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Comparative study of the environmental impacts of used cooking oil valorization options in Thailand

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Abstract

Used cooking oil (UCO) is a valuable resource that can be utilized in different ways. Appropriate management of UCO waste can provide environmental and economic benefits, compared to improper disposal practices. This study assessed the environmental impacts of potential UCO valorization options in Thailand. Altogether, 14 scenarios, including 10 for alternative energy recovering processes (S1-10) and other options such as soap production (S11), use in dry pig feed (DPF) production (S12), synthesis of plastics (S13) and polyol (S14), were considered. The defined system boundaries for each scenario include pretreatment, material and energy consumption, and waste treatment stages for the treatment of 1000 kg UCO. Environmental impacts in terms of global warming potential (GWP), freshwater eutrophication potential (FEP), fossil resource scarcity (FRS), and freshwater, terrestrial, and marine eco-toxicity (FE, TE, and ME, respectively) were analyzed using the ReCiPe Midpoint (H) method. The results revealed that all the current waste valorization options create an environmental burden and contribute towards GWP. Scenarios 7 and 10 showed environmental credits for FEP, FE, and ME indicators while scenario 9 did so for FRS. The processes direct energy consumption resulted in the highest contribution to GWP in Scenarios 1, 5-8, 10, 12, and 13. Environmental effects of material consumption and waste treatments were found to be the highest in bio-oil and DPF production, respectively. However, co-products produced could not offset the burden created by energy and material consumption. Overall, the results showed better environmental performance from energy recovery-based UCO management options compared to alternative processes.

Keywords: Used cooking oil; waste valorization; energy recovery; life cycle assessment; environmental impacts; Circular economy

1 Introduction

Proper waste management gives rise to substantial benefits such as developing a cleaner and greener environment, conserving energy, creating employment options, and so on. Waste biomass has a great valorization potential, but much efforts need to be done for implementing these options in developing countries (Brunerová et al., 2017; Wilson et al., 2015). Used cooking oil (UCO) or waste cooking oil is a food waste generated domestically and industrially as a result of cooking and frying food using edible vegetable oil (Iglesias et al., 2012). Currently, the annual global UCO production is estimated to be 20-32 % of the total edible oil consumption of 41-52 Mt (Orjuela and Clark, 2020). It is evident that each year, large quantities of UCO are generated. According to Williams et al. (2012b), annual per capita fat, oil, and grease (FOG) consumption in developed countries is over 50 kg and approximately 20 kg in less developed countries. The European Biomass Industry Association states that domestic per capita UCO production in Europe is 2.5 L (EBIA, 2015). By 2025, global consumption of vegetable oils and fats is expected to increase by 25% (FAO, 2017). Nevertheless, as of now, only 2.5 % of UCO is recycled. Even though the potential of UCO generation is high in Thailand, the re-use of UCO is still in a nascent stage. Thailand does not have clear regulations on disposing of UCO (Intarapong et al., 2016). Direct burning to utilize UCO as a source of heat, and in soap and animal feed (AF) production are some common UCO valorization methods practiced in Thailand currently. Additionally, a few pilot-scale biodiesel prototypes have been reported in the literature (Intarapong et al., 2016; Jaruyanon and Wongsapai, 2000; Pleanjai et al., 2009).

UCO is a popular feedstock in the biofuel industry for the production of biodiesel, hydrogen gas, and low molecular weight hydrocarbons (Panadare, 2015). UCO has recently also become prominent as feedstock for a variety of bio-based materials (Moretti et al., 2020; Orjuela and Clark, 2020), in addition to its use in soap and AF production. UCO has the potential to be used in the production of surfactants, lubricants, polymers, plasticizers, etc. (Orjuela and Clark, 2020; Panadare, 2015). However, every year most of the household UCO is improperly disposed due to unconscious behaviors and lack of appropriate regulations or enforcement (Foteinis et al., 2020; Orjuela and Clark, 2020).

Inappropriate management of UCO leads to various socio-economic and environmental problems. Burning UCO in the open, and direct disposal into the soil and waterways are key improper UCO management methods. According to the Environmental Protection Agency (EPA) (EPA, 2015), UCO can coat animals and plants, and suffocate them and their environments by causing oxygen depletion. UCO causes rancid odors, fouls shorelines, clogs water treatment plants, and blocks domestic kitchen pipes. Since UCO is organic in origin, the effects of biogenic direct CO_2 emissions can be ignored when burning it in the open. However, other direct emissions, such as particulate matter (PM 2.5 and 10) and polycyclic aromatic hydrocarbons (PAH) create severe health issues (EPA, 2015). FOG or UCO in wastewater treatment plants degrade slowly and affect microbial activity, limiting the transfer of oxygen. This also slows down the degradation of other organic materials (EBIA, 2015). The toxic effects of UCO contaminated soil on animals, and plant germination and growth have been studied by Thode Filho et al. (2017) and Tamada et al. (2012). Other than informal disposal, one of the most detrimental uses of UCO is gutter oil, which is used for food processing after recovering UCO from drains and grease traps (Lu and Wu, 2014). Even though the practice has not been officially reported in Thailand, the potential threat to human health is significant as this is a common malpractice in several countries (Wallace et al., 2017; Williams et al., 2012a). Therefore, a proper UCO management system is necessary with a proper evaluation before choosing among the several possible options for UCO valorization.

Life cycle assessment (LCA) systematically evaluates environmental benefits and burdens associated with waste management systems. It analyses systems' performances and allows comparisons among alternatives and calibrates possible improvements to these systems (Hadzic et al., 2018). The application of LCA on UCO-based biofuel production is widely reported. LCA has been employed to evaluate and compare the environmental feasibility of alternative pathways of biodiesel production (Aghbashlo et al., 2020; Dias et al., 2014), bio-oil production, electricity, and heat generation (Lombardi et al., 2018; Ortner et al., 2016). Techno-economic and environmental liabilities of UCO valorization options are reported by Dias et al. (2014) (environmental impacts of soap production), Yi et al. (2015) (techno-economic evaluation of UCO as a bio-floating agent), and Moretti et al. (2020) (environmental impacts of polypropylene). In most studies, these UCO utilization pathways have been individually assessed (or within similar categories) and are limited to only a few impact categories. A direct comparison of all the potential utilization pathways has not been carried out yet. Such a comparison will also be important to assess different impact categories and compare their environmental benefits and drawbacks.

The objective of this study is to evaluate the environmental impacts of the potential and available UCO management options in Thailand. A comparative analysis of the environmental impacts of fourteen different options for UCO utilization was conducted using the ReCiPe Midpoint (H) method and the environmental attributes were identified. The sensitivity of the obtained results was assessed. A comprehensive and comparative assessment of the environmental impacts of available and potential UCO management systems will benefit stakeholders and policy and decision-makers in adopting sustainable waste management systems for UCO and protecting the environment.

2 Methodology

2.1 Quantification of UCO

The cooking procedure and the amount of vegetable oils used, determine the quantity of UCO produced during food preparation. It is only a fraction of the total consumption of vegetable oil. However, the amount of collected and valorized UCO could be less than or equal to the amount of produced UCO (Teixeira et al., 2018). For this study, the amount of vegetable oil consumption was estimated by considering ‘vegetable oil total’ and ‘food supply quantity’ elements as in the online database of the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2017). The amount of UCO produced was quantified using the following equations (1) and (2), as stated by Teixeira et al. (2018):

$$\text{UCO (kg/year)} = \infty \times \text{Total Vegetable Oil Consumption (kg/year)} \quad (1)$$

$$\text{Valorized UCO (kg/year)} = \beta \times \text{UCO (kg/year)} \quad (2)$$

where ∞=0.32 is the production factor of UCO. It indicates the relation between the amount of oil consumed to the UCO produced (per 1000 kg of the consumed vegetable oil, 320 kg of UCO are produced). β is the valorization factor and is 0.749 and 0.232 for better and underperforming countries, respectively (Teixeira et al., 2018).

