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Sustainability Assessment of Inedible Vegetable Oil-based Biodiesel for Cruise Ship Operation in Ha Long Bay, Vietnam

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Sustainability Assessment of Inedible Vegetable Oil-based Biodiesel for Cruise Ship Operation in Ha Long Bay, Vietnam

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ABBREVIATIONS AND SYMBOLS

ADIOS	Automated Data Inquiry for Oil Spills
BC	Biocapacity
BDF	Biodiesel fuel
EF	Ecological footprint
ER	Ecological risk
FAME	Fatty acid methyl esters
GHG	Greenhouse gas
HR	Human risk
JCO	Jatropha curcas oil
LC	Life cycle
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
LCSA	Life cycle sustainability assessment
PAHs	Polycyclic aromatic hydrocarbon
RBDF	Roselle biodiesel
S-LCA	Social life cycle assessment
SATREPS	Science and Technology Research Partnership for Sustainable Development
TBDF	Trau biodiesel
TRIPLE I	Inclusive Impact Index
WAF	Water accommodated fraction
WCO	Waste cooking oil

Equation Chapter (Next) Section 1

Chapter 1 - INTRODUCTION

1.1 GENERAL INFORMATION ABOUT BIODIESEL

Fossil fuel energy supply steadily increased by two times from more than 5,300 Mtoe in 1973 to around 11,110 Mtoe in 2014, remaining the share of more than 80% in total primary energy supply for four decades despite the increasing non-fossil energy (IEA 2016). This dominated complexion of fossil fuel is projected to continue until 2035 (BP 2016). Since fossil fuel is depletable, this will lead to a massive future burden on the natural resources. Furthermore, fossil fuel combustion is the key driver of the surge in global carbon dioxide (CO_2) emissions to reach the level of 32.2 $GtCO_2$ in 2013 (IEA 2015).

Therefore, the interest of global community in renewable and environmentally friendly fuel sources has increased rapidly for decades. Especially, this is much of concern to transport sector since the world's transportation contribtutes about 14% of global greenhouse gas emissions which mostly due to the combustion of fossil fuel (IPCC 2014). As a green fuel for the transportation, biodiesel has gained a rapidly increasing attention with a ten-time soaring in the production starting from just under seven million liters per day in 2004 to around 70 million liters per day in 2012 (U.S. Energy Information Administration 2015). There are several reasons for the popularity of the fuel which will be discussed later in next section. However, at first and foremost is it is renewable and has high applicability due to the similarly to petroleum diesel (petrodiesel) in engine performance and no other requirements for the modification of diesel engine when using up to B20 blend (20% biodiesel by volume in the fuel) (Alternative Fuels Data Center 2016).

1.1.1 Feedstock for biodiesel production

To date, biodiesel can be derived from vegetable oils (both edible and inedible), animal fats and waste cooking oil. Among the three categories, vegetable oils are considered as a promising feedstock for the production of biodiesel. There are more than feasible 350 oil-bearing crops for biodiesel production have been recorded (Atabani et al. 2012). Table 1.1 lists main feedstocks of biodiesel.

Table 1.1 Main feedstocks of biodiesel as summarized by Atabani et al. (2012)

Edible oils	Non-edible oils	Animal fats	Other sources
Soybean	Jatropha curcas	Pork lard	Bacteria
Rapeseed	Mahua	Beef tallow	Algae
Safflower	Pongamia	Poultry fat	Microalgae
Rice bran oil	Camelina	Fish oil	Tarpenes
Barley	Cotton seed	Chicken fat	Poplar
Sesame	Karanja		Switchgrass
Groundnut	Cumaru		Miscanthus
Sorghum	Cynara cardunculus		Latexes
Wheat	Abutilon muticum		Fungi
Corn	Neem		
Coconut	Jojoba		
Peanut	Passion		
Palm and palm kernel	Moringa		
Sunflower	Tobacco seed		
	Rubeer seed tree		
	Salmon oil		
	Tall		
	Coffee ground		
	Nagchampa		
	Croton megalocarpus		
	Pachira glabra		
	Aleurites moluccana		
	Termnalia belerica		

The first generation of biodiesel feedstock is edible oil. Although edible oil can provide good quality biodiesel, it has led to the great concern owing to food cropland conflict, food price increase and food security, forest land conversion, high feedstock cost and limited provision (Atabani et al. 2012; No 2011; Tietenberg and Lewis 2012). The edible oil crops are not feasible to plant in developing countries since their income highly depend on food crop land for agriculture and food price for their daily life. Thus, the extension of edible oil crops for biodiesel may threaten the development of developing countries. Then, the second generation of feedstock, inedible oils, for biodiesel production was introduced to complement those deficiencies of the first. Inedible vegetable oil is the oil that human being cannot consume due to the toxicity or low quality of the oil. Main inedible oil crops and their oil content are shown in Table 1.1 and Table 1.2. The third generation of biodiesel are derived from algae.

Table 1.2 Some inedible oil crops in Asia as summarized by (Atabani et al. 2013)

Inedible vegetable source	**Plant type**	**Plant part**	**Oil content**	
			Seed (wt%)	**Kernel (wt%)**
Calophyllum inophyllum L.	Tree	Seed, kernel	65	22
Cerbera odollam (sea-mango)	Tree	Seed, kernel	54	6.4
Croton tiglim	Herbaceous perennial	Seed, kernel	30-45	50-60
Crotalaria retusa L. (fabaceae)	Herbaceous annual	Seed	15	
Eruca sativa gars	Herbaceous perennial	Seed	35	
Hevea brasiliensis (rubber)	Tree	Seed	46-60	40-50
Idesia polycarpa var. vestita fruit oil	Tree	Fruit, seed	26.15-26.26	
Jatropha curcas L.	Tree	Seed, kernel	20-60	40-60
Melia azedarach	Shrub/tree	Seed, kernel	10-45	2.8
Pongamia pinnata (karanja)	Tree	Seed	25-50	30-50
Pongamia glabra (koroch seed)	Tree	Seed	33.6	
Sapium sebifeum L.	Tree	Seed, kernel	13-32	53-64
Sleichera triguga (kusum)	Tree	Seed		50-70
Samadera indica	Tree	Seed	~35	
Sapindus mukorossi (soapnut)	Tree	Seed, kernel	51.8	
Tung	Tree	Seed	35-40	
Vernicia montana L.(Trau) *	Tree	Seed, kernel	32.6	58.0
Hibiscus sabdariffa L. (Roselle) *	Shrub	Seed	20	

Note: *Unpublished data from a research group in Osaka Prefecture University

1.1.2 Inedible vegetable oil-derived biodiesel - a promising green fuel source for transportation

As a potential alternative fuel source to petroleum, inedible vegetable oil-derived biodiesel (from now on called biodiesel) has various merits which have been widely recognized, for example:

- Greenhouse gasses (GHG) emission reduction, energy supply diversity, job creation and rural development; renewability and easy biodegradability, non-toxic and safer handling than fossil fuels (Scarlat and Dallemand 2011; Rajagopal and Zilberman 2007; Agarwal and Das 2001; CheHafizan and Noor 2013; Janda, Kristoufek, and Zilberman 2012);
- Up to 20% can be used without adaptation of engine and less environmental impacts than petrodiesel (No 2011; Atabani et al. 2013);
- Biodiesel can be used as a strong solvent for removing petroleum oil spill (Hu et al. 2004);
- Regarding fuel combustion, a research about exhaust gasses of biodiesel in recreational boats notes that:
    - Carbon soot from fuel combustion can be reduced about 60-70%. Therefore, particulate matters and smoke capacity decreased significantly;
    - 70% decrease in polyaromatic hydrocarbons (PAHs)
    - Less impact on the water pollution due to its insolubility and high biodegradation rate. Thus, high expectation for the application of biodiesel in maritime transportation (Zhou et al. 2015).

1.1.3 Disadvantages of biodiesel

Nevertheless, biodiesel system also shows some limitations such as:

- Net GHG emission increase due to the use of petrodiesel in the transportation of input materials and distribution of biodiesel, other non-climate-related environmental impacts including soil erosion due to tillage, eutrophication led by fertilizer runoffs, and several adverse impacts to the ecosystem following the use of agricultural chemicals, land use change and food cropland conflicts, and the production cost is high (Farrell et al. 2006; Rajagopal and Zilberman 2007; Fargione et al. 2008; Hill et al. 2006).

- The quality of biodiesel is not stable because it strongly depends on oilseed and propagation condition, production technology, and weather condition;

Consequently, the development of biodiesel system could be either a rewarding effort or an unproductive action. This raises an urgent need for a proper answer to the question whether the biodiesel system is more sustainable than petrodiesel.

1.2 RESEARCH MOTIVATION

Recognizing the importance role of renewable energies, in 2007, Vietnam introduced a new Energy Development Scheme in which by 2015, about five million metric tons of ethanol 5% (E5) and biodiesel 5% (B5) shall come into national use and the total biofuel consumption shall reach the level of 36 million metric tons by 2025. Since then, several efforts and activities from both the government and private sector have been conducted. In accordance with the biofuel policy in Vietnam, a project namely ‘Multi-beneficial Measures for Mitigation of Climate Change in Vietnam and Indochina Countries by Development of Biomass Energy’ funded by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA), as one of the projects of Science and Technology Research Partnership for Sustainable Development (SATREPS) was implemented from 2011 to 2016 (hereinafter called SATREPS project). This project proposed a closed-loop system of biodiesel production and utilization, starting from oil plant cultivation to biodiesel end-use in cruise ships in Ha Long Bay, Quang Ninh Province, Vietnam. It is believed that this system can reduce the environmental problems and enhance the application of biodiesel supporting the economic development in Ha Long Bay

Ha Long Bay, located in the Northeast of Vietnam, possesses a stunning landscape with more than 1,600 limestone islands and islets. Ha Long has been inscribed in Natural World Heritage Sites since 1994 and is one of the most tourist attractions in Vietnam. However, coal mining, both open-pit mining and underground mining, as well as tourism related activities, has led to several environmental problems in the Bay. According to National Mining Development plan, all open-pit mines have to be closed by 2020. Therefore, approximately 6,699 ha of open-pit mine lands and mining dump sites needs to be reclaimed. The intercropping of *Hibiscus sabdariffa* L. (Roselle) and *Vernicia montana* L. (Trau) was highly recommended due to their ability to well-growth in low fertile soil and short-long term economic profit. Furthermore, as the extracted oils from the Roselle and Trau seeds are inedible, there would be no conflict with food production in Vietnam. Therefore, those plants can become feedstocks for the production of biodiesel that is supposed to use in cruise boats in Ha Long Bay which require about 22,000 kiloliters annually. It is critical to note that inedible oil referred in this study was not only the oil that could not eat due to its low quality or toxicity but also include the oil that is used neither for cooking nor in any other forms of food supplies.

On the other hand, Inclusive Impact Index (Triple I) is an indicator applied to access the sustainability of a system/project. This indicator consolidates ecological footprint (EF) analysis and environmental risk assessment under life cycle (LC) approach to evaluate environmental sustainability and economic feasibility of the studied system. Triple I is calculated based on EF, biocapacity (BC), ecological risk (ER), human risk (HR), cost and benefit. However, due to the lack of a proper guideline for the calculation, the application of Triple I is limited. Therefore, previous studies mostly used Triple I light which excludes ER and HR in its assessment. However, as a sustainable indicator, each parameter has its role and needs to be contemplated in Triple I. Therefore, to expand the application of Triple I, it is necessary to develop a appropriate guideline for its calculation.

1.3 Aims Of The Dissertation

This dissertation is conducted with two main aims which are:

- to contribute to the sustainability assessment of renewable energy for transportation by proposing a methodical estimation for Triple I;
- to assess the sustainability of inedible vegetable oil as feedstocks for biodiesel production and utilization for cruise ship operation in Ha Long Bay.

1.4 OUTLINE OF THIS DISSERTATION

This dissertation consists of 8 chapters. The main focus and results of each chapter and the relationship between chapters are as follows (Fig. 1.1):

Chapter 1 provides a general background of this dissertation. Firstly, an overview about biodiesel as an alternative to fossil fuel in transportation is given. Then, the current global trend of inedible vegetable oil-based biodiesel is introduced. In this part, several common inedible vegetable feedstocks for biodiesel production are reviewed and summarized. The aim of this study is clarified. Several maps show biodiesel feedstock potential for each region are introduced in ***Chapter 2***. Then, under the feedstock selection in Chapter 2, two promising feedstocks for biodiesel production and utilization in Ha Long bay are identified, described and characterized in ***Chapter 3***. In this chapter, the life-cycle system boundary of the dissertation is also announced. ***Chapter 4*** explains about basic principle of sustainability assessment and develops a framework for the calculation of Triple I, the single-index of sustainability assessment. Chapter 4 was completed through 3 steps, including: (1) conducting literature review to proposed an appropriate framework; (2) testing the initial developed framework under a light scale in ***Chapter 5*** to identify research gaps; and then (3) analyzing additional data to solve the gaps reported in Chapter 5 (***Chapter 6***). ***Chapter 7*** presents sustainability assessment findings from the application of the finalized framework with some recommendations for the development of biodiesel in Quang Ninh and Vietnam. ***Chapter 8*** summarizes all the conclusions of the dissertation.

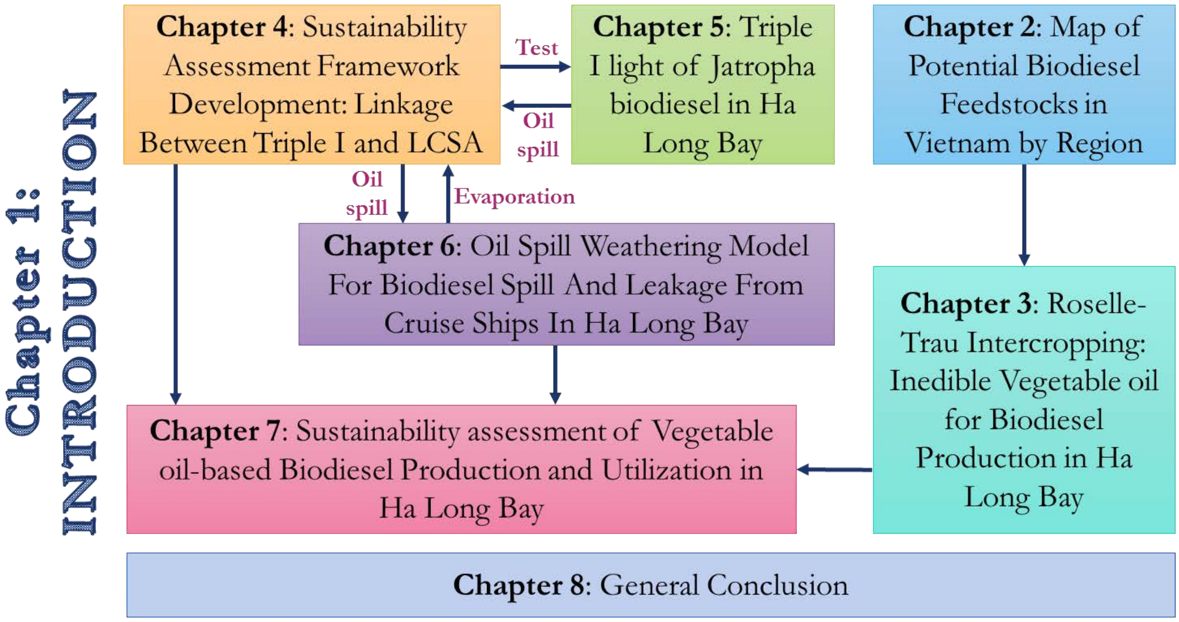


Fig. 1.1 Structure of the dissertation

Equation Chapter (Next) Section 1

REFERENCES

Agarwal, a. K., and L. M. Das. 2001. “Biodiesel Development and Characterization for Use as a Fuel in Compression Ignition Engines.” *Journal of Engineering for Gas Turbines and Power* 123 (2): 440. doi:10.1115/1.1364522.

Alternative Fuels Data Center. 2016. “Biodiesel Blends.” Accessed November 10. www.afdc.energy.gov/fuels/biodiesel_blends.html.

Atabani, A. E., A. S. Silitonga, Irfan Anjum Badruddin, T. M I Mahlia, H. H. Masjuki, and S. Mekhilef. 2012. “A Comprehensive Review on Biodiesel as an Alternative Energy Resource and Its Characteristics.” *Renewable and Sustainable Energy Reviews* 16 (4). Elsevier Ltd: 2070–93. doi:10.1016/j.rser.2012.01.003.

Atabani, A. E., A. S. Silitonga, H. C. Ong, T. M I Mahlia, H. H. Masjuki, Irfan Anjum Badruddin, and H. Fayaz. 2013. “Non-Edible Vegetable Oils: A Critical Evaluation of Oil Extraction, Fatty Acid Compositions, Biodiesel Production, Characteristics, Engine Performance and Emissions Production.” *Renewable and Sustainable Energy Reviews* 18. Elsevier: 211–45. doi:10.1016/j.rser.2012.10.013.

BP. 2016. “BP Energy Outlook 2016: Outlook to 2035.” doi:10.1017/CBO9781107415324.004.

CheHafizan, and Zaimon Zainura Noor. 2013. “Biofuel: Advantages and Disadvantages Based on Life Cycle Assessment (LCA) Perspective.” *Journal of Environmental Research and Development* 7 (4): 1444–49.

Fargione, Joseph, Jason Hill, David Tilman, Stephen Polasky, and Peter Hawthorne. 2008. “Land Clearing and the Biofuel Carbon Debt.” *Science* 319 (5867): 1235–38. doi:10.1126/science.1152747.

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O’Hare, and Daniel M. Kammen. 2006. “Ethanol Can Contribute to Energy and Environmental Goals.” *Science* 311 (5760): 506–8. doi:10.1126/science.1121416.

Hill, Jason, Erik Nelson, David Tilman, Stephen Polasky, and Douglas Tiffany. 2006. “Environmental , Economic , and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels.”

Hu, Jianbo, Zexue Du, Zhong Tang, and Enze Min. 2004. “Study on the Solvent Power of a New Green Solvent : Biodiesel,” 7928–31.

IEA. 2015. *CO2 Emissions from Fuel Combustion Highlights*. 2015thed. Paris, France: International Energy Agency (IEA). doi:10.1787/co2-table-2011-1-en.

———. 2016. “Key World Energy Statistics.” http://www.iea.org/statistics/statisticssearch/.

IPCC. 2014. *Climate Change 2014: Mitigation of Climate Change*. *Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. doi:10.1017/CBO9781107415416.

Janda, Karel, Ladislav Kristoufek, and David Zilberman. 2012. “Biofuels: Policies and Impacts.”

Agricultural Economics (Czech Republic), CUDARE Working Paper Series, 58 (8). University of California at Berkeley, Department of Agricultural and Resource Economics and Policy: 372–86.

No, Soo Young. 2011. "Inedible Vegetable Oils and Their Derivatives for Alternative Diesel Fuels in CI Engines: A Review." *Renewable and Sustainable Energy Reviews* 15 (1). Elsevier Ltd: 131–49. doi:10.1016/j.rser.2010.08.012.

Rajagopal, Deepak, and David Zilberman. 2007. "Review of Environmental, Economic and Policy Aspects of Biofuels." Policy Research Working Paper WPS4341. Policy Research Working Paper. Washington, DC: World Bank.

Scarlat, Nicolae, and Jean-Francois Dallemand. 2011. "Recent Developments of Biofuels/bioenergy Sustainability Certification: A Global Overview." *Energy Policy* 39 (3): 1630–46. doi:10.1016/j.enpol.2010.12.039.

Tietenberg, Tom, and Lynne Lewis. 2012. *Environmental and Natural Resource Economics, 9th Edition*. Pearson Education, Inc.

U.S. Energy Information Administration. 2015. "International Energy Statistics." *Independent Statistics & Analysis*.

Zhou, P L, A M Fet, O Michelsen, and K Fet. 2015. "A Feasibility Study of the Use of Biodiesel in Recreational Boats in the United Kingdom." In *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 217:149–58. doi:10.1243/147509003322255859.

Chapter 2 - POTENTIAL OF BIODIESEL PRODUCTION IN VIETNAM

2.1 INTRODUCTION

Vietnam is an S-shaped country located in Southeast Asia with a long coastal line of about 3,440 kilometers starting from the Gulf of Tonkin to the South China Sea and the Gulf of Thailand. Low mountains and hilly regions contribute to approximately three quarters of the total Vietnam's area. Deltas cover the remaining quarter including two major deltas are Red River Delta (16,700 km^2) in the North and Mekong River Delta in the South (40,000 km^2). (UNEP 2011).

Vietnam has a tropical monsoonal climate with high temperature and humidity.The nation has two main climate regions. In the north, the climate is highly humid tropical monsoon with four seasons including spring, summer, autumn and winter. The southern and central regions have a moderate tropical climate with dry and rainy seasons (ibid.).

Crude oil, natural gas, and coal are the three essential natural resources in Vietnam. With the blooming in the national economy and the increasing population, the exploitation of crude oil has been boosted for decades for both domestic uses and exportation. Under the current technology, the potential crude oil reserves of the country have remained at 4.4 billion metric tons since 2011 (U.S. EIA 2017b). However, as crude oil is a limited resource, current national crude oil production has decreased by about 20% from 403,000 barrels per day in 2004 to 320,000 barrels per day in 2016 (ibid.). Moreover, although Vietnam is a net exporter of crude oil, this nation is also a net importer of oil products in which approximately 67% of total petrodiesel consumption is from foreign sources (General Department of Vietnam Customs, n.d.; Le, Tran, and Pham 2016). Meanwhile, the world oil price is unstable and fluctuates year by year. It is crucial for Vietnam to diversify its fuel sources.

In Vietnam, transportation plays an importation role in the development the nation as a proper tool to strengthen economic activities and to support social welfare. However, transportation is also the most contributor to the increasing air pollution in the urban area, especially in Ho Chi Minh City and Hanoi, two most major cities of the nation. Currently, considerable amounts of particulate matter in the urban ambient air are the serious problem caused by the petroleum fuel combustion. Therefore, biofuel in general and biodiesel in particular is recognized as an essential solution for the potential energy insecurity and current environmental issue in urban areas of Vietnam.

On the other hand, the type of feedstock for biodiesel production and the quality of biodiesel strongly depend on propagation condition, production technology, and weather condition in each region. Therefore, this chapter aimed to develop a map illustrating the nationwide potential of biodiesel feedstock production in Vietnam. This map was supposed to provide an overview about promising feedstocks throughout Vietnam so that policy maker and an investor could refer to determine which area and what kind of feedstock they should consider.

2.2 METHODOLOGY

The development of the feedstock scenarios was from multi data sources. It started with the current Vietnamese polices on forest protection and development, land-use planning, socio-economic development scheme and coal mining development plan to figure out what activities could be supported and allowed in each region. Then, land-use status was obtained from the annual land-use report of Ministry of Environment and Natural Resources, Vietnam. This study analyzed data about land-use of Vietnam in 2013, rubber plantation area in 2014, and open-pit mines and mining dump site area in 2012 and 2014. After that, all those data were integrated with the information about feedstock yield, oil content and potential feedstock for each region based on SASTREPS Project pilot sites.

2.3 RESULTS AND DISCUSSION

To avoid the land use conflict between oilseed crop cultivation with other economic activities, especially food crop production, this research only considered unused low fertile and degraded land areas (including unused mountainous land, rocky mountains without forest and mining reclamation areas) and unused oilseeds as potential sources for biodiesel feedstock acquisition. Table 2.1 presents data on biodiesel production and yield and potential land-use types.

Table 2.1 BDF Production yield and potential land-use types

Variety	Seed yield (t/ha/year)	Oil content (%)	BDF* (t/ha/year)	Promising land-use types for cultivation
Hibiscus sabdariffa L.	8	20	1.46	Unused mountainous land** Rocky mountain without forest*** Open-pit mines and mining dump sites
Vernicia montana L.	10	32.6	3.03	
Rubber	0.3	24.7	0.069	Rubber plantation areas
Jatropha curcas L.	2	27.4	0.51	Unused mountainous land Rocky mountain without forest

Note: *Biodiesel production efficiency is 93%
**Mountainous areas of which land use has not been identified yet
***Barren areas in rocky mountains

2.3.1 Northern part of Vietnam

In the northern Vietnam, the intercropping of *Vernicia montana* L. (Trau) and *Hibiscus sabdariffa* L. (Roselle) was identified as a proper option for the biodiesel feedstock production. Location of northern provinces and potential cultivation areas and biodiesel yield are shown in Fig. 2.1 and Table 2.2, respectively.

Fig. 2.1 Location of provinces in northern Vietnam

Table 2.2 Land use status and potential biodiesel production in northern Vietnam by province

	Area (ha)					Potential biodiesel (metric tons)				
Province	Open-pit mines and mining dump sites	Unused mountainous land	Rocky mountain without forest	Rubber (2014)	Total available land	Open-pit mines and mining dump sites	Unused moutainous land	Rocky mountain without forest	Rubber (2014)	Total
Ha Giang	-	31,394	12,269	1,400	43,663	-	235,323	91,966	96	327,386
Tuyen Quang	-	5,067	5,277	-	10,344	-	37,981	39,555	-	77,537
Cao Bang	-	7,939	4,472	-	12,411	-	59,509	33,521	-	93,030
Lang Son	-	53,582	49,657	-	103,239	-	401,640	372,219	-	773,859
Bac Kan	-	41,195	3,244	-	44,439	-	308,789	24,316	-	333,106
Thai Nguyen	-	4,424	7,654	-	12,078	-	33,161	57,373	-	90,534
Phu Tho	-	11,628	1,867	200	13,495	-	87,161	13,995	14	101,170
Lao Cai	-	155,238	23,228	2,000	178,466	-	1,163,633	174,112	138	1,337,883
Yen Bai	-	45,621	3,494	2,100	49,115	-	341,966	26,190	145	368,301
Quang Ninh	6,699	31,435	7,523	-	38,958	50,214	235,630	56,391	-	342,236
Bac Giang	-	13,673	563	-	14,236	-	102,490	4,220	-	106,710
Lai Chau	-	46,357	1,972	12,700	48,329	-	347,483	14,782	875	363,140
Dien Bien	-	143,910	3,768	5,100	147,678	-	1,078,721	28,244	351	1,107,316
Son La	-	378,004	42,297	6,500	420,301	-	2,833,442	317,050	448	3,150,940

Hoa Binh	-	26,652	16,464	-	43,116	-	199,778	123,411	-	323,189
Vinh Phuc	-	1,215	220	-	1,435	-	9,107	1,649	-	10,756
Bac Ninh	-	28	-	-	28	-	210	-	-	210
Ha Noi	-	1,506	2,117	-	3,623	-	11,289	15,869	-	27,157
Hai Phong	-	415	849	-	1,264	-	3,111	6,364	-	9,475
Hai Duong	-	158	31	-	189	-	1,184	232	-	1,417
Hung Yen	-	-	-	-	-	-	-	-	-	-
Ha Nam	-	877	2,443	-	3,320	-	6,574	18,312	-	24,886
Nam Dinh	-	64	8	-	72	-	480	60	-	540
Thai Binh	-	-	-	-	-	-	-	-	-	-
Ninh Binh	-	1,159	2,065	-	3,224	-	8,688	15,479	-	24,166

Proposed land areas for feedstock cultivation in this area were unused mountainous land, rocky mountain without forest, and open-pit mines and mining dump sites.

2.3.2 Central and southern part of Vietnam

In the central and southern Vietnam, since the climate and soil condition of this area were appropriate for the cultivation of *Jatropha curcas* L. (Jatropha), it was expected to cultivate this plant in unused mountainous land and rocky mountain without forest areas. Moreover, rubber trees have been planted in this area for decades with a considerable area. As the rubber seeds were unused, they also could be considered as a promising feedstock for biodiesel production in this area. Location of central and southern provinces and potential cultivation areas and biodiesel yield for each region are shown in Fig. 2.2, Fig. 2.3, Table 2.3 and Table 2.4, respectively.

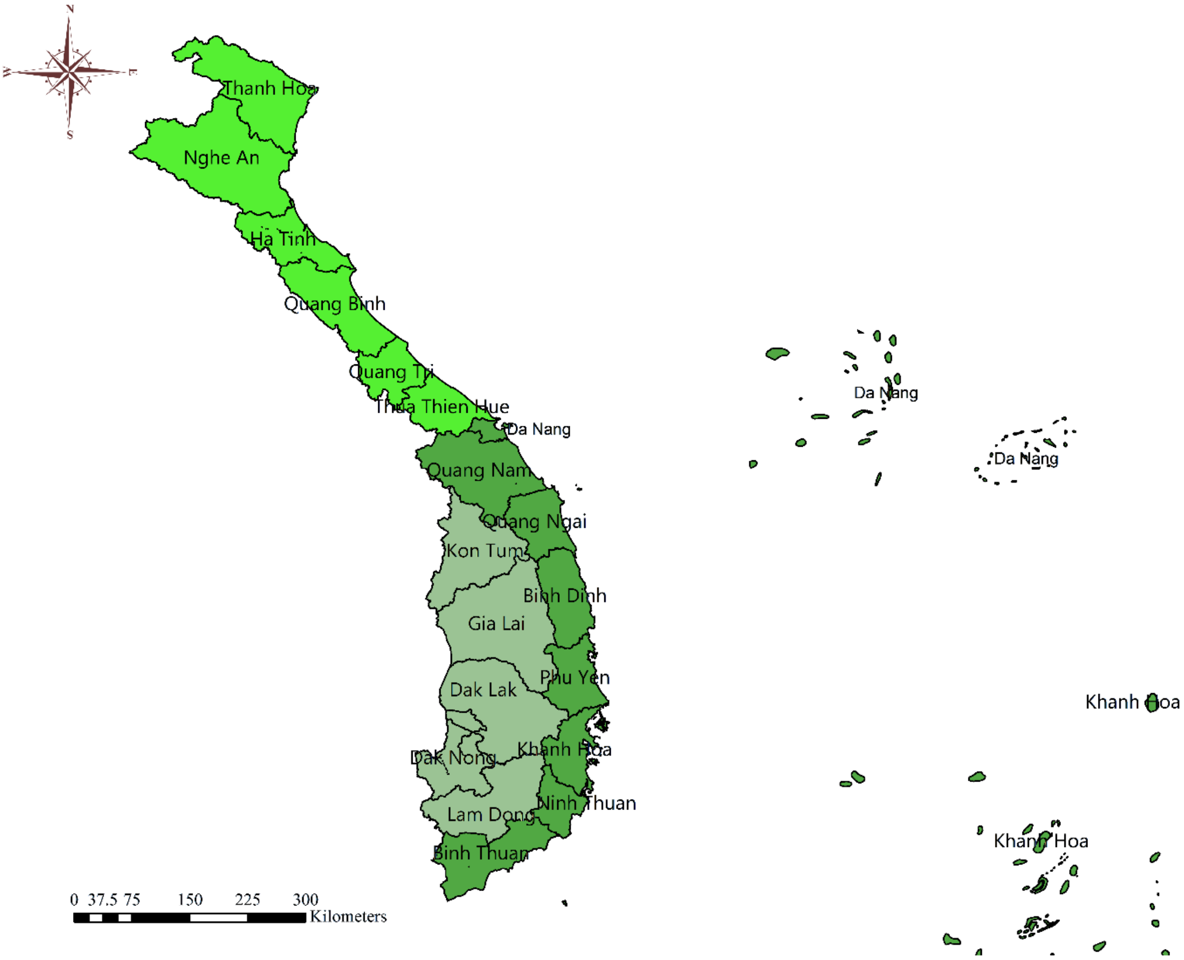


Fig. 2.2 Location of provinces in central Vietnam

Table 2.3 Land use status and potential biodiesel production in central Vietnam by province

	Area (ha)				Potential biodiesel (metrics tons)			
Province	**Unused mountainous land**	**Rocky mountain without forest**	**Rubber (2014)**	**Total available land**	**Unused mountainous land**	**Rocky mountain without forest**	**Rubber (2014)**	**Total**
Thanh Hoa	68,783	19,854	18,200	88,637	35,055	10,118	1,254	46,427
Nghe An	251,982	8,264	11,100	260,246	128,420	4,212	765	133,397
Ha Tinh	13,908	1,148	10,400	15,056	7,088	585	717	8,390
Quang Binh	16,624	7,671	16,300	24,295	8,472	3,909	1,123	13,505
Quang Tri	37,767	730	19,100	38,497	19,248	372	1,316	20,936

Thua Thien Hue	13,574	719	9,400	14,293	6,918	366	648	7,932
Da Nang	51	17	100	68	26	9	7	42
Quang Nam	89,843	2,001	12,900	91,844	45,788	1,020	889	47,696
Quang Ngai	36,817	950	1,500	37,767	18,763	484	103	19,351
Binh Dinh	24,860	2,389	100	27,249	12,670	1,218	7	13,894
Phu Yen	56,632	1,832	4,500	58,464	28,862	934	310	30,106
Khanh Hoa	88,159	4,708	500	92,867	44,929	2,399	34	47,363
Ninh Thuan	14,691	16,019	800	30,710	7,487	8,164	55	15,706
Binh Thuan	14,872	2,923	42,900	17,795	7,579	1,490	2,956	12,025
Kon Tum	64,486	1,333	74,900	65,819	32,865	679	5,162	38,706
Gia Lai	91,091	981	103,000	92,072	46,424	500	7,098	54,022
Dak Lak	62,614	33	40,200	62,647	31,911	17	2,770	34,698
Dak Nong	17,854	-	31,100	17,854	9,099	-	2,143	11,242
Lam Dong	19,286	87	9,800	19,373	9,829	44	675	10,549

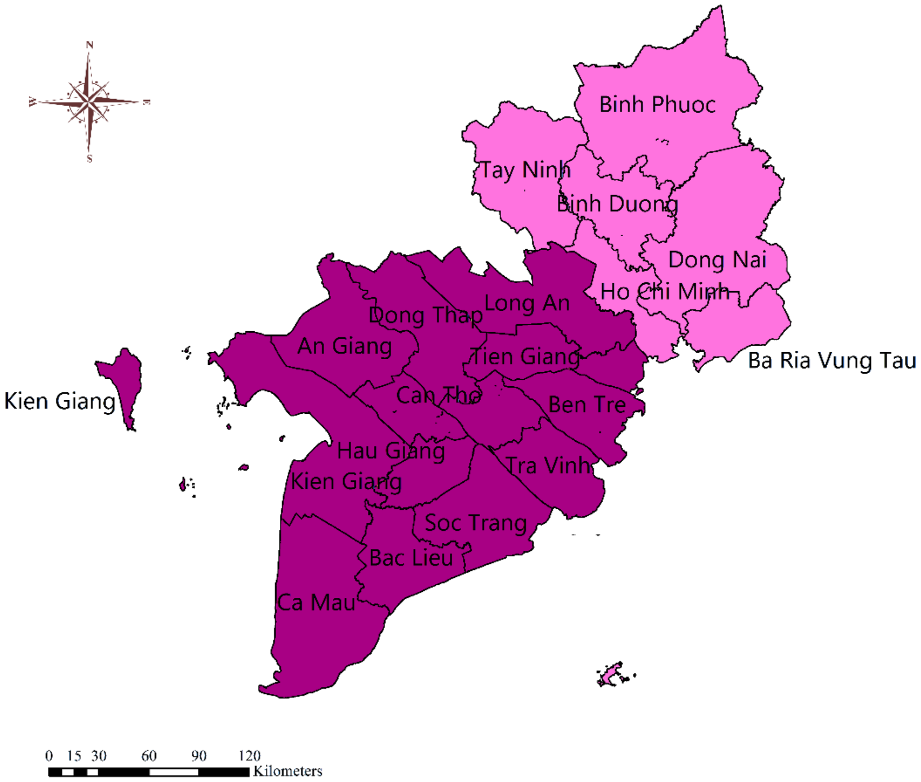


Fig. 2.3 Location of provinces in southern Vietnam

Table 2.4 Land use status and potential biodiesel production in southern Vietnam by province

	Area (ha)				Potential biodiesel (metric tons)			
Province	Unused moutainous land	Rocky mountain without forest	Rubber (2014)	Total available area	Unused moutainous land	Rocky mountain without forest	Rubber (2014)	Total biodiesel
Dong Nai	103	744	49,400	847	52	379	3,404	3,836
Binh Duong	-	-	134,200	-	-	-	9,248	9,248
Binh Phuoc	80	-	232,600	80	41	-	16,029	16,070
Tay Ninh	-	-	96,800	-	-	-	6,671	6,671
Ho Chi Minh	-	9	3,800	9	-	5	262	266
Ba Ria Vung Tau	948	106	24,000	1,054	483	54	1,654	2,191
Long An	1,616	2,000	100	3,616	824	1,019	7	1,850
Tien Giang	1,590	107	-	1,697	810	54	-	865
Ben Tre	4,278	60	-	4,338	2,180	31	-	2,211
Dong Thap	1,004	7,219	-	8,223	511	3,679	-	4,191
Vinh Long	-	-	-	-	-	-	-	-
Tra Vinh	2,312	-	-	2,312	1,178	-	-	1,178
Can Tho	-	-	-	-	-	-	-	-
Hau Giang	-	2,805	-	2,805	-	1,430	-	1,430
Soc Trang	5,433	265	-	5,698	2,769	135	-	2,904
An Giang	8,725	1,075	-	9,800	4,447	548	-	4,995
Kien Giang	28,545	39,707	-	68,251	14,548	20,236	-	34,784
Bac Lieu	4,706	-	-	4,706	2,398	-	-	2,398

Ca Mau	27,308	17,812	-	45,120	13,917	9,078	-	22,995

2.3.3 Nationwide potential of biodiesel feedstock production in Vietnam

Based on the data for each region, a national scale maps for the potential of biodiesel feedstock cultivation (Fig. 2.4) and production (Fig. 2.5) were made. Accordingly, mountainous areas, especially provinces dwelling near to national border, proved the highest amount of potential oilseed crop production. Therefore, the investment should focus on high mountainous areas.

