific data. This model may also be used to evaluate the trap grease-to-biodiesel fuel pathway against certain GHG-related programs (e.g. Renewable Fuel Standard).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.10.028.

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