2.2 Defining the goal and scope

The overall goal of this study was to systematically assess the environmental impacts of available and potential UCO valorization options in Thailand. The possible UCO management options were reviewed based on the literature and their environmental impacts were assessed using LCA. LCA was conducted according to the ISO 14040 and 14044 standards (ISO, 2006a, b). The SimaPro 9.0 software was used. An overview of the LCA methodological framework is presented in Figure 1S (supplementary information).

2.2.1 System boundaries and scenarios

The functional unit (FU) in this study is defined as assessments of the environmental impacts of different management options of the collected 1000 kg of UCO. Figure 1 depicts the system boundary of the study. The boundaries of the considered system included the pre-treatment of collected UCO and its treatment in utilization facilities. In addition to the available methods of UCO utilization, this study used hypothetical situations to compare possible UCO management options in Thailand. Therefore, UCO collection and transportation to the treatment facilities were excluded. The pre-treatment facilities were assumed to be at the same location as the main utilization facility. The zero burden assumption was made, whereby the environmental impacts from the upstream life cycle stages before UCO collection were excluded to align these stages with common waste-management oriented LCA methodologies (Laurent et al., 2014a; Laurent et al., 2014b). Similarly, environmental impacts of the infrastructure and capital goods were excluded, allowing the comparison of the scenarios in a neater manner. Moreover, emissions of biogenic greenhouse gases were assumed to be neutral.

Altogether, the environmental benefits and burdens of 14 alternative UCO management practices were considered. These are: conversion into biodiesel via acid and alkali catalyzed processes (Scenario 1 or S1, and 2 or S2, respectively); two-stepped acid catalyst followed by alkali catalyzed process (Scenario 3 or S3); immobilized lipase-catalyzed process (Scenario 4 or S4), non-catalytic supercritical methanol process (Scenario 5 or S5), and hydrogenated process (Scenario 6 or S6). Other utilization options include electricity and thermal energy generation via direct combined heat and a power generation plant (CHP) (Scenario 7 or S7), utilization in a municipal incineration plant (MIP) (Scenario 8 or S8), bio-oil production from pyrolysis (Scenario 9 or S9), biogas production in an agricultural biogas plant (Scenario 10 or S10), soap/detergent production (Scenario 11 or S11), dry pig feed (DPF) production (Scenario 12 or S12), polypropylene for utilization in plastic synthesis (Scenario 13 or S13), and polyol for use in slow release fertilizer coating synthesis (Scenario14 or S14).

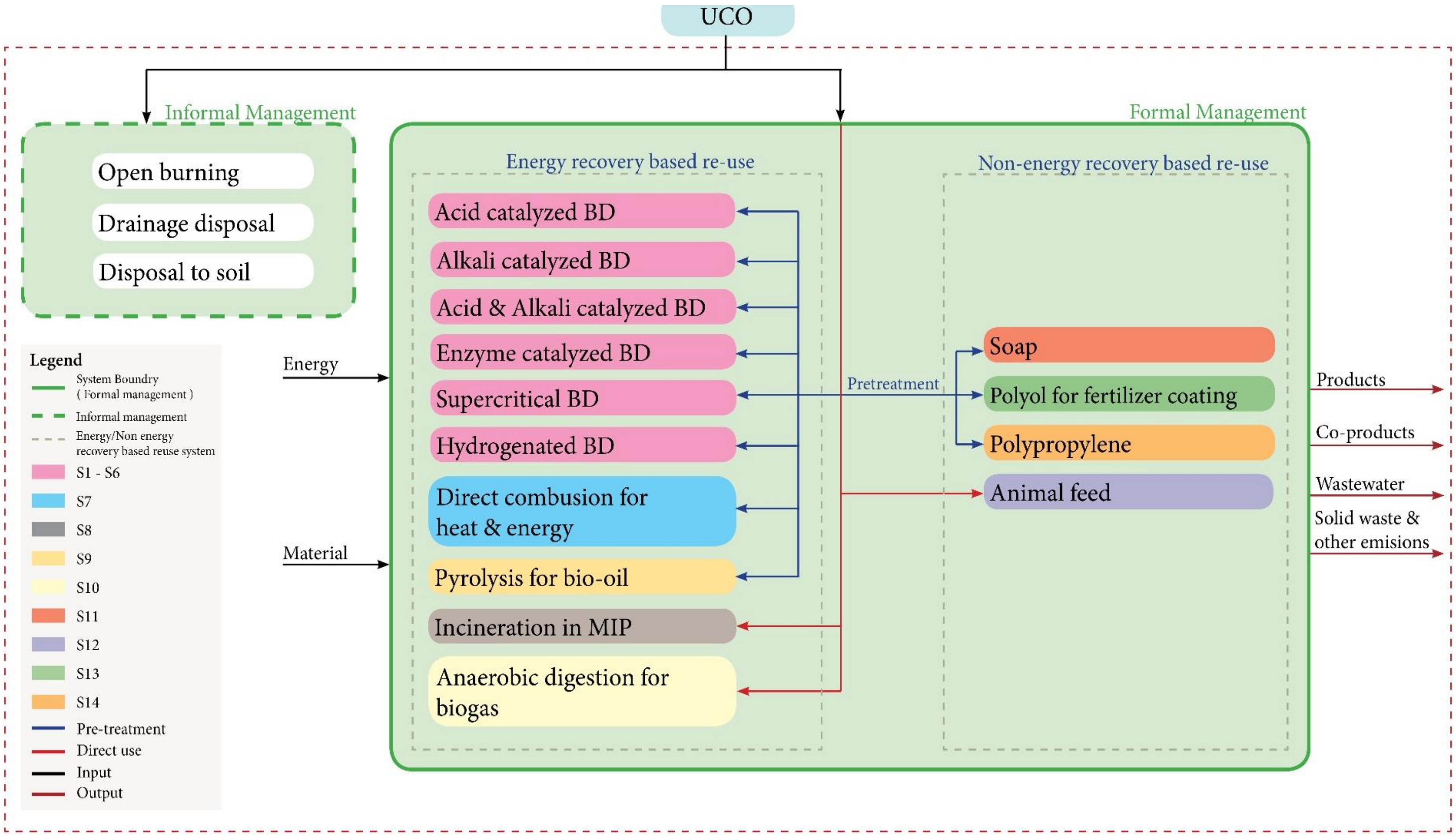


Figure 1 The system boundary of UCO valorization systems (Remarks: UCO: used cooking oil; BD: biodiesel; MIP: municipal incineration plant)

2.2.2 Impact coverage

The ReCiPe method has been developed by integrating damage and problem-oriented approaches. Moreover, the ReCiPe midpoint method has lower uncertainties compared to the endpoint approach (Huijbregts et al., 2017). Therefore, impact assessment was carried out using the ReCiPe 2016 Midpoint (H) method, as has been the case in several studies investigating global warming potential (GWP) (Goedkoop et al., 2009; Goedkoop et al., 2013). Six environmental impact categories including GWP (kg CO_2 eq), freshwater eutrophication potential (FEP) (kg P eq), fossil resource scarcity (FRS) (kg oil eq), and freshwater, terrestrial, and marine eco-toxicity (FE, TE, and ME, respectively) (kg 1,4-DCB respectively) were considered.