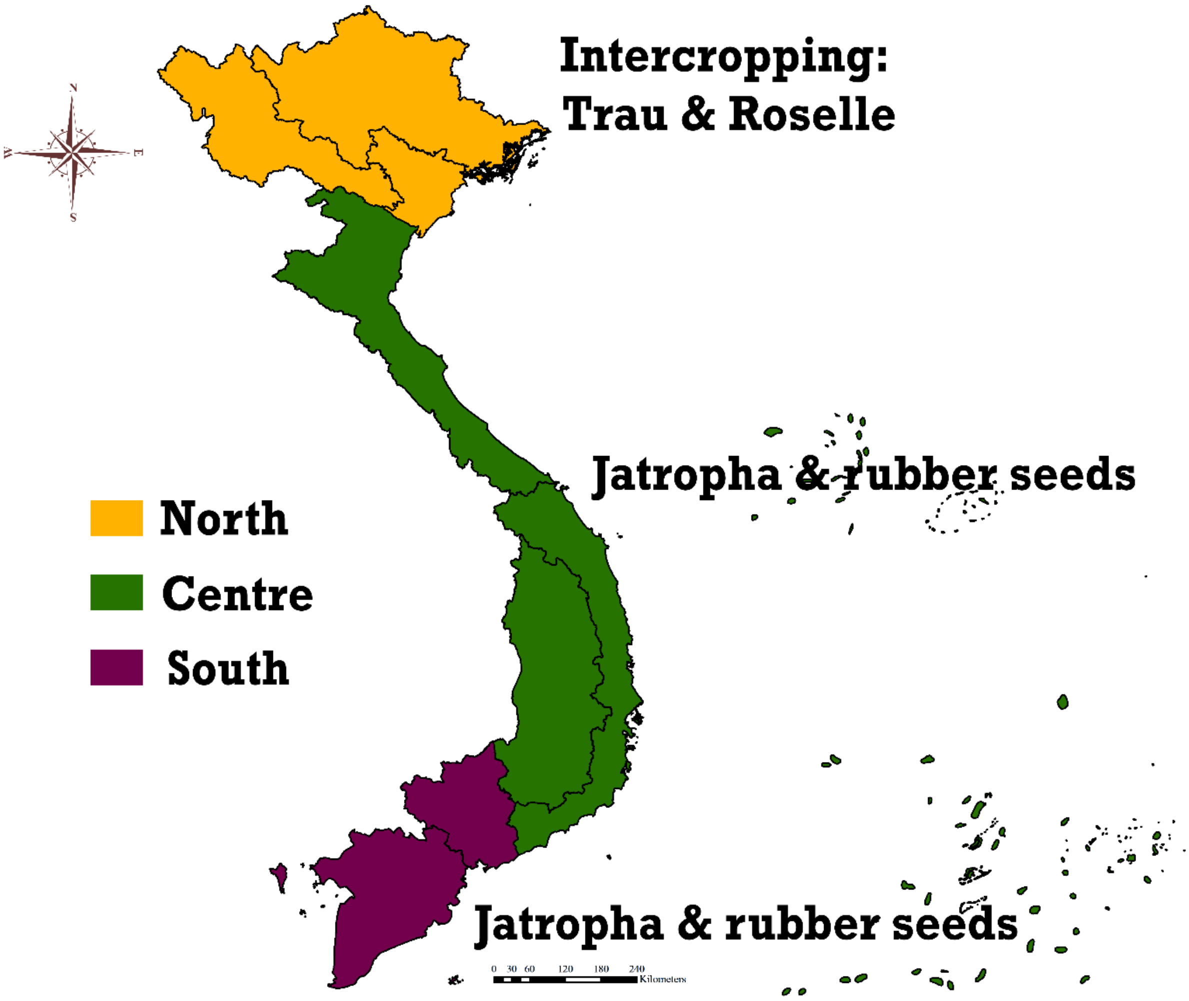


Fig. 2.4 Potential biodiesel feedstocks by region

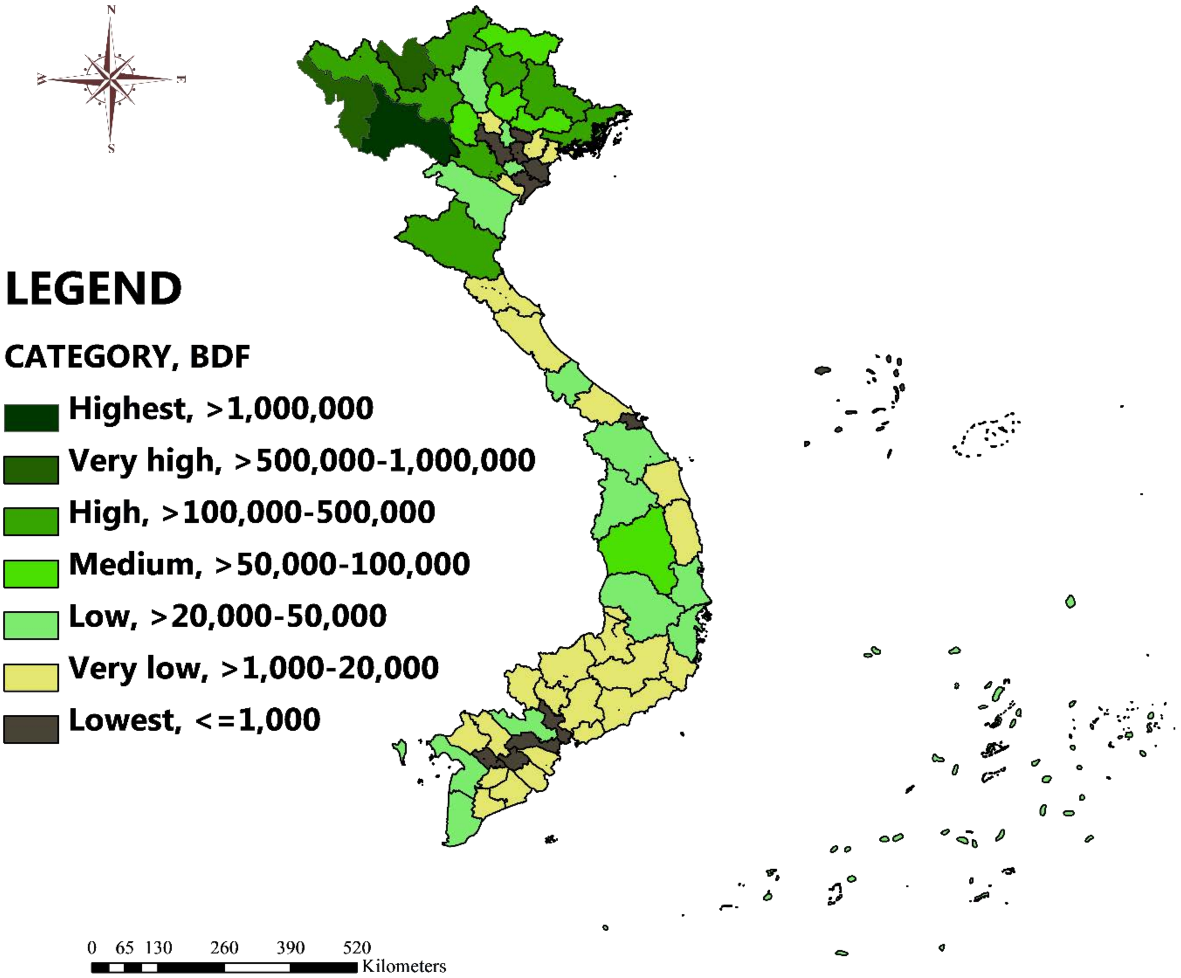


Fig. 2.5 Potential biodiesel production yield in Vietnam by province

Furthermore, under current policies of Vietnam, investment in those areas would be supported by several policies including polices on forest protection and development (Law on Forest Protection and Development 2004; Prime Minister 2007), land-use planning, and socio-economic development schemes include regional development, upland provinces development, and supporting provinces dwelling near Vietnam's frontier for economic development and national security (Planning on the Development of Vietnam-China Border Areas by 2020 2007).

Some recommendations for the biodiesel production in Vietnam are as follows:

- For the newly propagation crops, the identification of cultivation area should focus on mountainous areas, upland provinces located near Vietnam's frontier, least developed areas, and open-pit mines and mining dumpsites.

- With unused crops: rubber seed has high potential in term of seed yield with no other newly developed investment.

2.4 CONCLUSIONS

Oilseed crop promising cultivation areas and protential biodiesel production yield maps were developed. Findings from this study show that the highest potential of oil plant cultivation belongs to mountainous provinces dwelling near the national border zones with considerable unused marginal lands and high rate of poverty.

REFERENCES

General Department of Vietnam Customs. n.d. “Custom Trade Statistics - Scheduled Data.”

Law on Forest Protection and Development. 2004. *Law on Forest Protection and Development 2004*. Vietnam.

Le, Viet Trung, Quoc Viet Tran, and Van Chat Pham. 2016. “An Overview of Vietnam’s Oil and Gas Industry.” *Petrovietnam Journal* 10: 64–71.

Planning on the Development of Vietnam-China Border Areas by 2020. 2007. *Planning on the Development of Vietnam-China Border Areas by 2020*. Vietnam.

Prime Minister. 2007. *Vietnam Forestry Development Strategy 2006 - 2020. Decision No. 18/2007/QD-TTg*. Social Republic of Vietnam.

U.S. EIA. 2017. “Vietnam.” http://www.eia.gov/beta/international/analysis.cfm?iso=VNM.

UNEP. 2011. “Sustainable Buidling Policies on Energy Efficiency: Vietnam.”

Equation Chapter (Next) Section 1

Chapter 3 - ROSELLE AND TRAU PRODUCTION AND USE

3.1 INTRODUCTION

This chapter briefly introduced about the two potential feedstocks for biodiesel production on Quang Ninh Province. These two crops were supposed to intercrop to get both short-long term benefits.

3.2 INTERCROPPING OF ROSELLE AND TRAU - POTENTIAL FEEDSTOCKS FOR BIODIESEL PRODUCTION IN HA LONG BAY

3.2.1 Roselle

Roselle (*Hibiscus sabdariffa* L.) is an annual, erect shrub with an average height of about 2m which belongs to Malvaceae family and mostly distributed in tropical areas (Mohamed, Sulaiman, and Dahab 2012; McClintock and El Tahir 2004). Roselle also has several named such as sorrel and jelly okra. It is a multi-purpose plant where almost parts of it are edible and can be used as a vegetable, for calyx production or fiber production as well as medicinal supplies. Vietnam has started to plant Roselle since 1957, and this plant is, recently, gaining popularity for the calyx production. The favor climatic conditions for the growth of Roselle were identified as the humid weather with the temperature ranging from 16ºC to 38ºC and annual precipitation of 1,500 mm (Vietnamese Academy of Forest Sciences 2009a). In the North of Vietnam, the propagation begins from May to June and fruits can be harvested after six months. Roselle calyces are famous for food uses in Vietnam, for example making juice, wine, and jam or eating directly. Roselle seeds are provided only for sowing. Average oil content in the seed is about 20% (Hainida et al. 2008; Al Shooshi 1997; Morton 1974; McClintock and El Tahir 2004; Duke 1983).

3.2.2 Trau

Trau (*Vernicia montana* L.) is a wood tree up to 15 m tall which belong to Euphorbiaceae family (Oyen 2007). Other names of Trau include wood-oil-tree, mu-tree, and abrasion-oil tree. It is native to Southeast Asia and southern China (ibid.). Oil derived from Trau seed is a quick-drying oil, namely 'Abrasin oil' which is commonly used for manufacturing paint or Chinese black ink (Aguilar and Ong 2001). Trau can be grown in areas with annual rain fall of 1,600-2,500 mm with average annual temperature of 20-25ºC (Vietnamese Academy of Forest Sciences 2009b). In Vietnam, Trau is a native plant which mainly distributed in the mountainous areas in the Northern part and Central part. Trau quickly grows and its fruits start to bear after three years of sowing (Tran 1996). In the Northern Vietnam, Trau seeds are directly sold to China after harvested and sun-dried. Average oil content in the Trau seed is approximately 32.6%.

3.2.3 Promising feedstocks for biodiesel production

Recently, both the price of and the market demand for Trau oil have continuously decreased. Moreover, Roselle oil is an unused material in Vietnam. Additionally, it was proved that both Trau and Roselle could growth under low fertile soil and the precipitation of the North area, especially Quang Ninh, is favorable for the both species (Tran 1996). Thus, it is feasible to employ Roselle oil and Trau oil in the production of biodiesel in Quang Ninh Province.

3.2.4 Roselle-Trau intercropping system

Trau seeds were planted in the nursery for eight months for germination and then transplanted to the field. The plantation of Roselle was direct seed sowing. Since the Trau and Roselle were intercropped, the appropriate tree density of Trau was 400 trees ha^{-1} (Vietnamese Academy of Forest Sciences 2009b), and of Roselle was 25,000 trees ha^{-1} and then thinning to around 10,000 trees ha^{-1} (Vietnamese Academy of Forest Sciences 2009a). Except for the first year, the cultivation was under a rain-fed system with annual additional fertilizing with urea, phosphorus and potassium fertilizers. The amount of mineral fertilizer use was changed due to the application of composts from Roselle leaves and Roselle-Trau oil cake. The management of the cultivation such as tillage, pruning, and harvesting were done manually.

3.3 OIL EXTRACTION

Three-phase solvent extraction system was used to obtain sugar, medicinal compounds (Vitamin E and Phytosterol) and oil (Fig. 3.1). This system was based on the newly developed oil extraction technology under a research group in Osaka Prefecture University as the contracted to SATREPS Project. In which, water, methanol, and n-hexane were applied to extract sugar, Vitamin E and Phytosterol, and vegetable crude oil, respectively. Several valuable co-products were derived with high extraction efficiency. Accordingly, it was reported that 90% of Vitamin E and Phytosterol and 95% of sugar and oil as their contents in the seed were derived. Most of the solvents were recycled (90%), however about 10% of total used solvents emitted to the air due to the high volatility. Due the low component of medical compounds in Roselle seed, only sugar and oil extraction were prefered.

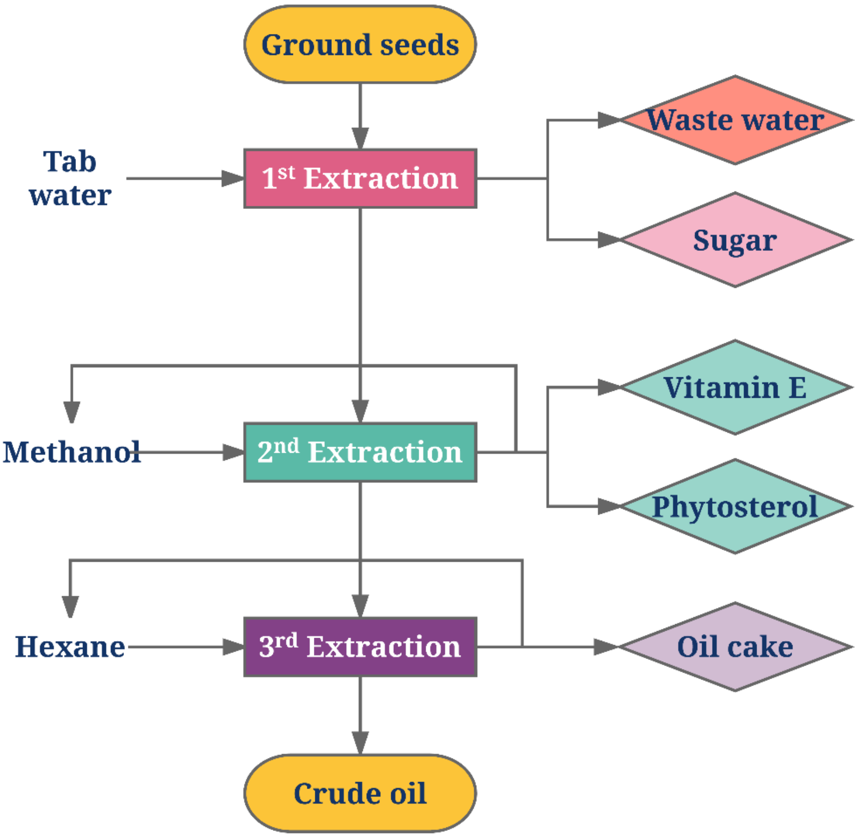


Fig. 3.1 Three-phase solvent oil extraction

3.4 BIODIESEL PRODUCTION

- Biodiesel production: Two-phase reaction of biodiesel production from vegetable oil is illustrated in Fig. 3.2. The obtained crude oil was collected and transferred to a transesterification reactor to produce biodiesel. The transesterification process was perform in 30 minutes with methanol:to:oil molar ratio of 1:4 and 0.3 wt% KOH, and 10% (wt/wt) acetone as co-solvent. After the reaction, approximately 90% of acetone and 25% of methanol were recovered. Following the separation of glycerin, the solution was washed and dried. The conversion yield of biodiesel was around 99%, and total 93% by mass was obtained from crude oil. Current capacity of biodiesel pilot plant of Satreps project in Vietnam is 500 metric tons per year and will be upgraded to 1,500 metric tons per year;

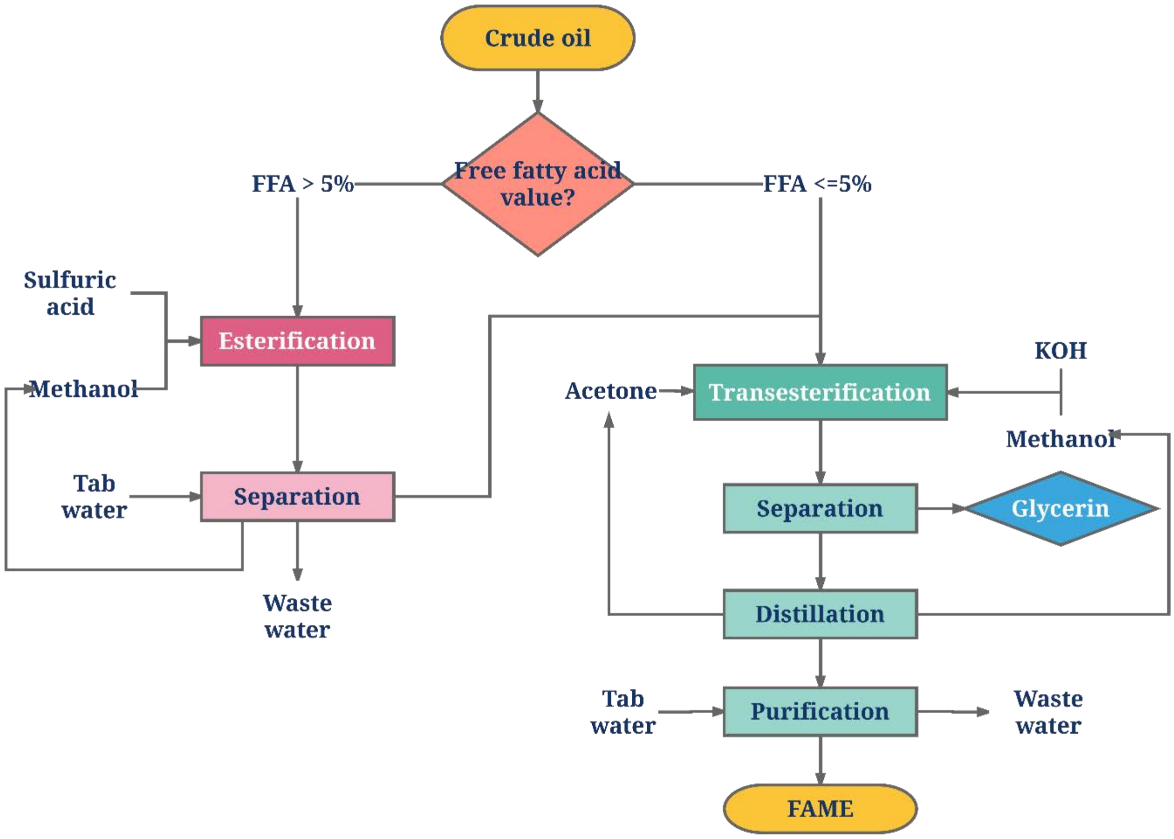


Fig. 3.2 Two-stage reaction of biodiesel production from vegetable oil

- Blending: Previous studies denoted that, although biodiesel from Roselle can meet almost quality requirements according to biodiesel standards of Vietnam (TCVN/QCVN) and other countries such as JIS K2390, ASTM D6175 and EN 14214 (Anwar et al., 2010; Nakpong and Wootthikanokkhan, 2010; Nguyen and Otsuka, 2016), the yield of Roselle seed (200 – 1,500 metric tons ha^{-1}) was not as high as Trau seed (1,800 - 3,000 metric tons ha^{-1}). However, Trau biodiesel was beyond almost requirements of biodiesel standards (Manh et al., 2011). Therefore, an optimal blend of Roselle biodiesel and Trau biodiesel was considered as a sufficient solution. It was showed that the volumetric mixture of 70% Roselle biodiesel and 30% Trau biodiesel was an appropriate combination (Nguyen and Otsuka, 2016).

- Distribution and combustion: Neat biodiesel (B100) was blended with petrodiesel and distributed to cruise ship port in Ha Long Bay.

3.5 IDENTIFICATION OF ROSELLE-TRAU BIODIESEL

3.5.1 Preparation of fuel samples

No. 2 petrodiesel was purchased at a local gas station in Osaka, Japan. Trau (*Vernicia montana* L.) and Roselle (*Hibiscus sabdariffa* L.) crude oils obtained from Vietnam were used to produce Trau BDF (TBDF) and Roselle BDF (RBDF). In this study, the production of BDF encompassed two main stages including an esterification process and a transesterification process (Fig. 3.2). Firstly, the esterification was performed in 3 hours using the molar ratio of methanol to oil of 1:1, one wt.% H_2SO_4, 60°C. Then, the 2-hour transesterification was managed under the conditions of 6:1 methanol-to-oil molar ratio, 1.5 wt.% KOH, 40°C, and 20% (wt./wt.) acetone as co-solvent. Depending on free fatty acid (FFA) values, the two-stage (starting from esterification) and simplified one-stage (transesterification only) reactions were employed for Roselle oil (FFA 2.26 ± 0.1 wt%) and Trau oil (FFA 0.75 ± 0.1 wt%), respectively. The difference was applied to guaranty the fatty acid methyl esters (FAME) conversion yield. Following the reaction, qualified BDF with higher than 98% FAME was acquired. Then, various mixtures of Roselle-Trau biodiesel were prepared following volumetric blending portions of 75-25% (R75T25), 70-30% (R70T30), 65-35% (R65T35), 60-40% (R60T40), and 50-50% (R50T50).

3.5.2 Analysis of biodiesel properties

The FAME content of samples was determined by the percentage of the FAME's signal area reported by a Shimadzu LC-10AD HPLC. The density of samples was measured by pycnometer flask following OECD guideline for the testing of chemicals (OECD 2012). The kinematic viscosity (KV) of samples was determined by the Ostwald-type *capillary* viscometer. Acid values (AV) and iodine values (IV) were analyzed by acid-base titration method (EN ISO 660: 2009) and Wijs method (EN ISO 3961: 1996), respectively. The water content of samples was determined by an MKS-501 Karl Fisher Moisture Titrator (ASTM E203). Each measurement was conducted three times consecutively.

Data about biodegradability and toxicity of biodiesel and biodiesel blends compared to petrodiesel were collected through literature review. Both petrodiesel and biodiesel are mostly insoluble in water, and a very small amount of fuel disperses into the aqueous phase. However, the toxicity of a fuel depends on the exposure period of aquatic organisms to the fuel, which means the concentration of fuel in the water column. Therefore, this study focused on the water-accommodated fractions concentration of different spilled oils.

Interfacial tension values of samples were calculated based on the equation for determining surface tension of FAME and biodiesel proposed by (Phankosol et al. 2014). The estimation of biodiesel surface tension is in agreement with the FAME composition, the carbon numbers, and the number of double bonds, as in (Eq. 3.1), (Eq. 3.2), and (Eq. 3.3).

$$\gamma = 60.211 - 0.4307 z_{avg} - 0.1125T + 0.00207 z_{avg} T + 3.676 m_{avg} - 0.00893 m_{avg} T \qquad (3.1)$$

$$z_{avg} = \sum_{i=1}^{n} x_i z_i \quad (3.2) \qquad\qquad m_{avg} = \sum_{i=1}^{n} x_i m_i \quad (3.3)$$

where γ is surface tension value (mN/m^2), z_{avg} is the average carbon number of the FAME, m_{avg} is the average number of double bonds of the FAME, T is the temperature in Kevin, x_i is mole fraction of FAME i.

Regarding solubility testing, water-accommodated fractions (WAF) of biodiesel blends were prepared following low-energy mixing method introduced by (Singer et al. 2000). Depending on research purposes, various oil-to-water loading rates and mixing/settling duration were employed in oil pollution studies. To simulate actual behaviors of biodiesel spills in the environment, a ratio of 1:100 oil-to-water (Hollebone et al. 2008; Moles, Rice, and Korn 1979; Katz 1973; Maher 1982) with 16-hour low-energy stirring and 30-min resting of solution (U.S. EPA 2002) were chosen. Subsequently, one gram of each biodiesel blend was gently added to a conical flask loaded with 100 ml artificial seawater. The flask was capped, placed in low light - room temperature, and stirred for 16 hours. Then, the mixture was stood in separating funnel for 30 minutes. A 30-ml water was removed from the lower aqueous layer of the funnel. After that, the aliquot was extracted three times with 30ml n-hexane, treated with anhydrous sodium sulfate, filtered, concentrated and measured with an internal standard (methyl heptadecanoate).

FAME components of samples and each extracted solution were analysed on a Hewlett-Packard (HP) 6890 Series Gas Chromatography with Flame ionization detector (GC-FID). A 30m length, 0.25 mm I.D. and 0.25 μm film thickness SP^{TM}-2380 fused silica capillary column was used. Helium as the carrier gas at 2.5 mL/min constant flow and splitless injection were set. The oven temperature was programmed as follows: 2-min hold at 50°C, ramp to 160°C at 10°C/min then ramp to 215°C at 4°C/min, and 2-min hold at 215°C.

3.5.3 FAME compositions and properties of biodiesel

After reacting, more than 99% and 98% FAME contents of RBDF and TBDF, respectively, were obtained. The FAME compositions of RBDF and TBDF are shown in Table 1. Both RBDF and TBDF had high unsaturated FAME content of 74.5 wt.% and 92.8 wt.%, respectively. Especially, the FAME of TBDF consisted an extensive amount of methyl elaeostearate with conjugated double bonds which significantly affected the IV of the fuel. The IV and the kinetic viscosity at 40°C of RBDF were 99.082 g I_2/100g and 4.39 mm^2/s; and those of TBDF were approximately 156.905 g I_2/100g and 7.70 mm^2/s, respectively. The IV and kinetic viscosity of TBDF could not meet common biodiesel quality standards. Therefore, several mixtures of RBDF and TDBF, including R75T25, R70T30, R65T35, R60T40, and R50T50 were analyzed to determine the optimum volume fraction of the blends. Regarding IV and viscosity, R70T30 was identified as a suitable combination. Main properties of RBDF, TBDF and R70T30 are shown in Table 2.

3.5.4 Conclusion

The volumetric mixture of 70% RBDF and 30% TBDF was identified as an optimum combination of the two biodiesels which can meet almost of the requirements in the fuel standards of United States, European Union, Japan, and Vietnam. The production and use of this blends can support both environmental protection and economic development of the target area.

Table 3.1. Fame composition of Roselle biodiesel and Trau biodiesel

Fatty acid methyl aster (FAME)	Unit	RBDF	TBDF
Methyl myristate (14:0)	wt.%	1.1	0
Methyl palmitate (16:0)	wt.%	18.0	1.8
Methyl palmitoleate (16:1)	wt.%	2.0	0.0
Methyl stearate (C18:0)	wt.%	3.8	2.4
Methyl oleate (C18:1)	wt.%	33.1	7.8
Methyl linoleate (C18:2)	wt.%	40.8	11.2
Methyl elaeostearate (C18:3)	wt.%	0.0	72.6
Methyl eicosenoate (20:1)	wt.%	0.2	1.4
Methyl ecosadienoic (20:2)	wt.%	0.0	0.7
Methyl behenate (22:0)	wt.%	0.5	0.0
Others	wt.%	0.0	0.3
Saturated FAMES	wt.%	23.7	4.2
Unsaturated FAMES	wt.%	73.9	91.7

Table 3.2. FAME composition of Roselle biodiesel and Trau biodiesel

				R70T30	*Biodiesel standards*			
Property	*Unit*	*RDBF*	*TBDF*	*BDF*	TCVN/QCVN[a]	JIS K2390	ASTM D6751	EN 14214
Ester content	% mass	99.4	98.3	99.1	> 96.5	> 96.5		> 96.5
Kinematic viscosity at 40 °C	mm^2/s	4.393 (0.006)	7.703 (0.007)	5.461 (0.000)	1.9 - 6.0	3.50 - 5.00	1.9 - 6.0	3.50 - 5.00
Density at 15 °C	g/ml	8.8526 (0.021)	9.0671 (0.010)	8.8986 (0.029)	0.86 - 0.90	0.86 - 0.90		0.86 - 0.9
Flash point	°C	156[b]	167[c]	159.3		> 120	> 130.0	> 101
Water & sediment content	mg/kg	< 250	< 250	< 250	< 500	< 500	< 500	< 500
Acid value	mg KOH/g	0.295 (0.006)	0.17 (0.024)	0.052 (0.017)	< 0.50	< 0.50	< 0.50	< 0.50
Iodine value	g iodine/100 g	99.082 (0.114)	159.905 (0.299)	118.3 (0.056)	< 120	< 120		< 120
Total glycerol	% mass	<0.1	<0.1	<0.1	< 0.24	< 0.25	< 0.24	< 0.25
Solubility at 25 °C	ppm WAF concentration	1.86 (0.7745)	5.28 (0.2919)	2.20 (0.1246)	-	-	-	-
Interfacial tension	mN/m^2	30.84	32.66	31.38	-	-	-	-

REFERENCES

Aguilar, N.O., and H.C. Ong. 2001. "Vernicia Lour." In *Plant Resources of South-East Asia 14: Vegetable Oils and Fats*, edited by H.A.M. van der Vossen and B.E. Umali, 229. Leiden, Netherlands: Backhuys Publishers.

Al Shooshi, Wafa Gamal Abdalh. 1997. "Chemical Composition of Some Roselle (Hibiscus Sabdariffa) Genotypes." University of Khartoum.

Duke, James A. 1983. *Handbook of Energy Crops*. https://hort.purdue.edu/newcrop/duke_energy/Hibiscus_sabdariffa.html.

Hainida, Emmy, Amin Ismail, Normah Hashim, Norhaizan Mohd.-Esa, and Ainul Zakiah. 2008. "Effects of Defatted Dried Roselle (Hibiscus Sabdariffa L.) Seed Powder on Lipid Profiles of Hypercholesterolemia Rats." *Journal of the Science of Food and Agriculture* 88 (6). John Wiley & Sons, Ltd.: 1043–50. doi:10.1002/jsfa.3186.

Hollebone, B.P., B. Fieldhouse, M. Landriault, K. Doe, and P. Jackman. 2008. "Aqueous Solubility, Dispersibility and Toxicity of Biodiesels." In *International Oil Spill Conference Proceedings*, 2008:929–36. American Petroleum Institute. doi:10.7901/2169-3358-2008-1-929.

Katz, L M. 1973. "The Effects of Water Soluble Fraction of Crude Oil on Larvae of the Decapod Crustacean Neopanope Texana (SAYI)." *Environmental Pollution* 5: 199–204. doi:10.1016/0013-9327(73)90088-8.

Maher, W A. 1982. "Preparation and Characterization of Water-Soluble Fractions of Crude and Refined Oils for Use in Toxicity Studies." *Bulletin of Environmental Contamination and Toxicology* 272: 268–72. doi:10.1007/BF01706227.

McClintock, N.C., and I.M. El Tahir. 2004. "Hibiscus Sabdariffa L." In *Plant Resources of Tropical Africa 2. Vegetables*, edited by G.J.H. Grubben and O.A. Denton, 668. Wageningen, Netherlands: PROTA Foundation. https://books.google.co.jp/books?id=6jrlyOPfr24C.

Mohamed, Bahaeldeen Babiker, Abdelatif Ahmed Sulaiman, and Abdelhafiz Adam Dahab. 2012. "Roselle (Hibiscus Sabdariffa L .) in Sudan , Cultivation and Their Uses." *Bulletin of Environment, Pharmacology and Life Sciences* 1 (6): 48–54.

Moles, Adam, Stanley D Rice, and Sid Korn. 1979. "Sensitivity of Alaskan Freshwater and Anadromous Fishes to Prudhoe Bay Crude Oil and Benzene." *Transactions of the American Fisheries Society* 108 (4): 408–14. doi:10.1577/1548-8659(1979)108<408:SOAFAA>2.0.CO;2.

Morton, Julia F. 1974. "Renewed Interest in Roselle (Hibiscus Sabdariffa L.), the Long-Forgotten 'Florida Cranberry.'" *Florida State Horticultural Society*, 415–25.

OECD. 2012. "OECD Guideline for the Testing of Chemicals: Density of Liquids and Solids." In *OECD Guideline for the Testing of Chemicals*. http://www.oecd-ilibrary.org/environment/oecd-guidelines-for-the-testing-of-chemicals_chem_guide_pkg-en.

Oyen, L.P.A. 2007. “Vernicia Montana Lour.[Internet] Record from PROTA4U.” Edited by H.A.M. van der Vossen and G.S. Mkamilo. Wageningen, Netherlands: PROTA (Plant Resources of Tropical Africa / Ressources végétales de l’Afrique tropicale). http://www.prota4u.org/protav8.asp?en=1&p=Vernicia+montana+Lour.

Phankosol, Suriya, Kaokanya Sudaprasert, Supathra Lilitchan, and Kornkanok Aryusuk. 2014. “Estimation of Surface Tension of Fatty Acid Methyl Ester and Biodiesel at Different Temperatures.” *FUEL* 126. Elsevier Ltd: 162–68. doi:10.1016/j.fuel.2014.02.054.

Singer, M M, D Aurand, G E Bragin, J R Clark, G M Coelho, and M L Sowby. 2000. “Standardization of the Preparation and Quantitation of Water-Accommodated Fractions of Petroleum for Toxicity Testing” 40 (11): 1007–16.

Tran, Quang Viet. 1996. “Research on Ecological Characteristics of Trau and Propagation Techquies to Increase Trau Fruit Yield (Góp Phần Nghiên Cứu Một Số Đặc Điểm Sinh Thái Cây Trẩu (Vernicia Montana Lour) và Một Số Biện Pháp Kỹ Thuật Trồng và Cải Tạo Rừng Trồng Để Tăng Sản Lượn.” Vietnamese Academy of Forest Sciences.

U.S. EPA. 2002. “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions-Draft Technical Report.”

Vietnamese Academy of Forest Sciences. 2009a. “Basic Techniques for Propagating Hibiscus Sabdariffa (Kỹ Thuật Trồng Cây Giâm Bụt Giấm).” http://vafs.gov.vn/vn/2009/03/ky-thuat-trong-cay-giam-but-giam/.

———. 2009b. “Basic Techniques for Propagating Trau (Vernicia Montana Lour.) (Kỹ Thuật Trồng Cây Trẩu Lá Xẻ).” http://vafs.gov.vn/vn/2009/03/ky?thuat?trong?cay?trau?la?xe?vernicia?montana?lour/.

Equation Chapter (Next) Section 1

Chapter 4 - TRIPLE I - LIFE CYCLE APPROACH: METHODOLOGICAL ASPECT

4.1 INTRODUCTION

Fossil fuel energy supply steadily increased by two times from more than 5,300 Mtoe in 1973 to around 11,110 Mtoe in 2014, remaining the share of more than 80% in total primary energy supply for four decades despite the increasing non-fossil energy (IEA 2016). This dominated complexion of fossil fuel is projected to continue until 2035 (BP 2016). Since fossil fuel is depletable, this will lead to a massive future burden on the natural resources. Furthermore, fossil fuel combustion is the key driver of the surge in global carbon dioxide (CO_2) emissions to reach the level of 32.2 $GtCO_2$ in 2013 (IEA 2015). As carbon dioxide emissions are the most contributor to climate change, several substitutions of fossil fuel are of major concern to international communities regarding future energy guarantee and environmental and human wellbeing protection. Vegetable oil-derived biodiesel is considered as an ideal alternative to petrodiesel in the transport sector. This type fuel is renewable and environmentally friendly which having the potential of climate change mitigation, and causing less harmful to human health (Haas et al. 2006; Agarwal and Das 2001; Achten 2010). However, several disadvantages of biodiesel were also indicated, for example, higher impacts on the ecosystem due to fertilizer and other agricultural chemical use, land use change and higher net production costs (Fargione et al. 2008; Farrell et al. 2006; Rajagopal and Zilberman 2007). Due to both pros and cons of the biodiesel production and utilization, scholars have been argued about the net benefits and the sustainable potential of biodiesel for years. To settle this controversy, biodiesel has to be put under an appropriate sustainability assessment tool that can without fail to consider the trade-off between pros and cons of biodiesel.

The term ‘sustainable development’ was first defined in the Brundtland report as ‘a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations’(World Commission on Environment and Development 1987). Sustainable development does not mean to preserve the natural environment but rather aim to promote a proper trade-off between socio-economic development and environmental protection and to emphasize the responsibility of humankind to their future generations. With an effort toward a future-oriented society, various sustainability assessment methods were developed based on the ‘triple bottom line - economic prosperity, environmental quality, and social justice’ concept (Elkington 1998). Out of those methods, Life Cycle Sustainability Assessment (LCSA) is a popular framework for the assessment which evaluates environmental and socio-economic impacts from cradle-to-grave of a product system. As a framework, nevertheless, LCSA only means to provide a guideline for each impact assessment. It is important to note that there is no final index for LCSA. Another sustainability assessment method is the Inclusive Impact Index (Triple I). By integrating ecological footprint, cost and benefit, ecological risk and human risk assessments, Triple I seeks to evaluate and combine the three-dimension sustainability over the whole life cycle of a product system into a single index (Otsuka 2011). Triple I was applied in several previous sustainable studies in, for example, marine technologies (Otsuka 2011; Yoshimoto, Tabeta, and Hakuta 2010; Duan, Yamaguchi, and Kawabuchi 2011; Yuzui and Kaneko 2011), and energy sector (Takahashi and Sato 2015; Nguyen, Kuroda, and Otsuka 2015). Although Triple I is recognized as a proper tool for the decision making, the application of it varied case by case. In most cases, since the calculation of the Triple I is complicated, a simplified Triple I was used which omitted some parameters, for example, ecological risk and human risk. This obstacle was due to the lack of a feasible guideline for the calculation of Triple I’s parameters. Overall, since Triple I is a single-quantitative-index for the sustainability assessment throughout the life cycle of a product system, and LCSA is a framework providing a proper pathway for the assessment, it is necessary to connect the two methods to get an all-inclusive result with a systematic approach.

Therefore, to contribute to the sustainability assessment of renewable energy for transportation, the authors aim to propose a methodical estimation for Triple I through integrating with the LCSA framework.

4.2 LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)

4.2.1 The concept of life cycle sustainability assessment

LCSA is a decision-making support tool based on systematic approach towards all-in assessment of environmental and socio-economic impacts from cradle-to-grave of a product

(UNEP/SETAC 2011). The well-known conceptual framework for the Life Cycle Sustainability Assessment (LCSA) is as follows (Kloepffer 2008; Finkbeiner et al. 2010):

$$LCSA = LCA + LCC + S\text{-}LCA \qquad (4.1)$$

where LCA is (Environmental) Life Cycle Assessment, LCC is Life Cycle Costing, and S-LCA is Social Life Cycle Assessment. The three parameters in this formulation represent for the three key issues of the sustainable assessment, including environmental impacts, economic impacts, and social impacts and need to be conducted in parallel.