2.3 Life cycle inventory

The life cycle inventory (LCI) was developed following ISO 14040 standards. The complete LCI data for all potential utilization alternatives are based on the available literature, including reports, journal articles, and the Eco invent 3 databases, and are presented in Section 2.3.4. LCI includes representative average data when reporting secondary sources, as detailed below (Table 1 and 2). Table 1 contains the required material and energy flows (inputs) and products, co-products, emissions, and wastes flow (outputs) for each energy recovery process under consideration. Inventories for soap, DPF, polyol-based fertilizer, and polypropylene production are presented in Table 2.

2.3.1 Reference flow characterization

The foreground system is directly involved with reference flow management. The background system is linked with the foreground system including energy production and avoided materials. The consequences of the background system were accounted for in the analysis by including the avoided effects caused by the products and co-products (Lombardi et al., 2018; Weidema et al., 2004). In multi-functional systems, such as S1-10, co-products substitute the products which are produced through marginal processes. Appropriate Eco invent database records were considered in the inventory to include avoided products, as also done in Lombardi et al. (2018).

2.3.2 UCO Collection, transportation to the treatment plant, and pre-treatment

This study focuses on currently available and future potential applications of UCO management options in Thailand. A proper UCO management program including a wellestablished collection system is currently missing in Thailand (Intarapong et al., 2016). Therefore, the transportation of UCO from households or restaurants to a collection point and further to treatment plants were not considered for this study. This creates a minor impact on the overall process output, as stated in several studies (Ortner et al., 2016), and also allow the comparison of the many scenarios in a simpler way.

Pre-treatment of collected UCO is necessary for all formal management alternatives except for biogas production using anaerobic digestion, and when used in incineration plants with other municipal waste. The data obtained from Lombardi et al. (2018) was employed in the inventory for this study. During the pre-treatment stage, collected UCO is typically stored at 40 °C to ensure homogeneity. Subsequently, screened UCO is pre-heated and decanted and then stored at 60 °C in a tank. Decanting allows further sedimentation of particles in the oil. Also, pre-heating decreases the potential amount of volatile compounds in the oil (Lombardi et al., 2018). The residual ends in wastewater and is treated accordingly.

2.3.3 Electricity consumption

It was assumed that all electricity requirements would be met by Thailand's national electricity grid which comprises 'medium voltage under the electricity country mix', as reported in Simapro 9.0, and Eco invent database version 3. This outlines Thailand's electricity shares in 2012-2014. It accounts for natural gas (67.5 %), coal/lignite (19.5 %), fuel oil and diesel (0.7 %), and bioenergy (12.3 %) as sources of electricity generation (Weidema et al., 2013).

2.3.4 Scenario assessed for valorization options

S1 to S5 are focused on biodiesel production from trans-esterification. The process schematic diagrams are shown in Figure 2S. In S1, pre-treated UCO is converted into biodiesel via direct acid catalyzed simultaneous esterification and the trans-esterification process using H_2SO_4 as the catalyst. The average data obtained from Lombardi et al. (2018), Morais et al. (2010), and Varanda et al. (2011) were employed to develop the inventory. S2 was the alkali catalyzed one-step trans-esterification reaction using NaOH as the catalyst. Process inventory data and required details were taken from Pleanjai et al. (2009) and Yang et al. (2017). In S3, acid and alkali catalyzed two-step esterification and trans-esterification process were deployed to produce biodiesel from pre-treated UCO (Dufour and Iribarren, 2012; Lombardi et al., 2018; Morais et al., 2010). H_2SO_4 and NaOH were used to catalyze the esterification and trans-esterification reactions, respectively in S3. In S4, an immobilized lipase-catalyzed enzyme was used to produce biodiesel using 1000 kg of UCO (Peñarrubia Fernandez et al., 2017; Watanabe et al., 2000). S5 considered biodiesel production using the non-catalytic supercritical methanol process and data presented in Kiwjaroun et al. (2009), Lombardi et al. (2018), and Morais et al. (2010), were used to develop the inventory. In S6, environmental impacts of the use of 1000 kg of UCO for hydrogenated biodiesel production were considered. Average values of the process's input and output data as presented in Bezergianni et al. (2014) and Yano et al. (2015) were considered.

S7 used pre-treated UCO for combined heat and electricity generation in a co-generation plant with a diesel engine. Average data from Lombardi et al. (2018) and Ortner et al. (2016) were considered in developing the inventory. S8 is the incineration of UCO with other municipal waste. A steam turbine with 15 % energy recovery was considered. The inventory for the UCO re-use process was developed following Yano et al. (2015). S9 considered the valorization of 1000 kg of UCO in a pilot-scale pyrolysis plant in Thailand which uses liquid petroleum gas (LPG) and electricity as its base energy sources (Intarapong et al., 2016). Treatment of UCO to produce biogas was considered in S10. Because the impurities in UCO can be utilized in anaerobic co-digestion, this process excludes the pre-treatment of UCO. UCO was treated in an agricultural biogas plant. The resulting biogas was collected and burned in a cogeneration unit (Ortner et al., 2016).

The use of UCO for the production of non-energy-based products was considered in S11, S12, S13, and S14. The inventory for S11 was developed according to Kim et al. (2015), Lucchetti et al. (2019) and the Eco-invent database, due to the lack of data for this use. Process schematic diagram is shown in Figure 3S. S12 considers the environmental load of the use of UCO in DPF production. Pre-treated waste cooking oil is an economical source with a fat content of about 3-5 % (Panadare, 2015; Park et al., 2009). The use of 1000 kg of UCO as a substitute for fats in poultry feed was considered. Due to the lack of relevant data on the usage of UCO for poultry food production, appropriate data as reported in Salemdeeb et al. (2017) and Kim and Kim (2010) for DPF production from food waste was adopted and used in the study. UCO is sterilized and dehydrated by air-drying at 390 °C with the rest of the food waste that is being shredded and filtered for contaminants (Figure 4S). S13 deals with the use of UCO for polyol production which is used in slow-release fertilizer coating. The process's steps include synthesis of polyol via the trans-esterification of pre-treated UCO with Triethanolamine at 170 °C, and treatment with diphenylmethane diisocyanate to produce polyurethane (Fridrihsone et al., 2020; Liu et al., 2017). S14 assesses the environmental impacts of UCO-derived polypropylene production according to Moretti et al. (2020).

Table 1 Inventory for energy-based UCO re-use alternatives

	Inputs and outputs	Unit	S1[a]	S2[b]	S3[c]	S4[d]	S5[e]	S6[f]	S7[g]	S8[h]	S9[i]	S10[j]
Pretreatment	**Input**											
	UCO	kg	1000	1000	1000	1000	1000	1000	1000		1000	
	Electricity	kWh	40	40	40	40	40	40	40		40	
	Water	L	50	50	50	50	50	50	50		50	
	Output											
	Treated UCO	kg	950	950	950	950	950	950	950		950	
	Wastewater	L	50	50	50	50	50	50	50		50	
Process	**Materials/Energy**											
	UCO	kg	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
	Methanol	kg	208.6	146.5	112.3	260.0	109.4					
	Sulfuric acid	kg	147.0		9.4							
	NaOH	kg		8.8	9.2							
	Enzyme	kg				29.1						
	Catalyst-pyrolysis	kg									187.0	
	Electricity	kWh	1.2	31.6	29.1	9.1	22.0	136.3	210.2		803.5	102.9
	Steam/Heat	kWh	2378.0	891.9	877.0	860.0	329.8	4943.0	861.5			346.2
	LPG	kg									217.4	
	Water (processing/ washing/ cooling)	kg	28.0	2672.6	34.7	14750						

CaO	kg	84.0		0.08							
H_3PO_4	kg		4.5	7.4							
Tert butyl alcohol	kg				6.0						
Propane	kg					0.02					
Product/ Co-product											
Biodiesel	kg	985.2	892.9	901.7	970	1003.6	715.4				
Glycerol	kg	104	142	49.8	98.0	104.8					
Off gas (H_2-99 %, CH_4-1 %)	kg						40.4				
Biogas	m^3										757.35
Electricity	kWh							4203.1	1527.8		2058.8
Heat	kWh							4307.3			1731.1
Bio-oil	kg									307	
Gasoline	kg									73	
Kerosene	kg									140	
Fuel oil	kg									370	
Residual oil	kg									35	
Syngas	kg									66	
Waste											
Methanol	kg	12.6				7.7					
Salt to landfill waste	kg	203.4		55.7							

Liquid waste	m^3	0.1	1.3	0.02	0.3

Note-References are denoted as a: (Lombardi et al., 2018; Morais et al., 2010; Varanda et al., 2011); b: (Lombardi et al., 2018; Pleanjai et al., 2009; Ripa et al., 2014); c: (Dufour and Iribarren, 2012; Lombardi et al., 2018; Morais et al., 2010); d:(Lombardi et al., 2018; Raman et al., 2011); e: (Lombardi et al., 2018; Morais et al., 2010); f: (Bezergianni et al., 2014; Lombardi et al., 2018; Yano et al., 2015); g: (Lombardi et al., 2018; Ortner et al., 2016; Yano et al., 2015); h: (Yano et al., 2015); i: (Intarapong et al., 2016; Lombardi et al., 2018); j: (Ortner et al., 2016)

Table 2 Inventory for non-energy-based UCO re-use alternatives

	Inputs and Outputs	Unit	S11[a]	S12[b]	S13[c]	S14[d]
Pretreatment	**Input**					
	UCO	kg	1000		1000	1000
	Electricity	kWh	40		40	40
	Water	L	50		50	50
	Output					
	Treated UCO	kg	950		950	950
	Wastewater	L	50		50	50
Process	**Materials/Energy**					
	UCO	kg	1000	1000	1000	1000
	NaOH	kg	333.25			0.98
	NaCl	kg	97.19			
	H_3PO_4	kg				0.57
	Processed chemicals	kg				2
	Food waste	kg		153846.2		
	Triethanolamine	kg			492	
	Catalyst	kg			2.23	
	Water	kg	23019.7	389.23		102
	Electricity	kWh	73.6	3784.61	716.4	34
	Steam/Heat	MJ	2457.4			224*

GAS	kg		500	26.26	4.81
H_2	kg				34
N_2	g				32
Products/ Co-products					
Soap	kg	1475			
DPF	kg		20000		
Polyol	kg			1492.5	
Polypropylene	kg				7.64
Waste					
Steam/Heat*	kg				38.96
Solid waste	kg	526.33	9230.76	1492.5	10.2
Liquid waste	m^3	1296.01	70.3		0.12

Note -*steam in kg

-References are denoted as a: (Kim et al., 2015; Lombardi et al., 2018; Lucchetti et al., 2019); b: (Kim and Kim, 2010; Salemdeeb et al., 2017); c: (Fridrihsone et al., 2020; Liu et al., 2017; Lombardi et al., 2018); d: (Lombardi et al., 2018; Moretti et al., 2020)

2.4 Contribution analysis

Modeling assumptions, unrepresentative or missing data, and data variability create uncertainty in the results of LCA studies (Clavreul et al., 2012). In this study, energy and material inputs and outputs associated with each process were collected from secondary sources/ data. The collected data showed a considerable variability that could have had a significant influence on the final results. A contribution analysis visualizing the environmental debits and credits was performed to obtain a quick overview of the important contributors (Clavreul et al., 2012; Heijungs and Kleijn, 2001). Scenario uncertainties were analyzed by changing the energy carrier for direct electricity consumption (Curran et al., 2005; Ortner et al., 2016).

3 Results and Discussion

3.1 Quantification/Potential of UCO

According to the Organization for Economic-Co-operation and Development, Thailand produced 4.1×10^9 kg of vegetable oil in 2019. The amount of total vegetable oil consumption, other than biofuel production, was 2.4×10^9 kg in 2019 (OECD, 2019). If this amount was used for cooking, it is expected that 7.8×10^8 kg of UCO was produced (Equation 1) and about 1.8-5.8 $\times 10^8$ kg valorized (Equation 2). However, Intarapong et al. (2016) stated that Thailand produces approximately 1.8×10^{10} kg of UCO per year. According to Sakulsuraekkapong et al. (2018), that is more than 1.0×10^8 L. These numbers are excluding the UCO generated in household cooking. According to (Intarapong et al., 2016) and (Lucchetti et al., 2019), 19 % residual oil is estimated to be produced after cooking. If the average annual per capita consumption of vegetable oil is considered to be roughly 25 kg (Lucchetti et al., 2019), Thailand produced over 3.3×10^9 kg of UCO in 2019. Even though the results of the amount of UCO produced in Thailand are contradictory, they indicate that UCO generation is potentially quite significant. Yet, UCO management is not optimally carried out and there are no clear regulations on UCO disposal, leading to socioeconomic and environmental problems. Identifying potential valorization options and their environmental sustainability is a possible way to prevent illegal and improper management.

3.2 Environmental impacts of UCO valorization options

3.2.1 Global warming potential

Figure 2 presents the GWP of all the considered scenarios in terms of total kg CO_2 eq emissions. All the scenarios investigated were found to result in net greenhouse gas (GHG) burden (environmental loads). UCO-based DPF production process showed the highest environmental load of 9548 kg CO_2 eq. This is due to the required energy and subsequent waste treatment during the production of 20,000 kg of DPF, similar to process conditions in (Kim and Kim, 2010; Salemdeeb et al., 2017). However, there are some instances where the direct addition of UCO into the AF as a source of fat has been reported. If UCO is directly added to the processed dry feed, the environmental burden of the process can be decreased by approximately about 5 % (Kim and Kim, 2010; Salemdeeb et al., 2017; Tres et al., 2013). The impacts of energy recovery-based UCO management options range from a minimum of 108 kg for enzyme-catalyzed biodiesel production to a maximum value of 1346 kg CO_2 eq for bio-oil production. An increase in CO_2 emissions in the bio-oil production process is due to the high consumption of fossil-derived fuel. Avoided impacts of the heat, electricity and glycerin produced due to the energy production alternatives were found not to offset the direct impacts of material and energy consumption. For all the different biodiesel production options, environmental burdens resulting from pre-treatment and waste treatment are in a similar range. Of them, the acid catalyzed biodiesel production process contributed to the highest GWP of 924 kg CO_2 eq due to high fossil-based energy and material use. Besides, energy-saving from the pre-treatment stage was found to decrease the environmental impact compared to energy recovery options in S8 and S10.