4.2.2 Life cycle initiative methodological framework

Initially, life cycle assessment framework was introduced and standardized for environmental life cycle assessment studies under/within/in ISO 14040:2006 (ISO 2006a). This framework, later on, has also been applied to both LCC and S-LCA (UNEP/SETAC 2011; Kloepffer 2008; Finkbeiner et al. 2010).

According to ISO 14040, there are four steps for conducting an LCA study, including goal and scope definition, inventory analysis, impact assessment, and interpretation. The key factors for the success of a life cycle study are to have an explicit system boundary followed by a thorough set of inventory, a proper selection of impact category and assessment method, and a precise evaluation of all results from the inventory and impact assessment phases.

Due to the presence of various life cycle assessment models (section 4.2.3, 4.2.4, 4.2.5), the discovery and evaluation of the life cycle inventory have become the most challenging work in environmental and economic life cycle studies. The inventory analysis phase means to recognize all input-output flows of the whole chains in a product system. Input elements can be categorized as energy inputs, raw material inputs, and other physical inputs. Outputs can be products, co-products and waste, emission to air, and water and soil. The elements of input-output flow of may be unique for all three assessment but the validation of data collected depends on the life cycle-based method whether it concern about environmental impacts or economic value or social implication.

The crucial milestone for the integration is all the three assessment have to share the same system boundary (Kloepffer 2008) and inventory data. Table 4.1 shows shared phases and different sample indicators for LCA in life cycle impacts assessment (LCIA) of the three models.

Next three sections will summarize main approaches and well-known methods developed for and applied in environmental, economic, and social and socio-economic LCA. The selection among those methods is flexible depending on research purposes.

4.2.3 Environmental Life Cycle Assessment (LCA)

Among the three life cycle-based methods, LCA dealing with environmental aspect has been widely used as a reference for the environmental management schemes (Finkbeiner et al. 2010). LCA is a tool to measure 'potential environmental impacts throughout a product's life cycle.' Its framework was standardized in ISO 14040:2006 and ISO 14044:2006 (ISO 2006a; ISO 2006b) which has been extended to applied in LCC and S-LCA studies with certain revision. Regarding impact assessment in LCA, LCIA aims to quantify the potential environmental impacts of the whole product life cycle system. Principle components of LCIA are, for example, identify impact categories, category indicators, and characterization models, assignment of life cycle impact (LCI) results to the selected impact categories (classification), calculation of category indicator results (characterization).Various methodologies were developed which difference from each other either in using midpoint or endpoint approaches or combining the both methods and also in defined impact categories (EC 2010).

Table 4.1 Example shared and separated phases of LCA, LCC and S-LCA under LCSA adapted from UNEP/SETAC (2011) & Traverso et al. (2012)

Life cycle stages	**Inventory**	**Indicators**		
		LCA	**LCC**	**S-LCA**
- Raw - material acquisition - Raw material Transportation - Production - Product distribution - Use - Disposal & recycling	Inputs - Facilities & equipment - Raw materials - Energy - Natural resources - Manpower Output - Products, co-products, by-products - Emissions to air	- Embodied energy - Global warming potential - Human toxicity potential - Photochemical oxidation - Acidification - Eutrophication - Abiotic depletion - Ozone layer depletion	- Extraction costs - Manufacturing costs - Finishing costs - Waste disposal costs - Energy costs - Equipment costs - Revenues - Raw material costs - Product costs - Labor costs	- Salary per employee - Percentage of female workers - Percentage of females at the administration level - Percentage of employees with limited contracts - Percentage of workers with yearly check up - Number of accidents - Percentage of child labor - Number of discrimination cases - Social benefits per employee

	- Emissions to water - Emissions to soil	- Terrestrial eco-toxicity	- Transport costs

Some of the well-known LCIA methodologies are CML 2002, Eco-indicator 99, ReCiPe and MEEup from Netherlands, Impact 2002+ and Swiss Ecoscarcity 07 from Switzerland, LIME from Japan, TRACI from the USA, and ESP 2000 from Sweden (referring to (EC 2010) for general information of each method). In general, those methods mostly consider impacts on climate change, human health, natural environment quality, and natural resource use. However, each model applied different approach and developed a varied set of indicators. Some adopt midpoint modeling (problem-oriented) including, for example, CML2002, MEEuP, and TRACI; some employ endpoint modeling (damage-oriented) including Eco-indicator 99 and EPS 2000; and some combine the two approaches including Impact 2002+, LIME, ReCiPe, for instance (EC 2010). The selection of used model mostly depends on purposes of studies and study location.

Furthermore, basing on the variety purposes of life cycle-based studies, several adapted and extended LCA methods have been developed, including:

- Greenhouse Gas (GHG) LCA: This method focuses on identifying and accounting total greenhouse gasses emitted over product's life cycle and their climate change impact (Hondo 2005);
- Life Cycle-based Ecological Footprint Assessment: Ecological footprint (EF) expresses how much bioproductive area (both land and water) is needed to regenerate all the resources consumed and to absorb the waste formed by a population (Huijbregts et al. 2008). Life cycle-based EF presents aggregate land area both directly and indirectly occupied across the whole product life cycle system. Indirect land occupation concerns nuclear energy use and CO_2 emissions from fossil energy use and cement burning;
- Ecologically-based LCA (Eco-LCA) that aim to account the usage of ecosystem goods and services and its impacts on ecosystem quality over life cycle of a product (Y. I. Zhang, Anil, and Bakshi 2010);
- Life Cycle Risk Assessment (LCRA): LCRA is a methodological approach that integrates the ordinary RA with LC thinking to assess potential human health and ecological impacts throughout the life cycle of a system. It seeks to broadly identify and screen for potential human health and ecological impacts by incorporating LC stages of

a product while analyzing 'multi-media environmental fate and transport, *exposure*, and effects on both ecological receptors and human health.'(Eason et al. 2011)

4.2.4 Life Cycle Costing (LCC)

Life cycle costing is a tool to evaluate economics aspect of a product over its life cycle. LCC calculates total cost and benefit of a product over its life cycle. LCC consists of various elements, including initial capital costs, the lifetime of the asset, discount rate, operating and maintenance costs, disposal cost, information and feedback, uncertainty and sensitivity analysis. (Huppes et al. 2004) applied four-level categories of cost to summary various sophisticated types of costs ranging from general cost (1st level: budget cost and market costs, for instance) to specific expenses (4th level: materials, buildings, taxes and wastewater treatment, for example) (Table 4.2). Those costs might be derived from private or social sources, from direct or indirect accounting, from tangible or intangible costs. To avoid double accounting between LCA and LCC, LCC method only considers true monetary input (cost) and output (revenue) flow of each unit process within specific system boundary (Kloepffer 2008). Therefore, within LCSA, intangible costs, such as alternative cost and social cost, are not quantified. Since LCC deals with the whole life cycle of a product, the cost can be either one-time payment, such as investing in infrastructure and purchasing facilities and equipment, or annual costs, such as labor cost, material costs, and taxes. To aggerate those costs, several methods were suggested, for example, Net Present Value of Cost (NPV), profit, payback time, steady state costs and average yearly cost, and inflation and discount rate (Huppes et al. 2004). Previous studies mostly suggested and used steady state costs/average yearly cost for the life cycle costing under life cycle assessment. Nevertheless, this research recommended the use of net present values or discount rate cooperating with payback time to obtain more precise results regarding economic dimension. The application of those methods is discussed in section 4.4.3.

4.2.5 Social Life Cycle Assessment (S-LCA)

The third and the most controversial component in LCSA is S-LCA which evaluates direct social and socio-economic impacts of a product and service throughout its cradle-to-grave (UNEP/SETAC 2009). Social and socio-economic impacts are site-specific and vary case by case. Indicators and assessment methods of LCSA are at their early stage and have not yet been standardized. Stakeholder involvement can be workers/employees, local communities, societies (national and international), consumers (either at the end-use state or within the supply chain), value chain actors, and other groups, such as non-governmental organizations (NGOs) and public authorities/state (UNEP/SETAC 2009). Common impact categories under S-LCA are, for example, human and indigenous rights, working conditions, cultural heritage, poverty, health and safety, and governance and political conflict (UNEP/SETAC 2009; Eason et al. 2011). Table 4.1 presents some example indicators of S-LCA. The evaluation of social impacts is very complicated and easily overlap with environmental impacts (human health impacts, for instance) and economic impacts (job creation and labor income). Therefore, the choice of S-LCA indicators under LCSA has to be thoroughly taken into account.

Table 4.2 Examples of cost categories (Huppes et al. 2004)

1st level: in economics	Budget cost Market cost Alternative cost Social cost
2nd level: life cycle stages	R&D Primary production Manufacturing Use Disposal management
3rd level: activity types	development extraction purchase sales reuses management design agriculture manufacturing public relations recycling administration research testing packaging transport maintenance waste treatment infrastructure
4th level: exemplary elements	Personnel equipment loans (rent) direct taxes damage prevention overheads materials indirect taxes wastewater treatment disposal communication excises exhaust gas reduction investment food production levies rehabilitation costs service electricity office cost subsidies building costs warranties infrastructure depreciation

4.3 INCLUSIVE IMPACT INDEX (TRIPLE I)

Inclusive Impact Index (Triple I) is a quantitative evaluation tool to assess the sustainability of a system, which was developed by the Inclusive Marine Pressure Assessment and Classification Technology (IMPACT) Research Group in 2006 (Otsuka 2011). Following the theory of LCSA, Triple I also considers environmental, economic, and social impacts along the whole life cycle of the studied system. It employs ecological footprint, financial flow, and environmental impacts (both ecological risk and human risk) for the estimation, and integrates them into a single index of world-average bioproductivity area so-called global hectares (gha) (Otsuka 2011; Duan, Yamaguchi, and Kawabuchi 2011). Triple I (III) is determined by the following equation:

$$III = [(EF - BC) + \gamma ER] + \alpha[(C - B) + \beta HR] \text{ (gha)} \quad (4.2)$$

where EF is ecological footprint (gha), BC is biocapacity (gha), ER is ecological risk, C is cost (US \$), B is benefit (US \$), HR is human risk, and α, β, and γ are the conversion factor from economic value (US \$) to gha, from HR value to economic value (US \$), and from ER value to gha, respectively.

Moreover, the ratio (III^*) between the burdens and the benefits within Triple I can be used as a proper reference under policy dimension (Eq. 4.3) (Otsuka 2011).

$$III^* = \frac{EF + \gamma ER + \alpha(C + \beta HR)}{BC + \alpha B} \quad (4.3)$$

To convert from economic value to global hectare, the ratio of total EF of the country/region, where the target system is implemented, to its GDP in the same year was applied (Otsuka 2011; Duan, Yamaguchi, and Kawabuchi 2011; Omiya and Sato 2011; Nguyen, Kuroda, and Otsuka 2015) (Eq. 2).

$$\alpha = \frac{EF_{region}}{GDP_{region}} \text{ (gha US \$}^{-1}\text{) } 4.4$$

HR, as a parameter of TRIPLE I, means both human health impacts and social and socio impacts. Therefore, the computation of β depends on which impact is under consideration.

Regarding β and γ, there are several available indices of ER (Potentially Disappeared Fraction (PDF), Lethal/Effective Concentration (LC/EC), and No observable/lowest observable effect concentration (NOEC/LOEC), for instance) and HR (Disability Adjusted Life Years (DALY) and Years of Lost Life (YOLL) in term of human health impact, for example). Therefore, the conversion of ER and HR values to economic value varies case by case. Session 4.4.5 produce some options for the conversion.

Triple I not only can assess the sustainability of a product system but also can be used as a global and transboundary tool to compare technologies and products among various countries due to the application of global hectare.

4.4 LINKAGE BETWEEN TRIPLE I AND LCSA IN THE ASSESSMENT OF VEGETABLE OIL-BASED BIODIESEL

4.4.1 Integration framework of Triple I and LCSA for assessing biodiesel

Although Triple I is not a method developed under LCSA scheme, there is a close relationship between Triple I and LCSA. Triple I and LCSA are both making efforts to measure the sustainability of the whole life cycle of a product/service. They can support and boost each other to reach their final expected destination. Regarding LCSA, Triple I can be considered as an optimal quantitative tool for the sustainability evaluation of the studied product/service. Initially, the cooperation of different life cycle approaches in Triple I requires a concurrent study goal, functional unit, and system boundary. Then, the flexible application of the three-dimension life cycle assessment in LCSA is a vital issue determining the success in Triple I final estimation. Fig. 4.1 illustrates the Triple I estimation pathway using relative life cycle assessment technique under LCSA. It is noteworthy that since biodiesel is considered as an alternative to petrodiesel, all impacts, including impacts on the environment, human being, and society, of petroleum's life cycle can be treated as a business-as-usual baseline. Therefore, the assessment of BDF potential always has to take into account the different impacts between BDF and petrodiesel. However, due to the lower energy content of biodiesel, from more than 35.6 MJ kg^{-1} to less than 44 MJ kg^{-1} (Atabani et al. 2013), comparing to petrodiesel, approximately 45 MJ kg^{-1}, fuel efficiency has to be taken into account when comparing the two fuel sources.

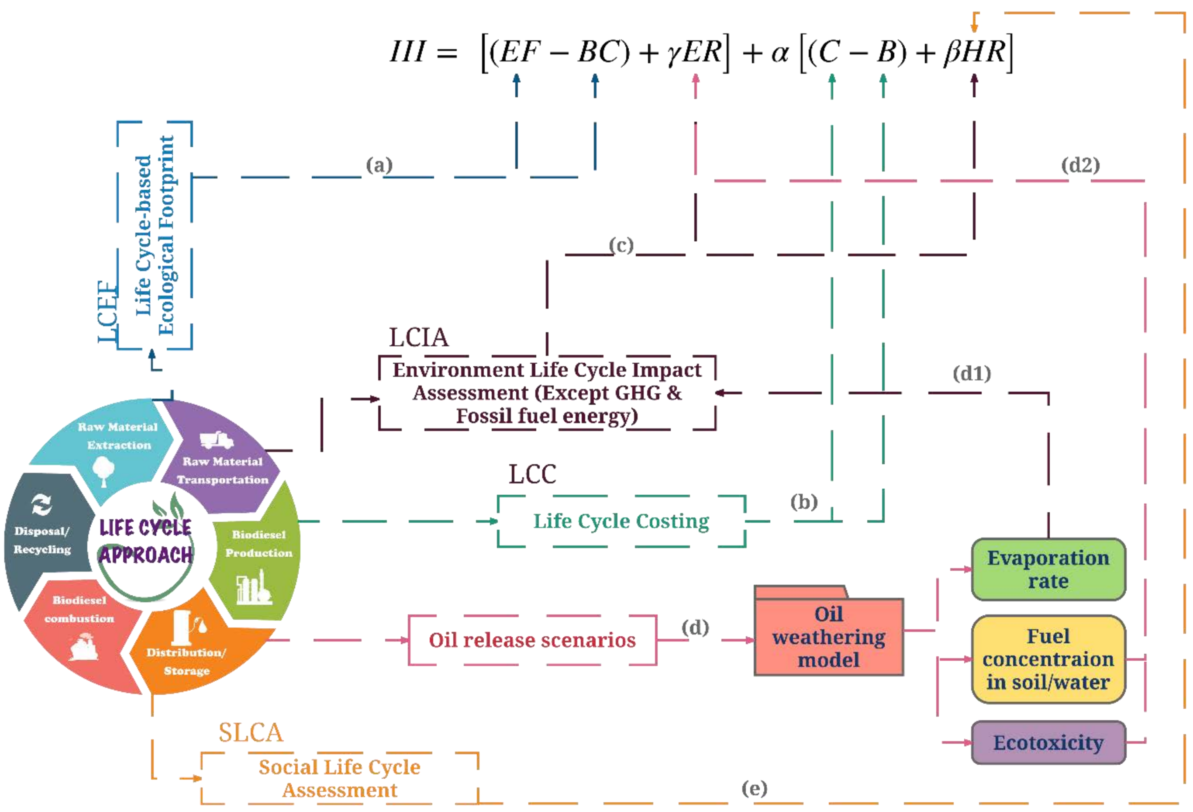


Fig. 4.1 BDF sustainability assessment framework

4.4.2 Life cycle-based ecological footprint

EF and BC in Triple I can be calculated using life cycle-based ecological footprint assessment (LCEF) approach. The entire LCEF is contributed by total EF of direct land use, carbon footprint, and nuclear energy footprint (Eq. 4.5) (Huijbregts et al. 2008).

$$EF = EF_{direct} + EF_{CO_2} + EF_{nuclear} \text{ (gha) (4.5)}$$

Nevertheless, EF, under the context of Triple I, only covers the total carbon footprint from the life cycle of a product system (Otsuka 2011). Carbon footprint (EF_{CO_2}) is the indispensable forest area needed to absorb all the CO_2 emitted into the air due to the burning of fossil fuel, cement production, and land use change. The total carbon footprint of a product system is calculated as follows (Lin et al. 2016; Ewing et al. 2010; Huijbregts et al. 2008):

$$EF_{CO_2} = \sum_{t=0}^{n} P_{CO_2,t} \times FI_{CO_2} \text{ (gha)} \qquad (4.6)$$

where n is the project lifetime, $P_{CO_2,t}$ is total greenhouse gas emissions in year t (t CO_2), FI_{CO_2} is the footprint intensity of CO_2 (gha (t CO_2)$^{-1}$).

$$FI_{CO_2} = \frac{1 - F_{CO_2}}{S_{CO_2}} \times EqF_f \text{ (gha (t CO}_2\text{)}^{-1}\text{ yr}^{-1}\text{)} \quad (4.7)$$

where F_{CO_2} is the fraction of CO_2 absorbed by oceans (-), S_{CO_2} is the sequestration rate of CO_2 by biomass (t CO_2 wha^{-1} yr^{-1}), EqF_f is the equivalence factor of forests (gha wha^{-1}). Table 4.3 shows the value of some identified parameters applied in EF estimation.

Table 4.3 Values of identified parameters for the ecological footprint estimation (Lin et al. 2016)

Parameter (unit)	**Abbreviation**	**Value**
Equivalence factor forest (gha wha^{-1})	EqF_f	1.28
Equivalence factor built-up land (gha wha^{-1})	EqF_b	2.52
Equivalence factor cropland (gha wha^{-1})	EqF_c	2.52
Equivalence factor pasture (gha wha^{-1})	EqF_p	0.43
Equivalence factor marine area (gha wha^{-1})	EqF_m	0.35
Fraction CO_2 absorbed by the ocean (-)	F_{CO_2}	0.281
Sequestration rate of CO_2 (t CO_2 wha^{-1} yr^{-1})	S_{CO_2}	3.59
Footprint intensity of carbon (gha (t CO_2)$^{-1}$ yr^{-1})	FI_{CO_2}	0.256
Fossil fuel emission intensity of CO_2 (t CO_2 GJ^{-1})	I_{CO_2}	5.73E-02

In LCEF assessment, biocapacity (*BC*) is a reverse form of ecological footprint that indicates the total bioproductive area gained of land-use type a (SA_a) corresponding with either increasing primary productivity, or reducing CO_2 emission, or decreasing nuclear energy use through the whole life cycle of a product during the project life time (*n*) (Monfreda, Wackernagel, and Deumling 2004; Duan, Yamaguchi, and Kawabuchi 2011; Otsuka 2011). Biocapacity is calculated as follows:

$$BC = \sum_{t=0}^{n} \sum_{a} SA_{ta} \times YF_a \times EqF_a \text{ (gha)} \quad (4.8)$$

where *n* is the project lifetime, SA_{ta} is the bioproductive area gained of land-use type a in year *t* (ha), EqF_a is the equivalence factor of land-use a (gha wha^{-1}), YF_a is the yield factor of land-use a calculated by dividing the national average yield of land-use a (Y_{Na}) by world average yield of land-use a (Y_{Wa})(Eq. 4.9, 4.10) (Ewing et al. 2010).

$$YF_{cr} = \frac{\sum_{i \in U} Y_{\mathrm{N},i}}{\sum_{i \in U} Y_{w,i}} \text{ (ha wha}^{-1}\text{) (4.9)} \qquad YF_a = \frac{Y_{Na}}{Y_{Wa}} \text{ (ha wha}^{-1}\text{) (4.10)}$$

where i is the type of crop and U is the set of cultivation crops. Eq. 4.9 is used for cropland since the cultivation normally includes several types of crops and Eq. 4.10 is used for other land-use types as they only have one primary product.

4.4.3 Life cycle costing

Cost and benefit considered under Triple I are aggregated results from life cycle costing based on the money input-output flows. Consequently, the cost is the total money input/investment for the start-up, operation, maintenance, and waste disposal of all processes in the product life cycle system (Huppes et al. 2004), and the benefit is the total monetary value of products, by-products, and co-products obtained from the system. Capital costs are one-time expenses (during a project lifetime) including, for example, payments for land use, biodiesel plant construction and facility set-up, and preliminary cultivation of perennial biodiesel feedstock (seeds and seedlings) (Haas et al. 2006; Ong et al. 2012). Annual costs are costs of input materials for the BDF production, utilities, labor, maintenance, taxes, and insurance, loan interest, and depreciation, for instance (ibid.). To properly estimate the time-aggerate cost of the whole system, it is important to apply two cost aggregation methods, namely net present value (NPV) and payback time.

4.4.3.1 Net present value (NPV)

NPV, the present value of cost, is a tool to compare the present monetary value of an investment to the dollar value of that investment in the future (Huppes et al. 2004). The computation of NPV is as follows:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \text{ (US \$)} \qquad (4.11)$$

where n is the period of assessment (year), r is the discount rate, C_t is the estimated costs in year t. In Triple I, the time-equivalent value of total one-time payment (TP) are considered under NPV, in which n is the project lifetime, and C_t is the average amount of TP over project lifetime period. The discount rate (r) is a key factor in the estimation of NPV mostly influenced by the inflation and interest rate (Eq.4.12) (Davis et al. 2005).

$$r = \frac{Rate_{Interest} - Rate_{Inflation}}{1 + Rate_{Inflation}} \qquad (4.12)$$

4.4.3.2 Payback time

Payback time is another important technique in economic life cycle assessment which denotes the possible period for recovering all the initial investment (Huppes et al. 2004). Payback period not only shows the economic potential of the whole life cycle of a product but also projects how many years that the interest rate needed to be considered as an annual cost. The payback time is (*PBT*) calculated as follows (Huppes et al. 2004):

$$PBT = \frac{C_0}{B} \text{ (year)} \qquad (4.13)$$

where C_0 is an initial investment (US \$), and B is annual net benefits (US \$ year^{-1}).

4.4.4 Estimation of ecological risk and human health risk

Fig. 4.1 (c, d, d1, d2) presents the pathway to assess total ecological impacts and human health impacts of a product system from cradle-to-grave. Both direct emissions including ordinary and potential emissions from each stage in BDF life cycle, and indirect emissions from the production of input materials for the system are considered. Ordinary emissions from BDF's life cycle are emissions derived from, for example, fertilizer use in cultivation stage, energy consumption, chemical for oil extraction and BDF manufacturing, and BDF and conventional diesel combustion (Ginn et al. 2013). The occurrence of potential chemical releases possibly associated with fuel leakages from a storage tank (either above ground or underground), engine operation, fuel pipeline and transportation vehicles, or even more substantial releases due to traffic accidents, shipwrecks, and other coincidental incidents (ibid.).

It is worth noting that air emissions from BDF production are leakages from the storage of material and the operation of BDF manufacturing equipment. Several previous studies show that the total emissions are not high and their incident is infrequent. Under a thorough management, they can be controlled and do not cause risks to both human health and ecosystem (Sheehan et al. 1998; Charman et al. 2012). Therefore, the assessment of those emissions can be avoided. Other potential hazards would come from the transportation of input materials and substances due to, for example, transport accidents, fires, and leakage. In the industrial context, their incident and impacts are common and perceptible and are customarily controlled under risk response and mitigation scheme (Charman et al. 2012). Thus, they also can be omitted from the risk assessment.

4.4.4.1 Life cycle impact assessment

Current life cycle impacts assessment methods can be applied in the assessment of potential ecological impacts and human health impacts of the ordinary emission from the system (Fig. 4.1 (c)). Several LCIA methods were briefly introduced in section 4.2.3. Since GHG emissions are examined under ecological footprint in Triple I, to avoid double counting, it is essential to check whether or not the chosen LCIA method can separate impacts of those emissions from impacts of other emissions. Basing on impact indicators, IMPACT 2002+ which developed a framework to integrate the midpoint-oriented method with the damage-oriented method is recommended (Jolliet et al. 2003). IMPACT 2002+ categorizes LCI results into 14 midpoint categories which then are combined into four damage categories, including human health, ecosystem quality, climate change, and resources (ibid.). Accordingly, two out of these categories, the human health and ecosystem quality can be applied in Triple I as the human health risk (HR) and ecological risk (ER), respectively. Fig. 4.3 illustrates the pathway between human health impacts and ecological impacts and their related midpoint categories covered by IMPACT 2002+.

4.4.4.2 Oil weathering

Regarding environmental releases, biodiesel and petrodiesel possibly release into the air, water (including groundwater), and soil due to leakages from above/underground storage tanks, accidental spills from fuel tankers (both ship and lorry) (Charman et al. 2012), and releases from the operation of diesel engines. The releases of fuel into the environment obviously depend on different natural and socio-economic conditions of study areas. Therefore, the development of fuel release scenarios has to cover current and historical data of the study area, for example, information about accidents (both man-made and extreme weathers affected) related to tankers, current fuel storage and transportation technology, status of diesel engines in operation (Ginn et al. 2013; Charman et al. 2012). After identifying releases scenarios, the behaviors of spilled biodiesel and petrodiesel in the environment is analyzed under oil spill models (Fig. 4.1 (d)). Various oil weathering models were formed regarding spillages and leakages on the land surface, in-land subsurface, and in water environment, including river and marine environment. Data of common oil spill processes estimated under oil weathering model are (Simmons and Keller 2003; Vos 2005):

- Both inland and off-land spills/leaks: area of surface spreading, evaporation rate of oil on the surface, (bio)degradation rate;
- In-land spills/leaks: infiltration rate and drainage rate into subsurface soil, an amount of oil enters groundwater table;
- Spills/leaks in water environment: formation of emulsification (water-in-oil emulsion) and dispersion (oil-in -water emulsion), dissolution of hydrocarbons from oil slicks, sedimentation, and shoreline stranding.

Although these models apply various calculation methods, they share almost similar input data set including information on oil properties, for example, viscosity, emulsification, density, distillation cuts, surface tension, interfacial tension, solubility, pour point, flash point, and (bio)degradation coefficient; information on the natural conditions of spill site, for example:

- Both inland and off-land spills/leaks: weather, wind speed and direction;
- In-land spills/leaks: soil properties, including soil type, mineral content, water retention, and bulk density, and land surface properties, including, topography, roughness, and macropores (Simmons and Keller 2003);
- Spills/leaks in water environment: wave height and direction, and river/sea current (Vos 2005).

Results from oil weathering models are used to identify the concentration of biodiesel and petrodiesel in soil and water (water accommodated fraction (WAF)) basing on the remaining amount on the land/water surface, amount of fuel enter subsurface and groundwater table, and the dissolved amount of spilled fuel into water column and sediment; and the leases of biodiesel and petrodiesel into air regarding the natural evaporation. Followingly, current data about ecotoxicity of biodiesel and petrodiesel in soil and water environment is applied to identify ecological impacts of the spill (Fig. 4.1 (d2)). Moreover, since the evaporation is responsible for more than 70 percent of petroleum mass loss (National Research Council (U.S) 1975; Transportation Research Board and National Research Council 2003), it needs to be taken into account. Therefore, petroleum vapors are treated as another emission to air of the BDF and petrodiesel's life cycle (Fig. 4.1 (d1)).

On the other hand, the application of an integrated model of oil weathering and environmental effects of spilled oil and fuel is another option. The Spill Impact Model Application Package (SIMAP) (French-McCay 2004), for example, uses three-dimensional physical fate model to estimate the behavior of spilled oil at sea and biological effects model to evaluate adverse impacts on the mortality or decreased production of marine organisms due to the exposure to certain concentrations of spilled oil on sea surface, in water column, and on sediment.

4.4.5 Monetary evaluation of environmental impacts

Regarding environmental impacts, one research from SCORELCA in 2013 evaluated the possibility of available monetary valuation methods as a tool for the monetarization of environmental impacts in LCIA studies (B. Weidema, Brandão, and Pizzol 2013). Several methods and their previous application were reviewed and benchmarked, including market approach/observed preferences: market price method; revealed preferences: averting behavior, travel cost and hedonic pricing methods; stated preferences: contingent valuation and conjoint analysis methods; abatement cost method; budget constraint method; restoration costs method; and review/statistical method (B. Weidema, Brandão, and Pizzol 2013; NEEDS 2006). Among those methods, market price, contingent valuation, conjoint analysis: choice experiment, budget constraint, and restoration costs methods and their combination are high potential tools for monetarizing environmental impacts. Most of the previous LCA studies applied those tools, in which (Pizzol et al. 2015; B. Weidema, Brandão, and Pizzol 2013):

- a market price method values a good and service based on its existing market price;
- both contingent valuation and conjoint analysis: choice experiment methods are monetarization tools for non-market goods and services which based on the answers of

respondents under a specific hypothetical scenario. Contingent valuation method applies direct questionnaires about respondents' willingness to pay/accept as compensation for an adverse impact on the availability of a product/service. Contingent choice method, meanwhile, requires for respondents' trade-off choices among sets of goods/services having 'different availability of the same attributes and different total price';

- a budget constraint method is a particular tool for the monetarization of human wellbeing impacts. This method based on the data about estimated economic production per capita per year to value the economic implication of changing in wellbeing life year (in both additional or lost situations) (B. P. Weidema 2009; Dalal and Svanström 2015); and
- a restoration costs method is the monetarizing method referring to total cost for the recovery of human-made damages to the environment as the monetary value of the affected ecosystem (NEEDS 2006).

4.4.5.1 Monetarization of human health impacts (β)

IMPACT 2002+ adopts Disability Adjusted Life Year (DALY) as a damage index of human health. DALY is an indicator that measures the burden of disease by incorporating total 'years of life lost (YLL) due to premature mortality' and total 'years lost due to disability (YLD)' (Eq.4.14) (Dalal and Svanström 2015)

$$DALY = YLL + YLD \quad (4.14)$$

DALY quantitatively denotes the difference between a disease affected population and a healthy population. A unit of DALY is equivalent to a one-year decrease in healthy life.

Budget constraint method (B. P. Weidema 2009; Dalal and Svanström 2015) can be used to value the DALY. Since a 'healthy' individual can contribute to a country's economy during that person's lifetime, the number of years lost due to death and disability means the non-economic-contributing period of that person. Therefore, the monetary value of DALYs is computed by multiplying the DALYs value by GDP per capita (β) in the same year (Dalal and Svanström 2015). Stated preferences approach is another option for monetary evaluation of DALY, including contingent valuation method (Steen 1999; Desaigues et al. 2011; Ahlroth and Finnveden 2011) and conjoint analysis method (Itsubo and Inaba 2015; Itsubo et al. 2012).

Under contingent valuation's questionnaire, respondents are asked to state how much they are willing to pay/accept for a one-year increase in wellbeing life year. Regarding conjoint analysis, respondents make their choices among various policies, in which a certain impact, for example, on human health (loss of life expectancy per person), on social assets (loss of social assets per person), on biodiversity (disappearance of species of organisms), and on primary production (inhibition of plant growth) are set followed by a particular tax increase (Itsubo et al. 2012; Itsubo and Inaba 2015). Results from conjoint analysis questionnaires are used for both human health and ecological impacts.

4.4.5.2 Monetarization of ecological impacts (γ)

Regarding ecosystem quality (ecological risk in Triple I), the damage index of ecosystem impacts is Potentially Disappeared Fraction of species (PDF m^{-2} yr^{-1}) under IMPACT 2002+ (Jolliet et al. 2003), and Lethal/Effective Concentration (LC/EC) under ecotoxicity assessment of biodiesel and petrodiesel (Bluhm et al. 2012; Wedel 1999; Ginn et al. 2013; Birchall, Newman, and Greaves 1995; Lapinskiene, Martinkus, and Rebždaite 2006). In addition to conjoint analysis method mentioned above, market price, contingent validation and restoration costs are other monetarization methods for ecological impacts that used by several biological valuations and LCA studies (Ahlroth and Finnveden 2011; Nunes and van den Bergh 2001; Veisten et al. 2004; NEEDS 2006). Since PDF directly related to biodiversity, it can be valuated under contingent valuation, conjoint analysis, and restoration costs methods. Lethal concentration (LC_a) and effective concentration (EC_a) are the median concentrations of chemical in soil or water environment that lead to a degree of mortality or a certain level of effect (a%) in the test organism, respectively (Hollebone et al. 2008; Leite et al. 2011). Since lethal concentration and effective concentration denote the effects of released biodiesel and petrodiesel on the availability amounts of organisms in their habitat which directly related to the production capacity of that ecosystem, they can be estimated through market price method.

4.4.6 Social life cycle assessment

Result from the social life cycle assessment is one of the contributor to the human risk (HR) parameter of Triple I (Fig. 4.1 (e)). Social life cycle assessment in Triple I deals with the impacts of studied system on human wellbeing including, for example, human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions

(UNEP/SETAC 2009). The pathway and indicators to integrate S-LCA with Triple I are still under development. Therefore, there are no further discussion about this issue in current study.

4.4.7 Adaptation and extension in the application of Triple I

As all the values of ecological risk and human health risk are supposed to be monetarized (section 4.4.5), current equation of Triple I can be reorganized as follows:

$$III = (EF - BC) + \alpha[(C - B) + \beta HR + \gamma ER]\,(\text{gha}) \quad (4.15)$$

where α, β, and γ are the conversion factor from economic value (US \$) to gha, and from HR value and from ER value to economic value (US \$), respectively.

The preparedness for installing a new technology or product requires an immense volume of investment, including natural capital, human capital, social capital, manufactured capital, and financial capital. The recovery of those invested capitals entirely depends on annual revenue of the technology/product, and it may take a certain time duration. As an investor, whether a business individual or a policy maker, it is importance to know when the investment can be totally recovered. Therefore, Triple I can be developed into three types for more flexible and diverse applications:

- Triple $I_{initial}$ is Triple I assessing all the capital costs and emissions from the preparedness and start-up of a product life cycle system ($EF_{initial}$, $ER_{initial}$, $HR_{initial}$);
- Triple I_{annual} is Triple I considering annual costs (C_{annual} and B_{annual}) and emissions from the product life cycle system (EF_{annual}, BC_{annual}, ER_{annual}, HR_{annual});
- Triple I_{total} is average Triple I evaluating all costs and emissions from the whole life cycle of the product within a project lifetime.

Accordingly, Triple I payback time ($III_{payback}$) of a product is calculated as follows:

$$\forall III_{annual} < 0 \Rightarrow III_{payback} = \frac{III_{initial}}{\left|III_{annual}\right|}\,(\text{year}) \qquad (4.16)$$

It is important to note that, the Triple I framework developed in this study can be applied in other type of research with the adaptation in the inventories.

4.5 Life Cycle Inventory Of Vegetable Oil-Based Biodiesel For Triple I

The lifetime of a project is identified follows the lifetime of biodiesel production plant and perennial BDF feedstock.

4.5.1 System boundary and key assumptions

Fig. 4.2 shows general boundaries of vegetable oil-based biodiesel system and petrodiesel as a reference system. In general, key phases in petrodiesel life cycle include extraction of crude oil from the earth and pretreatment, transport of crude oil to an oil refinery, refinement of crude oil to produce conventional diesel fuel, distribution and storage of petrodiesel fuel, and utilization in a diesel engine (Sheehan et al. 1998). Regarding biodiesel application, a ‘cradle-to-grave’ system of BDF comprises all the stages starting from feedstock cultivation, feedstock transportation, oil extraction, BDF production and blending, BDF distribution and use, to the practice of composting and application of compost from organic waste back in cultivation area. Principle issues in comparison and linkage between conventional diesel and biodiesel are also displayed in Fig. 4.2.

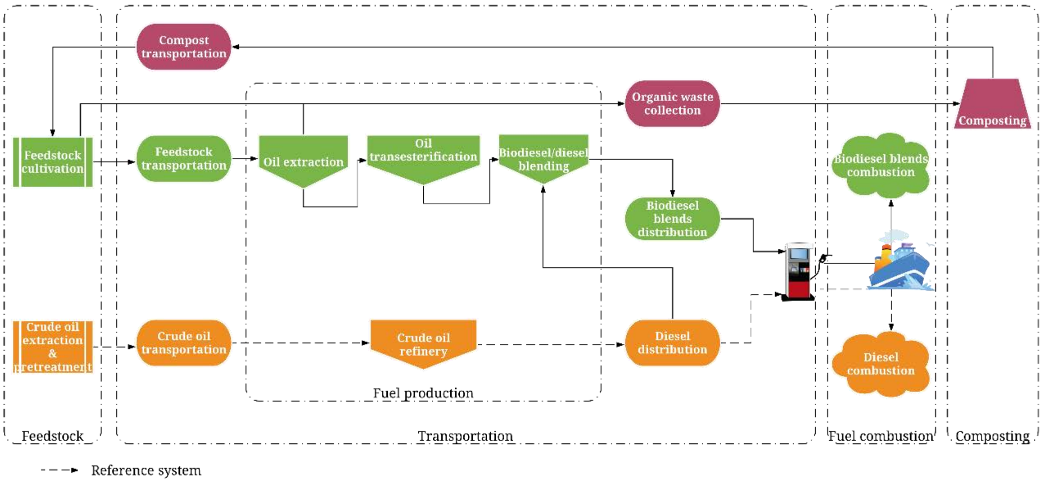


Fig. 4.2 System boundaries of vegetable oil-based biodiesel system and petrodiesel system adapted from (Nguyen, Kuroda, and Otsuka 2015; Sheehan et al. 1998; Atabani et al. 2013; Achten 2010)

4.5.2 Summarization of common emissions from vegetable oil-based biodiesel system

Main life cycle stages and relevant sub-processes of biodiesel system are as follows (Whitaker and Heath 2009; Achten 2010; Atabani et al. 2013; Sheehan et al. 1998):

- Feedstock agriculture: the cultivation of biodiesel feedstock includes seedling practice (not all crops need this step), planting operation and management, harvest practice. Key input materials are, for example, CO_2 uptake by plants, plastic bags used in seedling, fertilizers and agricultural chemicals (pesticides and herbicides), energy for operating agricultural equipment and other supporting systems (for example, petrodiesel, electricity, and gasoline), water used for irrigation, land area. In some cases, CO_2 uptake by plants is considered as zero because CO_2 is released back to the atmosphere due to the decay of plant residue after harvesting.
- Vegetable oil-based BDF production: Three main steps in this stage are kernel separation and oil extraction, biodiesel production through oil transesterification, and blending between biodiesel and petrodiesel. Various techniques were developed and applied for all these three steps. To extract oil from its kernel, three state-of-art approaches are mechanical extraction, solvent extraction (chemical extraction), and enzymatic oil extraction. Furthermore, the extraction can be supported by ultrasonication technique to get higher oil yield and reduce time consumption (Thanh et al. 2010b; Thanh et al. 2010a). Depending on feedstock oil properties (free fatty acid (FFA) value, for example) and producing techniques, biodiesel can be obtained via one-step/two-step transesterification, and with/without co-solvent and ultrasonic supporter (Thanh et al. 2010b; Luu et al. 2014). Input materials of this stage include, for example, chemicals for each process (hexane, ethyl acetate, sulfuric acid, methanol, and acetone), water for oil extraction and washing biodiesel, energy for machinery and plant operation (electricity and petrodiesel),
- Biodiesel and its blends combustion: As an alternative fuel to mineral diesel, biodiesel and its blends are supposed to be used in current diesel engines. Engine performance and tailpipe emission characteristics of biodiesel and its blends vary according to different biodiesel feedstocks and blended volumes. In general, the majority of scholars reported that the combustion of biodiesel and its blends decreases carbon monoxide CO, particulate matter (PM), hydrocarbon (HC) and sulfur dioxide (SO_2) but increase

nitrogen oxides (NO_X) emission (Atabani et al. 2013; Morris et al. 2003; Jaichandar and Annamalai 2011).