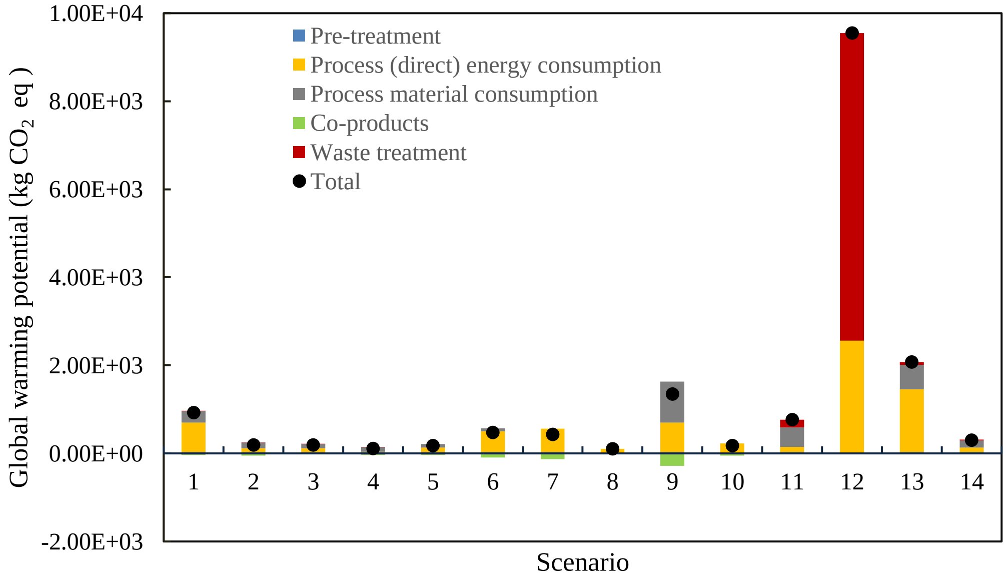


Figure 2 Global warming potential of the UCO valorization options

Remarks: 1- 4, biodiesel production via catalysts; 5, supercritical methanol process; S6, hydrogenated process; 7, CHP generation; 8, utilization in a MIP; 9, bio-oil production; 10, 11, 12, biogas, detergent, and DPF production, respectively; 13, polypropylene synthesis; and 14, polyol synthesis

3.2.2 Freshwater eutrophication potential

The results of the FEP are presented in Figure 3. According to Figure 3, DPF production resulted in the highest potential (1.7 kg P eq), followed by soap production (1.5 kg P eq). The most significant factors that affect FEP are chemical oxygen demand (COD), phosphate, ammonia, and nitrogen oxides (Zhang et al., 2019). However, the high fossil-derived electricity consumption in S12 compared to the other scenarios contributed to the resulting high FEP. That is likely due to related nitrogen oxide emissions in fossil-based energy sources. Besides, S12 generated a high amount of food residuals with high nutrient content. Nitrogen and phosphorous enrichment occurring in different forms in the organic or food waste leads to eutrophication. In addition to that, NH_3 and N_2O released during the anaerobic digestion of residual food waste can increase the FEP in S12 (Al-Rumaihi et al., 2020). In addition, soap production consumes a high amount of water compared to other processes generating considerably a large amount of wastewater. Wastewater generated in the detergent production process contains high organic matter and shows low biodegradability due to high COD (Mousavi and Khodadoost, 2019). Also, the potential high amount of N_2O emissions in such wastewater is identified as one of the main factors for freshwater eutrophication (Zhang et al., 2019). Therefore, it can be concluded that the high FEP in S12, and S11 compared to other processes is due to the generation of a high amount of solid and liquid wastes, in addition to the high fossil-derived electricity consumption. Direct electricity generation of combined heat and power generation (-0.02 kg P eq) and biogas production (-0.01 kg P eq) resulted in net environmental benefit. This is likely due to the avoided impacts of the co-products.

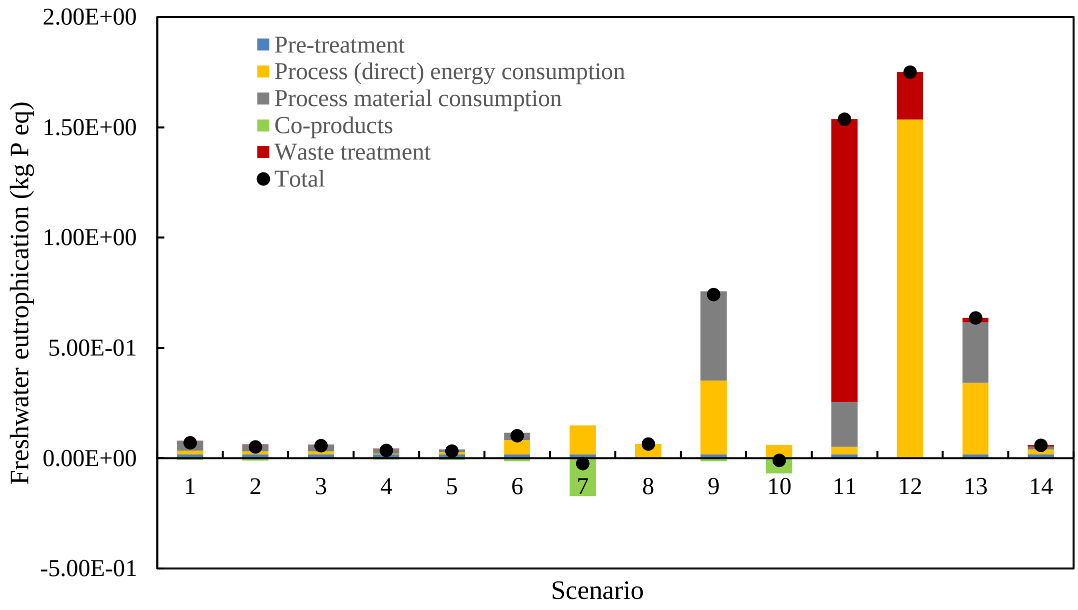


Figure 3 Freshwater eutrophication potential of the UCO valorization options

Remarks: 1- 4, biodiesel production via catalysts; 5, supercritical methanol process; S6, hydrogenated process; 7, CHP generation; 8, utilization in a MIP; 9, bio-oil production; 10, 11, 12, biogas, detergent, and DPF production, respectively; 13, polypropylene synthesis; and 14, polyol synthesis

3.2.3 Fossil resources scarcity

FRS was used to assess abiotic resource use potential (Huijbregts et al., 2017). Figure 4 presents the FRS of all the scenarios in terms of total kg oil eq. UCO-based bio-oil production contributed to the lowest FRS, indicating a net environmental benefit. Acid-catalyzed biodiesel production showed the highest FRS for energy recovery-based management options. This is likely due to high fossil-based energy and materials, such as methanol and H_2SO_4 consumption in S1 as in the GWP indicator (Kiss et al., 2010). However, S13 and S12 consumed more cumulative fossil-based energy and materials compared to energy recovery options and resulted in the highest FRS of 921 and 770 kg oil eq, respectively.

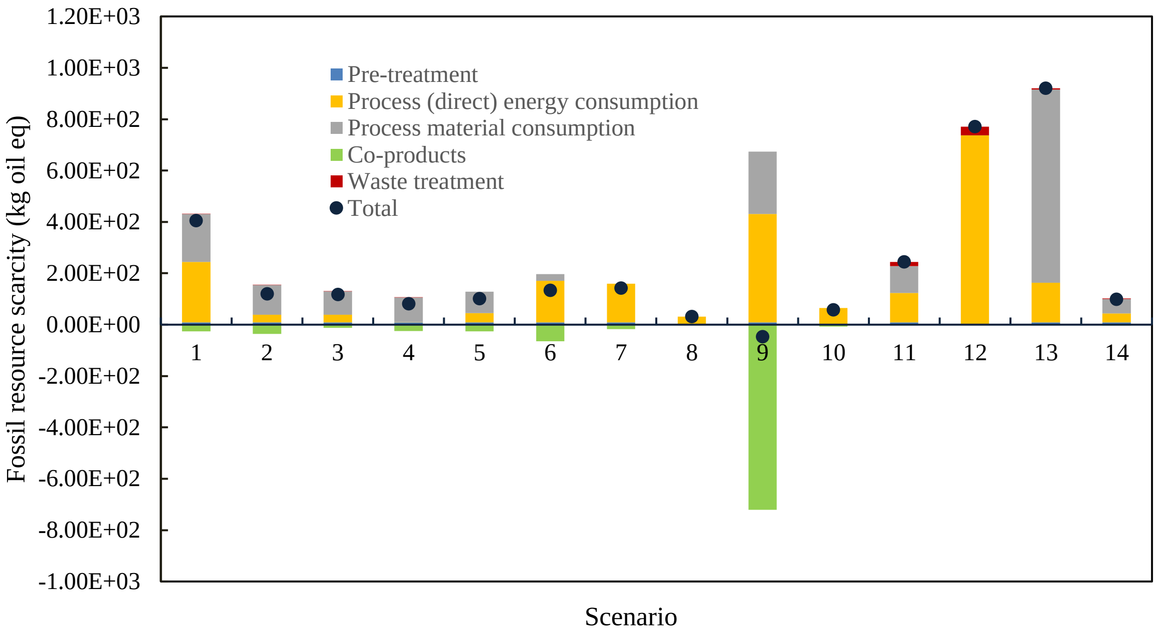
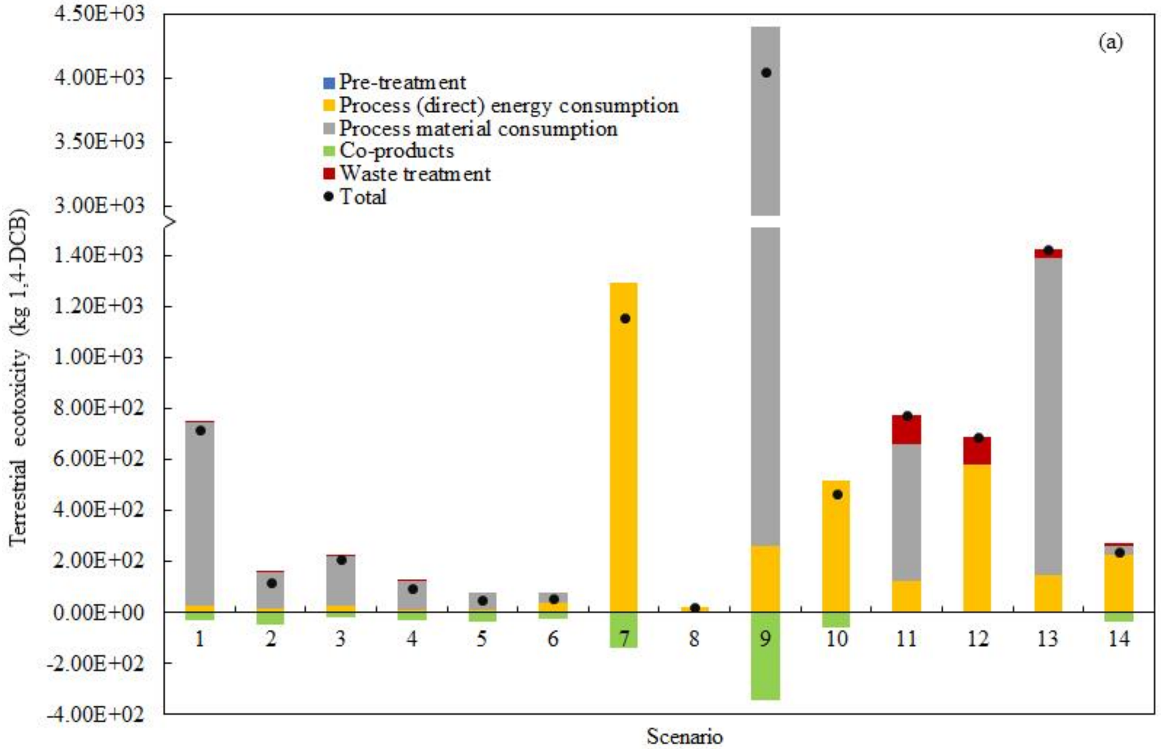


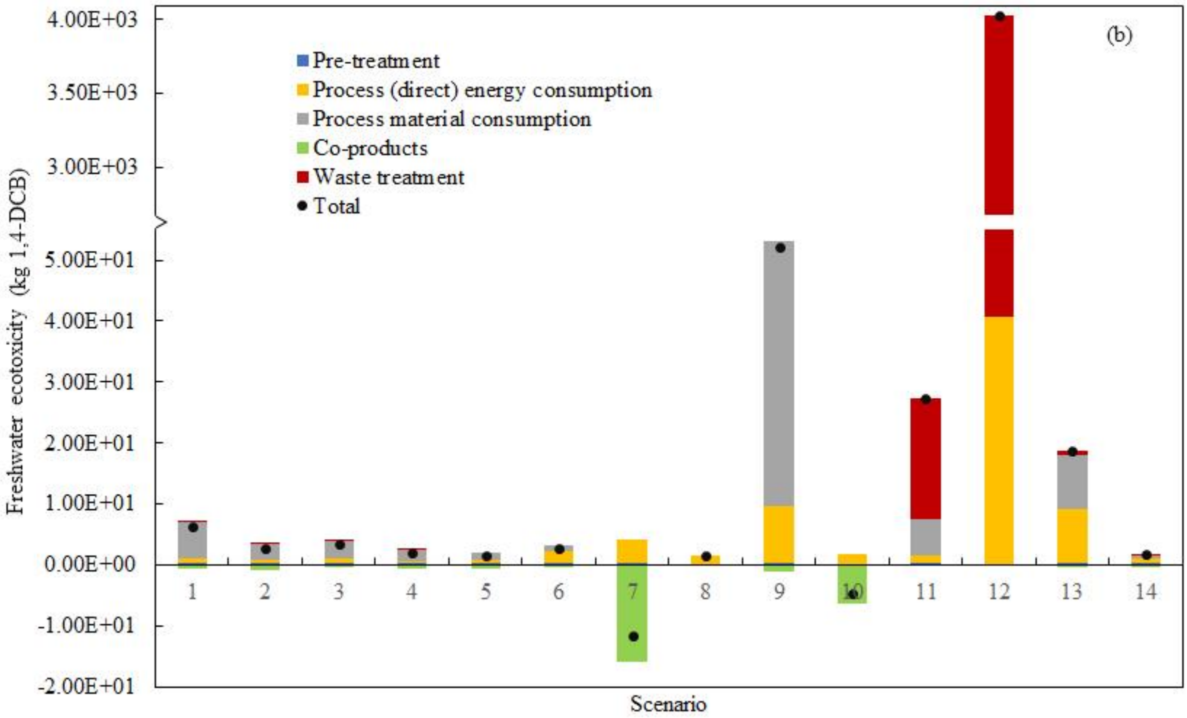
Figure 4 Fossil resources scarcity of the UCO valorization options