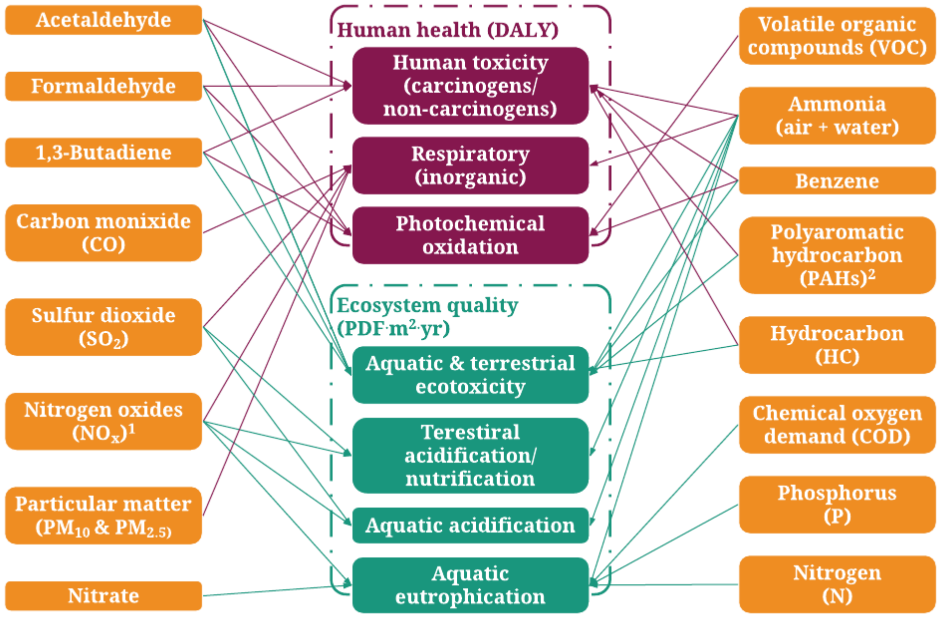
- Composting: Wooden stems and leaves from the field, fruit husk and oilseed cake from oil extraction can be gathered and composted.
- Compost use at the field: The derived compost can be used as a substitute to chemical fertilizers.
- Transportation: The transportation of feedstock from cultivation area to biodiesel plant, biodiesel and it blends from production plant to storage location, biomass waste to composting plant, and compost from the composting plant back to biodiesel feedstock field are also included. Input material of this stage is petrodiesel fuel for transport vehicle operation.

Expected direct emissions due to the use of input materials from each life cycle stage of vegetable oil-derived biodiesel system are presented in Table 4.4. Moreover, as mentioned in section 4.4.4, other indirect emissions from the production and preparation of input materials for all life cycle stages of the biodiesel system including biodiesel plant construction and facility set-up are also analyzed. Fig. 4.3 provides some example about the determination of environmental impacts of some emissions from biodiesel life cycle system.

4.5.3 Potential ecological impacts of biodiesel and its blends spill and leak

4.5.3.1 Biodegradation of biodiesel.

Previous related studies indicate more prominent in biodegradation rate of BDF than petrodiesel. In aquatic environments, within 28 days, various feedstock-based BDF degrade about 87% in average which is three times higher than conventional diesel. Moreover, through co-metabolism, BDF in a mixture can boost the biodegradation of petrodiesel and consequently, the biodegradation rates of biodiesel/petrodiesel mixtures are higher than petrodiesel alone (X. Zhang et al. 1998; Wedel 1999). In soil, within 28 days, biodiesel degrades about 88% in average - approximate 1.7 times higher than pure petrodiesel. Furthermore, an interesting result shows that the blend of 20% vegetable oil-based BDF has higher biodegradable potential than that of pure vegetable oil-based BDF (100% biodiesel) (Ginn et al. 2013).



Note: [1]Include nitrogen dioxide (NO_2), nitrogen oxide (NO), and nitrogen oxides (NO_x)
[2]Exclude benzene

Fig. 4.3 Human health and ecological impacts and pathway related to vegetable oil-based biodiesel under IMPACT 2002+ framework adapted from Jolliet et al. (2003)

4.5.3.2 Aquatic toxicity

Comparing to petrodiesel, several studies observe significant lower toxicity to aquatic environment of BDF. According to CytoCulture, the concentration required to kill 50% of the population (LC50) for different species of larval fishes and shrimps exposed to BDF varies from 122 ppm to 736 ppm. Meanwhile, that of petrodiesel, ranges from 2.9 ppm to 39 ppm (Wedel 1999). This indicates that BDF has from 19 to 42 times less toxic than conventional diesel.

Another research from Institute of Arable Crop Research also demonstrates a noticeable stress reduced from fuel spills of BDF compare to that of petrodiesel. For example, at the dose rate of 1.25g liter^{-1}, while the development of Lemma minuta (least duckweed) was completely stopped in petrodiesel, it could remain 60% in biodiesel. Regarding impacts on mortality rate and weight loss of aquatic species, BDF also presented remarkable improvement (Birchall, Newman, and Greaves 1995).

Table 4.4 Expected emissions from vegetable oil-based biodiesel system by unit process adapted from (Sheehan et al. 1998; GenSolutions 2007; CalEPA 2011)

Stage of life cycle	Inputs	Emissions to air	Emissions to water	Emissions to soil	Releases of products
Biodiesel feedstock agriculture	N:P:K fertilizers Pesticides Composts Electricity Plastic bags Petrodiesel fuel Water	$CO_{2fossil}$, $CO_{2biomass}$[a], methane (CH_4), dinitrogen monoxide (N_2O), carbon monoxide (CO), unburnt hydrocarbon (HC), volatile organic compounds (VOCs), total particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x)[b], ammonia (NH_3), polyaromatic hydrocarbon (PAHs)	Agricultural chemicals, BOD5, COD, metals, ammonia (NH_4+, NH_3 as N), nitrates	Solid wastes (hazardous & non-hazardous)	-
Feedstock transportation	Petrodiesel fuel	$CO_{2fossil}$, CH_4, N_2O, CO, HC, VOCs, Total PM, SO_2, NO_x, NH_3, PAHs	BOD5, COD, metals, ammonia (NH_4+, NH_3 as N), nitrates	Solid wastes (hazardous & non-hazardous)	-
Dehusking & oil extraction	Fruits Hexane Ethyl acetate Water Electricity Natural Gas	$CO_{2fossil}$, CH_4, N_2O, CO, HC, VOCs, Total PM, SO_2, NO_x, NH_3, PAHs	BOD5, COD, metals, ammonia (NH_4+, NH_3 as N), nitrates	Solid wastes (hazardous & non-hazardous)	-
BDF Production	Jatropha crude oil Methanol Sulfuric acid KOH Acetonitrile Acetone Water Electricity	[Total PM, SO_2, NO_x, VOCs, CO, Lead, HAPs (methanol)][c]	Waste water	NA	BDF leaks
BDF & petrodiesel blending	Petrodiesel fuel Electricity	NA	NA	NA	BDF and Petrodiesel leaks
BDF and its blends transportation	Petrodiesel fuel Electricity	$CO_{2fossil}$, CH_4, N_2O, CO, HC, VOCs, Total PM, SO_2, NO_x, NH_3, PAHs	BOD5, COD, metals, ammonia (NH_4+, NH_3 as N), nitrates	Solid wastes (hazardous & non-hazardous)	BDF blend leaks & spills
BDF and BDF blends combustion [d]	BDF blends	-CO_2, -PM, -CO, -VOCs, -HC, -SO_2, +NO_x, +CH_4, PAHs			BDF blend leaks & spills

Organic waste collection	Petrodiesel fuel	$CO_{2fossil}$, CH_4, N_2O, CO, HC, VOCs, Total PM, SO_2, NO_x, NH_3, PAHs	BOD5, COD, metals, ammonia (NH_4+, NH_3 as N), nitrates	Solid wastes (hazardous & non-hazardous)	-
Composting	Organic wastes Water	CH_4, N_2O	NA	NA	-
Compost transportation and distribution	Petrodiesel fuel	$CO_{2fossil}$, CH_4, N_2O, CO, HC, VOCs, Total PM, SO_2, NO_x, NH_3, PAHs	BOD5, COD, metals, ammonia (NH_4+, NH_3 as N), nitrates	Solid wastes (hazardous & non-hazardous)	-
Compost use as an alternative to chemical fertilizer	Composts	Benefits of applying compost includes: - Increase soil carbon storage: 0.256 $MTCO_{2eq}$ per ton of feedstock - Decrease water use: - 1.633 ton of water per ton of compost used in one year - Decrease soil erosion: - 95.028 kg of soil per ton of compost used in one year - Decrease herbicide use: an assumption of 100% replacement			

[a] Carbon dioxide absorbed by the plant.

[b] NO_x includes nitrogen dioxide, nitrogen oxide, and nitrogen oxides.

[c] Emissions from BDF production facilities within BDF plant.

[d] Differences in the amount of exhaust emissions from BDF blend-used engine in comparison with petrodiesel-used engine. (-) means probable decrease; and (+) means probable increase.

4.5.3.3 Toxicity in soil

(Lapinskiene, Martinkus, and Rebždaite 2006) in their study on assessing the different in eco-toxicity potential between biodiesel and petrodiesel fuel in aerated soil found out that up to 12% (by weight) of concentration, BDF has no toxic impacts, while petrodiesel fuel is toxic at 3% of concentration (by weight) (Lapinskiene, Martinkus, and Rebždaite 2006).

4.5.3.4 Examples of life cycle cost inventory

Following life cycle costing approach, total life cycle costs of biodiesel system include one-time investment costs and annual costs.

Table 4.5 shows main common costs of biodiesel system. Capital costs of BDF production's life cycle is a one-time investment including costs of land-use area, plant construction, storage and process facilities and equipment, utility equipment, installation cost, and other relevant costs. Operating costs are an annual payment for labors, utilities, require materials for the BDF production, and other supplementation costs.

4.6 CONCLUDING REMARKS

In this first part of the study, a methodological framework for the estimation of Triple I has developed based on the context of LCSA. Under the framework, the equation of Triple I was adapted to the new conversation factors where both human health and ecosystem quality impacts are monetarized first, then converted to global hectare together with the LCC data. Overall, this framework can promote the application of Triple I in biofuel field as it provides several proper methods for the estimation and suggests various scenarios needed to be taken into account in case of biofuel use. Furthermore, this study also head to a new application of Triple I, so-call Triple I payback. Triple I payback denotes the recovery period for a total burden of the studied system. Part II of this study will demonstrate the application of this framework in case of biodiesel.

Table 4.5 Sample inventory of life cycle cost of vegetable oil-based biodiesel system adapted from Lisboa et al. (2014), Yaakob et al. (2013), Haas et al. (2006) & Woodward (1997)

Item	Description
Initial capital costs	One-time investment
Preliminary cultivation cost	Payment for sowing seeds, seedling practices and post-cultivation soil preparation regarding perennial feedstocks
Fixed capital	Purchases costs of storage facilities, process equipment, utility equipment
Installation cost	Cost of plant construction, machinery installation, and worker training
Indirect costs	Costs of licenses and engineering
Operating and maintenance costs	Annual costs
Raw material costs	Costs of input materials for every stage including their transportation
Labor costs	Manpower for the operation, maintenance, supervisory, and fringe benefits
Utilities cost	Costs of electricity, cooling water, and steam
Waste treatment	Costs for wastewater and solid waste treatment
General works	Costs of administration, property taxes, property insurance
Supply costs	Maintenance supplies and operating supplies
Depreciation	Discount rate of return
Payback period	Necessary period to recover initial investment costs
Benefits	Prices of biodiesel and co-products

REFERENCES

Achten, Wouter. 2010. "Sustainability Evaluation of Biodiesel from Jatropha Curcas L . A Life Cycle Oriented Study." University of Leuven.

Agarwal, a. K., and L. M. Das. 2001. "Biodiesel Development and Characterization for Use as a Fuel in Compression Ignition Engines." *Journal of Engineering for Gas Turbines and Power* 123 (2): 440. doi:10.1115/1.1364522.

Ahlroth, Sofia, and Göran Finnveden. 2011. "Ecovalue08-A New Valuation Set for Environmental Systems Analysis Tools." *Journal of Cleaner Production* 19: 1994–2003. doi:10.1016/j.jclepro.2011.06.005.

Atabani, A. E., A. S. Silitonga, H. C. Ong, T. M I Mahlia, H. H. Masjuki, Irfan Anjum Badruddin, and H. Fayaz. 2013. "Non-Edible Vegetable Oils: A Critical Evaluation of Oil Extraction, Fatty Acid Compositions, Biodiesel Production, Characteristics, Engine Performance and Emissions Production." *Renewable and Sustainable Energy Reviews* 18. Elsevier: 211–45. doi:10.1016/j.rser.2012.10.013.

Birchall, Caroline, Jonathan R Newman, and Michael P Greaves. 1995. "Degradation and Phytotoxicity of Biodiesel Oil."

Bluhm, Kerstin, Sebastian Heger, Thomas-Benjamin Seiler, Arnold V. Hallare, Andreas Schäffer, and Henner Hollert. 2012. "Toxicological and Ecotoxicological Potencies of Biofuels Used for the Transport Sector—a Literature Review." *Energy & Environmental Science* 5 (6): 7381. doi:10.1039/c2ee03033k.

BP. 2016. "BP Energy Outlook 2016: Outlook to 2035." doi:10.1017/CBO9781107415324.004.

CalEPA. 2011. "Method for Estimating Greenhouse Gas Emission Reductions From Compost From Commercial Organic Waste." California, USA.

Charman, Nick, Nigel Edmonds, Marika Egyed, and Mathieu Rouleau. 2012. *Human Health Risk Assessment for Biodiesel Production, Distribution and Use in Canada*. Ottawa: Health Canada.

Dalal, Koustuv, and Leif Svanström. 2015. "Economic Burden of Disability Adjusted Life Years (DALYs) of Injuries." *Health* 7: 487–94. doi:10.4236/health.2015.74058.

Davis, Megan, Regina Coony, Scott Gould, and Allan Daly. 2005. *Guidelines for Life Cycle Cost Analysis*. Standford: Stanford University. doi:10.1080/15732470701322818.

Desaigues, B., D. Ami, A. Bartczak, M. Braun-Kohlová, S. Chilton, M. Czajkowski, V. Farreras, et al. 2011. "Economic Valuation of Air Pollution Mortality: A 9-Country Contingent Valuation Survey of Value of a Life Year (VOLY)." *Ecological Indicators* 11. Elsevier Ltd: 902–10. doi:10.1016/j.ecolind.2010.12.006.

Duan, Fengjun, Hajime Yamaguchi, and Makoto Kawabuchi. 2011. "Inclusive Environmental Impact Assessment for Water Purification Technologies." In *Proceedings of the Twenty-First (2011) International Offshore and Polar Engineering Conference*, 1:818–25. Maui, Hawaii: International Society of Offshore and Polar Engineers (ISOPE).

Eason, Tarasha, David E Meyer, Mary Ann Curran, and Venkata K K Upadhyayula. 2011. “Guidance to Facilitate Decisions for Sustainable Nanotechnology.” Cincinnati.

EC. 2010. *ILCD Handbook: Analysis of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment*. Ispra: European Comission, Joint Research Centre, Institute for Environment and Sustainability.

Elkington, J. 1998. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Conscientious Commerce. New Society Publishers. https://books.google.co.jp/books?id=dIJAbIM7XNcC.

Ewing, Brad, Anders Reed, Alessandro Galli, Justin Kitzes, and Mathis Wackernagel. 2010. *Calculation Methodology for the National Footprint Accounts, 2010 Edition*. *Global Footprint Network*. 2010thed. Oakland, CA: Global Footprint Network.

Fargione, Joseph, Jason Hill, David Tilman, Stephen Polasky, and Peter Hawthorne. 2008. “Land Clearing and the Biofuel Carbon Debt.” *Science* 319 (5867): 1235–38. doi:10.1126/science.1152747.

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O’Hare, and Daniel M. Kammen. 2006. “Ethanol Can Contribute to Energy and Environmental Goals.” *Science* 311 (5760): 506–8. doi:10.1126/science.1121416.

Finkbeiner, Matthias, Erwin M Schau, Annekatrin Lehmann, and Marzia Traverso. 2010. “Towards Life Cycle Sustainability Assessment.” *Sustainability* 2 (10): 3309. doi:10.3390/su2103309.

French-McCay, D. P. 2004. “Oil Spill Impact Modeling: Development and Validation.” *Environmental Toxicology and Chemistry* 23 (10): 2441–56. doi:10.1897/03-382.

GenSolutions. 2007. “Risk Assessment for Bioenergy Manufacturing Facilities in Alberta.” Admonton.

Ginn, Timothy R, Tyler J Hatch, Thomas E. McKone, and David W Rice. 2013. “California Biodiesel Multimedia Evaluation: Final Tier III Report.”

Haas, Michael J., Andrew J. McAloon, Winnie C. Yee, and Thomas A. Foglia. 2006. “A Process Model to Estimate Biodiesel Production Costs.” *Bioresource Technology* 97: 671–78. doi:10.1016/j.biortech.2005.03.039.

Hollebone, B.P., B. Fieldhouse, M. Landriault, K. Doe, and P. Jackman. 2008. “Aqueous Solubility, Dispersibility and Toxicity of Biodiesels.” In *International Oil Spill Conference Proceedings*, 2008:929–36. American Petroleum Institute. doi:10.7901/2169-3358-2008-1-929.

Hondo, Hiroki. 2005. “Life Cycle GHG Emission Analysis of Power Generation Systems: Japanese Case.” *Energy* 30 (11): 2042–56. doi:10.1016/j.energy.2004.07.020.

Huijbregts, Mark A.J., Stefanie Hellweg, Rolf Frischknecht, Konrad Hungerbühler, and A. Jan Hendriks. 2008. “Ecological Footprint Accounting in the Life Cycle Assessment of Products.” *Ecological Economics* 64 (4): 798–807. doi:10.1016/j.ecolecon.2007.04.017.

Huppes, Gjalt, Martijn van Rooijen, René Kleijn, Reinout Heijungs, Arjan de Koning, and Lauran van Oers. 2004. “Life Cycle Costing and the Environment.” Leiden, Netherlands.

IEA. 2015. *CO2 Emissions from Fuel Combustion Highlights*. 2015thed. Paris, France: International Energy Agency (IEA). doi:10.1787/co2-table-2011-1-en.

———. 2016. “Key World Energy Statistics.” http://www.iea.org/statistics/statisticssearch/.

ISO. 2006a. *Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040)*. Geneva, Switzerland: International Organization of Standardization.

———. 2006b. *Environmental Management - Life Cycle Assessment - Requirements and Guidelines (ISO 14044)*. Geneva, Switzerland: International Organization for Standardization.

Itsubo, Norihiro, and Atsushi Inaba. 2015. “LIME2 Life-Cycle Impact Assessment Method Based on Endpoint Modeling - Chapter 3 : Integration and Environment Impacts.” *JLCA News Letter*.

Itsubo, Norihiro, Masaji Sakagami, Koichi Kuriyama, and Atsushi Inaba. 2012. “Statistical Analysis for the Development of National Average Weighting Factors-Visualization of the Variability between Each Individual’s Environmental Thought.” *International Journal of Life Cycle Assessment* 17: 488–98. doi:10.1007/s11367-012-0379-x.

Jaichandar, S, and K Annamalai. 2011. “The Status of Biodiesel as an Alternative Fuel for Diesel Engine – An Overview.” *Carbon* 2: 71–75.

Jolliet, Olivier, Manuele Margni, Raphaël Charles, Sébastien Humbert, Jérôme Payet, and Gerald Rebitzer. 2003. “Presenting a New Method IMPACT 2002 + : A New Life Cycle Impact Assessment Methodology.” *International Journal of Life Cycle Assesment* 8 (6): 324–30. doi:10.1007/BF02978505.

Kloepffer, Walter. 2008. “Life Cycle Sustainability Assessment of Products.” *The International Journal of Life Cycle Assessment* 13 (2): 89. doi:10.1065/lca2008.02.376.

Lapinskiene, Asta, Povilas Martinkus, and Vilija Rebždaite. 2006. “Eco-Toxicological Studies of Diesel and Biodiesel Fuels in Aerated Soil.” *Environmental Pollution* 142 (3): 432–37. doi:10.1016/j.envpol.2005.10.023.

Leite, Maria Bernadete Neiva Lemos, Milena Maria Sampaio de Araújo, Iracema Andrade Nascimento, Andrea Cristina Santos da Cruz, Solange Andrade Pereira, and Núbia Costa do Nascimento. 2011. “Toxicity of Water-Soluble Fractions of Biodiesel Fuels Derived from Castor Oil, Palm Oil, and Waste Cooking Oil.” *Environmental Toxicology and Chemistry* 30 (4). John Wiley & Sons, Inc.: 893–97. doi:10.1002/etc.444.

Lin, David, Laurel Hanscom, Jon Martindill, Michael Borucke, Lea Cohen, Alessandro Galli, Elias Lazarus, et al. 2016. *Working Guidebook to the National Footprint Accounts: 2016 Edition*. Oakland: Global Footprint Network. http://www.footprintnetwork.org/images/article_uploads/NFA 2014 Guidebook 7-14-14.pdf.

Lisboa, Pedro, Ana Rita Rodrigues, José Luis Martín, Pedro Simões, Susana Barreiros, and

Alexandre Paiva. 2014. "Economic Analysis of a Plant for Biodiesel Production from Waste Cooking Oil via Enzymatic Transesterification Using Supercritical Carbon Dioxide." *The Journal of Supercritical Fluids* 85. Elsevier B.V.: 31–40. doi:10.1016/j.supflu.2013.10.018.

Luu, Phuong Duc, Hoa Thi Truong, Boi Van Luu, Lan Ngoc Pham, Kyoshi Imamura, Norimichi Takenaka, and Yasuaki Maeda. 2014. "Production of Biodiesel from Vietnamese Jatropha Curcas Oil by a Co-Solvent Method." *Bioresource Technology* 173. Elsevier Ltd: 309–16. doi:10.1016/j.biortech.2014.09.114.

Monfreda, C, M Wackernagel, and D Deumling. 2004. "Establishing National Natural Capital Accounts Based on Detailed Ecological Footprint and Biological Capacity Assessments." *Land Use Policy* 21 (3): 231–46. doi:10.1016/j.landusepol.2003.10.009.

Morris, R E, A K Pollack, G E Mansell, C Lindhjem, Y Jia, and G Wilson. 2003. "Impact of Biodiesel Fuels on Air Quality and Human Health: Summary Report." Novato, California.

National Research Council (U.S). 1975. *Petroleum in the Marine Environment*. Washington, DC: National Academy of Sciences.

NEEDS. 2006. "Intergrated Project. Deliverable D.4.2.-RS 1b/WP4: 'Assessment of Biodiversity Losses.'" http://www.needs-project.org.

Nguyen, T A, K Kuroda, and K Otsuka. 2015. "Inclusive Impact Index of Biodiesel Production and Cruise Ship Utilization." In *Proceedings of the Twenty-Fifth (2015) International Ocean and Polar Engineering Conference*, 1:1139–46. Kona, Big Island, Hawaii: International Society of Offshore and Polar Engineers (ISOPE).

Nunes, Paulo A L D, and Jeroen C J M van den Bergh. 2001. "Economic Valuation of Biodiversity: Sense or Nonsense?" *Ecological Economics* 39 (2): 203–22. doi:http://dx.doi.org/10.1016/S0921-8009(01)00233-6.

Omiya, Toshitaka, and Toru Sato. 2011. "A Proposal of Methodology to Calculate Triple I Intended for CO2 Ocean Sequestration." In *Proceedings of the Twenty-First (2011) International Offshore and Polar Engineering Conference*, 8:785–90. Maui, Hawaii: International Society of Offshore and Polar Engineers (ISOPE).

Ong, H C, T M I Mahlia, H H Masjuki, and Damon Honnery. 2012. "Life Cycle Cost and Sensitivity Analysis of Palm Biodiesel Production." *Fuel* 98: 131–39. doi:http://dx.doi.org/10.1016/j.fuel.2012.03.031.

Otsuka, Koji. 2011. "Inclusive Impact Index 'Triple I' and Its Application for Ocean Nutrient Enhancer." In *Proceedings of the Twenty-First (2011) International Offshore and Polar Engineering Conference*, 1:777–84. Maui, Hawaii, USA: International Society of Offshore and Polar Engineers (ISOPE).

Pizzol, Massimo, Bo Weidema, Miguel Brandão, and Philippe Osset. 2015. "Monetary Valuation in Life Cycle Assessment: A Review." *Journal of Cleaner Production* 86: 170–79. doi:10.1016/j.jclepro.2014.08.007.

Rajagopal, Deepak, and David Zilberman. 2007. "Review of Environmental, Economic and Policy Aspects of Biofuels." Policy Research Working Paper WPS4341. Policy Research

Working Paper. Washington, DC: World Bank.

Sheehan, John, Vince Camobreco, James Duffield, Michael Graboski, and Housein Shapouri. 1998. "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. Final Report." doi:10.2172/658310.

Simmons, C S, and J M Keller. 2003. "Status of Models for Land Surface Spills of Nonaqueous Liquids." Richland, Washington. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-14350.pdf.

Steen, Bengt. 1999. "A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000 - Models and Data of the Default Method." http://www.cpm.chalmers.se/document/reports/99/1999_4.pdf.

Takahashi, Tomoki, and Toru Sato. 2015. "Inclusive Environmental Impact Assessment Indices with Consideration of Public Acceptance: Application to Power Generation Technologies in Japan." *Applied Energy* 144. Elsevier Ltd: 64–72. doi:10.1016/j.apenergy.2015.01.053.

Thanh, Le Tu, Kenji Okitsu, Yasuhiro Sadanaga, Norimichi Takenaka, Yasuaki Maeda, and Hiroshi Bandow. 2010a. "A Two-Step Continuous Ultrasound Assisted Production of Biodiesel Fuel from Waste Cooking Oils: A Practical and Economical Approach to Produce High Quality Biodiesel Fuel." *Bioresource Technology* 101 (14). Elsevier Ltd: 5394–5401. doi:10.1016/j.biortech.2010.02.060.

———. 2010b. "Ultrasound-Assisted Production of Biodiesel Fuel from Vegetable Oils in a Small Scale Circulation Process." *Bioresource Technology* 101 (2). Elsevier Ltd: 639–45. doi:10.1016/j.biortech.2009.08.050.

Transportation Research Board and National Research Council. 2003. *Oil in the Sea III: Inputs, Fates, and Effects*. *Issues in Science and Technology*. Washington, DC: The National Academies Press. doi:10.17226/10388.

Traverso, Marzia, Matthias Finkbeiner, Andreas Jørgensen, and Laura Schneider. 2012. "Life Cycle Sustainability Dashboard." *Journal of Industrial Ecology* 16 (5): 680–88. doi:10.1111/j.1530-9290.2012.00497.x.

UNEP/SETAC. 2009. *Guidelines for Social Life Cycle Assessment of Products*. Edited by Catherine Benoît and Bernad Mazijn. Paris, France: UNEP/SETAC Life Cycle Initiative.

———. 2011. *Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products*. Edited by Sonia Valdivia, Cassia Maira Lie Ugaya, Guido Sonnemann, and Jutta Hildenbrand. Paris, France: UNEP/SETAC Life Cycle Initiative. http://www.unep.org/pdf/UNEP_LifecycleInit_Dec_FINAL.pdf.

Veisten, Knut, Hans Fredrik Hoen, Ståle Navrud, and Jon Strand. 2004. "Scope Insensitivity in Contingent Valuation of Complex Environmental Amenities." *Journal of Environmental Management* 73 (4): 317–31. doi:http://dx.doi.org/10.1016/j.jenvman.2004.07.008.

Vos, R.J. 2005. "Comparison of 5 Oil-Weathering Models."

Wedel, Randall von. 1999. "Technical Handbook for Marine Biodiesel In Recreational Boats." California. http://www.cytoculture.com/Biodiesel Handbook.htm.

Weidema, Bo, Miguel Brandão, and Massimo Pizzol. 2013. "The Use of Monetary Valuation of Environmental Impacts in Life Cycle Assessment: State of the Art, Strengths and Weaknesses."

Weidema, Bo Pedersen. 2009. "Using the Budget Constraint to Monetarise Impact Assessment Results." *Ecological Economics* 68 (6). Elsevier B.V.: 1591–98. doi:10.1016/j.ecolecon.2008.01.019.

Whitaker, Michael, and Garvin Heath. 2009. "Life Cycle Assessment of the Use of Jatropha Biodiesel in Indian Locomotives." Colorado, USA.

Woodward, David G. 1997. "Life Cycle Costing-Theory , Information Acquisition and Application" 15 (6): 335–44.

World Commission on Environment and Development. 1987. *Our Common Future*. Oxford; New York: Oxford University Press.

Yaakob, Zahira, Masita Mohammad, Mohammad Alherbawi, Zahangir Alam, and Kamaruzaman Sopian. 2013. "Overview of the Production of Biodiesel from Waste Cooking Oil." *Renewable and Sustainable Energy Reviews* 18. Elsevier: 184–93. doi:10.1016/j.rser.2012.10.016.

Yoshimoto, Haruki, Shigeru Tabeta, and Keiichiro Hakuta. 2010. "Inclusive Environmental Impact Assessment for Artificial Upwelling Technology Using Seabed Mound." *Journal of the Japan Society of Naval Architects and Ocean Engineers* 11: 221–27. doi:10.2534/jjasnaoe.11.221.

Yuzui, Tomohiro, and Fujio Kaneko. 2011. "Development of Cost Effectiveness Index of Oil Tankers Based on Triple I -Triple I of Oil Tanker-." In *Proceedings of the Twenty-First (2011) International Offshore and Polar Engineering Conference*, 1:791–98. Maui, Hawaii: International Society of Offshore and Polar Engineers (ISOPE).

Zhang, X, C Peterson, D Reece, Gregory Moller, and Randall Haws. 1998. "Biodegradability of Biodiesel in the Aquatic Environment." *Transactions of the ASAE* 41 (5): 1423–30. http://www.biodiesel.org/reports/19950601_mar-009.pdf.

Zhang, Y. I., Baral Anil, and Bhavik R. Bakshi. 2010. "Accounting for Ecosystem Services in Life Cycle Assessment Part II: Toward an Ecologically Based LCA." *Environmental Science and Technology* 44 (7): 2624–31. doi:10.1021/es900548a.

Equation Chapter (Next) Section 1

Chapter 5 - LIFE CYCLE-BASED INCLUSIVE IMPACT INDEX OF BIODIESEL UTILIZATION IN CRUISE SHIPS

5.1 INTRODUCTION

Biodiesel fuel (BDF) is widely considered to be an alternative energy source which is renewable and environmentally friendly (Eshton, Katima, and Kituyi 2013). Over the last decade, the production of biodiesel has increased gradually from just under 7 million liters per day in 2004 to almost 70 million liters per day in 2012 (U.S. Energy Information Administration 2015). The benefits of biodiesel are well recognized, such as greenhouse gas (GHG) emissions reduction, energy supply diversification and security, energy price stabilization, job creation, rural development (Rajagopal and Zilberman 2007), renewability, easy biodegradability, non-toxic and safer handling than fossil fuels (Agarwal and Das 2001). Several scholars, nevertheless, pointed out that producing and using biodiesel also have some disadvantages such as deforestation and biodiversity loss due to land-use change, net GHGs emission increase, non-climate-related environmental impacts such as soil erosion due to tilling, eutrophication due to fertilizer runoffs, impacts of exposure to pesticides, habitat, and not economical fuel source (Farrell et al. 2006; Rajagopal and Zilberman 2007). Biodiesel's returned profits and burden vary case by case. Therefore, to date researchers seldom stated that the application of biodiesel always brings net benefits.

In 2007, Vietnam has introduced a new Energy Development Scheme which planned to produce and use about 250 thousand metric tons ethanol 5% (E5) and biodiesel 5% (B5) and 1.8 million tons E5 and B5 by 2015 and 2025, respectively. Since then, several related researches and experiments have been conducted, in which there's a highly expected project is Multi-beneficial Measures for Mitigation of Climate Change in Vietnam and Indochina Countries by Development of Biomass Energy funded by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA), as one of the projects of Science and Technology Research Partnership for Sustainable Development (SATREPS) from 2011 to 2016 (hereinafter called SATREPS project). In this Project, a scenario was designed to develop a closed-loop system of BDF production and utilization, starting from oil plant cultivation to BDF end-use in Ha Long Bay, Quang Ninh Province, Vietnam. In the designed system, this Project supposed to solve the environmental problems and enhance the application of biodiesel supporting the economic development in Ha Long Bay.

As it was mentioned, BDF production and application can generate both benefits and handicaps. Thus, this study aimed to assess and evaluate impacts on the environment, energy balance and economics of some parts in BDF production and utilization chain proposed by SATREPS project. Since the assessment concentrates on three dimensions including environment, economics, and energy, an Inclusive Impact Index, so-call Triple I that was used for the calculation. Triple I was developed by a research group on Inclusive Marine Pressure Assessment and Classification Technology (IMPACT) in the Japan Society of Naval Architects and Ocean Engineers (JASNAOE) in 2006. This indicator consolidates ecological footprint (EF) analysis and environmental risk assessment to evaluate environmental sustainability and economic feasibility of the studied system.

5.2 MATERIALS AND METHODS

5.2.1 Study site

Ha Long Bay located in Quang Ninh Province (in the Gulf of Tonkin); Vietnam is one of the World Natural Heritage Sites and one of the New Seven Wonders of Nature (Fig. 5.1). It possesses a beautiful, unique seascape with more than 1,600 islands and islets, 90% of which are limestone. However, Ha Long Bay has recently to bear with several environmental problems caused by coal mining and tourism related activities. With regards to coal mining has led to the deforestation, forest degradation, soil erosion, abandoned mine lands and water pollution. On the other hand, approximately 600 cruise boats operating in Ha Long Bay consume about 21,600 kiloliters of fuel per year (Otsuka 2014). Uncollected solid wastes, wastewater discharge and fuel oil leakage from those boats and floating restaurants are other drivers of water quality degradation in this area. The production and utilization of BDF is considered an ideal solution for this area.

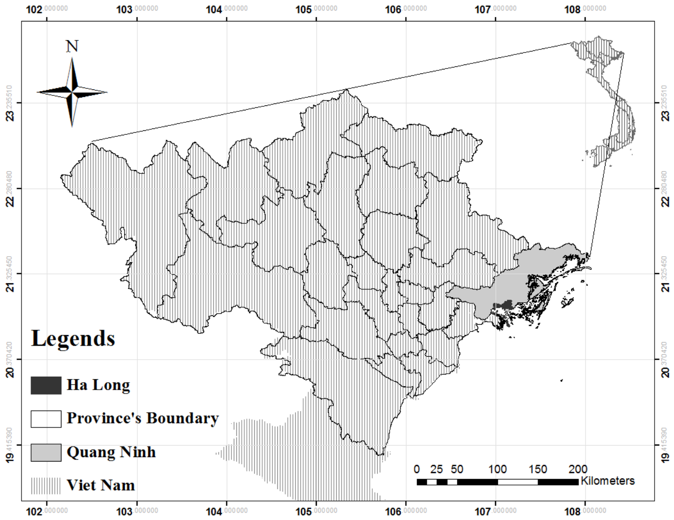


Fig. 5.1 Location of study area in the north region of Vietnam

5.2.2 System Boundary and System Description

A 'cradle-to-grave' system of BDF production and utilization supposed to be implemented in Ha Long Bay (Fig. **5.2**) comprises all the stages from Jatropha (*Jatropha curcas* L.) cultivation (1a), waste collection from floating village and restaurants and cruise boats (1b, 1c), feedstock and waste cooking oil delivery (2a, 2b), BDF production and blending (3), BDF distribution and utilization in cruise boats and a waste carrier boat (4a, 4b, 5a, 5c), to the application of compost from organic waste back in cultivation areas (6a, 6b, 7 and 8).

To develop an appropriate methodology for estimation of the total co-benefits of this system, this research firstly focus on the two core stages of the system (a gate-to-grave system) including the production of BDF from Jatropha oil (JCO) and waste cooking oil (WCO) and the application of BDF in cruise boats and the application of compost from organic waste (Fig. **5.2**: (3), (4a), (5a), (6a), (8)) as a case study for the estimation of the co-benefit of the whole system.

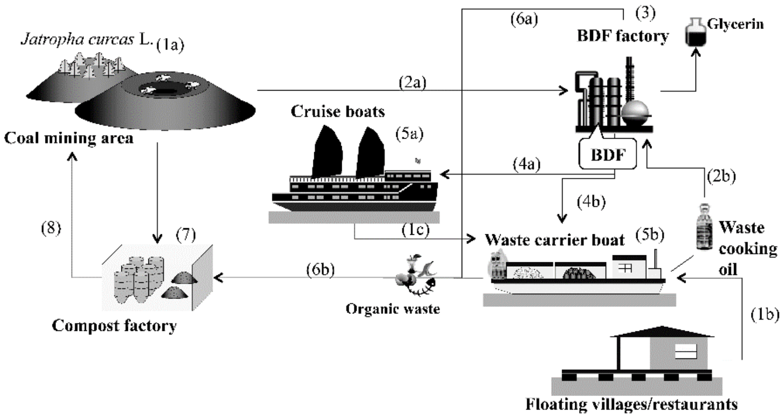


Fig. 5.2 Proposed BDF life cycle stages applied in Ha Long Bay

5.2.3 BDF Production Processes

BDF production from JCO. This study presents the examination in the BDF production from JCO (from now on called JCO-BDF) model developed in laboratory-scale experiments. The production of JCO-BDF encompasses two main stages including the esterification process and the transesterification process. Firstly, the esterification is performed using the molar ratio of methanol to free fatty acids (FFA) of 6:1, 1wt% H_2SO_4, 65°C, and co-solvent is 30% (wt/wt) acetonitrile. Then, the transesterification is managed under the conditions of 6:1 methanol-to-oil molar ratio, 1wt% KOH, 40°C, and 20% (wt/wt) acetone as co-solvent. With the completion of these steps, we obtained qualified BDF with a 99% fatty acid methyl esters (FAME) yield, a 0.23% FFA content, and an 187 mg/kg water content (Luu et al. 2014; Maeda et al. 2011). Whole processes and material input/output flows of JCO-BDF production are presented in Fig. 5.3.