Remarks: 1- 4, biodiesel production via catalysts; 5, supercritical methanol process; S6, hydrogenated process; 7, CHP generation; 8, utilization in a MIP; 9, bio-oil production; 10, 11, 12, biogas, detergent, and DPF production, respectively; 13, polypropylene synthesis; and 14, polyol synthesis

3.2.4 Ecotoxicity potential

The ecotoxicity indicator accounts for the persistence and the effect of chemicals in terrestrial, freshwater, and marine water environments. TE is expressed as the fate and effects of chemical emissions in terrestrial ecosystems (Huijbregts et al., 2017). TE of all the considered scenarios resulted in environmental loads. Results are shown in Figure 5 (a). The highest burden is shown by the production of bio-oil (4052 kg 1,4-DCB), followed by polyol (1422 kg 1,4-DCB), CHP (1155 kg 1,4-DCB), and soap ((774 kg 1,4-DCB). According to Aberilla et al. (2020), trace metals are considered as one of the main contributors (>98%) to the TE of biomass fuels. However, the use of zeolite as a catalyst in S9 is the main contributor to high TE and FE potential in bio-oil production (Blom, 2010; HERA, 2004). FE and ME indicators range between a minimum of -11.4 and -14.0 (for CHP production), to a maximum of 4024 and 5280 kg 1,4-DCB (DPF production) respectively (Figure 5 (b) and (c)). As stated by Talens Peiró et al. (2010), fossil-derived electricity production contributes to about 85 % of aquatic ecotoxicity. In addition, S12 generated a high amount of solid waste that are considered to be disposed to a sanitary landfill. Primary pollutants, such as heavy metals, and other potential emissions, such as sulphur dioxide, hydrogen fluoride, benzene, CO, CO_2, and nitrogen oxides released through waste treatment facilities can lead to marine and freshwater toxicity (Zaman, 2010). On the other hand, Zhang et al. (2019) stated that ME is sensitive to water and diesel fuel. Therefore, along with the high amount of solid waste generated, fossil-derived electricity consumption for the production of 20 000 kg of DPF likely caused the high FE and ME potential in S12.




(b)
Pre-treatment
Process (direct) energy consumption
Process material consumption
Co-products
Waste treatment
Total
Freshwater ecotoxicity (kg 1,4-DCB)
4.00E+03
3.50E+03
3.00E+03
5.00E+01
4.00E+01
3.00E+01
2.00E+01
1.00E+01
0.00E+00
-1.00E+01
-2.00E+01
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Scenario

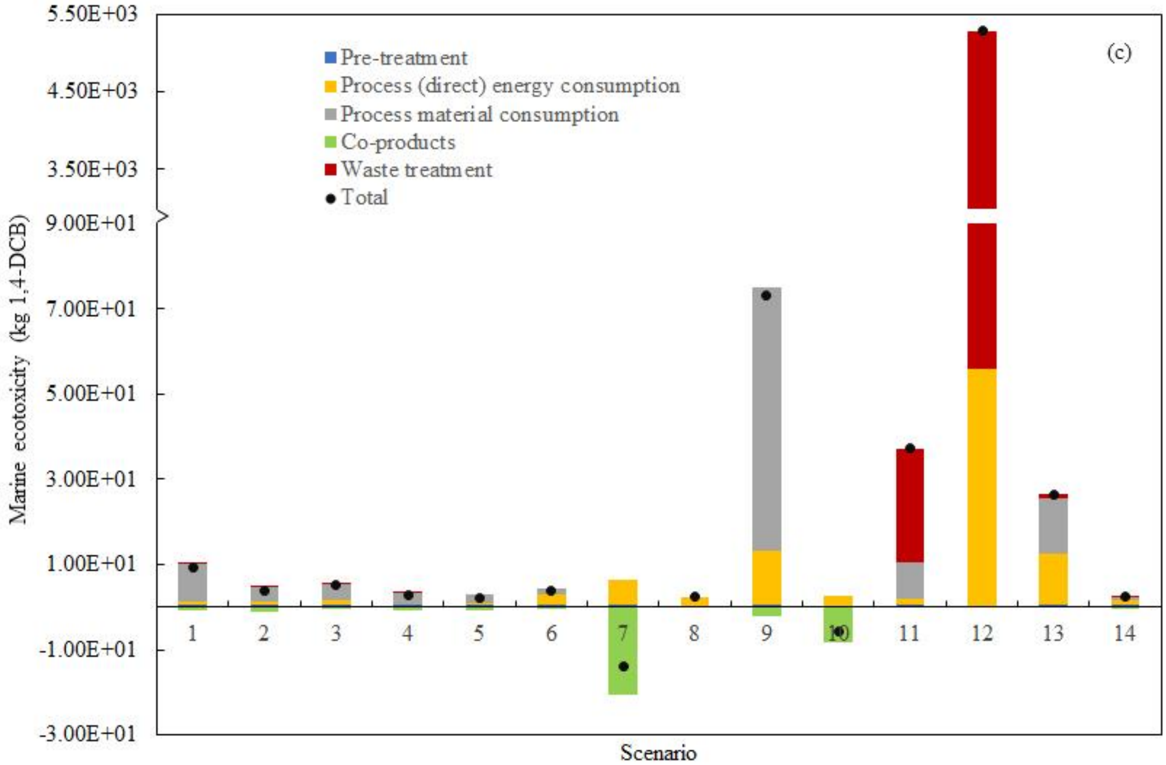

(c)
Pre-treatment
Process (direct) energy consumption
Process material consumption
Co-products
Waste treatment
Total
Marine ecotoxicity (kg 1,4-DCB)
5.50E+03
4.50E+03
3.50E+03
9.00E+01
7.00E+01
5.00E+01
3.00E+01
1.00E+01
-1.00E+01
-3.00E+01
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Scenario

Figure 5 (a) Terrestrial ecotoxicity; (b) Freshwater ecotoxicity; (c) Marine ecotoxicity potential of the UCO valorization options

Remarks: 1- 4, biodiesel production via catalysts; 5, supercritical methanol process; S6, hydrogenated process; 7, CHP generation; 8, utilization in a MIP; 9, bio-oil production; 10, 11, 12, biogas, detergent, and DPF production, respectively; 13, polypropylene synthesis; and 14, polyol synthesis

3.3 Contribution analysis

The detailed results for the process contribution analysis in terms of GWP are shown in Figure 6 (a). The pre-treatment stage is excluded in S8, 10, and 12 assuming that UCO was used directly without treatment. It was found that a process's energy consumption was the highest contributor to GWP except in S2, 3, 4, 9, and 14. Since, S7, 8, and 10 do not consume materials in the processing stage, environmental burdens are associated with the pre-treatment stage and energy consumption. All the co-products generated in the scenarios considered give environmental benefits; however, these benefits do not outperform the corresponding environmental burdens, as seen for S1-7, 9-10, and 14. S1-4 (biodiesel production) and S10-14 (soap, DPF, polyol, and polypropylene production) contributed to GHG emissions during downstream waste treatments. The details of process contribution for FEP are presented in Figure 5S. Waste treatment showed the highest contribution to FEP in S11. In line with the GWP, environmental burdens for S7, 8, and 10 are associated with the pre-treatment stage and energy consumption. However, the environmental benefits due to co-products found to outperform the burdens in S7 and 10.