Table 5.1 summarizes the inputs and outputs of the BDF production from JCO system. Data were collected from literature and expert consultation in January, 2015. To enable the later computation, the data were calculated and listed relevant to one kg BDF production.

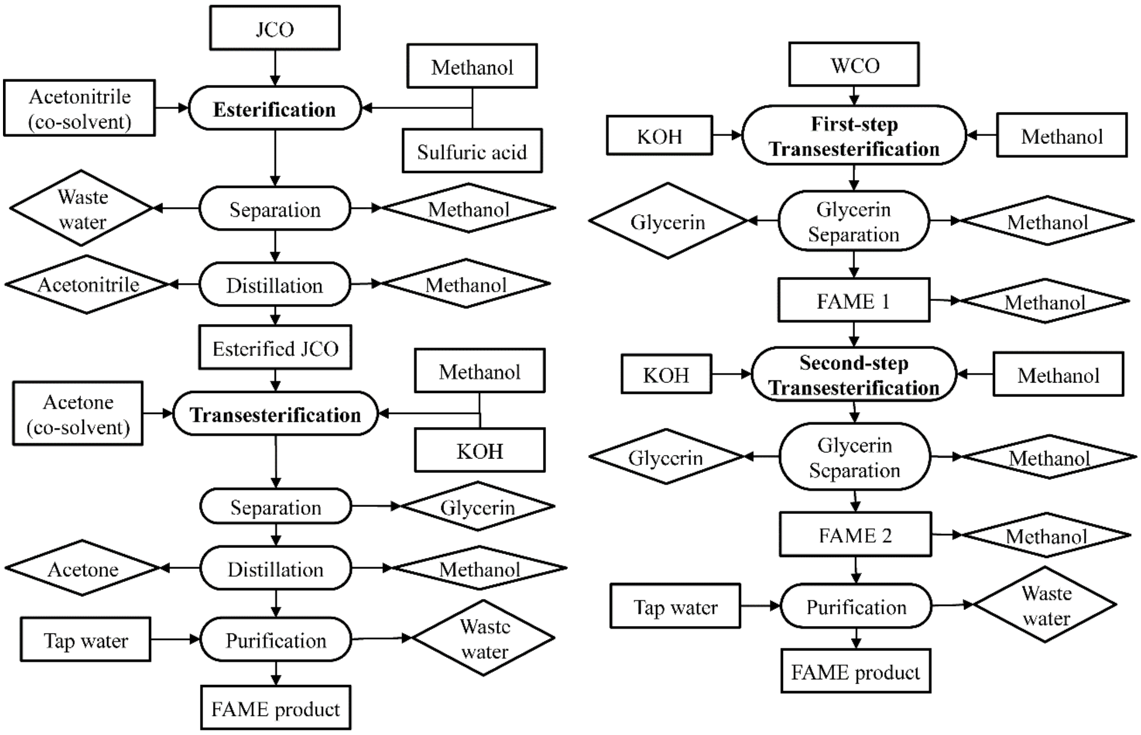


Fig. 5.3 Production of BDF from JCO and WCO adapted from Luu et al. (2014) and Thanh et al.(2010)

Table 5.1 Inventory data of 1 kg BDF production from Jatropha fruit[a]

Compounds (unit)	Input	Output	Total input
Fruit (kg)[b]	6.753		6.753
Petrodiesel (MJ)[b]	0.625		0.625
Electricity (kWh)[b]	0.650		0.650
JCO (kg)	1.111		1.111
Acetonitrile (kg)	0.333	0.300	0.033
Acetone (kg)	0.200	0.160	0.040
Methanol (kg)	0.343	0.170	0.173
Sulfuric acid (kg)	0.011		0.011
KOH (kg)	0.010		0.010
Electricity (kWh)	0.051		0.051
Water (kg)	0.300		0.300
Biodiesel (kg)		1.000	
Glycerin (kg)		0.106	
Seed coat &Seedcake (kg)[b]		5.520	
Wastewater (kg)		0.322	

[a] Own computation basing on (Luu et al. 2014) and expert interviews in 2015.
[b] Data adapted from (Abebe 2013).

BDF production from waste cooking oil (WCO). The data used for the system of generating BDF from WCO (hereinafter called WCO-BDF) were taken from the pilot plant-scale research. An ultrasound-assisted two-step process is applied to generate BDF from WCO. In the first step, a methanol-to-WCO molar ratio of 2.5:1 and 0.7 wt% KOH are used for the transesterification. For the second-step transesterification, the process is conducted with the molar ratio of methanol to initial WCO of 1.5:1 and 0.3 wt% KOH. The FAME yields of the first and second step are 81% and 99%, respectively. Ultrasonic reactor is used and the glycerin separation is carried out in both steps. The final BDF acquired meet with the standards JIS K2390 and EN 14103. WCO-BDF production model and material input/output flows are outlined in Fig. 5.3.

The list and quantity of inputs and outputs for producing BDF from WCO are synopsized in Table 5.2. Data were collected from literature and recalculated for one kg of BDF production.

Table 5.2 Inventory data of 1 kg BDF production from WCO adapted from (Thanh et al. 2010)

Compounds (unit)	Input	Output	Total input
WCO (kg)	1.066		1.066
Methanol (kg)	0.156	0.039	0.117
KOH (kg)	0.011		0.011
Electricity (kWh)	0.089		0.089
Water (kg)	0.639		0.639
Biodiesel (kg)		1.000	
Glycerin (kg)		0.145	
Wastewater (kg)		0.671	

5.2.4 BDF/Petrodiesel Blending and Transportation

According to the designed system for the BDF production, BDF and petrodiesel are blended within the BDF factory, and the final blended will be distributed for utilization in cruise boats afterward. Baseline input data of this stage were derived from literature; in which required electric power per one ton of blended fuel is 8.7 kWh (Paz and Vissers 2011), and consumed petrodiesel fuel per ton-km blended fuel transportation is 0.023 kg (*BioGrace* 2012). Since the BDF plant has been supposed to be located in Quang Ninh Province, we assumed the maximum distance of the BDF distribution is 50 km.

5.2.5 BDF Utilization

In this stage, our research aimed to estimate the total potential emissions of greenhouse gases (GHGs) from utilizing BDF in cruise ships in Ha Long Bay. Several previous studies on exhaust emissions of diesel engines using BDF have been carried out. Main gases have been highlighted from the utilization of BDF including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), hydrocarbons (HC), and particulate matter (PM) emissions, and these emission rates are varied depending on biofuel sources and volume % biodiesel in biodiesel/petrodiesel blended fuel (EPA 2002; Jayaram et al. 2009; Lin, Wu, and Chang 2007; Zhu et al. 2010). In comparison with conventional diesel, evidences show that impacts of utilizing BDF on exhaust gases are as follow: CO, HC, and PM decreased by more than 10%, concurrently, NO_x increased by more than 1% (EPA 2002; Jayaram et al. 2009). Nevertheless, due to the variation of the difference in the amount of CO_2 emissions between conventional diesel and BDF, recent studies could not assertively conclude the effect of BDF on CO_2 emissions (EPA 2002). Since our research focused on ecological footprint of BDF utilization, we only assessed data about CO_2 emission of diesel engines used different biodiesel/petrodiesel blended fuel. These data were provided by experts from SATREPS project (Fig. 5.4).

According to (Otsuka 2014), total number of overnight cruise ships and day cruise ships operating in Ha Long Bay in 2013 were 190 and 337, respectively. They consumed about 21,611 kl conventional diesel per year. Due to approximate ten-percent-lower energy content of BDF to conventional diesel (EPA 2002; Otsuka 2014), the CO_2 emissions estimation was applied to 21,611 kl conventional diesel and to 23,772.1 kl BDF. The emission factor of CO_2 from conventional diesel fuel used was 2.67 kg liter^{-1} (EPA 2005).

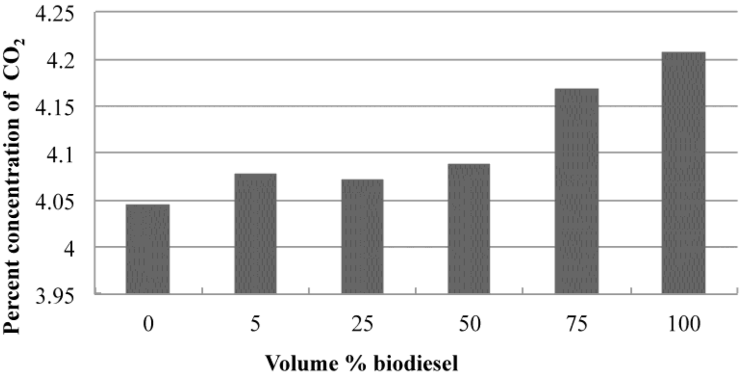


Fig. 5.4 Biodiesel impacts on CO_2 emissions

5.2.6 Inclusive Impact Assessment

Triple I. To evaluate co-benefits of the selected processes, an integrated method using life-cycle assessment approach to estimate the Inclusive Impact Index (Triple I) was chosen. Triple I can be obtained by subtracting biocapacity (*BC*) and generated benefits (*B*) from total ecological footprint (*EF*), ecological risk (*ER*), human risk (*HR*) and costs (*C*) caused by the system (Eq. 4.15) (Otsuka 2011; Yoshimoto and Tabeta 2011).

$$III = EF - BC + \alpha[(C - B) + \beta HR + \gamma ER] \quad \text{[gha]} \quad \text{(Eq. 4.15)}$$

where α, β and γ are the conversion factor from economic value to ecological footprint value (gha) and from *HR* and *ER* to economic value, respectively.

Triple I light and Triple I light star. In a study using Triple I for the assessment of an ocean nutrient enhancer, (Otsuka 2011) suggests that due to the lower accuracies of *ER* and *HR* to other parameters, such as *EF*, *BC*, *C* and *B*, and their on-going development of methodology, a simple Triple I (Triple I light) could be applied (Eq. 5.1).

$$III = EF - BC + \alpha(C - B) \quad \text{[gha]} \quad (5.1)$$

Moreover, the ratio between adverse impacts and biocapacity and benefits (Triple I_{light}^{*}) of the studied system is one interest of policy makers (Eq. 5.2) (ibid.).

$$III_{light}^{*} = \frac{EF + \alpha C}{BC + \alpha B} \quad (5.2)$$

Several scholars have applied the ratio of *EF* to *GDP* of the country where the studied system is implemented, as the conversion factor α (Otsuka 2011; Yoshimoto and Tabeta 2011). Therefore, in this study α was calculated as follow:

$$\alpha = \frac{EF_{Vietnam}}{GDP_{Vietnam}} = \frac{1.206\,\mathrm{x}\,10^{8}}{7.741\,\mathrm{x}\,10^{10}} = 1.557\,\mathrm{x}\,10^{-3} \quad (5.3)$$

where $1.206\mathrm{x}10^{8}$ [gha] is the EF of Vietnam in 2007 (Global Footprint Network 2010), and $7.741\mathrm{x}10^{10}$ [US \$ year^{-1}] is GDP of Vietnam in 2007 (World Bank 2015).

With regards to ecological footprint, costs and benefits of the system were estimated based on the collected data of all input and output material, energy and emissions of the BDF production, blending, transportation and utilization (Table 5.1 & Table 5.2). Ecological footprint was computed by combining sum of GHG emissions from the production of input material and sum of GHG emissions from total energy used. Ecological footprint for the GHG emissions (EF_{CO2}) of products is calculated as follows:

$$EF_{CO_2} = P_{CO_2} \times \left(\frac{1 - S_{Ocean}}{Y_{CO_2}}\right) \times EqF_f \; (5.4)$$

where P_{CO2} is annual emissions of CO_2, S_{Ocean} is the fraction of CO_2 absorbed by oceans, Y_{CO2} is the sequestration rate of CO_2 by biomass, and EqF_f is equivalence factor of forests (Ewing et al. 2010; Wackernagel et al. 2005). In this research, we applied $S_{Ocean} = 0.3$, $Y_{CO2} = 0.4$ kgCO$_2$ m^{-2} (Wackernagel et al. 2005), and $EqF_f = 1.26$ gha ha^{-1} (Ewing et al. 2010).

Crop yield increases when replacing chemical fertilizer with de-oiled Jatropha cake from JCO production (Chaturvedi and Kumar 2012; Pandey et al. 2012; Wani et al. 2014). Therefore, biocapacity was calculated as the required area of cultivation land to obtain equivalent potential surplus crop yield. The application of Jatropha seed cake can increase crop yield ranging from 7.37% (wheat) (Carels, Sujatha, and Bahadur 2012) to 8.28% (Maize) (Wani et al. 2014). In this research, we used the mean value from those studies, 8%, as the percentage of yield increased. The dose of 120 kg chemical fertilizer per ha cultivation is recommended concerning the best yield (Carels, Sujatha, and Bahadur 2012; Wani et al. 2014). Using one kg of Jatropha seedcake in soil is equivalent to applying 0.15 kg of N:P:K (40:20:10) mineral fertilizer (Openshaw 2000), thus, total Jatropha seedcake required for one ha cultivation is

120/0.15 = 800kg. Biocapacity for cropland is calculated as follow (Ewing et al. 2010; Wackernagel et al. 2005):

$$BC = A_{cr} \times YF_{cr} \times EqF_{cr} \qquad [\text{gha}] \quad (5.5)$$

where A_{cr} is the area of cropland (ha) needed to obtain equivalent surplus crop, and YF_{cr} is yield factor of cropland and EqF_{cr} is equivalence factor of cropland. In this research, we used EqF_{cr} = 2.51 gha ha^{-1} (Ewing et al. 2010). A_{cr} was calculated as follow:

$$A_{cr} = \frac{M_{JS}}{800} \times 8\% \qquad [\text{ha}] \quad (5.6)$$

where M_{JS} is total Jatropha seed cake obtained. Yield factor of cropland of Vietnam was calculated as follow (Ewing et al. 2010):

$$YF_{cr} = \sum_{i \in U} \frac{P_i}{Y_w} \Big/ \sum_{i \in U} \frac{P_i}{Y_{VN}} \qquad (5.7)$$

where P_i is the total national growth of crop i, Y_w and Y_{VN} are world and Vietnam yields, respectively. Data for this calculation was obtained from (FAOSTAT 2015).

5.3 RESULTS AND DISCUSSION

5.3.1 Estimation of Input-output GHG Emissions, Energy Used and Costs of BDF Production

All direct and indirect energy input and output, direct and indirect GHG emissions and cost and benefits generated throughout the production and blending of JCO-WCO-BDF, and distribution to and utilization in cruise ships in Ha Long Bay are shown in Tables 3~6. Indirect energy means energy needed to produce all inputs and outputs for the system. Direct energy means energy used for the production, for example, consumed petrodiesel, electricity, and fuel. Indirect GHG emissions are emissions generated from the production of inputs and outputs of the studied system. Direct GHG emissions are gasses emitted from the production, transportation, and utilization of BDF.

In this study, we considered two options for making BDF including from JCO and WCO. The production of BDF resulted in GHG emissions, energy gain and potential revenue (Table

5.3 & Table 5.4). The effects and requirements of JCO-BDF production and WCO-BDF production are noticeably different from each other. GHG emissions from the JCO-BDF production are approximately three times higher than WCO-BDF. However, it was interesting that the remarkable net energy gain and revenue of JCO-BDF production about six times and nine times was shown more than that of WCO-BDF production, respectively. The factor contributed more than 45% to the gross energy generated from JCO-BDF production was seed coat and seedcake derived from the JCO extraction.

Then, as fertilizing the Jatropha cultivation field, seed coat and seedcake presented high potential of biocapacity enhancement. As shown in Table 5.1, about 5.5 kg seed coat and seedcake are derived from the production of 1 kg JCO-BDF from 6.8kg Jatropha fruit. Moreover, 800 kg seed coat and seed cake could fertilize 1 ha cultivation area (refer to method and materials session for more information). Annually, one ha cultivated Jatropha yields about 2,500 kg fruit (Heller 1996; Tewari 2007). Integrating those data, it is important to note that seed coat and seedcake obtained from one kg JCO-BDF production can support the next production of about 2.6 kg JCO-BDF. This result can explain and support for the result of Triple I light star later.

Concerning GHG emissions in exhaust gas from cruise ships using BDF (), the exact data on total CO_2 emitted from diesel engine utilizing biodiesel were used to calculate Triple I light and Triple I light star. To acquire real impacts of the studied system, we did not apply the carbon neutral principle for exhaust gasses from cruise ships. Carbon absorption potential of Jatropha cultivation to BDF production and utilization chain will be assessed separately in our future research.

Table 5.3 Summary of GHG emissions, energy consumption and costs of 1 metric ton JCO-BDF production[a]

Compounds	GHG emissions ($kgCO_2eq$)	Energy equivalent input (GJ)	Cost[l] (US $)
Petrodiesel[f]	54.804	0.725	18.760
Electricity[f]	366.633	[d]6.504	[g]46.175
Acetonitrile	-	-	[h]166.667
Acetone	[c]96.8	[c]2.588	[h]180
Methanol	341.909	5.698	[h]86.278
Sulfuric acid	2.308	0.043	[h]5.778
KOH	19.263	[b]0.199	[h]12

Electricity	28.914	[d]0.513	[g]3.642
Water	[e]0.09	[b]0.003	0.150
Biodiesel	-	[d]-37.300	[j]-888
Glycerin	-	[d]- 2.708	[i]-58.178
Seed coat &Seedcake[f]	-	[d]-34.336	[k]-318.928
Wastewater	[e]0.045	-	0.093
Total	910.766	-58.07	-745.563

[a]Own computation based on literature mostly from (*BioGrace* 2012). [bcdef]Adapted from (ISCC 2011; Mohammadshirazi et al. 2014; Prueksakorn et al. 2010; Wu et al. 2008; Abebe 2013). [g]Price of production electricity from Vietnam Ministry of Industry and Trade in 2014. [hi]Price of chemicals and crude Glycerin from Alibaba.com website (2015). [j]Price of biodiesel in Asia in 2013: US $ 0.888/kg. [k]Calculated basing on price of NPK fertilizer from Binh Dien Fertilizer Joint Stock Company in 2014. [l]Minus value of energy input and cost mean energy equivalent and potential benefit generated from the production.

Table 5.4 Summary of GHG emissions, energy equivalent and costs of 1 metric ton WCO-BDF production[a]

Compounds	GHG emissions (kgCO$_2$eq)	Energy equivalent input[b] (GJ)	Cost[b] (US $)
WCO	-	[c]26.644	[d]806.788
Methanol	231.869	3.864	58.510
KOH	20.530	[c]0.212	12.789
Electricity	50.168	0.890	6.318
Water	0.192	[c]0.006	0.320
Biodiesel	-	-37.300	-888
Glycerin	-	- 3.708	-79.660
Wastewater	0.094	-	0.195
Total	302.852	-9.392	-82.740

[a]Own computation based on literature presented in Table 3. [b]Minus value of energy input and cost mean energy equivalent and potential benefit generated from the production. [c]Adapted from (Mohammadshirazi et al. 2014). [d]1 kg waste cooking oil costs US $0.757 (Bui et al. 2014).

Table 5.5 Summary of GHG emissions, energy consumption and costs for blending biodiesel/petrodiesel provided to cruise ships[a]

Vol. % BD	Total mass (ton)	Electricity (kWh)	GHG emissions (tCO$_2$eq)	Energy input (GJ)	Cost (US $)
0	17,937	-	-	-	-
5	19,790	172,175	27	1,722	12,224
25	20,028	174,244	27	1,742	12,371
50	20,325	176,829	28	1,768	12,555
75	20,622	179,414	28	1,794	12,738
100	20,919	-	-	-	-

[a]The calculation was applied to 21,611 kl petrodiesel and 23,772 kl biodiesel/petrodiesel blended in different rate. Density of biodiesel equivalent to 0.88 kg/l and of petrodiesel equivalent to 0.83 kg/l were applied (European Biofuels Technology Platform 2011).

Since JCO-BDF and WCO-BDF were supposed to be utilized together in Ha Long Bay, it is worth to examine how much we should produce and their proportion in total BDF used. The determination could base on their net effects in both environment and economics. Therefore, three scenarios were developed in which the production rate of the two types of BDF were as follow: Scenario 1 (S1): 5% WCO-BDF and 95% JCO-BDF; Scenario 2 (S2): 10% WCO-BDF and 90% JCO-BDF; Scenario 3 (S3): 15% WCO-BDF and 85% JCO-BDF. Due to the limited amount of WCO in Ha Long Bay, the scenario for a higher rate of WCO was not developed (Table 5.7).

Table 5.6 Summary of GHG emissions, energy consumption and costs for biodiesel/petrodiesel distribution and utilization in cruise ships[a]

Vol. % BD	[b]GHG emissions (tCO_2eq)	Energy equivalent input (GJ)	Cost (US $)	Biodiesel (ton)	[c]GHG emissions (tCO_2)
0	4,090	53,063	25,733	-	57,701
5	4,513	58,545	28,392	1,046	64,176
25	4,567	59,249	28,733	5,230	64,828
50	4,635	60,128	29,159	10,460	66,060
75	4,703	61,007	29,586	15,690	68,355
100	4,770	61,886	30,012	20,919	69,993

[a]The calculation was applied to the transportation of 21,611 kl petrodiesel and 23,772 kl biodiesel/petrodiesel. Data of truck for liquid transportation (capacity 2ton) is used: Fuel efficiency: 1.01MJ/t.km; transport exhaust gas emissions 0.005 gCH_4/t.km (*BioGrace* 2012). Transportation distance was set to 50 km. [b]Total GHG emission from transportation of fuel including exhaust gasses from truck and emission factor of the used petrodiesel. [c]Potential exhaust gasses from cruise ships using BDF.

5.3.2 Triple I Light and Triple I Light Star Calculation

Calculated results. Using on Eqs.5.1 ~5.7, ecological footprint and biocapacity were calculated to estimate the value of Triple I light and Triple I light star in the three scenarios (Tables 8~10). In all three scenarios, the value of Triple I light was not a minus number and of Triple I light star was more than 1, except B100 case. These results mean this system is mostly unsustainable, unless the B100 was utilized. In the three scenarios, the data indicated a growing biocapacity when changing the application from 5% BDF (B5) to 100% BDF (B100). This increase of biocapacity could lessen the gap between the higher costs and the lower benefits of BDF production (both environmental and economic aspects), which resulted in decreasing value of Triple I light and Triple I light star from B5 to B100 in all three scenarios. Regarding B100 in all three scenarios, it was considerable to note that Triple I light had minus value and Triple I light star was less than 1. These results showed sustainability potential for the application of B100. Furthermore, comparing to B25, B50, B75 and B100, B5 had more than eight times smaller potential to become sustainable and its net production energy was significantlyly lower than that other blends, even had minus value. Among the three scenarios, scenario 1 has the highest composition of JCO-BDF. As shown above, although JCO-BDF production emitted more GHG than WCO-BDF production, it brought greater revenue with higher potential of biocapacity increase. Furthermore, the more biodiesel blended, the greater sustainability potential BDF was. Thus, the application of high-blended JCO-BDF was particularly recommended.

Sensitivity analysis. Being based on vary situations and conditions, a sensitivity analysis was conducted to estimate which factors affect the most in Triple I light, Triple I light star and net energy of the BDF production. The factors under consideration included changes in the proportion of WCO-BDF and JCO-BDF, changes in the price of biodiesel, changes in fuel consumption, and changes in delivery distance of blended BDF, changes in the price of electricity (Fig. 5.5). The figure shows that triple I light values of all blends are affected by the change of BDF plant location (the distance of BDF distribution) (Fig. 5.5 (a)). Following the change from B5 to B100, the sensitivity of the system increased. Consequently, the B100 - system was significantly sensitive to all factors in the three scenarios and became unsustainable when distribution distance increased to 100km. When the price of biodiesel increased by 10%, the B75-system in scenarios 1 also became sustainable. Similarly, Triple I light star values of all BDF blends responded to the change in the distance of blended petrodiesel transportation (Fig. 5.5 (b)). B75 - system in scenario 1 and B100 - system also became sustainable and unsustainable with 10% increase in biodiesel price and 100 km increase in BDF distribution distance, respectively. Nevertheless, different from the Triple I light, the trend of Triple I light star responses to all factors was the same in different BDF blends.

Table 5.7 Summary of the total GHG emissions, net energy, and costs of the 3 scenarios

BDF		Scenario 1			Scenario 2			Scenario 3		
Vol. %	Total vol. (ton)	GHG emissions (tCO_2eq)	Net energy (GJ)	Revenue (US $)	GHG emissions (tCO_2eq)	Net energy (GJ)	Revenue (US $)	GHG emissions (tCO_2eq)	Net energy (GJ)	Revenue (US $)
5	1,046	69,636	-2,073	704,558	69,605	-4,619	669,893	69,573	-7,165	635,228
25	5,230	74,027	229,980	3,684,766	73,868	217,251	3,511,442	73,709	204,522	3,338,118
50	10,460	79,931	520,047	7,410,026	79,613	494,588	7,063,379	79,295	469,130	6,716,731
75	15,690	86,899	810,113	11,135,287	86,422	771,926	10,615,315	85,945	733,738	10,095,344
100	20,920	93,181	1,102,000	14,873,469	92,545	1,051,083	14,180,174	91,909	1,000,166	13,486,879

Assessing the movement of system net energy following the invested conditions in each scenario, it was rational why the further distance of fuel transportation and more fuel consumption in cruise ships significantly influence net energy (Fig. 5.5 (c)). Since the truck for fuel transportation uses petrodiesel to operate, it directly contributed to the total energy consumption of the system, thus leading to net energy decrease. As discussed earlier, the production of BDF generated high energy equivalent, especially JCO-BDF. The more fuel requirement means, the bigger BDF production needed. This would lead to more energy be generated.

5.4 CONCLUSIONS

In this study, we applied Triple I light, Triple I light star and net energy balance assessment to evaluate impacts and benefits of BDF production and utilization in cruise ships in Ha Long Bay. The results show that the BDF system in the studied stages is not sustainable (except the application of B100) but energy benefited. It is worth to note that with the higher net energy gain and economic revenue compare to WCO-BDF, JCO-BDF showed high potential as future energy for cruise ship in Ha Long Bay. However, this system need to be reconsidered about production structure and design to reduce the indirect adverse impacts on environment, in terms of GHG emissions from the production of chemicals and materials used, and increase revenue

Table 5.8 Triple I light and Triple I light star estimation in Scenario 1[a]

Vol. % BD	EF (gha)	BC (gha)	III_{light} (gha)	III_{light}^{*}	Net energy (GJ)
5	15,355	1.87	14,256	8	-2,073
25	16,323	9.34	10,576	2.04	229,980
50	17,625	18.68	6,069	1.30	520,047
75	19,161	28.02	1,796	1.06	810,113
100	20,546	37.36	-2,649	0.94	1,102,000

[a]Scenario 1: 5%WCO-BDF ; 95%JCO-BDF in total BDF production

Table 5.9 Triple I light and Triple I light star estimation in Scenario 2[a]

Vol. % BD	EF (gha)	BC (gha)	III_{light} (gha)	III_{light}^*	Net energy (GJ)
5	15,348	1.77	14,303	8.10	-4,619
25	16,288	8.85	10,812	2.07	217,251
50	17,555	17.70	6,539	1.32	494,588
75	19,056	26.55	2,501	1.08	771,926
100	20,406	35.40	-1,708	0.96	1,051,083

[a]Scenario 2: 10%WCO-BDF ; 90%JCO-BDF in total BDF production

Table 5.10 Triple I light and Triple I light star estimation in Scenario 3[a]

Vol. % BD	EF (gha)	BC (gha)	III_{light} (gha)	III_{light}^*	Net energy (GJ)
5	15,341	1.67	14,350	8.21	-7,165
25	16,253	8.36	11,047	2.11	204,522
50	17,485	16.72	7,010	1.35	469,130
75	18,951	25.07	3,207	1.11	733,738
100	20,266	33.43	-767	0.98	1,000,166

[a]Scenario 3: 15%WCO-BDF ; 85%JCO-BDF in total BDF production

Concerning the application of B5 in cruise ships, it should be planned thoroughly considering all factors may affect the system, especially the distribution scheme. Among biodiesel/petrodiesel blends, the potential of becoming sustainable fuel source B5 is the lowest and data about exhaust gasses of biodiesel provided by experts from SATREPS project (Fig. 5.4) present a lower CO_2 concentration of B25 than that of B5. Moreover, since 20 percent biodiesel blend was identified as optimum concentration of biodiesel, regarding higher thermal efficiency and exhaust emission reduction (Agarwal and Das 2001), our research suggests that Government of Vietnam should consider the application of B20 or B25 instead of B5. On the other hand, considering all three parameters including Triple I light, Triple I light star and net energy and three scenarios, high-blended JCO-BDF is needed to be contemplated. However, due to its high sensitivity, a comprehensive production and utilization plan is necessary.

It was noted that assessment and findings were made based on some parts in the chain of BDF production and utilization, which was supposed to start from Jatropha cultivation, the results from this research should thus be treated as a reference for further full chain research. Moreover, the main purpose of this paper was to develop and test methodology to evaluate the co-benefits of BDF production and utilization in cruise ships in Ha Long Bay. Regarding GHG emission impacts and cost-benefit assessment, Triple I light and Triple I light star showed high sufficiency, especially for policy makers. Investigating and expanding the research boundary are currently in the process to assess impacts of BDF plant construction and oil leakage from cruise ship using BDF. For the expanded study, the full Triple I should be applied. Thus, further research also needs to develop methodology for risk estimation on environment protection and human health risk, and especially meeting with its application in coastal areas of Vietnam.

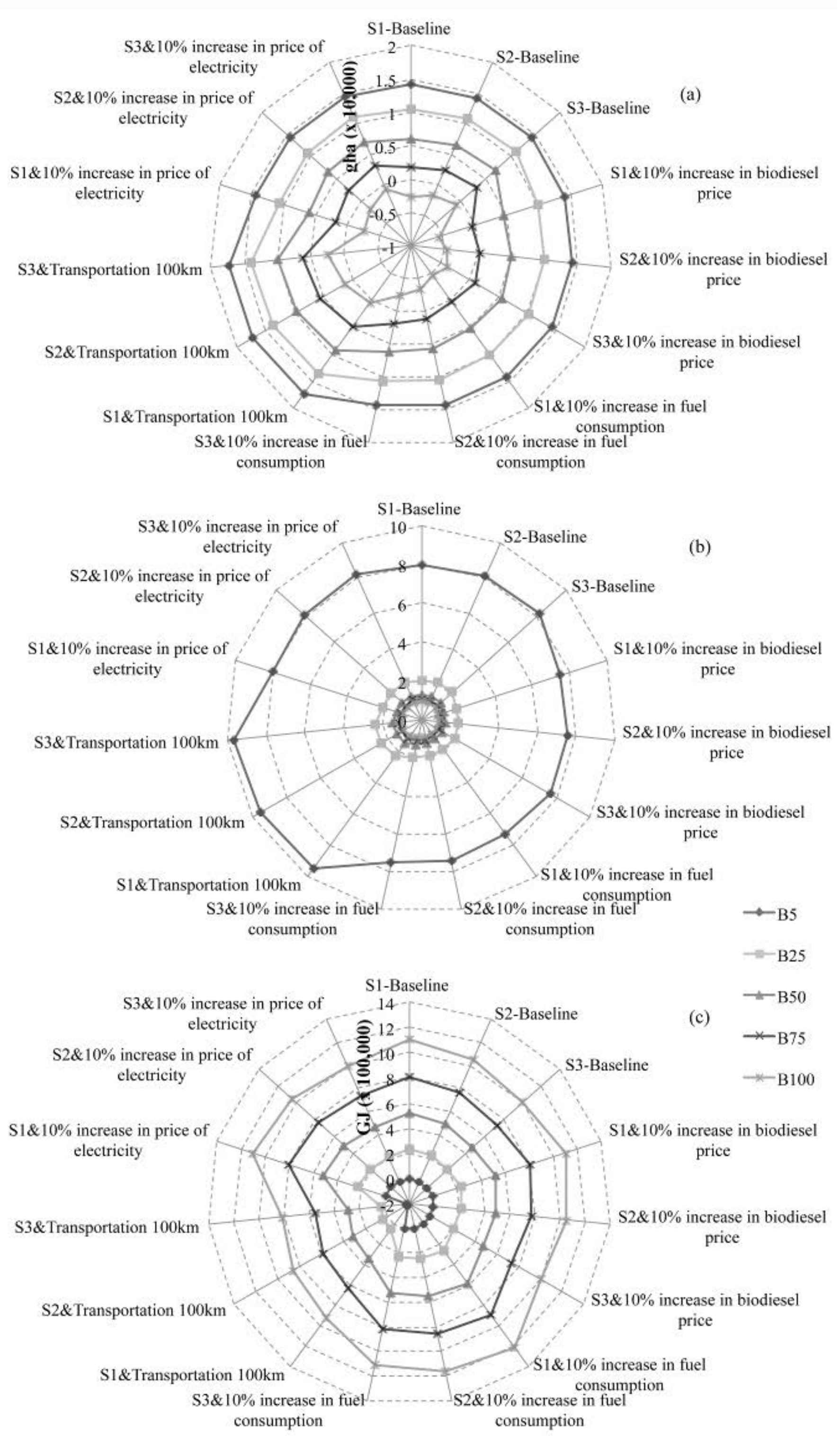


Fig. 5.5 Sensitivity analysis of factors related to Triple I light (a), Triple I light star (b) and Net energy (c) of BDF production.

REFERENCES

Abebe, Dereje Kebede. 2013. “A Life Cycle Assessment on Liquid Biofuel Use in the Transport Sector of Ethiopia.” University of South Africa.

Agarwal, a. K., and L. M. Das. 2001. “Biodiesel Development and Characterization for Use as a Fuel in Compression Ignition Engines.” *Journal of Engineering for Gas Turbines and Power* 123 (2): 440. doi:10.1115/1.1364522.

BioGrace. 2012. GHG Calculation Tool. BioGrace.

Bui, Thi Buu Hue, Trong Tuan Nguyen, Van Dat Nguyen, and Quoc Nhien Pham. 2014. “Biodiesel Fuel Research: Research Period 01 December 2013 - 17 October 2014.” Final report. Can Tho: Yanmar Agriculture Research Institute.

Carels, N., M. Sujatha, and B. Bahadur. 2012. *Jatropha, Challenges for a New Energy Crop: Volume 1: Farming, Economics and Biofuel*. Vol. 1. Jatropha, Challenges for a New Energy Crop. Springer.

Chaturvedi, S, and A Kumar. 2012. “Bio-Diesel Waste as Tailored Organic Fertilizer for Improving Yields and Nutritive Values of Lycopercicum Esculatum (Tomato) Crop.” *Journal of Soil Science and Plant Nutrition* 12: 801–10.

EPA. 2002. “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions: Draft Technical Report.” EPA420-P-02-001. Washington, DC: United States Environmental Protection Agency.

———. 2005. “Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasonline and Diesel Fuel.” EPA420-F-05-001. Washington, DC: United States Environmental Protection Agency.

Eshton, Bilha, Jamidu H.Y. Katima, and Evans Kituyi. 2013. “Greenhouse Gas Emissions and Energy Balances of Jatropha Biodiesel as an Alternative Fuel in Tanzania.” *Biomass and Bioenergy* 58 (0): 95–103. doi:10.1016/j.biombioe.2013.08.020.

European Biofuels Technology Platform. 2011. “Fatty Acid Methyl Esters (FAME).” *Biofuel Fact Sheet*.

Ewing, B., A. Reed, A. Galli, J. Kitzes, and Mathis Wackernagel. 2010. *Calculation Methodology for the National Footprint Accounts*. 2010thed. Oakland, CA: Global Footprint Network.

FAOSTAT. 2015. “FAOSTAT.” *Food and Agriculture Organization of the United Nations, Statistic Division*.

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O’Hare, and Daniel M. Kammen. 2006. “Ethanol Can Contribute to Energy and Environmental Goals.” *Science* 311 (5760): 506–8. doi:10.1126/science.1121416.

Global Footprint Network. 2010. “National Ecological Footprint and Biocapacity for 2007.” Global Footprint Network.

Heller, Joachim. 1996. *Physic Nut. Jatropha Curcas L. Promoting the Conservation and Use of Underutilized and Neglected Crops. 1.* Rome, Italy: International Plant Genetic Resources Institute.

ISCC. 2011. “ISCC 205 GHG Emissions Calculation Methodology and GHG Audit.” Germany: International Sustainability and Carbon Certification.

Jayaram, Varalakshmi, J. Wayne Miller, Harshit Agrawal, William A Welch, and David R Cocker. 2009. “Effect of Biodiesel on Emissions from a Tier II Marine Propulsion Engine.” Final Report. California, USA: University of California.

Lin, Ya-fen, Yo-ping Greg Wu, and Chang-Tang Chang. 2007. “Combustion Characteristics of Waste-Oil Produced Biodiesel/diesel Fuel Blends.” *Fuel* 86 (12â€“13): 1772–80. doi:10.1016/j.fuel.2007.01.012.

Luu, Phuong Duc, Hoa Thi Truong, Boi Van Luu, Lan Ngoc Pham, Kyoshi Imamura, Norimichi Takenaka, and Yasuaki Maeda. 2014. “Production of Biodiesel from Vietnamese Jatropha Curcas Oil by a Co-Solvent Method.” *Bioresource Technology* 173. Elsevier Ltd: 309–16. doi:10.1016/j.biortech.2014.09.114.

Maeda, Yasuaki, Le Tu Thanh, Kiyoshi Imamura, Katsutoshi Izutani, Kenji Okitsu, Luu Van Boi, Pham Ngoc Lan, Nguyen Cong Tuan, Young Eok Yoo, and Norimichi Takenaka. 2011. “New Technology for the Production of Biodiesel Fuel.” *Green Chemistry* 13 (5): 1124–28. doi:10.1039/C1GC15049A.

Mohammadshirazi, Ahmad, Asadolah Akram, Shahin Rafiee, and Elnaz Bagheri Kalhor. 2014. “Energy and Cost Analyses of Biodiesel Production from Waste Cooking Oil.” *Renewable and Sustainable Energy Reviews* 33 (0): 44–49. doi:10.1016/j.rser.2014.01.067.

Openshaw, Keith. 2000. “A Review of Jatropha Curcas: An Oil Plant of Unfulfilled Promise.” *Biomass and Bioenergy* 19 (1): 1–15. doi:10.1016/S0961-9534(00)00019-2.

Otsuka, Koji. 2011. “Inclusive Impact Index ‘Triple I’ and Its Application for Ocean Nutrient Enhancer.” In *Proceedings of the Twenty-First (2011) International Offshore and Polar Engineering Conference*, 1:777–84. Maui, Hawaii, USA: International Society of Offshore and Polar Engineers (ISOPE).

———. 2014. “Investigation of Co-Benefits Evaluation Method for BDF Ultilization.” Mid-term Report. Ha Noi: Osaka Prefecture University.

Pandey, Vimal Chandra, Kripal Singh, Jay Shankar Singh, Akhilesh Kumar, Bajrang Singh, and Rana P. Singh. 2012. “Jatropha Curcas: A Potential Biofuel Plant for Sustainable Environmental Development.” *Renewable and Sustainable Energy Reviews* 16 (5): 2870–83. doi:http://dx.doi.org/10.1016/j.rser.2012.02.004.

Paz, Ander, and Peter Vissers. 2011. “Greenhouse Gas Calculations Jatropha Value Chain Sun Biofuels Mozambique.” *October*, no. March: 1–35.

Prueksakorn, Kritana, Shabbir H. Gheewala, Pomthong Malakul, and SÃ©bastien Bonnet. 2010. “Energy Analysis of Jatropha Plantation Systems for Biodiesel Production in Thailand.” *Energy for Sustainable Development* 14 (1): 1–5. doi:10.1016/j.esd.2009.12.002.

Rajagopal, Deepak, and David Zilberman. 2007. “Review of Environmental, Economic and Policy Aspects of Biofuels.” Policy Research Working Paper WPS4341. Policy Research Working Paper. Washington, DC: World Bank.

Tewari, D.N. 2007. *Jatropha & Bio-Diesel*. Ocean Books.

Thanh, Le Tu, Kenji Okitsu, Yasuhiro Sadanaga, Norimichi Takenaka, Yasuaki Maeda, and Hiroshi Bandow. 2010. “A Two-Step Continuous Ultrasound Assisted Production of Biodiesel Fuel from Waste Cooking Oils: A Practical and Economical Approach to Produce High Quality Biodiesel Fuel.” *Bioresource Technology* 101 (14). Elsevier Ltd: 5394–5401. doi:10.1016/j.biortech.2010.02.060.

U.S. Energy Information Administration. 2015. “International Energy Statistics.” *Independent Statistics & Analysis*.

Wackernagel, Mathis, Chad Monfreda, Dan Moran, Paul Wermer, Steve Goldfinger, Diana Deumling, and Michael Murray. 2005. “National Footprint and Biocapacity Accounts 2005: The Underlying Calculation Method.” Oakland, CA: Global Footprint Network.

Wani, SP, G Chander, KL Sahrawat, P Narsimha Rao, and others. 2014. “Integrated Nutrient Management Using Deoiled Jatropha Cake for Sustained and Economic Food Production.” *International Journal of Plant Production* 8 (4): 549–562.

World Bank. 2015. “World Development Indicators.”

Wu, May, Michael Wang, Jiahong Liu, and Hong Huo. 2008. “Assessment of Potential Life-Cycle Energy and Greenhouse Gas Emission Effects from Using Corn-Based Butanol as a Transportation Fuel.” *Biotechnology Progress* 24 (6): 1204–14. doi:10.1002/btpr.71.

Yoshimoto, Haruki, and Shigeru Tabeta. 2011. “A Study on the Scaling of Ecological and Economic Values in the Inclusive Impact Index.” In *Proceedings of the Twenty-First (2011) International Offshore and Polar Engineering Conference*, 1:804–9. Hawaii, USA: International Society of Offshore and Polar Engineers (ISOPE).

Zhu, Lei, C.S. Cheung, W.G. Zhang, and Zhen Huang. 2010. “Emissions Characteristics of a Diesel Engine Operating on Biodiesel and Biodiesel Blended with Ethanol and Methanol.” *Science of The Total Environment* 408 (4): 914–21. doi:10.1016/j.scitotenv.2009.10.078.

Equation Chapter (Next) Section 1

Chapter 6 - BEHAVIOR OF BIODIESEL SPILL AND LEAKAGE

6.1 INTRODUCTION

Approximately 600 cruise boats operating in Ha Long Bay consume about 21,600 kiloliters of petrodiesel fuel per year (Otsuka 2014). The spill of fuel from those boats due to daily operation and shipwrecks is one of the main sources of oil pollution in this area. Because biodiesel is readily biodegradable (Zhang et al. 1998; Wedel 1999; Ginn et al. 2013) and has lesser toxicity than fossil fuel (GenSolutions 2007; Wedel 1999; Birchall, Newman, and Greaves 1995; Lapinskiene, Martinkus, and Rebždaite 2006), the application of biodiesel in cruise boats might reduce the severe of the oil-contaminated water on the Bay. Although the better impact of neat biodiesel on human health and ecosystem is widely recognized, it is unclear about how much its superior considering the fate oil spill in the marine ecosystem. Moreover, scholars also question about the advantage of biodiesel blends compare to fossil diesel (Fingas 2014).

Therefore, this study aimed to determine blending options for Roselle-Trau biodiesel and estimate the difference in the environmental impacts of vegetable oil-based biodiesel and its blends compare to petrodiesel when discharging into Ha Long Bay.

6.2 MATERIALS AND METHODS

6.2.1 Environmental impact assessment

Fig. 6.1 shows main steps in the estimation of the potential environmental impacts of an oil spill. Firstly, environmental behavior of BDF blends and neat petrodiesel discharging to the Bay were estimated by a simple oil weathering model so-call ADIOS (Automated Data Inquiry for Oil Spills), which developed by U.S. National Oceanic and Atmospheric Administration (NOAA). ADIOS can project the change of oil properties, and the percentage of evaporation, dispersant, and remaining oil in the marine environment. Input data of the model are as follows: (1) spill location information, including sea current, sea/soil state, speed and direction of wind, and water temperature; (2) Fuel characteristics, including viscosity, solubility, emulsification, evaporation, flash point and cloud point; and (3) spill volume (Lehr et al. 2002), which was based on worst case of fuel release in Ha Long Bay taking into account daily oil leakage from the operation of cruise boats and shipwrecks due to accidents and disasters.

ADIOS, however, only predicts the fate of oil spill up to 5 days and does not consider about biodegradation, which mostly affects the remaining of the oil spill after that. Therefore, data about biodegradation of BDF blends and petrodiesel were integrated with the result from ADIOS model to estimate the cumulative concentration of oil spills. Then, the difference in ecotoxicity between BDF blends and neat petrodiesel was synthesized and analyzed to evaluate and compare their environmental impacts.

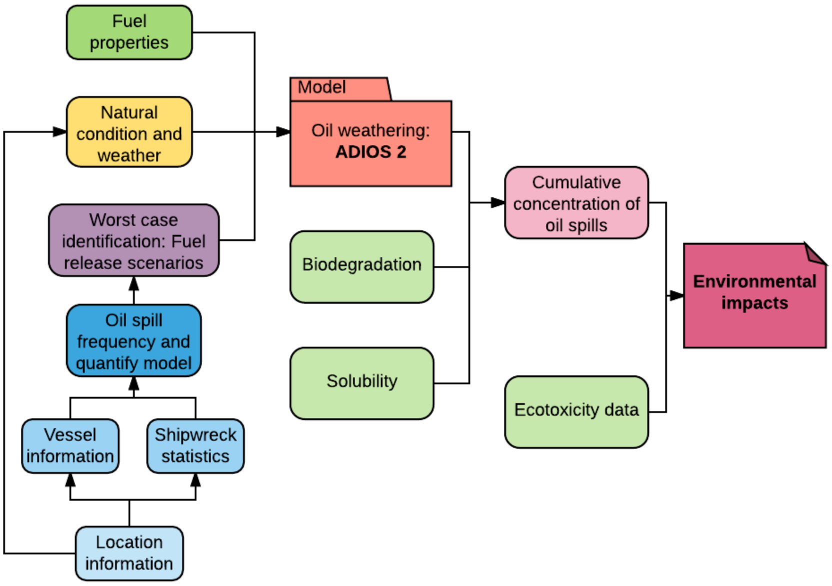


Fig. 6.1 Framework of environmental impact assessment

6.2.2 Study site

6.2.2.1 Natural condition

Located in the northeast of Vietnam, Ha Long Bay has a long coastal line of approximately 120 km with a unique natural beauty consisting of more than 1,900 limestone islands and islets. The Bay has been inscribed on the World Heritage List since 1994 and is one of the most famous tourist attractions of Vietnam. Ha Long has tropical monsoon climate characterized by a cold, dry winter and a hot, humid summer with average annual temperature, wind speed, and dominant wind direction are 24°C (around 30°C in July and August), 6 m/s (storm: 35-50 m/s), and South-West 45° (North in July and August), respectively(Tran et al. 2011; Windfinder.com 2016). Average annual wave height is 0.34 m and maximum 1.75 m in the storm period. The Bay holds around 6.7 billion liters of water in average (Tran et al. 2011).

6.2.2.2 Operation of cruise boats and identification of oil spill

Regarding the operation of cruise boats in Ha Long Bay in the last seven years, a total of 16 severe shipwrecks due to storms, accidents and fires were reported, in which four cases were in 2010, and other four were in 2014. Therefore, in this study, oil spills from four sunken cruise boats per year were simulated. The mean fuel spill volume of each case was 571 liters.

On the other hand, the consumption of about 59 kiloliters petrodiesel of cruise boats per day also led to the certain amount of fuel leaks to the Bay. As consulting with marine engine experts in Ha Long bay, the fuel leaking rates of 2% and 1% were applied to the old engines (operating before 2010) and new engines (operating from 2010). Moreover, an addition of 10% was adapted to the consumption of neat BDF due to its lower energy content to conventional diesel (U.S. EPA 2002).

6.3 RESULTS AND DISCUSSION

Since around 0.876 metric tons of petrodiesel fuel from cruise boats continuously discharged into the Bay within a day and less than 0.35 metric tons hr^{-1} could not be considered under the weathering model, the cumulative of daily fuel leakage in the Bay was determined based on biodegradation rate. Results from previous studies present an approximately 2-time higher biodegradation rate of vegetable oil-based BDF than that of petrodiesel. In 28 days, the biodegradability of BDF and the cumulative amounts of different spilled oils in Ha Long Bay due to cruise boat operation and boat sinking are shown in table 4. The daily leakage volumes of approximately 0.876 metric tons of petrodiesel, 1.057 metric tons of TBDF, 1.029 metric tons of RBDF and 1.045 metric tons of R70T30BDF and their biodegradation rate were employed to estimate the present of fuel in the Bay. The cumulative amounts of petrodiesel, TBDF, RBDF and R70T30BDF were about 20.33 metric tons, 11.31 metric tons, 11.01 metric tons, and 11.16 metric tons, respectively. Accordingly, the oil-in-water concentration of petrodiesel, TBDF, RBDF, R70T30BDF were 6.09 10^{-6} ppm, 8.94 10^{-7}ppm, 3.06 10^{-7} ppm, and 3.67 10^{-7} ppm, respectively.

Regarding to oil spills from sunken cruise boat due to storms, accidents and fires, two scenarios were taken into account, including three cases per a stormy day and once case in normal weather. During the storm, the concentration in aqueous phase of petrodiesel, RBDF, TBDF, and R70T30BDF were approximately 6.36 10^{-6} ppm, 3.47 10^{-7} ppm, 1.01 10^{-6} ppm, and 4.17 10^{-7} ppm on the first day, respectively; and around 6.25 10^{-6} ppm, 3.1 10^{-7} ppm, 9.05 10^{-7} ppm, and 3.72 10^{-7} ppm in the 28th day, respectively. The results show that the WAF concentration of RBDF, TBDF and R70T30BDF decreased significantly by about 11% after 28 days. Meanwhile, the WAF concentration of petrodiesel only reduced around 2% in the same period. Moreover, the cumulative WAF concentration of biodiesel was from seven to twenty-time lower than that of petrodiesel. Of the biodiesel blends, the WAF concentration of RBDF and R70T30BDF appeared to be roughly 2-time lesser than TBDF.

However, referring to previous studies about the toxicity of BDF and petrodiesel, the WAF concentrations of biodiesel and petroleum in Ha Long Bay were significantly smaller than those tests. The acute ecotoxicity tests conducting within 96 hours presented that the minimum of WAF concentration which resulting in some significant symptoms in aquatic organisms is around one ppm (Hollebone et al. 2008; Khan, Warith, and Luk 2007; Birchall, Newman, and Greaves 1995). This concentration is markedly higher than the practical WAF concentration of oil spill in the environment due to oil weathering (Transportation Research Board and National Research Council 2003). Moreover, the exposure of the aquatic organisms to the WAF is mostly in long-term because the dissolved oil enters their natural habitat and would remain there for an extended period. Therefore, it is necessary to study more about the chronic ecotoxicity of oil spills, especially in biodiesel case, to understand thoroughly about impacts of an oil spill to the environment in general and the effects of biodiesel fuel in the marine environment comparing to conventional diesel in particular. Furthermore, this information is critical for the Ha Long Bay dwellers since most of their marine products are from nearshore fishing and aquaculture which directly affected by the oil contaminated areas.

Table 6.1 Cumulative amounts of different oil spills and their WAF concentrations in Ha Long Bay

			Sunken: Storm				*Sunken: Accident & fire*			
	Daily operation		1st day		28th day		1st day		28th day	
Fuel	Total (tonnes)	WAF (ppm)	Total (tonnes)	WAF (ppm)	Total (tonnes)	WAF (ppm)	Total (tonnes)	WAF (ppm)	Total (tonnes)	WAF (ppm)
Petrodiesel	20.33	6.09E-06	21.24	6.36E-06	20.88	6.25E-06	20.64	6.18E-06	20.51	6.14E-06
RBDF	11.01	3.06E-07	12.48	3.47E-07	11.16	3.1E-07	11.50	3.2E-07	11.06	3.07E-07
TBDF	11.31	8.94E-07	12.79	1.01E-06	11.46	9.05E-07	11.80	9.33E-07	11.36	8.98E-07
R70T30BDF	11.16	3.67E-07	12.66	4.17E-07	21.24	6.36E-06	11.66	3.84E-07	11.21	3.69E-07

REFERENCES

Birchall, Caroline, Jonathan R Newman, and Michael P Greaves. 1995. “Degradation and Phytotoxicity of Biodiesel Oil.”

Fingas, Merv. 2014. “Vegetable Oil Spills.” In *Handbook of Oil Spill Science and Technology*, 79–91. John Wiley & Sons, Inc. doi:10.1002/9781118989982.ch4.

GenSolutions. 2007. “Risk Assessment for Bioenergy Manufacturing Facilities in Alberta.” Admonton.

Ginn, Timothy R, Tyler J Hatch, Thomas E. McKone, and David W Rice. 2013. “California Biodiesel Multimedia Evaluation: Final Tier III Report.”

Hollebone, B.P., B. Fieldhouse, M. Landriault, K. Doe, and P. Jackman. 2008. “Aqueous Solubility, Dispersibility and Toxicity of Biodiesels.” In *International Oil Spill Conference Proceedings*, 2008:929–36. American Petroleum Institute. doi:10.7901/2169-3358-2008-1-929.

Khan, Nalissa, Mostafa a Warith, and Grace Luk. 2007. “A Comparison of Acute Toxicity of Biodiesel, Biodiesel Blends, and Diesel on Aquatic Organisms.” *Journal of the Air & Waste Management Association (1995)* 57 (3): 286–96. doi:10.1080/10473289.2007.10465333.

Lapinskiene, Asta, Povilas Martinkus, and Vilija Rebždaite. 2006. “Eco-Toxicological Studies of Diesel and Biodiesel Fuels in Aerated Soil.” *Environmental Pollution* 142 (3): 432–37. doi:10.1016/j.envpol.2005.10.023.

Lehr, William, Robert Jones, Mary Evans, Debra Simecek-Beatty, and Roy Overstreet. 2002. “Revisions of the ADIOS Oil Spill Model.” *Environmental Modelling & Software* 17 (2): 189–97. doi:10.1016/S1364-8152(01)00064-0.

Otsuka, Koji. 2014. “Investigation of Co-Benefits Evaluation Method for BDF Utilisation.” Ha Noi: Osaka Prefecture University.

Tran, Thanh Duc, Minh Van Tran, Trang Thu Thi Cao, Vinh Duy Vu, and Tu Anh Tran. 2011. *Suc Tai Moi Truong Vinh Ha Long - Bai Tu Long (Environmental Carying Capacity of Ha Long - Bai Tu Long Bay)*. Publishing House for Natural Science and Technology.

Transportation Research Board and National Research Council. 2003. *Oil in the Sea III: Inputs, Fates, and Effects*. *Issues in Science and Technology*. Washington, DC: The National Academies Press. doi:10.17226/10388.

U.S. EPA. 2002. “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions-Draft Technical Report.”

Wedel, Randall von. 1999. “Technical Handbook for Marine Biodiesel In Recreational Boats.” California. http://www.cytoculture.com/Biodiesel Handbook.htm.

Windfinder.com. 2016. “Bach Long Vi/Gulf of Tonkin.” *Wind & Weather Statistics*. https://www.windfinder.com/windstatistics/bach_long_vi_gulf_of_tonkin?utm_source=

www.windfinder.com&utm_medium=web&utm_campaign=redirect.

Zhang, X, C Peterson, D Reece, Gregory Moller, and Randall Haws. 1998. “Biodegradability of Biodiesel in the Aquatic Environment.” *Transactions of the ASAE* 41 (5): 1423–30. http://www.biodiesel.org/reports/19950601_mar-009.pdf.

Equation Chapter (Next) Section 1

Chapter 7 - SUSTAINABILITY ASSESSMENT OF INEDIBLE VEGETABLE OIL-BASED IN HA LONG BAY

7.1 INTRODUCTION

Ha Long Bay, located in the northeast of Vietnam, possesses a stunning landscape with more than 1,600 limestone islands and islets. Ha Long has been inscribed in Natural World Heritage Sites since 1994 and is one of the most tourist attractions in Vietnam. However, coal mining, both open-pit mining and underground mining as well as tourism related activities have led to several environmental problems in the Bay. According to National Mining Development plan, all open-pit mines have to be closed by 2020. Therefore, approximately 6,699 ha of open-pit mine lands and mining dump sites needs to be reclaimed. The intercropping of *Hibiscus sabdariffa* L. (Roselle) and *Vernicia montana* L. (Trau) was highly recommended due to their ability to well-growth in low-fertile soil and short-long term economic profit. Furthermore, as the extracted oils from Roselle and Trau seeds are inedible, there would be no conflict with food production in Vietnam. Therefore, those plants can become feedstocks for the production of biodiesel that is supposed to use in cruise boats in Ha Long Bay which require about 22,000 kiloliters annually. It is critical to note that inedible oil referred in this study was not only the oil that could not eat due to its low quality or toxicity but also include the oil that is not used neither for cooking nor in any other forms of food supplies.

As it was mentioned, the implementation of biodiesel system does not always mean the win-win outcome. Thus, this study aimed to assess and evaluate the sustainability of the whole life cycle of biodiesel system in Ha Long Bay. The Inclusive Impact Index (Triple I) framework developed in Part I of the research was used in the sustainability evaluation of the biodiesel system.

7.2 MATERIAL AND METHODS

7.2.1 Goal and scope of the research

The goal of this study was to evaluate the impact of inedible vegetable oil-based biodiesel on five main enviro-economic categories including ecological footprint, biocapacity, ecosystem quality impact, human health impact, and cost and benefits. The scope of this study is limited to Quang Ninh Province of Vietnam.

7.2.2 System boundary and functional unit

The boundaries started with the production Trau oil and Roselle oil (raw material acquisition) and ended with the combustion of Roselle-Trau-oil-derived biodiesel and its blend in cruise ship engines. Fig. 7.1 illustrates the system boundaries for the lifecycle assessment of biodiesel fuel use in a cruise ship. The whole life cycle of biodiesel production in Ha Long Bay was supposed to comprise all the stages from the intercropping of Roselle and Trau in mining dump site; harvesting, sun-drying and transportation of oilseeds; extraction of oil and other medicines and co-products from those seeds; esterification of Roselle-Trau crude oil to obtain biodiesel (methyl ester); distribution and use of biodiesel in cruise ships in Ha Long Bay; Roselle leaves and Roselle-Trau de-oiled cake using as compost back to the cultivation field to offset a certain amount of mineral fertilizer use according to the nutrient component in dry matter.

Trau trees have a long lifetime of about 50-70 years old (Nipakhonsom et al. 2012), and their maximum production can last until 30-40 years old (Julia Frances Morton 1987; Bernál et al. 2014). Moreover, the lifetime of oil mill for oil extraction and chemical plant for the esterification of vegetable oil mostly ranges from 25 to 50 years (Azadi et al. 2014; Jungbluth et al. 2007). Therefore, the project lifetime in this study was set to 30 years. Functional unit for the Life Cycle Assessment (LCA) was one-year biodiesel combustion in a cruise ship. Annually, more than 550 cruise ships operating in Ha Long bay consume approximately 22,000 kl fuel.

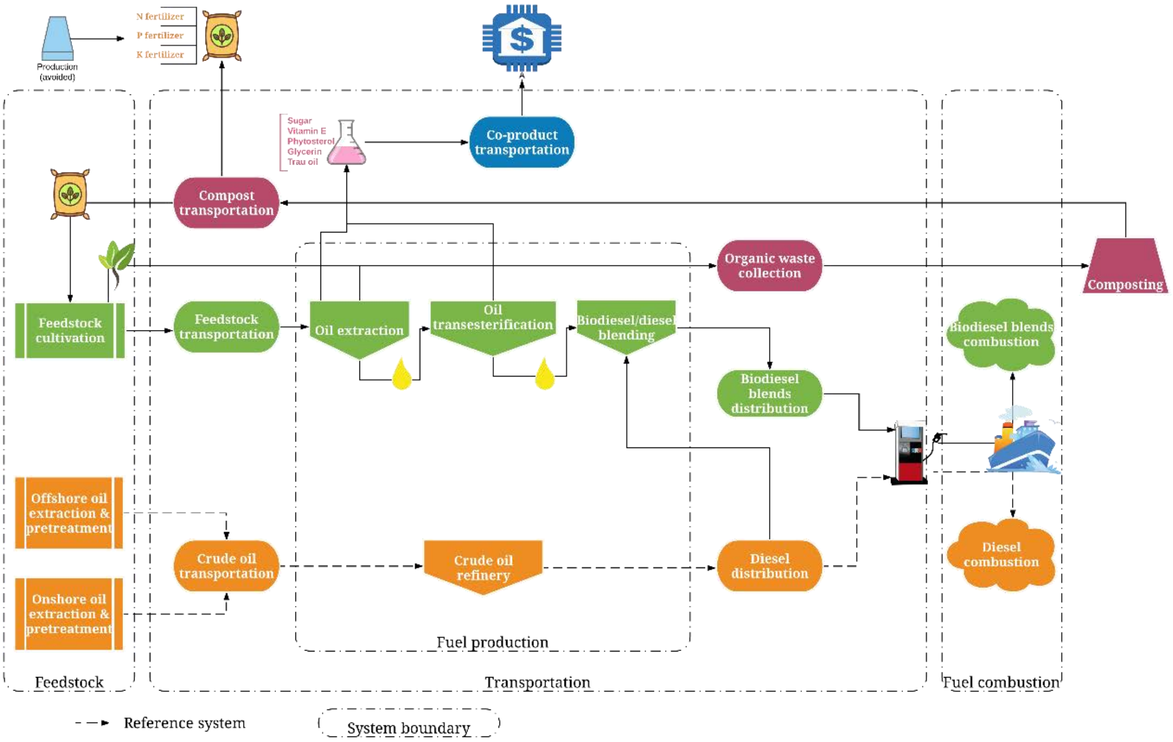


Fig. 7.1: System boundary of biodiesel production and use in Ha Long Bay

7.2.3 Methodology and categories

7.2.3.1 Inclusive Impact Index (Triple I)

The newly developed Triple I was used as a final indicator for the sustainability assessment of biodiesel system (Eq. 4.15).

$$III = (EF - BC) + \alpha[(C - B) + \beta HR + \gamma ER] \quad \text{(Eq. 4.15)}$$

where EF is ecological footprint (gha), BC is biocapacity (gha), ER is ecological risk, C is cost (US \$), B is benefit (US \$), HR is human risk, and α, β, and γ are the conversion factor from economic value (US \$) to gha, from HR value to economic value (US \$), and from ER value to gha, respectively.

The estimation of all parameters in Triple I was conducted following the Triple I framework developed in Chapter 4 of this dissertation. Accordingly, an LCA tool so-called IMPACTS 2002+ was adopted to estimate the HR - human health impacts (DALY pers^{-1}) and ER - ecosystem quality impacts (PDF m^{-2} year^{-1}). EF and BC were calculated under the life cycle-based ecological footprint assessment (Huijbregts et al. 2008) regarding updated equivalent factors according to a new guideline from Global Footprint Network (Lin et al. 2016). Life cycle costing (LCC) was applied to estimate cost and benefit parameter of Triple I. The development and calculation of the whole system was operated by integrating Simapro 8 with spreadsheet.

Moreover, to get a thorough view about the all-in recover period of the biodiesel system, an Triple $I_{payback}$ also estimated (Eq. 4.16)

$$\forall III_{annual} < 0 \Rightarrow III_{payback} = \frac{III_{initial}}{|III_{annual}|} \quad \text{(Eq. 4.16)}$$

where Triple $I_{initial}$ is the Triple I assessing all the capital costs and emissions from the preparedness and start-up of a product life cycle system ($EF_{initial}$, $ER_{initial}$, $HR_{initial}$); and Triple I_{annual} is Triple I considering annual costs (C_{annual} and B_{annual}) and emissions from the product life cycle system (EF_{annual}, BC_{annual}, ER_{annual}, HR_{annual}).

7.2.3.2 Ecological footprint and biocapacity estimation method

Ecological footprints related to the production of raw materials and their transportation, and energy used were supported by Simapro 8. Carbon neutral theory were not use in this study. This study considered yearly-average carbon storage in the standing biomass (Trau) and harvested products - oil from seed. Other agricultural residues and the carbon content in oil cake were not considered because the absorbed CO_2 would release back to the environment due to burning or composting. Moreover, due to carbon cycle, CO_2 content in calyces used for food supplies would release back to environmental right after the consumption. Yield factor was calculated with data from FAOSTAT for 2014 (FAOSTAT 2017). Accordingly, yield factor for cereals is 1.43 ha wha^{-1} and oil crops is 1.05 ha wha^{-1}. Land occupation were not included in this calculation.

When using an area for oil crop propagation, this area will turn into arable land. Since the cultivation was practiced in mine dumping sites with no benefit, it would result in the gain of agricultural productive area which mean the biocapacity increase. The calculation of the biocapacity was managed based on annual fuel consumption of cruise ship, different blends, Roselle-Trau crop yield and biodiesel production efficiency. If the total required area to obtain the relevant expected amount of biodiesel is less than available area of mining dump site in Ha Long, this meant the (+) biocapacity of the system. Vice versa, if the total required area is larger than available one, this means ecological footprint or (-) biocapacity. And the final biocapacity was the sum of (+) and (-) biocapacity.

7.2.3.3 Conversion factor calculation

According to the Global Footprint Network (Lin et al. 2016), GPD per capita and EF per capita of Vietnam, as of 2012, are US $1,532 and 1.7 gha.

$$\alpha = \frac{EF_{2012}}{GDP_{2012}} = \frac{1.7}{1,532} = 1.1 \times 10^{-3} \qquad \text{(gha US \$}^{-1}\text{)} \ (7.1)$$

β = US $2,111 GPD per capita of Vietnam in 2015 (World Bank 2016).

With an effort to develop a worldwide database about the value of ecosystem services, The Foundation of Sustainable Development collected and summarized various researches related to monetary valuation of ecosystem services (van der Ploeg, De Groot, and Wang 2010). According to the database, the monetary values of coral reefs and mangroves in Vietnam with different services, including recreation, food, raw materials, medical, gene pool, and nursey, varied from 0.165 US$ ha^{-1} $year^{-1}$ to 2,363.8 US$ ha^{-1} $year^{-1}$. Followingly, the conversion factor γ was estimated as average monetary values of ecosystem services in Vietnam. γ = 526.417 US$ ha^{-1} $year^{-1}$.

7.3 LIFE CYCLE INVENTORY (LCI)

7.3.1 Determination of cruise ship exhaust gasses composition

In fact, the effects of biodiesel and it blends on engine performances and emissions varies due to the differences, for instance, in the origin of biodiesel and also in the climate condition where the oil seeds grow, in the type of engine and in the working condition of the engine (Atabani et al. 2013; No 2011). In general, there were no detail research about exhaust gases of biodiesel in cruising ships and the information about the combustion gases of Roselle biodiesel and Trau biodiesel (some related studies were (Jindal and Goyal 2012; Kumar 2013; Sorate 2013; Dilip and Rao 2015; Biriok 2012) was limited and not evident enough for the calculation. Therefore, to determine the difference in the exhaust gases of petroleum and biodiesel blends in cruise ship performances, this study integrated the base case emissions of petrodiesel in maritime navigation from a report about emissions of transport in the Netherlands (Klein et al. 2016) and the regression model for predicting the percent change in exhaust emissions based on the concentration of biodiesel in the blend developed by United States Environmental Protection Agency (U.S. EPA 2002). Although these findings may not a quantitively exact prediction of the difference, it could provide a proper trend data for the comparison.

7.3.1.1 Base case emissions from petroleum combustion

The base case emissions of petrodiesel was obtained from the spreadsheet data attached with the report on the calculation method of the transport emissions in the Netherlands (Klein et al. 2016)

Characteristics of exhaust gasses from diesel engine in maritime navigation and light lorry were used. All the data were in 2014, however, data of 1999 was used for SO_2 due to the petrodiesel standard of 1999 is the same as petrodiesel current standard in Vietnam with the sulphur content of 500ppm. Since the sulphur content within the fuel is positive correlation with the emission of sulphur dioxide (SO_2) in exhausted gas (IPCC 2006; Kristensen 2012), the SO_2 was extract from the percentage of biodiesel in the fuel. According to Biodiesel standard of Vietnam (QCVN 1:2015), the sulphur content in biodiesel is less than 10ppm, and petrodiesel is less than 500ppm.

In the report, Klein and his colleagues considered several sources of emissions from the engine operation. Total emissions from road transport, for example, include tailpipe emissions, evaporative emissions from road vehicles, and PM emissions from tyre and brake wear and road abrasion. In case of maritime navigation, only exhaust emissions including SO_2, N_2O, NH_3, heavy metals and VOC/PAH components were assessed.

Emission factor for calculating transport emission of cruise ship are presented in Table 7.1 .The data was analyzed under the condition of Dutch transportation system.

Table 7.1 Emission factors for cruise ships (Klein et al. 2016)

Emission	Emission factor (g/kg fuel)
NO_x	54.2
PM	6.83
SO_2	19.8
CO	11.6
CO_2	3,173
Acetaldehyde	0.0361
Ethylbenzene	0.0095
Formaldehyde	0.1102
Naphthalene	0.012863
CH_4	0.076

According to Klein et al., Combustion emissions includes: CO/VOC, NOx, PM10, N20, NH3, CH4, SO2, CO2, VOC/PAH components, dioxins, Metals; and Evaporative emissions: VOC component (only accounted in case of petrol used)

7.3.1.2 Effect of biodiesel fuel on combustion emissions (Regulated pollutants and carbon dioxide)

US EPA (U.S. EPA 2002) developed regression models for estimating the percent change in exhaust emissions as a function of the concentration of biodiesel in conventional diesel fuel. This study has been widely recognized and applied in various biodiesel assessment reports (Charman et al. 2012; AQEQ 2011; Lapuerta, Armas, and Rodríguez-Fernández 2008). Default equation was change basing on the scope of the study.

Regression equations were applied to estimate the difference between the use of biodiesel and petrodiesel in Ha Long Bay. The estimation was made using following equation:

$$SF_x = e^{(a_x \times vol\%bdf)} \quad (7.2)$$

where SF_x is emission scaling factor of emission x and a_x is coefficient related to emission x which were considered as statistically significant with 95% confident (Table 7.2), and vol%bdf is the volumetric percentage of biodiesel in the blend ranging from 0 to 100.

7.3.1.3 Biodiesel effects on gaseous toxics

Scaling factors of toxic gaseous for different BDF blends relative to petrodiesel were calculated as follows (U.S. EPA 2002):

$$SF_{TG} = a_{TG} \times vol\%bdf + 1 \quad (7.3)$$

where a_{TG} is coefficient related to emission x which were considered as statistically significant with 90% confident (Table 7.2).

Table 7.2 Coefficients basic emission correlations (U.S. EPA 2002)

Emission	Coefficient
NO_x	0.0010375
PM	-0.047395
HC	-0.0118443
CO	-0.0058238
CO_2	0.0000177
Acetaldehyde	-0.001606
Ethylbenzene	-0.006970
Formaldehyde	-0.001696
Naphthalene	-0.002847
Xylene	-0.004078

Percentage differences of combustion emissions between petrodiesel and biodiesel blends are shown in Fig. 7.1. Due to the reduction of toxic emissions in the exhaust gas of biodiesel, the mitigation of human health impacts following the combustion of biodiesel was expected.

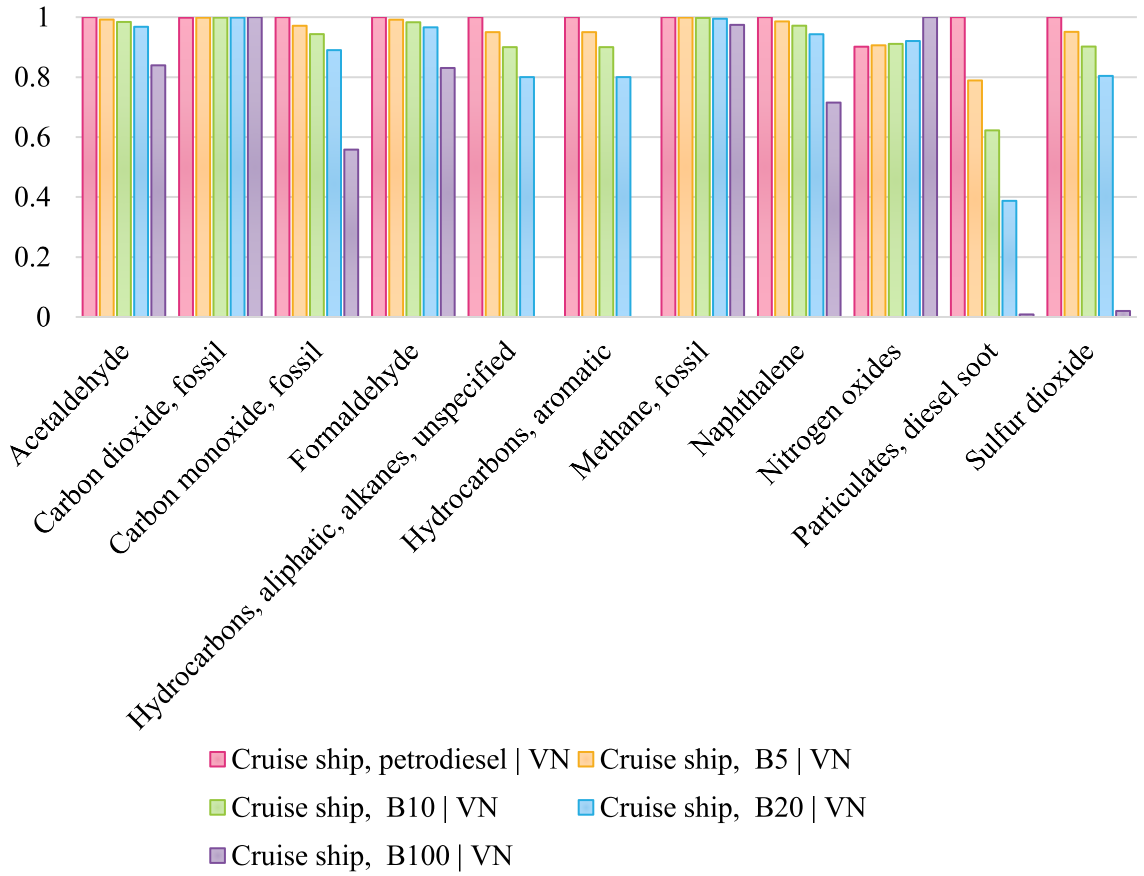


Fig. 7.1 Percentage differences of exhaust gasses between petrodiesel and biodiesel blends

7.3.1.4 Fuel leakage and use

As consulting with maritime engine expert in Ha Long Bay, one percent and two percent fuel leakage were applied to new (operating from 2010) and old (operating before 2010) engines, respectively. According to board registration record, there were 81% of ships registered before 2010 and the others accounted for 19%. Thus, the fuel leakage rate was set to 1.8%.

Other researches on biodiesels derived from soybean (U.S. EPA 2002) and Hibiscus cannabinus (Jindal and Goyal 2012; Sorate 2013) claimed that fuel consumption of pure biodiesel is from nine percent to 12% more than that of petrodiesel due to the lower calorific value and higher density. However, it is not evident enough to determine which part was due to the lower calorific value and which part was the contribution of density. The functional unit of the system was based on volumetric consumption of fuel (kiloliter per year) then allocated to the mass value considering the different in density of the fuel. Therefore, to avoid the double counting, no adjustment in fuel consumption between biodiesel and petrodiesel was employed.

Annually, more than 550 cruise ships operating in Ha Long Bay consumes about 22,000 kiloliters petrodiesel fuel. According to fuel density, annual mass fuel consumptions were changed following the type of biofuel use (Table 7.3)

Table 7.3 Annual fuel consumption by biodiesel and it blends

	B0 (metric ton)	B5 (metric ton)	B10 (metric ton)	B20 (metric ton)	B100 (metric ton)	Leakage per day (metric ton)
Petrodiesel (B0)	17,712	-	-	-	-	0.876
Roselle biodiesel	-	17,772	17,832	17,951	18,908	0.936
Roselle-Trau biodiesel	-	17,785	17,858	18,003	19,168	0.948

7.3.1.5 Evaporation weathering

Evaporation rate and components of petrodiesel vapors were estimated through the previous study about petrodiesel components and weathering behaviors.

Table 7.4 lists the components of petrodiesel from a study from Wang and his colleagues in which analyzed the composition of petrodiesel fuel oil no.2 from Canada (Wang et al. 2003).

Table 7.4 Components of petrodiesel by hydrocarbon groups (Wang et al. 2003)

Component	Concentration (weight %)
Saturates	88.2
Aromatics	10.2
Resins	1.7
Waxes	1.7

Data from our previous study showed that in case of petrodiesel, 75% of oil spill was rapidly volatilized within 5 days after the spill (Nguyen and Otsuka 2016). This also in accordance with the study from The U.S National Research Council indicated that the evaporation weathering of petrodiesel and fuel oil no.2 spill would lead to 75% or more of fuel release into the atmosphere (National Research Council (U.S) 1975).