Electricity is a major consideration in performing any LCA and has a major influence on the overall results (Curran et al., 2005). The sensitivity of the reference system was analyzed by changing the energy carriers. The results were found to deviate in a small range (S2-14) when using biomass energy for electrical input compared to the reference system. The results of the scenario analysis changing the energy carrier are presented in Figure 6 (b).

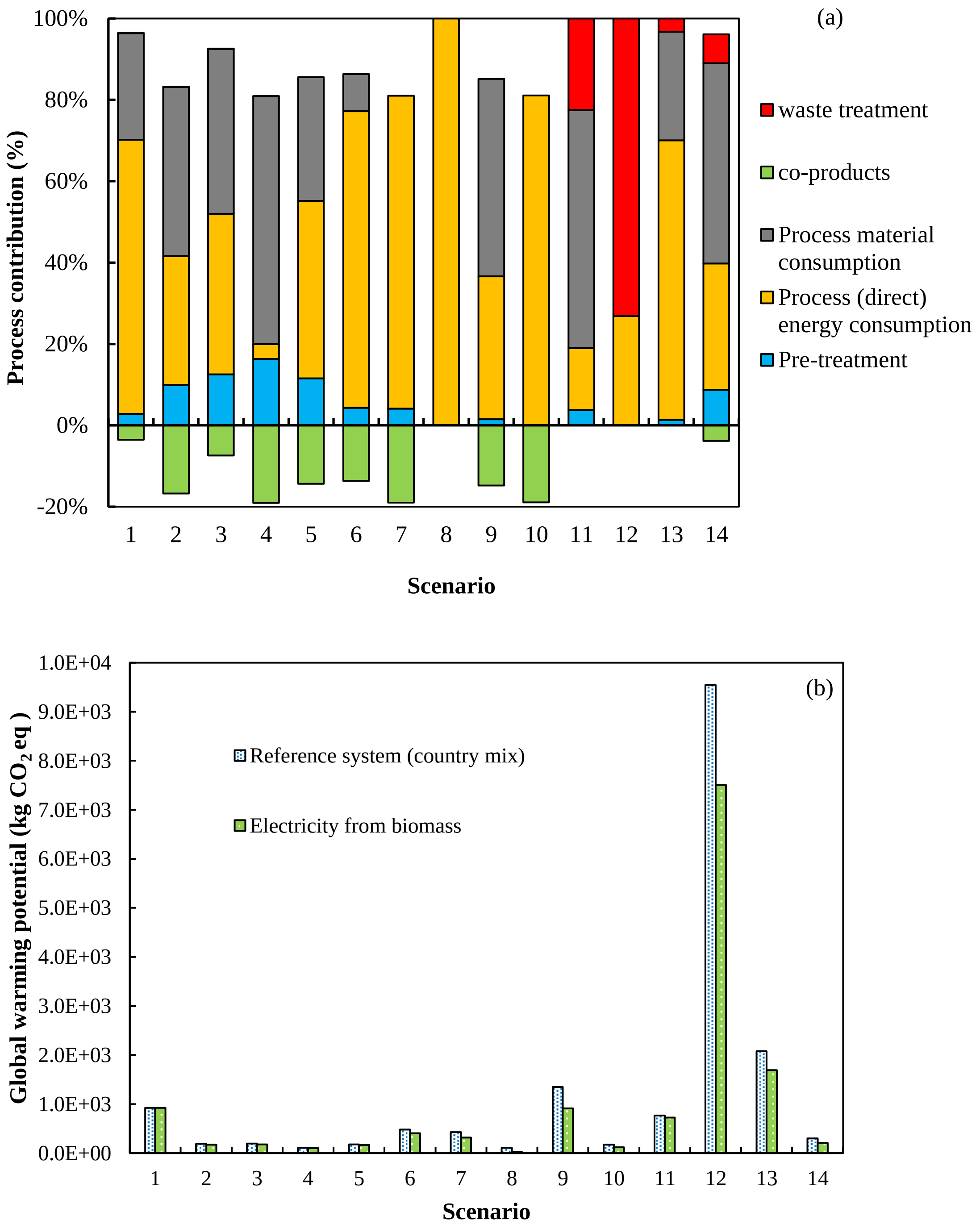


Figure 6 (a) Process contribution in terms of GWP; (b) scenario analysis by exchanging the energy carrier for electricity as biomass energy

Remarks: 1- 4, biodiesel production via catalysts; 5, supercritical methanol process; S6, hydrogenated process; 7, CHP generation; 8, utilization in a MIP; 9, bio-oil production; 10, 11, 12, biogas, detergent, and DPF production, respectively; 13, polypropylene synthesis; and 14, polyol synthesis

The results highlight that impact categories are highly influenced by energy consumption in all the scenarios. The electricity production mix in Thailand is based on natural gas (67.5 %), coal/ignite (19.5 %), fuel oil and diesel (0.7 %), and renewable energy (12.3 %). Since the major source of electricity is still based on fossil-derived fuels, the emissions related to the impact categories considered could be minimized by substituting it with electricity derived from renewable fuels (Talens Peiró et al., 2010).

In general, the use in biogas production and direct use in CHP production can be identified as the best alternatives of energy-recovery-based UCO management. DPF production created the highest burden except for FFS and TE. Since DPF production requires high energy consumption owing to process conditions and substantial amount of the end product, direct addition of pre-treated UCO to the processed dry feed would decrease the environmental burden to a greater extent (Kim and Kim, 2010; Salemdeeb et al., 2017; (Tres et al., 2013). Overall, all the considered utilization processes were found to reduce the detrimental environmental impacts caused by improper management and disposal. Thus, the considered systems of the production of high-value products from UCO can be identified as a promising avenue for achieving circular economy goals. This will help in decreasing fossil fuel dependency while reducing the demand for other valuable resources, such as virgin biomass.

3.4 Recommendations

It is recommended that future studies should expand the system boundary to identify potential environmental impacts of UCO generation, collection, and transportation. Since most of these options are still in the pilot stage or at the lab scale, further studies are required to understand available opportunities and the actual impacts on the environment and cost-effectiveness once these are implemented on a large scale to identify the state of the UCO in the circular economy. Besides, a systematic analysis of the direct and indirect impacts of improper disposal practices in Thailand would be beneficial to justify the value of UCO in a suitable market. Moreover, creating awareness right from the school level and among the general public while formulating required policy measures will likely reduce informal disposal practices. As yet, Thailand needs to identify an incentive system for proper UCO collection and a suitable market to capture the benefits of the valorization of this waste resource. In line with international projects that have succeeded in doing this, improved technologies for UCO valorization need to be introduced.

4. Conclusions

The results of the study show that all 14 valorization processes for UCO showed environmental burden in terms of GWP. However, co-product substitutions in S1-7, 9-10, and 14 contributed to considerable savings in GWP. The results of the sensitivity analysis confirm that the impact of GWP decreases by substituting the electricity derived from fossil fuels by biomass energy in S2-14. Biogas and CHP production showed net environmental benefits for FEP, FE, and ME indicators and were identified as the best alternatives for energy-recovery-based management. Furthermore, the energy recovery-based UCO management options showed lower environmental burden compared to alternative practices. Therefore, the considered alternatives provide a promising avenue for achieving circular economy goals while reducing detrimental impacts due to improper management practices. Additionally, future investigations are recommended to expand the system boundaries to identify potential environmental impacts of UCO generation, collection, and transportation.

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