Aliphatic and aromatic compounds contribute about 98.4% of petrodiesel mass. Since the total petroleum hydrocarbons comprise huge amount of various components and varied between fuels, and it was impossible to obtain a detail physiochemical of petrodiesel fuel (Brewer et al. 2013). This study down scale total percent of saturates and aromatics to 75% with the equal allocation. Furthermore, the weathering solution process also affects the amount components exists in the fuel and effects the evaporation (National Research Council (U.S) 1975). Although aromatics have higher water solubility than aliphatic, they also show higher vapor pressure. Therefore, in this LC assumption, the equal downscale allocation was kept. This made the evaporation rates of aliphatics and aromatics become 67% and 8%, respectively. Since the present of biodiesel does not affect the evaporation behavior of petrodiesel component in the blend (DeMello et al. 2007), the rate of evaporation of oil spill was allocated basing on its volumetric contribution.

7.3.1.6 Allocation methods

Regarding the allocation methods for the products and co-products obtained through the biodiesel's life cycle system, several allocation approaches applied were as follows:

- cut-off approach was used for the marketable co-products of the system and the compost from Roselle leaves and Roselle-Trau oil cake. Accordingly, sugar, medicinal compounds, Roselle calyces and glycerin were immediately sold to the market without further process. Regarding reapplied compost, the amount of compost applied back to the field were determined based on nutrient components of its origin and requirements from the cultivation;
- consequential approach for surplus composts that were not supposed to apply back to the field. Based on the nutrient components of Roselle leaves and Roselle-Trau oil cake, the study assumed that surplus composts could be used to avoid the relevant amount of mineral fertilizer including urea, phosphorus fertilizer and potassium fertilizer; and closed-loop scenario: reapplied compost into the field.

7.3.1.7 Net present value (NPV) and discount rate calculation

The computation of NPV was as follows (Huppes et al. 2004):

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \text{ (US \$) (7.4)}$$

where n is the period of assessment (year), r is discount rate, C_t is the estimated costs in year t. In Triple I, the time-equivalent value of total one-time payment (TP) are considered under NPV, in which n is the project lifetime, and C_t is the average amount of TP over project lifetime period. The discount rate (r) is a key factor in the estimation of NPV mostly influenced by the inflation and interest rate (Eq.4.12) (Davis et al. 2005).

$$r = \frac{Rate_{Interest} - Rate_{Inflation}}{1 + Rate_{Inflation}} = \frac{6.50\% - 2.67\%}{1 + 2.67\%} = 3.74\% \, (7.5)$$

The average inflation rate in Vietnam from January 2016 to December 2016 was 2.67% (calculated based on consumer prices) (Trading Economics 2017); Interest rate was 6.50% (The State Bank of Vietnam).

7.3.2 Base case assumption

There were no information about the fertilizer use in Roselle-Trau intercropping. Therefore, the base case assumption of annual fertilizer use was developed from the literature review and took into account the situation of Ha Long. In mountainous areas of Vietnam, the propagation of Trau was direct seed sowing with no care and fertilizer use. The amount of fertilizer use for Trau was only when is plant alone and no fertilizer need when intercropping with annual crops (Vietnamese Academy of Forest Sciences 2009b). Therefore, the fertilizer use for Roselle monoculture was used as the annual fertilizer input of the field. However, since Roselle and Trau were supposed to be planted in low-fertilized soil, urea was used as 100kg to ensure the growth of tree and seed yield. This assumption was based on the application of Malawi in which applied 50kg N/ha to increase the fruit yield (Julia Frances Morton 1987).

Roselle leaves, and Roselle-Trau seed cake was used to offset a certain amount of fertilizer used in the field. A number of composts applied to the field was calculated from the nutrient components of the leaves and seeds for each year using literature review. The average nutrient composition of Roselle leaves, and seedcake and Trau seedcake are described in Table 7.5.

Table 7.5 Nutrient components in Roselle leaves, Roselle oil cake and Trau oil cake
(Duke 1983; McClintock and El Tahir 2004; Al Shooshi 1997; Hainida et al. 2008; Julia F Morton 1974)

Component	Nitrogen (N)	Phosphorus (P)	Potassium (K)
Roselle fresh leaves	2.08%	1.17%	0.29%
Roselle oil cake	4.94%	0.63%	0.03%
Trau oil cake	3.50%	0.97%	0.50%

The assumption was also made that there would be no change in fuel consumption in the future.

7.3.3 Base case scenario

7.3.3.1 The market of petrodiesel in Vietnam

- Domestic offshore crude oil was dervived from Bach Ho offshore oil field, which contributed to more than a half of country's crude oil production (EIA 2012);
- Foreign crude oil was imported from Middle East onshore fields (Azerbaijan);
- The Dung Quat refinery, the first large-scale refinery of Vietnam, used mixed crude oil, in which 80% was domestic oil and 20% foreign crude oil to produce petrodiesel (Le, Tran, and Pham 2016).
- The total amount of petrodiesel in the market of Vietnam consisted of around 33% domestic and 67% imported petrodiesel (General Department of Vietnam Customs, n.d.; Le, Tran, and Pham 2016).

In general, key phases in petrodiesel life cycle in Vietnam included: extraction of crude oil from offshore (domestic) and onshore (Middle East); transport of crude oil to an oil refinery (Dung Quat) to produce petrodiesel fuel which contributed about 33% of petrodiesel market in Vietnam; then the another 67% of petrodiesel was imported from other countries, mostly from Singapore, Thailand, and China.

7.3.3.2 Roselle-Trau biodiesel life cycle in Quang Ninh

The inventory data for biodiesel system including Roselle-Trau intercropping, vegetable oil extraction, biodiesel production, and transportation stages is clarified in Table 7.6. Life cycle stages of biodiesel production and use in Ha Long Bay, Quang Ninh were as follows:

- ***Feedstock propagation***: Trau seeds were planted in the nursery for 8 months for germination and then transplanted to the field. The plantation of Roselle was direct seed sowing. Since the Trau and Roselle were intercropped, the appropriate tree density of Trau was 400 trees ha^{-1} (Vietnamese Academy of Forest Sciences 2009b), and of Roselle was 25,000 trees ha^{-1} and then thinning to around 10,000 trees ha^{-1} (Vietnamese Academy of Forest Sciences 2009a). Except for the first year, the cultivation was under a rain-fed system with annual additional fertilizing with urea, phosphorus and potassium fertilizers. The amount of mineral fertilizer use was changed due to the application of composts from Roselle leaves and Roselle-Trau oil cake. The management of the cultivation such as tillage, pruning, and harvesting were done manually;
- ***Oil extraction***: Three-phase solvent extraction system was used to obtain sugar, medicinal compounds (Vitamin E and Phytosterol) and oil. This system was based on the newly developed oil extraction technology under a research group in Osaka Prefecture University as the contracted to SATREPS Project. In which, water, methanol, and n-hexane were applied to extract sugar, Vitamin E and Phytosterol, and vegetable crude oil, respectively. Several valuable co-products were derived with high extraction efficiency. Accordingly, it was reported that 90% of Vitamin E and Phytosterol, and 95% of sugar and oil as their contents in the seed were derived. Most of the solvents were recycled (90%), however about 10% of total used solvents emitted to the air due to the high volatility. Due the low component of medical compounds in Roselle seed, only sugar and oil extraction were preferred;

Table 7.6 Life cycle inventory for one metric ton biodiesel production in Quang Ninh Province by unit process

No	Process	Input		Output				
				Air		Water		Co-/products
1	***Rose-Trau propagation***							
	Fertilizer	(US $)	284.60					
		N (kg)	12.18	NO_x (kg)	1.09	Nitrate (kg)	43.00	
		P (kg)	270.80	NH_3 (kg)	5.66	Phosphorus (kg)	0.67	
		K (kg)	136.20	N_2O (kg)	5.19			
				CO_2 (kg)	19.18			
		Manure (kg)	2,581.00					
	CO2 (kg)		33,700.00					
	Land (ha)		2.58					
	Labor cost	(US $)	508.00					
	Transport	(US $)	18.30					

No	Process	Input		Output					
				Air		Water		Co-/products	
		(tkm)	20.73						
	Operating	(US $)	224.00						
	Roselle seed (kg)		.						4,090.00
	Trau seed (kg)								8,430.00
	Roselle calyx							(kg)	1,025.00
								(US $)	5,550.00
	Urea (kg)								139.58
	Phosphate fert. (kg)								10.80
	Potassium fert. (kg)								1,534.02
2	***Vegetable oil extraction plant***								
	Solvent	(US $)	1,619.00						
		Hexane (kg)	8,200.00	Hexane (kg)	820.0				
		MeOH (kg)	6,660.00	Methanol (kg)	666.0				
	Water	(kg)	12,520.00						
		(US $)	7.26						
	Electricity	(US $)	209.30						
		MJ	10,750.00						
	Transport	(US $)	294.70						
		(tkm)	352.00						
	Labor cost	(US $)	34.44						
	Maintenance	(US $)	138.60						
	Tax and insurance	(US $)	4.78						
	Others	(US $)	0.02						
	Roselle oil (kg)								769.00
	Trau oil (kg)								2,610.00
	De-oiled cake							(kg)	9,140.00
	Sugar							(kg)	213.40
								(US $)	63.40
	Phytosterol							(kg)	2.93
								(US $)	439.00
	Vitamin E							(kg)	6.26
								(US $)	626.00
3	***Biodiesel esterification plant***								
	Chemical	(US $)	239.93						
		Acetone (kg)	107.50	Acetone (kg)	21.50				
		MeOH (kg)	161.92	MeOH (kg)	8.10				
		KOH (kg)	5.38			KOH (kg)	3.23		
	Water	(kg)	690.00						
		(US $)	0.4						

				Output			
No	**Process**	**Input**		**Air**	**Water**	**Co-/products**	
	Electricity & heat	(MJ)	171.58				
		(US $)	2.85				
	Transport	tkm	5.87				
		(US $)	4.54				
	Labor cost	(US $)	4.08				
	Tax and insurance	(US $)	1.39				
	Maintenance	(US $)	35.20				
	Wastewater treatment	(US $)	15.80				
	Biodiesel (Roselle-Trau)					(kg)	1,000
						(US $)	766
	Glycerin					(kg)	100
						(US $)	50
	Trau oil (kg)					(kg)	2,300
						(US $)	4,610

- ***Biodiesel production***: The obtained crude oil was collected and transferred to a transesterification reactor to produce biodiesel. The transesterification process performed in 30 minutes with a methanol:to:oil molar ratio of 1:4 and 0.3 wt% KOH, and 10% (wt/wt) acetone as co-solvent. After the reaction, approximately 90% of acetone and 25% of methanol were recovered. Following the separation of glycerin, the solution was washed and dried. The conversion yield of biodiesel was around 99% and total 93% by mass was obtained from crude oil. Current capacity of biodiesel pilot plant of SATREPS project in Vietnam is 500 metric tons per year and will be upgraded to 1,500 metric tons per year;
- ***Blending***: Previous studies denoted that, although biodiesel from Roselle can meet almost quality requirements according to biodiesel standards of Vietnam (TCVN/QCVN) and other countries such as JIS K2390, ASTM D6175 and EN 14214 (Nakpong and Wootthikanokkhan 2010; Anwar et al. 2010; Nguyen and Otsuka 2016), the yield of Roselle seed (200 - 1500 metric tons ha^{-1}) was not as high as Trau seed (1,800 - 3,000 t ha^{-1}). However, Trau biodiesel was beyond almost requirements of biodiesel standards (Manh et al. 2011). Therefore, an optimal blend of Roselle biodiesel and Trau biodiesel was considered as a sufficient solution. It was showed that the

volumetric mixture of 70% Roselle biodiesel and 30% Trau biodiesel was an appropriate combination (Nguyen and Otsuka 2016).

- ***Distribution and combustion***: Neat biodiesel (B100) was blended with petrodiesel and distributed to cruise ship port in Ha Long Bay.
- ***Transportation***: The transportation of input materials and output products and co-products was also analyzed in this study.

7.3.4 Scenarios development

The application of several biodiesel blends was contemplated, including the volumetric blend of 5% biodiesel and 95% petrodiesel (B5), 10% biodiesel and 90% petrodiesel (B10), and 20% biodiesel and 80% petrodiesel (B20).

7.3.5 Sensitivity analysis approach

Sensitivity analysis was conducted to determine and estimate which factors influence the Triple I and its parameter. Several conditions were considered as follows:

- Fuel price: According to annual fuel price record and focus of U.S. EIA from January 2016 to June 2018, the lowest price and highest price of fuel were around 20% lower and 15% higher than the current price of fuel, respectively (U.S. EIA 2017). Therefore, two scenarios were made following the 20% decrease and 15% increase in fuel prices.
- Regarding Roselle yield: The best case was set based on provided data of some farmers in the North of Vietnam, the maximum yield of Roselle fruits was ten metric tons per hectare which mean approximately 2.2 tons of seeds. The worst case was set following the average lowest yield of one tree reported at the Project annual meeting (Pham 2016) in other countries which leading to the 45% decrease in Roselle yield.
- Trau seed yield: Since the yield of Trau strongly depended on the condition of soil and weather and the rate of male and female flowers in the tree (Tran 1996), the scenarios which analyzed 20% increase and a decrease of Trau seed yield were made.
- Since many studies claimed that one disadvantage of biodiesel system was using petrodiesel for transportation of raw materials and distribution of biodiesel. In order to see how it affected the system, three abstractions were developed in which, B100 was used for the all the transportation within the system including both raw materials and

biodiesel and co-products transport made following a ten-time increase of input materials transport distance and biodiesel transport distance.

- Agriculture, especially the use of fertilizer was the most contributor to the ecosystem impacts of the biodiesel production system (Achten 2010; Rajagopal and Zilberman 2007). Thus, two scenarios were made according to the 50% increase and a decrease of fertilizer use.

7.4 RESULTS AND DISCUSSION

7.4.1 Differences in exhaust gasses impacts of petrodiesel and biodiesel and its blends

Fig. 7.2 illustrates the different impacts of exhaust gasses between petroleum (B0) and various biodiesel blends. As the higher rate of nitrogen dioxide in exhaust gasses, biodiesel system denoted a little more harmful to the ecosystem than petrodiesel. Fortunately, due to the lesser of toxic compounds, the combustion of B100 and its blends resulted in about 73% maximum reduction in potential impacts on human health compare to petrodiesel.

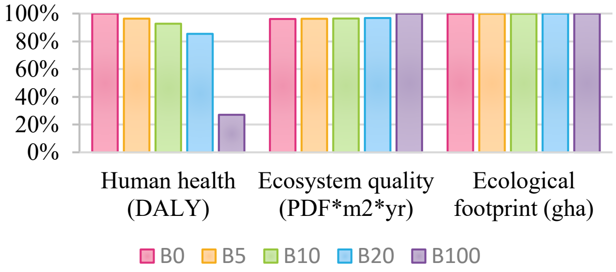


Fig. 7.2 Exhaust gas impacts of different biodiesel blends

7.4.2 Human health and ecosystem quality impacts

Table 7.7 summarized main findings from LCA and LCC of the biodiesel system in Ha Long Bay.

Overall, biodiesel system showed fewer impacts on human health than petrodiesel. The more biodiesel existed in the blend, the lesser impacts on human health were observed. The share in the total impacts of main processes in the life cycle of B100 is described in Fig. 7.3. Accordingly, the extraction of seed and the combustion of fuel were the first and second largest contributors to human health impacts. These were on account of solvent releases in oil extraction plant and toxic compounds in the exhaust gasses from a cruise ship, respectively. It was noteworthy that the total human health impacts of B100 system were only half of which caused by petrodiesel system.

Table 7.7 Main results from LCA and LCC

	B0	B5	B10	B20	B100
Human health (DALY pers^{-1} yr^{-1})	52,208	50,935	49,675	47,128	26,801
Ecosystem quality (PDF m^{-2} yr^{-1})	9,217,934	43,906,412	77,800,595	145,513,536	687,239,501
Ecological footprint (gha)	16,758	10,251	3,769	-9,249	-113,402
Biocapacity (gha)	N/A**	206	412	273	-4,216
Land occupation (ha)	0	2,336	4,672	9,343	46,716
Capital costs* (US$)	N/A	289,371	578,744	1,157,487	5,785,467
Operating costs (US$)	N/A	20,493,241	24,539,216	32,684,639	97,548,227
Benefit (US$)	N/A	25,721,314	37,523,343	61,108,049	249,823,439
Payback period (year)	N/A	8.41	6.06	5.38	4.93

Note: *Average capital cost allocated for 30 years of project lifetime with the discount rate of 3.74%.

**N/A: Data which were not considered in this study.

In the context of ecosystem quality, it was a reverse situation. The burden on the ecosystem of biodiesel was significantly higher than that of petroleum. Most of the impacts were owing to the application of fertilizer in the Roselle-Trau cultivation which accounted for roughly 90% of total ecosystem impacts.

7.4.3 Net Carbon Dioxide emissions

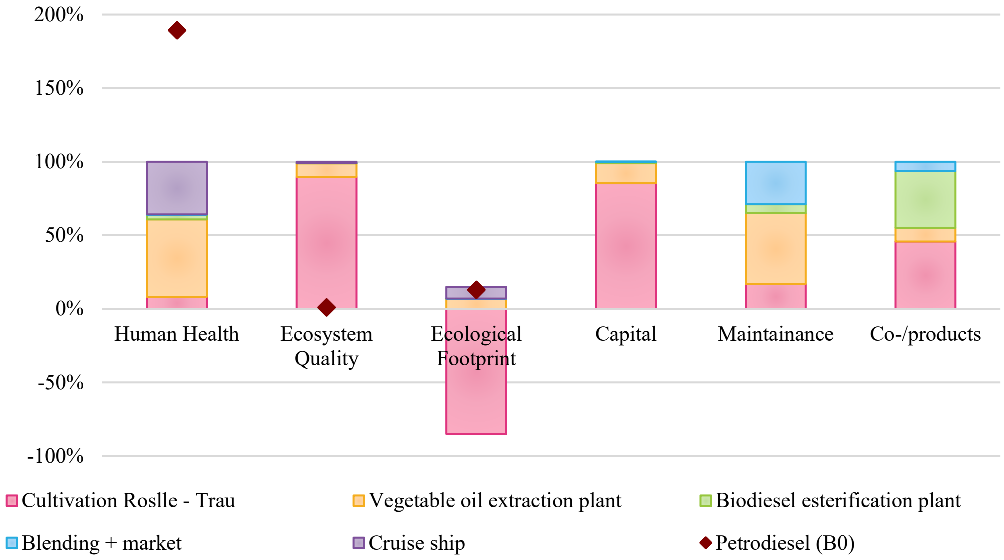


Fig. 7.3 Contribution of unit processes in total life cycle impacts of B100 compare to petrodiesel system

The level of carbon dioxide uptake by standing Trau trees was beyond the total carbon dioxide emitted from various activites in the whole life cycle of biodiesel system. Consequentially, there were minus values of the ecological footprint in B20 and B100 systems and a considerable reduction in the outcome of ecological footprint in B5 and B10 systems comparing to petrodiesel system.

In this study, the results about the impacts of biodiesel's life cycle system on human health, ecosystem quality and net carbon dioxide were by previous studies (CheHafizan and Noor 2013; Achten 2010; Rajagopal and Zilberman 2007; Janda, Kristoufek, and Zilberman 2012).

7.4.4 Biocapacity

The results recorded the gain in biocapacity in B5, B10, and B20 system. B100 system, unfortunately, presented an ecological footprint by extended land occupation. The land requirement data claimed the provision of up to blend B13 (13 vol.% biodiesel and 87 vol.% petrodiesel) under the circumstance of Quang Ninh Province. Nevertheless, B20 system still resulted in positive biocapacity due to the trade-off between the productive value gain from converting degraded land to arable land and the enlarged arable land occupation.

In general, biodiesel systems of all blends proved a noticeable mitigation in ecological footprint referring to petrodiesel system.

7.4.5 Economic evaluation

The cost and benefit estimation of various biodiesel blend systems were conducted following LCC method (Table 7.7 & Fig. 7.3). The results indicated the highest share of agriculture in total capital cost. This was mostly due to the large area need to produce a certain amount of biodiesel, land preparation and seedlings in the post-cultivation stage were the most money consuming processes. Payment for the operation and maintenance of biodiesel systems, nevertheless, mostly went to biodiesel plant which covered all biodiesel production processes from vegetable oil extraction process to vegetable oil esterification and biodiesel blending. Benefits of the whole system were a half from agriculture (Roselle calyces) and a half from the biodiesel plant (biodiesel, glycerin, sugar, Vitamin E and Phytosterol). As the system of higher blends showed higher revenue, the payback period declined from B5 to B100 systems. According to these data, it is possible to state the economic efficiency of the studied system, and the investment for installing the whole biodiesel system should firstly consider about the agricultural stage.

7.4.6 Triple I

Fig. 7.4 presents all the parameters of Triple I after applying conversion factors and Triple I values of the four biodiesel blends. Although neat biodiesel (B100) had the highest impact on the ecosystem quality and land occupation (presented in the minus value of biocapacity), it supported for a significant decrease in human health impacts and ecological footprint. Moreover, the revenue from B100 system was also the highest. When the value of Triple I is less than zero, the studied system is identified as a sustainable system. As shown in Fig. 7.4, out of the four blends, only the B100 system proved the sustainability. Since other blends still used petrodiesel in their final products, the human health effects were particularly high and less revenue. Therefore, it can briefly conclude that the biodiesel system in term of blend use is not sustainable. However, the biodiesel system was proposed in order to combat with natural resources depletion and supposed to reduce the amount of petrodiesel use. Furthermore, the existence of biodiesel was not expected to raise the total fuel consumption or to form a new fuel system in parallel with petroleum system. As an alternative source, biodiesel system should be considered under the business-as-usual scenario (with 100% petrodiesel use) to delineate what human beings and the environment could gain from implementing this system. Therefore, the different influences between the current petroleum system and the execution biodiesel system were incorporated into Triple I and its parameter, hereinafter referred to as avoided scenarios. It is indicated that, when cruise ships in Ha Long Bay use biodiesel and its blends instead of neat petrodiesel, all of the biodiesel systems are sustainable. Results of Triple I payback time for biodiesel system with/without petrodiesel avoided is introduced in Table 7.8. Because B5, B10 and B20 system was only considered as sustainable systems under petrodiesel avoided scenario, there was no payback time for these systems in the normal case. According to petrodiesel avoided scenario, similar to cost payback time, Triple I payback time also decreased as the composition of biodiesel in the blend increased since the B100 show more sustainable potential. It is necessary to note that the Triple I payback time was smaller the cost payback time of the same blend. This trend demonstrated for a higher advantage of biodiesel system since it also benefited the human being and the environment.

7.5 SENSITIVITY ANALYSES

Triple I and its parameters were put under difference conditions (Fig. 7.5 & Fig. 7.6) to examine which factors could affect the system. Different analyzed cases were as follows:

- Case 1: B100 was used for the transportation of raw materials and biodiesel and co-products;
- Case 2 and case 3: 15% increase and 20% decrease in fuel price, respectively;
- Case 4 and case 5: Roselle seed yield increase to 2.2 ton/ha and decrease 45%, respectively;
- Case 6 and case 7: Trau seed yield increase and decrease by 20%, respectively;
- Case 8 and case 9: The distance for biodiesel and it blends transportation increase to 50km and 300km, respectively;
- Case 10 and case11: Total fertilizer use increase and decrease by 50%, respectively;
- Case 12: 50% decrease in price of all co-products

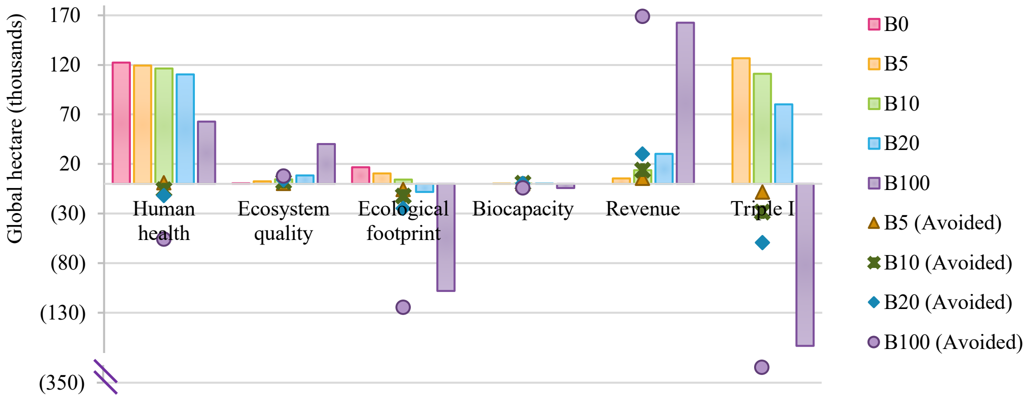


Fig. 7.4 Sustainability evaluation and total life cycle impacts of different biodiesel blends by global hectare

Table 7.8: Payback time of the sustainable system

	B5	**B10**	**B20**	**B100**
Triple $I_{payback}$ (year)	-	-	-	1.2
Avoided- Triple $I_{payback}$ (year)	0.8	0.4	0.3	0.2

Within the 12 cases, the responses of Triple I's parameters were varied. Overall trends of the influence on parameters of Triple I showed that the use of neat biodiesel for the transportation (Case 1), the increase and decrease of fuel price (Case 2 and 3) did not affect much on all the parameters and Triple I final results.

The most affected and controversy factor to the whole system was the yield of Roselle (case 4 and case 5). As the decrease and increase of Roselle yield, the significant fluctuation of all parameters was observed. The diminish of Roselle seed yield resulted in more impacts on human health, ecosystem quality and decreased the biocapacity. Meanwhile, it lowered the ecological footprint and increased the net revenue. The explanation for this case was because Roselle biodiesel shares the higher part in the Roselle-Trau biodiesel mixture when the yield decreases, the cultivation area needs to be extended to fulfill the annual fuel demand. As discussed in section 7.4.2, agriculture practice and oil extraction process were the most contributors to the ecosystem quality and human health impact, respectively. Hence, the more area used for the propagation the more impacts on human health. Moreover, if the same intercropping system is applied to the extended area, the increase of Trau seeds would raise the amount of solvent used for the oil extraction which also means to have more effect on human health. This system will just produce more co-products with no-efficiency of fuel production. Furthermore, revenues from all biodiesel systems noticeably affected by the change in Roselle yield, Trau yield, fertilizer use and the price of co-products. Other factors affected the system were the use of fertilizer (case 10 and case 11) which cause more human health impacts and the increase in the distance of biodiesel distribution. The two factors, nevertheless, only showed the significant impact on the B100 system. Moreover, overall, the B100 system was the most sensitive to different influences.

Regarding the result of Triple I (Fig. 7.6), when considering biodiesel system as an independent factor for energy production, only B100 shows the sustainable of the system. As an alternative to petrodiesel, the use of biodiesel of all blends from B5 shows the sustainable value.

However, the sustainability of the B5 system was right on edge between sustainable and unsustainable one and even almost became unsustainable when the price of co-products deceased and the Roselle yield increase. This raised the extremely economically dependent issue of the B5 system. As the upshot of Triple I, fertilizer use only show the substantial impacts on the B100 system. Of the 12 factors, only the change in the yield of Roselle showed significant impacts on all of the blends.

Integrating Triple I's results and the context of Quang Ninh, the sustainability of the biodiesel system would occur if the implementation complies with the following principles:

- The cultivation area would not exceed the total area of open-pit mining and mining dumpsite to prevent the land occupation side-effect of oil crops cultivation. This issue is supported by the suggestion from Fargione and his colleagues that the cultivation of oil crops should be placed on marginal land to reduce the carbon footprint and avoid the conflict with food crops and food security (Fargione et al. 2008);
- Moreover, data about land use of each biodiesel presented that within current seed yield the biodiesel system in Ha Long can provide up to blend B13. In the best case, if Roselle

seed reached the yield of 2.2 metric tons per year, the system could provide up to B20 blends;

- Since the results of this study proved that the transport of up to 300km did not significantly affect all the parameters and final result of Triple I, Roselle seeds for oil extraction could be transport from surrounding areas to increase the amount of qualified biodiesel in this area;
- Acting as an alternative to petrodiesel, biodiesel systems of all the studied blends, including B5, B10, B20 and B100, demonstrated their promising potential of an enviro-economic benefited renewable sources. However, the sustainability determination of the higher blends were higher than the lower ones. Subsequently, under the certain circumstance, the application of higher biodiesel blends is recommended.
- It is worth to note that the replacement of petrodiesel contributed to the great enhancement in human health. Biodiesel system, nevertheless, led to the diminution of ecosystem quality. As the increase of biodiesel proportion in the blend, its pros and cons increased respectively.

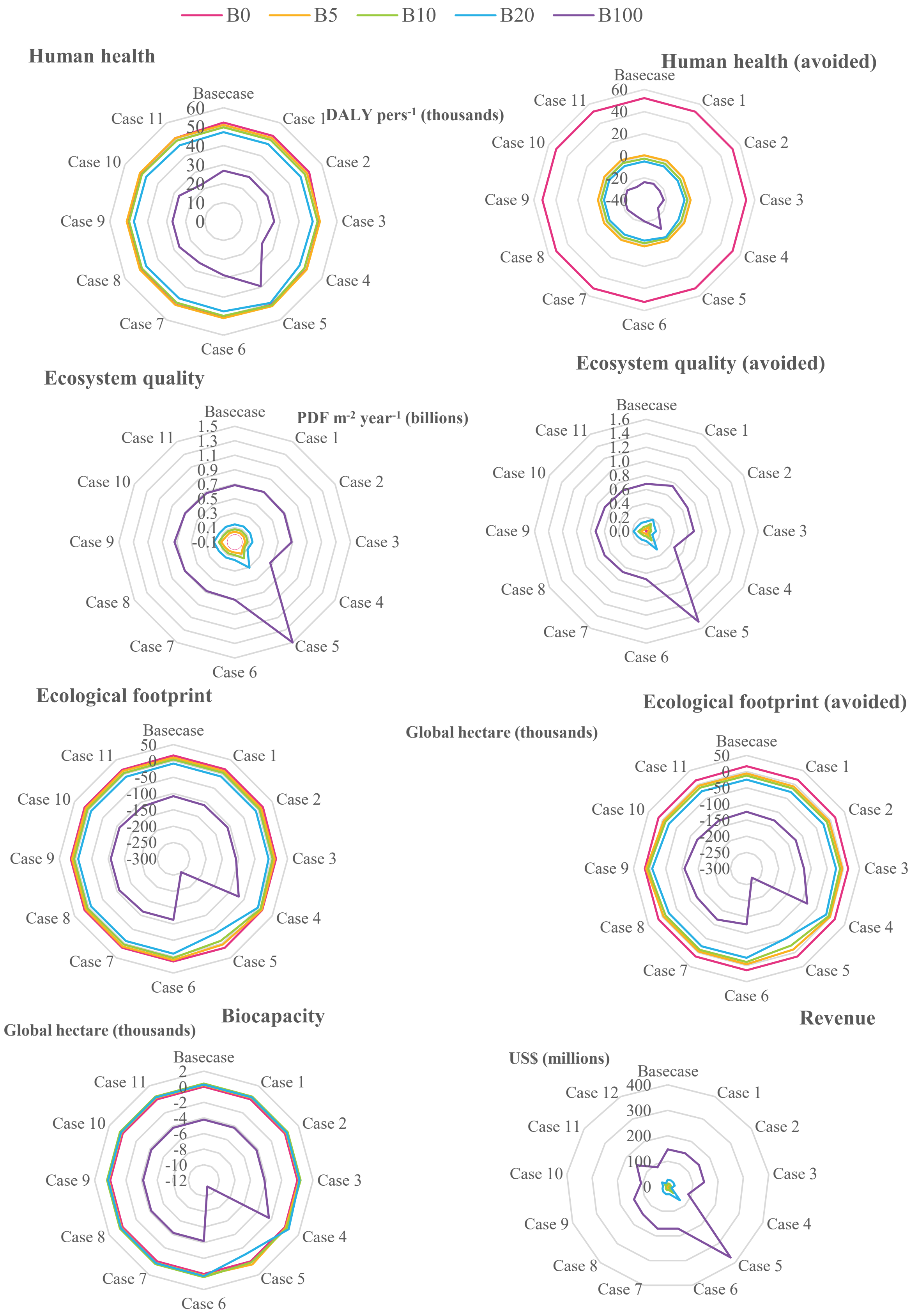
Overall, an appropriate biodiesel system has to be neutral and balance between the three-pillar of sustainable development, including economic impacts, environmental impacts and social impacts (World Commission on Environment and Development 1987; Elkington 1998). Taking into account all the discussed factors, a biodiesel system of up to B20 is preferred. Moreover, considering the stability of the biodiesel system, the higher blends of B10 and B20 area highly recommended. Similar with the findings from this study, U.S Department of Energy also indicates the equilibrium of B20 since it presents ‘a good balance of cost, emissions, cold-weather performance, and materials compatibility’ (Alternative Fuels Data Center 2016). Moreover, the application of up to B20 does not require diesel engine modification, and have similar engine performance with neat petrodiesel (No 2011).

7.6 CONCLUSIONS

Triple I framework developed in the Part I of this studied was applied to estimate the sustainability of 4 blends including B5, B10, B20, and B100. The result noted the sustainability of B100 system even if it was evaluated as a stand-alone system. Although the lower blends did not reach the sustainability level, if considering them as an alternative fuel sources of petrodiesel, the trade-off between the two applications led to the sustainability of the lower blend systems. Since the most importance issue for a sustainable enviro-economic decision is an equilibrium of various dimensions including human being security, ecosystem and environment protection and economic development, the utilization of B20 system was highly recommended.

Moreover, Triple I payback time required to recover the installation burden of the biodiesel system was less than cost payback time of the relevant system. This result strongly asserted the multi-dimensional benefits of biodiesel system.

Fig. 7.5 Sensitive analysis of factors affected Triple I's parameters


Human health

Human health (avoided)

Ecosystem quality

Ecosystem quality (avoided)

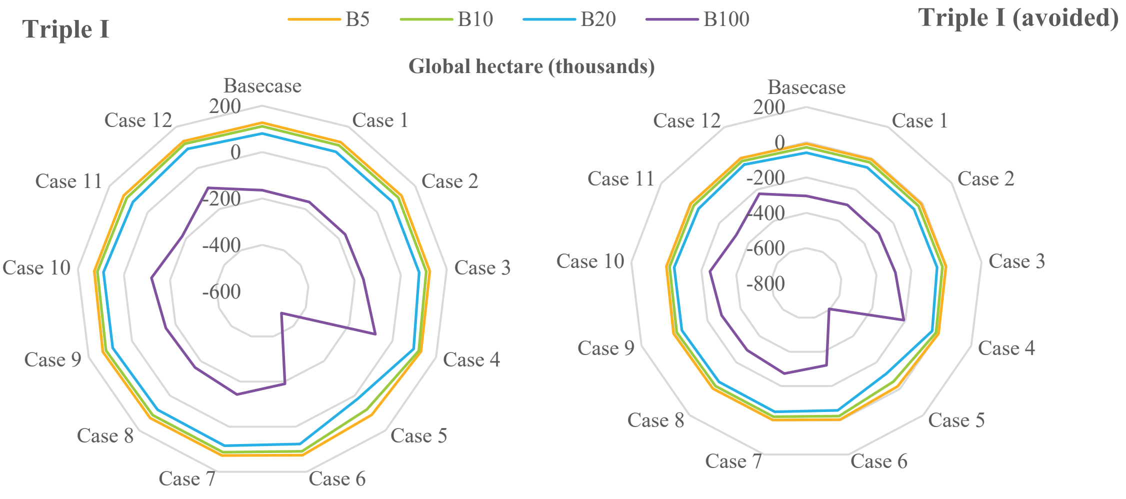
Ecological footprint

Ecological footprint (avoided)

Biocapacity

Revenue

Fig. 7.6 Sensitive analysis of factors affected the sustainability of biodiesel system



REFERENCES

Achten, Wouter. 2010. "Sustainability Evaluation of Biodiesel from Jatropha Curcas L . A Life Cycle Oriented Study." University of Leuven.

Al Shooshi, Wafa Gamal Abdalh. 1997. "Chemical Composition of Some Roselle (Hibiscus Sabdariffa) Genotypes." University of Khartoum.

Alternative Fuels Data Center. 2016. "Biodiesel Blends." Accessed November 10. www.afdc.energy.gov/fuels/biodiesel_blends.html.

Anwar, Farooq, Umer Rashid, Muhammad Ashraf, and Muhammad Nadeem. 2010. "Okra (Hibiscus Esculentus) Seed Oil for Biodiesel Production." *Applied Energy* 87 (3). Elsevier Ltd: 779–85. doi:10.1016/j.apenergy.2009.09.020.

AQEQ. 2011. "Road Transport Biofuels: Impact on UK Air Quality."

Atabani, A. E., A. S. Silitonga, H. C. Ong, T. M I Mahlia, H. H. Masjuki, Irfan Anjum Badruddin, and H. Fayaz. 2013. "Non-Edible Vegetable Oils: A Critical Evaluation of Oil Extraction, Fatty Acid Compositions, Biodiesel Production, Characteristics, Engine Performance and Emissions Production." *Renewable and Sustainable Energy Reviews* 18. Elsevier: 211–45. doi:10.1016/j.rser.2012.10.013.

Azadi, Pooya, George Brownbridge, Sebastian Mosbach, Andrew Smallbone, Amit Bhave, Oliver Inderwildi, and Markus Kraft. 2014. "The Carbon Footprint and Non-Renewable Energy Demand of Algae-Derived Biodiesel." *Applied Energy* 113 (128): 1632–44. doi:10.1016/j.apenergy.2013.09.027.

Bernál, Marcelo, Rosana De Cassia, De Souza Schneider, and Enio Leandro Machado. 2014. "Environmental Assessment of the Tung Cultivation through Life Cycle Analysis" 3 (1): 70–74. doi:10.14419/ijet.v3i1.1597.

Biriok, George Stephen. 2012. "Production and Performance Evaluation of Biodiesel from Hibiscus Sabdariffa and Hibiscus Surattensis." Ahmadu Bello University.

Brewer, Roger, Josh Nagashima, Michael Kelley, Marvin Heskett, and Mark Rigby. 2013. "Risk-Based Evaluation of Total Petroleum Hydrocarbons in Vapor Intrusion Studies." *International Journal of Environmental Research and Public Health* 10 (6): 2441–67. doi:10.3390/ijerph10062441.

Charman, Nick, Nigel Edmonds, Marika Egyed, and Mathieu Rouleau. 2012. *Human Health Risk Assessment for Biodiesel Production, Distribution and Use in Canada*. Ottawa: Health Canada.

CheHafizan, and Zaimon Zainura Noor. 2013. "Biofuel: Advantages and Disadvantages Based on Life Cycle Assessment (LCA) Perspective." *Journal of Environmental Research and Development* 7 (4): 1444–49.

Davis, Megan, Regina Coony, Scott Gould, and Allan Daly. 2005. *Guidelines for Life Cycle Cost Analysis*. Standford: Stanford University. doi:10.1080/15732470701322818.

DeMello, Jared a., Catherine a. Carmichael, Emily E. Peacock, Robert K. Nelson, J. Samuel Arey, and Christopher M. Reddy. 2007. “Biodegradation and Environmental Behavior of Biodiesel Mixtures in the Sea: An Initial Study.” *Marine Pollution Bulletin* 54 (7): 894–904. doi:10.1016/j.marpolbul.2007.02.016.

Dilip, G.V. Prudhvi, and K. Appa Rao. 2015. “Performance and Emission Analysis of a Four Stroke Diesel Engine Fueled with Hibiscus Oil.” *International Journal of Engineering Research & Technology* 4 (7): 1183–86. doi:http://dx.doi.org/10.17577/IJERTV4IS070796.

Duke, James A. 1983. *Handbook of Energy Crops*. https://hort.purdue.edu/newcrop/duke_energy/Hibiscus_sabdariffa.html.

EIA. 2012. “Country Analysis Briefs: Vietnam.”

Elkington, J. 1998. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Conscientious Commerce. New Society Publishers. https://books.google.co.jp/books?id=dIJAbIM7XNcC.

FAOSTAT. 2017. “Crop Statistics.” *Food and Agriculture Organization of the United Nations (FAO)*. http://www.fao.org/faostat/en/#data.

Fargione, Joseph, Jason Hill, David Tilman, Stephen Polasky, and Peter Hawthorne. 2008. “Land Clearing and the Biofuel Carbon Debt.” *Science* 319 (5867): 1235–38. doi:10.1126/science.1152747.

General Department of Vietnam Customs. n.d. “Custom Trade Statistics - Scheduled Data.”

Hainida, Emmy, Amin Ismail, Normah Hashim, Norhaizan Mohd.-Esa, and Ainul Zakiah. 2008. “Effects of Defatted Dried Roselle (Hibiscus Sabdariffa L.) Seed Powder on Lipid Profiles of Hypercholesterolemia Rats.” *Journal of the Science of Food and Agriculture* 88 (6). John Wiley & Sons, Ltd.: 1043–50. doi:10.1002/jsfa.3186.

Huijbregts, Mark A.J., Stefanie Hellweg, Rolf Frischknecht, Konrad Hungerbühler, and A. Jan Hendriks. 2008. “Ecological Footprint Accounting in the Life Cycle Assessment of Products.” *Ecological Economics* 64 (4): 798–807. doi:10.1016/j.ecolecon.2007.04.017.

Huppes, Gjalt, Martijn van Rooijen, René Kleijn, Reinout Heijungs, Arjan de Koning, and Lauran van Oers. 2004. “Life Cycle Costing and the Environment.” Leiden, Netherlands.

IPCC. 2006. “Chapter 2 - Energy.” In *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, 2.1-2.95. Intergovernmental Panel on Climate Change (IPCC). http://www.ipcc-nggip.iges.or.jp/public/gp/english/2_Energy.pdf.

Janda, Karel, Ladislav Kristoufek, and David Zilberman. 2012. “Biofuels: Policies and Impacts.” *Agricultural Economics (Czech Republic)*, CUDARE Working Paper Series, 58 (8). University of California at Berkeley, Department of Agricultural and Resource Economics and Policy: 372–86.

Jindal, S., and K Goyal. 2012. “Evaluation of Performance and Emissions of Hibiscus Cannabinus (Ambadi) Seed Oil Biodiesel.” *Clean Technologies and Environmental*

Policy 14 (4): 633–39. doi:10.1007/s10098-011-0426-5.

Jungbluth, N, Mike Chudacoff, A. Dauriat, F. Dinkel, G. Doka, M. Faist Emmenegger, E. Gnansounou, et al. 2007. "Life Cycle Inventories of Bioenergy." *Ecoinvent Report No.17*. Dübendorf, Switzerland. http://www.researchgate.net/publication/230725648_Life_Cycle_Inventories_of_Bioenergy._ecoinvent_report_No._17/file/9c96051b76e2fb8dce.pdf.

Klein, J., J. Hulskotte, Norbert Ligterink, and Gerben Geilenkirchen. 2016. "Methods for Calculating the Emissions of Transport in the Netherlands." http://www.emissieregistratie.nl/erpubliek/documenten/Lucht (Air)/Verkeer en Vervoer (Transport)/Methoderapporten Taakgroep Verkeer en Vervoer/Klein et al. (2016) Methods for calculating the emissions of transport in the Netherlands.pdf.

Kristensen, Hans Otto. 2012. "Energy Demand And Exhaust Gas Emissions of Marine Engines." http://www.skibstekniskselskab.dk/public/dokumenter/Skibsteknisk/Foraar 2013/25.02.2013/WP 2 - Report 5 - Energy demand and emissions of marine engines - December 2012.pdf.

Kumar, Rajneesh. 2013. "Process Optimization for Biodiesel Production from Tung (Aleurites Fordii .) Oil and Its Emissions Characteristics."

Lapuerta, Magín, Octavio Armas, and José Rodríguez-Fernández. 2008. "Effect of Biodiesel Fuels on Diesel Engine Emissions." *Progress in Energy and Combustion Science* 34 (2): 198–223. doi:10.1016/j.pecs.2007.07.001.

Le, Viet Trung, Quoc Viet Tran, and Van Chat Pham. 2016. "An Overview of Vietnam's Oil and Gas Industry." *Petrovietnam Journal* 10: 64–71.

Lin, David, Laurel Hanscom, Jon Martindill, Michael Borucke, Lea Cohen, Alessandro Galli, Elias Lazarus, et al. 2016. *Working Guidebook to the National Footprint Accounts: 2016 Edition*. Oakland: Global Footprint Network. http://www.footprintnetwork.org/images/article_uploads/NFA 2014 Guidebook 7-14-14.pdf.

Manh, Do Van, Yi-hung Chen, Chia-chi Chang, Mei-chin Chang, and Ching-yuan Chang. 2011. "Biodiesel Production from Tung Oil and Blended Oil via Ultrasonic Transesterification Process." *Journal of the Taiwan Institute of Chemical Engineers* 42 (4). Taiwan Institute of Chemical Engineers: 640–44. doi:10.1016/j.jtice.2010.11.010.

McClintock, N.C., and I.M. El Tahir. 2004. "Hibiscus Sabdariffa L." In *Plant Resources of Tropical Africa 2. Vegetables*, edited by G.J.H. Grubben and O.A. Denton, 668. Wageningen, Netherlands: PROTA Foundation. https://books.google.co.jp/books?id=6jrlyOPfr24C.

Morton, Julia F. 1974. "Renewed Interest in Roselle (Hibiscus Sabdariffa L.), the Long-Forgotten 'Florida Cranberry.'" *Florida State Horticultural Society*, 415–25.

Morton, Julia Frances. 1987. *Fruits of Warm Climates*. Miami, FL: Julia F. Morton.

Nakpong, Piyanuch, and Sasiwimol Wootthikanokkhan. 2010. "Roselle (Hibiscus Sabdariffa L .) Oil as an Alternative Feedstock for Biodiesel Production in Thailand." *Fuel* 89 (8).

Elsevier Ltd: 1806–11. doi:10.1016/j.fuel.2009.11.040.

National Research Council (U.S). 1975. *Petroleum in the Marine Environment*. Washington, DC: National Academy of Sciences.

Nguyen, Tu Anh, and K Otsuka. 2016. "Comparing Environmental Impacts of Biodiesel and Petroleum Diesel Spills from Cruise Boats in Ha Long Bay." In *OCEANS 2016 MTS/IEEE Monterey*, 6. IEEE. doi:10.1109/OCEANS.2016.7761435.

Nipakhonsom, Kittiya, Phairat Usubharatana, Harnpon Phungrassami, and Woranee Paengjuntuek. 2012. "A Study Environmental Impact of Biodiesel Production from Tung Oil Using LCA Method." In *International Conference of Ecological, Environmental and Bio-Sciences (ICEEBS'2012)*, 83–86. Pattaya.

No, Soo Young. 2011. "Inedible Vegetable Oils and Their Derivatives for Alternative Diesel Fuels in CI Engines: A Review." *Renewable and Sustainable Energy Reviews* 15 (1). Elsevier Ltd: 131–49. doi:10.1016/j.rser.2010.08.012.

Pham, Danh Ngoc. 2016. "Development of Technology for Selection and Cultivation of Hibiscus at Dak Nong and Highland." In *Multi-Beneficial Measure for Mitigation of Climate Change in Vietnam and Indochina Countries by Development of Biomass Energy: Annual 2015 - Joint Coordinating Committee Meeting Report*. Hanoi, Viet Nam: SATREPS (Science and Technology Research Partnership for Sustainable Development.

Rajagopal, Deepak, and David Zilberman. 2007. "Review of Environmental, Economic and Policy Aspects of Biofuels." Policy Research Working Paper WPS4341. Policy Research Working Paper. Washington, DC: World Bank.

Sorate, K A. 2013. "Biodiesel as a Blended Fuel in Compression Ignition Engines." *International Journal of Research in Engineering and Technology* 2 (12): 417–20. doi:10.15623/ijret.2013.0212069.

Trading Economics. 2017. "Vietnam Inflation Rate." http://www.tradingeconomics.com/vietnam/inflation-cpi.

Tran, Quang Viet. 1996. "Research on Ecological Characteristics of Trau and Propagation Techquies to Increase Trau Fruit Yield (Góp Phần Nghiên Cứu Một Số Đặc Điểm Sinh Thái Cây Trẩu (Vernicia Montana Lour) và Một Số Biện Pháp Kỹ Thuật Trồng và Cải Tạo Rừng Trồng Để Tăng Sản Lượn." Vietnamese Academy of Forest Sciences.

U.S. EIA. 2017. "Short-Term Energy Outlook (STEO) Forecast Highlights." http://www.eia.gov/outlooks/steo/.

U.S. EPA. 2002. "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions-Draft Technical Report."

van der Ploeg, Sander, R.S. De Groot, and Yafei Wang. 2010. "The TEEB Valuation Database: Overview of Structure, Data and Results." Wageningen, Netherlands. www.fsd.nl.

Vietnamese Academy of Forest Sciences. 2009a. "Basic Techniques for Propagating Hibiscus Sabdariffa (Kỹ Thuật Trồng Cây Giâm Bụt Giấm)." http://vafs.gov.vn/vn/2009/03/ky-thuat-trong-cay-giam-but-giam/.

———. 2009b. “Basic Techniques for Propagating Trau (Vernicia Montana Lour.) (Kỹ Thuật Trồng Cây Trẩu Lá Xẻ).” http://vafs.gov.vn/vn/2009/03/ky?thuat?trong?cay?trau?la?xe?vernicia?montana?lour/.

Wang, Z, B P Hollebone, M Fingas, B Fieldhouse, L Sigouin, M Landriault, P Smith, J Noonan, G Thouin, and J W Weaver. 2003. “Characteristics of Spilled Oils, Fuels, and Petroleum Products: 1. Composition and Properties of Selected Oils.” *Environmental Protection*.

World Bank. 2016. “Data Extract From World Development Indicators.” http://databank.worldbank.org/data/home.aspx.

World Commission on Environment and Development. 1987. *Our Common Future*. Oxford; New York: Oxford University Press.

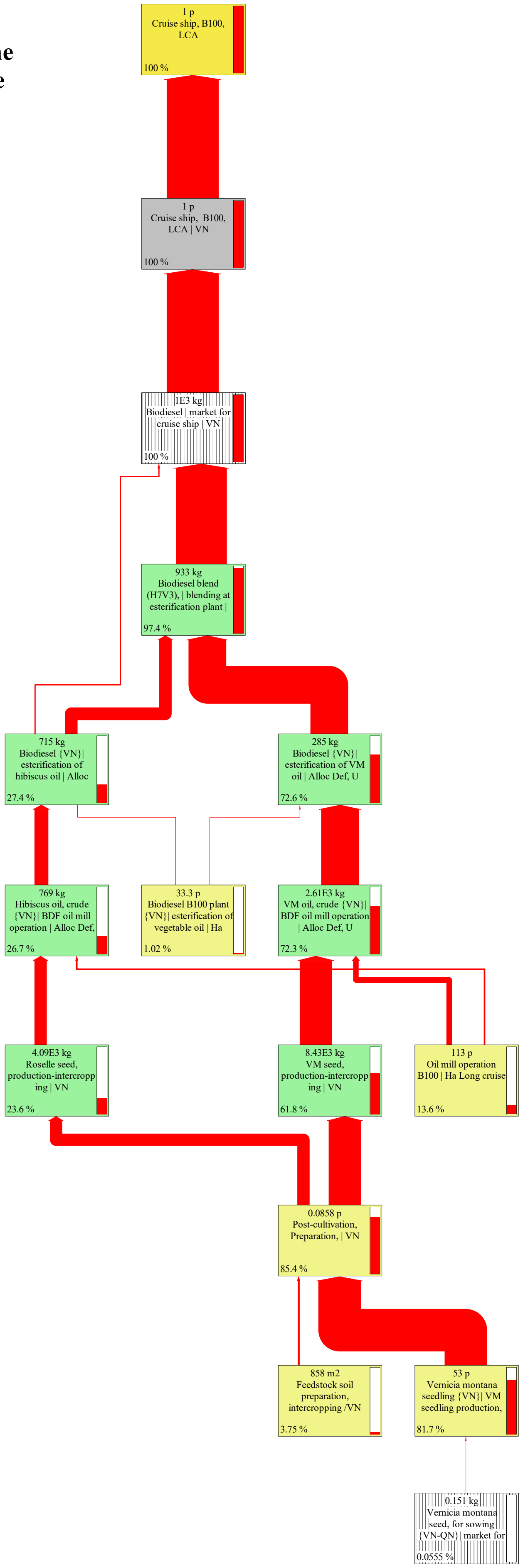


Fig. 7.7 Main requirement for the production and utilization of one metric ton biodiesel

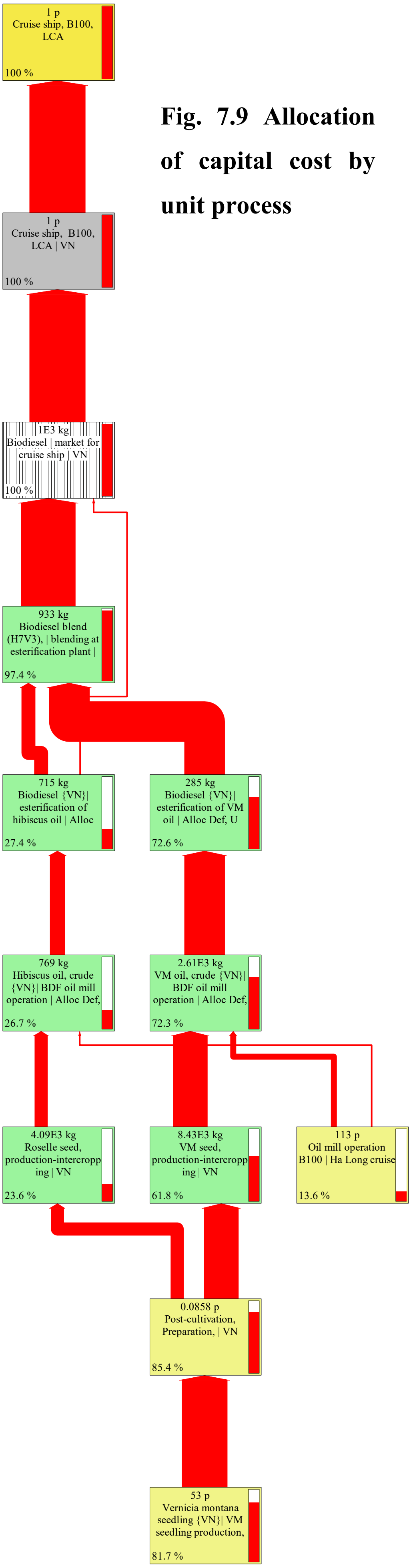


Fig. 7.9 Allocation of capital cost by unit process

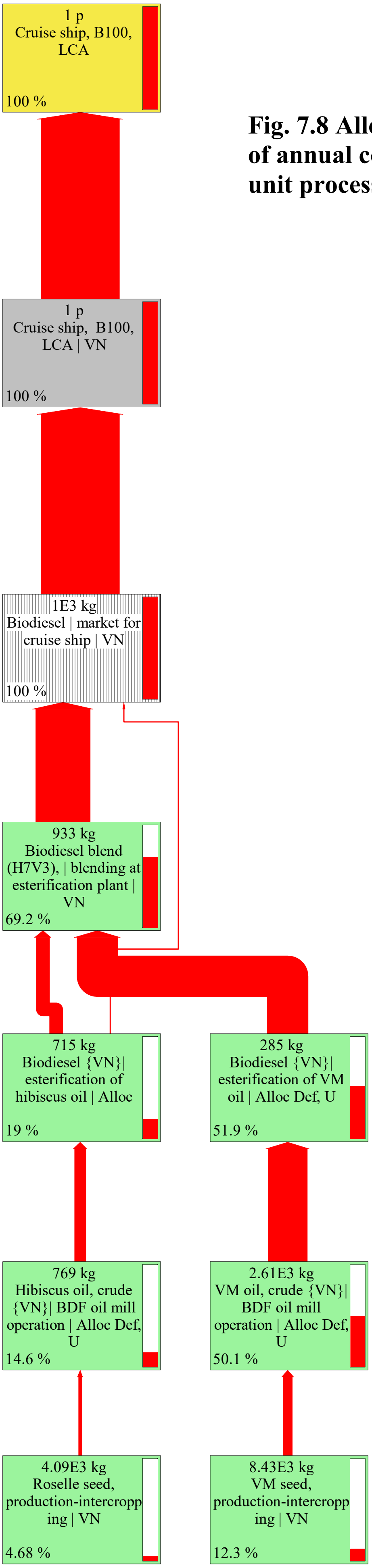
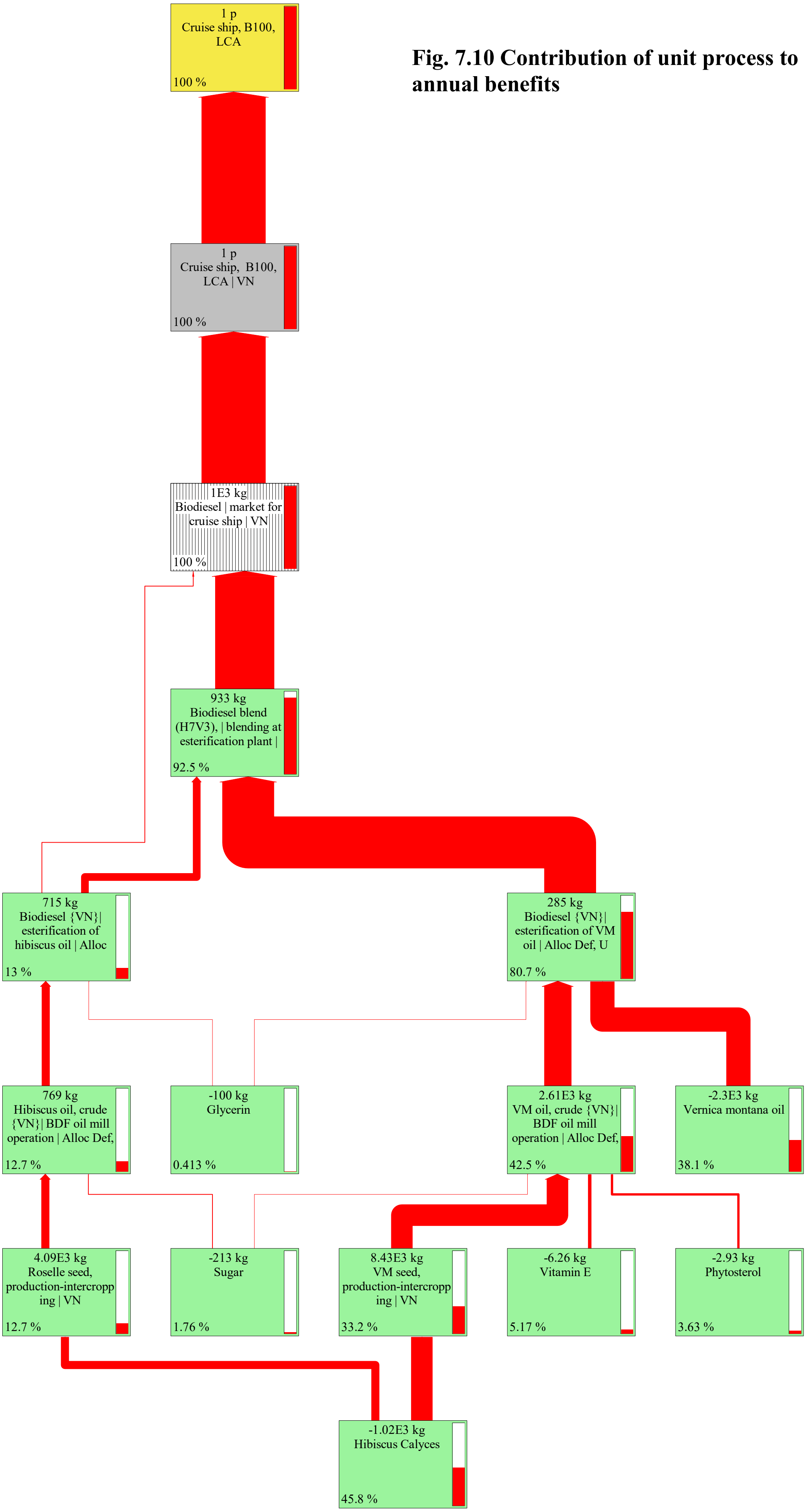


Fig. 7.8 Allocation of annual costs by unit process

Fig. 7.10 Contribution of unit process to annual benefits



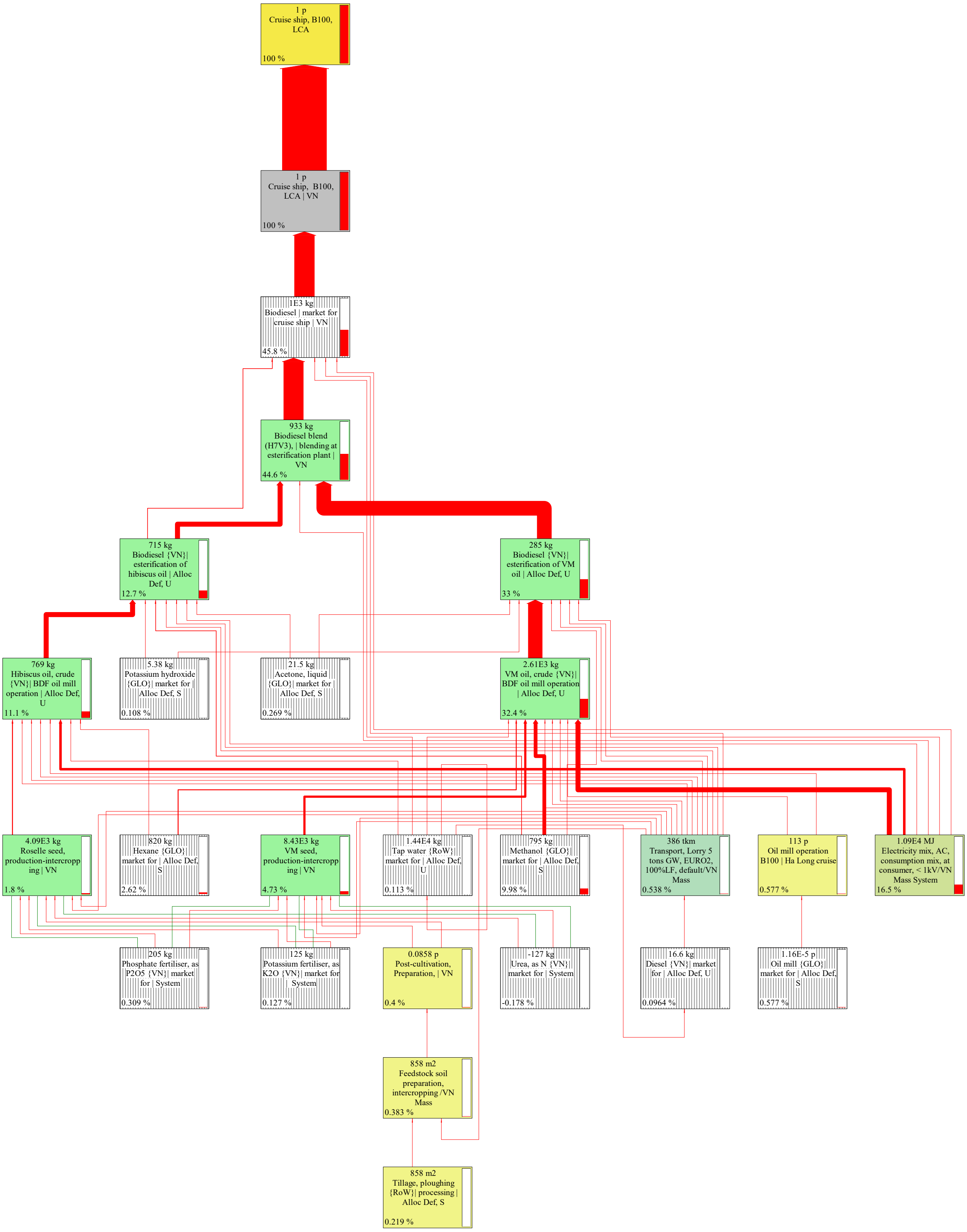


Fig. 7.11 Contribution of unit processes to DALY

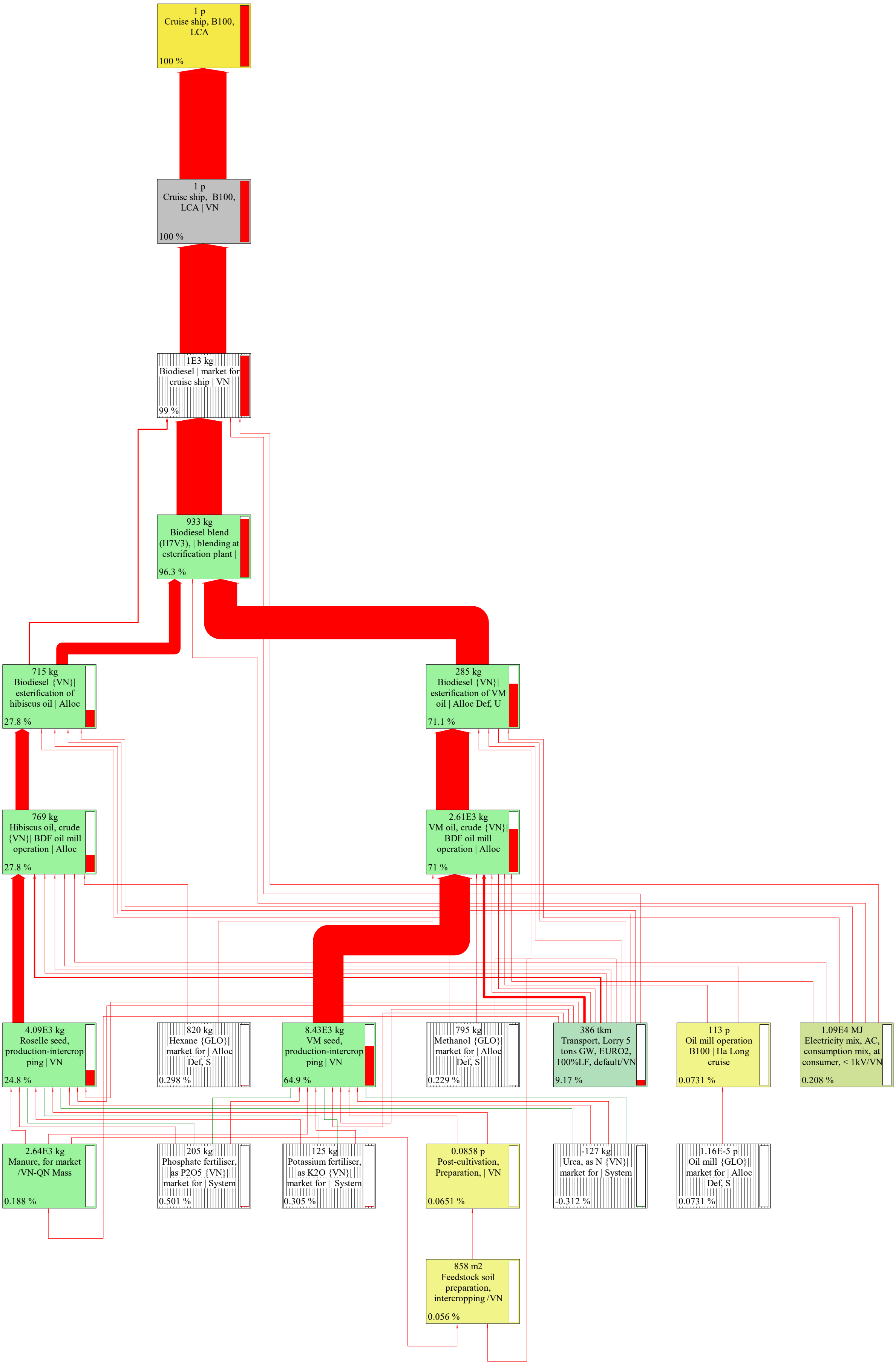


Fig. 7.12 Contribution of unit process to PDF

Note: The green color means the reduction in the ecosystem quality impacts,

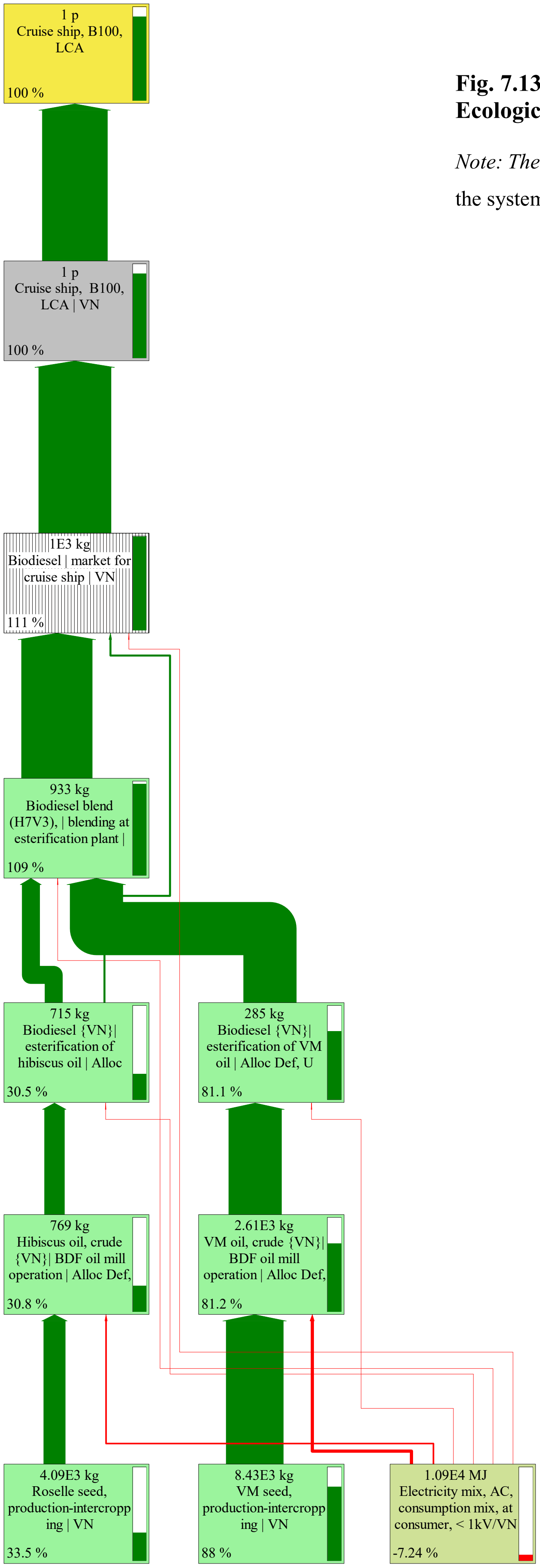


Fig. 7.13 Contribution of unit process to Ecological footprint

Note: The green color means increase in CO_2 absorption by the system.

Chapter 8 - GENERAL CONCLUSIONS

In this study, firstly, the linkage between the popular Life Cycle Sustainable Assessment framework and the quantitative sustainability assessment index namely Triple I was recognized and well developed. This would provide a proper tool for life cycle assessment community. Then, the sustainability of various blends of Roselle-Trau biodiesel was investigated. Recommendations related to situation of Ha Long was made.

With this study, I have fulfilled my two objectives which are to contribute to the sustainability assessment of renewable energy for transportation by proposing a methodical estimation for Triple I by integrating the index with the life cycle sustainability assessment framework; and to assess about the sustainability of Roselle and Trau as feedstocks for biodiesel production and utilization for cruise ship operation in Ha Long Bay. Some major contribution of this dissertation in summarized as follows:

Chapter 1 provides a general background of this dissertation. Firstly, an overview about biodiesel as an alternative to fossil fuel in transportation is given. Then, the current global trend of inedible vegetable oil-based biodiesel is introduced. In this part, several common inedible vegetable feedstocks for biodiesel production are reviewed and summarized. The aim of this study is clarified.

In ***Chapter 2***, a nationwide potential of biodiesel feedstock production based on data about land use of Vietnam is simulated. Several maps are made for each region of Vietnam with potential oil plants, cultivation areas, and yields. Finally, a whole map of Vietnam with biodiesel production rank is introduced. The map shows that the highest potential of oil plant cultivation belongs to mountainous provinces dwelling near the national border zones with considerable unused marginal lands and high rate of poverty.

Chapter 3 describes the state-of-the-art of the vegetable oil-based biodiesel production focusing on Vernicia montana L. (Trau) and Hibiscus sabdariffa L. (Roselle). This chapter sets out all the stages from cradle-to-grave of biodiesel production system in Ha Long Bay. The whole life cycle of biodiesel production in Ha Long Bay starts with the intercropping of Roselle-Trau in open-pit mines and mining dump sites (raw material acquisition); harvesting, sun-drying and transportation of oilseeds; extraction of oil and other medicines as co-products; co-solvent transesterification of Roselle-Trau crude oil to obtain biodiesel (methyl ester);

distribution and use of biodiesel in cruise ships in Ha Long Bay; and ending with the field application of Roselle leaves and Roselle-Trau de-oiled cake as composts to offset a certain amount of mineral fertilizer use according to their nutrient components.

Chapter 4 devotes to identify the linkage between Triple I and LCSA. By integrating LCSA, a methodical estimation for Triple I is proposed. In this chapter, promising options for the monetary evaluation of environmental impacts and human health impacts, which play as important conversion factors of various assessments under Triple I, are also recognized. Moreover, a more flexible application of Triple I is also propounded which accounts for the payback time of a project considering both environmental and economic burden.

Chapter 5 shows the result of the light-scale Triple I (only ecological footprint and economic issues were under consideration) applied to assess the sustainability of *Jatropha curcas* L. and waste cooking oil biodiesel production from gate-to-grave. The result profiles the unsustainability and much sensitive of the B5 system. Therefore, the development of B20 and above is recommended. The study in this chapter lays a foundation for the application of the full-scale Triple I presented in Chapter 7.

Chapter 6 projects the ecological risk of oil spills and leakages from the operation of cruise ships in the Bay. The purpose of this chapter is to provide data about potential ecotoxicity of the discharged fuel. The comparison is made between petrodiesel, neat biodiesel including Roselle biodiesel, Trau biodiesel, and Roselle70-Trau30 mixed biodiesel. ADIOS 2 – a simple oil weathering model and biodegradation and solubility of data of fuels are used for the estimation. It is stated that the cumulative water-accommodated fraction of neat biodiesel is from seven- to twenty-time lower than petrodiesel. There are, nonetheless, not evident enough to confirm the ecotoxicity of all examined fuels. The evaporation components of petrodiesel vapors should be taken into account since more than 70 percent of oil spill volatilized within the first five days.

Chapter 7 estimates the sustainability of Roselle-Trau biodiesel production system throughout its whole life cycle. The full-scale of Triple I is employed to evaluate the entire system under various scenarios. Triple I indicates the sustainability of neat biodiesel (B100) system itself. Unfortunately, other blends are not sustainable. When putting all the blends in the context of alternatives to fossil diesel, the implementation of the B5 system and higher blends providentially confirms their prominent potential as a sustainable energy source. Over whole life cycle stages of biodiesel production and utilization in Ha Long Bay, this system proves a substantial decrease in ecological footprint, which also results in an ecological reserve, comparing to petrodiesel system. Revenue of the biodiesel system is also considerably high due to the contribution of various co-products. Of all processes, nevertheless, the intercropping of Roselle-Trau and the extraction of crude oil from vegetable seeds show the highest burden on ecosystem quality and human health, respectively. Under a thorough consideration about nutrients, a possible solution for the agricultural practices is to replace mineral fertilizers with composts.

LIST OF PUBLICATIONS

No.	Title	Author(s)	Journal's/Conference's Name, Vol., Pages (year)	Corresponding Chapter
1	Inclusive Impacts Assessment for the Sustainability of Vegetable Oil-based Biodiesel. Part II: Sustainability Assessment of Inedible Vegetable Oil-based Biodiesel in Ha Long Bay, Vietnam	T. A. Nguyen Y. Maeda K. Kuroda K. Otsuka	Journal of Cleaner Production, submitted	Chapters 3 and 7
2	Inclusive Impacts Assessment for the Sustainability of Vegetable Oil-based Biodiesel. Part I: Linkage Between Inclusive Impact Index and Life Cycle Sustainability Assessment	T. A. Nguyen K. Kuroda K. Otsuka	Journal of Cleaner Production, submitted	Chapter 4
3	Possible Options for Risk Assessment in Inclusive Impact Index (Triple I)	T. A. Nguyen K. Kuroda K. Otsuka	Proceedings of the Seventh East Asia Workshop for Marine Environment and Energy (EAWOMEAN), 12 pages. (Keelung, Taiwan, 2015)	Chapter 4
4	Application of Inclusive Impact Index (Triple I) Assessment to Biodiesel Fuel Utilization for Cruise Boats in Ha Long Bay, Vietnam.	T. A. Nguyen K. Kuroda K. Otsuka	Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference (ISOPE 2015), pp. 1139–1146. (Kona, USA, 2015)	Chapter 5

5	Comparing Environmental Impacts of Biodiesel and Petroleum Diesel Spills from Cruise Boats in Ha Long Bay	T. A. Nguyen K. Otsuka	Proceedings of OCEANS 2016 MTS/IEEE Monterey, 6 pages (Monterey, USA, 2016)	Chapter 6