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An Eco-Efficiency Assessment of Bio-Based Diesel Substitutes: A Case Study in Thailand

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Abstract: The development of new bio-based diesel substitutes can improve their compatibility with diesel engines. Nevertheless, for actual implementation, their environmental and economic performance needs to be studied. This study quantified the eco-efficiency of three bio-based diesels, viz., fatty acid methyl ester (FAME), partially hydrogenated FAME (H-FAME), and bio-hydrogenated diesel (BHD), to address the perspective of producers as well as policymakers for implementing the advanced diesel alternatives. The eco-efficiency was assessed as a ratio of life cycle costing as the economic indicator and three different environmental damages—human health, ecosystem quality, and resource availability. The eco-efficiency of FAME was the most favorable among all the potential substitutes with regard to human health and ecosystem quality, but the least favorable for resource availability impact. Even though BHD was beneficial in terms of life cycle costing, it was the least preferable when considering human health and ecosystem quality, though it performed the best for resource availability. H-FAME was also promising, in line with FAME. It is suggested that the technologies for BHD production should be improved, especially the catalyst used, which contributed greatly to environmental impacts and costs.

Keywords: eco-efficiency; life cycle assessment; life cycle costing; bio-based diesel; palm oil

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Citation: Permpool, N.; Mahmood, A.; Ghani, H.U.; Gheewala, S.H. An Eco-Efficiency Assessment of Bio-Based Diesel Substitutes: A Case Study in Thailand. *Sustainability* **2021**, *13*, 576. https://doi.org/10.3390/su13020576

Received: 4 December 2020
Accepted: 6 January 2021
Published: 9 January 2021

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1. Introduction

The business of renewable energy has been promoted due to several perceived advantages. First, it is expected to facilitate the path to decarbonization as well as ameliorate other environmental impacts, particularly a reduction in the use of fossil resources [1,2]. Second, it may also contribute to economic growth due to the fact that new technologies/industries would be implemented. Third, it is hoped to generate local employment [3,4]. Industrial and economic development should always be assessed with environmental sustainability to ensure sustainable development [5]. To enable this in practice, eco-efficiency has often been used as a supporting tool to optimize the overall system, considering both environmental and economic dimensions. It provides many benefits to the actual implementation of products and can be assessed from several perspectives, namely the macro-economic, meso-economic, and micro-economic levels [6]. Eco-efficiency is also one of the industrial ecology concepts to promote sustainable development. It is a means of evaluating the combined economic and environmental pillars of sustainable development, in order to reduce the consumption of resources, as well as the impact on nature, while maintaining or enhancing the value of the manufactured product [7]. It has been endorsed as a new business concept for companies in the private sector [8]. It is calculated based on the ratio between the (added) value of what has been produced and the (added) environmental impacts of the product or service [9]. The concept has been applied to numerous products to point out the ways forward for improving the sustainability of products and companies [6,10].

Global population growth has led to a strain on natural resources and increased environmental emissions. Transportation is a major sector causing fossil resource depletion and air pollution. Global bio-based fuels have been launched to reduce fossil demand and abate the potential of climate change since early 2000 [11]. Thailand has set ambitious targets to meet global goals—for example, via the Thailand Integrated Energy Blueprint (TIEB) [1]. Thailand, as with many other developing nations, is keen to partially replace its imported fossil diesel with bio-based diesels which, in addition to being produced from local feedstocks, may also have greenhouse gas (GHG) emission reduction benefits [12–14]. For this purpose, fatty acid methyl ester (FAME, conventionally known as biodiesel) is commonly being used in Thailand as B10 (10% blend of FAME with fossil diesel). However, there are limitations to the percentage of FAME that can be blended with fossil diesel without a need for engine modification. This has led to the search for alternative bio-based diesel products which can overcome the blending percentage limitation associated with FAME. Partially hydrogenated FAME (H-FAME) and bio-hydrogenated diesel (BHD) are such alternative products which can serve as a replacement for FAME [12,15,16]. This has led to the study of additional options for bio-based diesel substitutes. Nevertheless, using advanced technologies in the new renewable energy business also requires additional primary energy inputs in their complex processing [12]. Moreover, their implementation may entail additional costs. These concerns are important for the actual implementation of biofuels on the macro scale. To ensure the sustainable launching of alternative fuels for substituting diesel in Thailand, evaluating the economic dimension along with an actual net reduction of environmental impacts is currently needed.

Several studies have used eco-efficiency as an indicator for environmental and economic sustainability assessment of bio-based products and bio-based energy systems—for example, biodiesel production from Jatropha curcas, hydrogen production from biomass gasification, cassava and sugarcane supply chains, biodiesel from waste cooking oil, etc. [17–21]. In Thailand, previous studies have mostly investigated the life cycle environmental sustainability of palm-oil based biodiesel—for instance, energy analysis by Pleanjai and Gheewala [22], environmental analysis by Sampattagul et al. [23], environmental and energy performance evaluation by Silalertruksa and Gheewala [24], and environmental sustainability assessment by Prapaspongsa et al. [25]. A recent study by Lecksiwilai and Gheewala [26] showed the trade-offs between environmental impact categories when evaluating biofuels in Thailand. It was found that considering only popular categories such as global warming while ignoring others such as the impact on freshwater, land, and other local impacts may result in unintended consequences. Interestingly, all these studies evaluated conventional biodiesel (i.e., FAME). However, a recent study by Permpool et al. [27] evaluated the environmental performance of advanced bio-based diesels as well (i.e., H-FAME and BHD) in Thailand.

Silalertruksa et al. [28] evaluated the economic performance of biodiesel by analyzing the life cycle costing and externalities. The results showed that depending on the blending level, biodiesel has a 3–76% lower environmental cost than conventional diesel. Kochaphum et al. [29] calculated the eco-efficiency of conventional biodiesel (i.e., FAME) using the socioeconomic performance and GHG emissions. The results showed that eco-efficiency will decrease with the increasing percentage of biodiesel (i.e., 2 to 10% FAME with conventional diesel); however, it would remain positive. Nevertheless, there has not yet been any study investigating the eco-efficiency of various bio-based diesel options, namely FAME, H-FAME, and BHD.

Thus, this study aims to assess the eco-efficiency of producing biofuels for substituting diesel to reduce costs and environmental impacts. The study is based on a micro-economic level to address the producer perspective and also implement the results to support policymakers for launching advanced diesel alternatives.

2. Methodology

To determine the effects of substituting the fossil diesel in Thailand with selected bio-based diesels, eco-efficiency analysis was performed by following the basic criteria for eco-efficiency stated in ISO 14,045 [30]. Eco-efficiency analysis includes four main steps: (1) Defining the functional unit, (2) Identification of products/processes, (3) Assessing the life cycle environmental and economic impacts of the products/processes, and (4) Eco-efficiency calculation. The production of the selected bio-based diesels is illustrated in Figure 1. The details of the calculation steps are provided in the sections below.

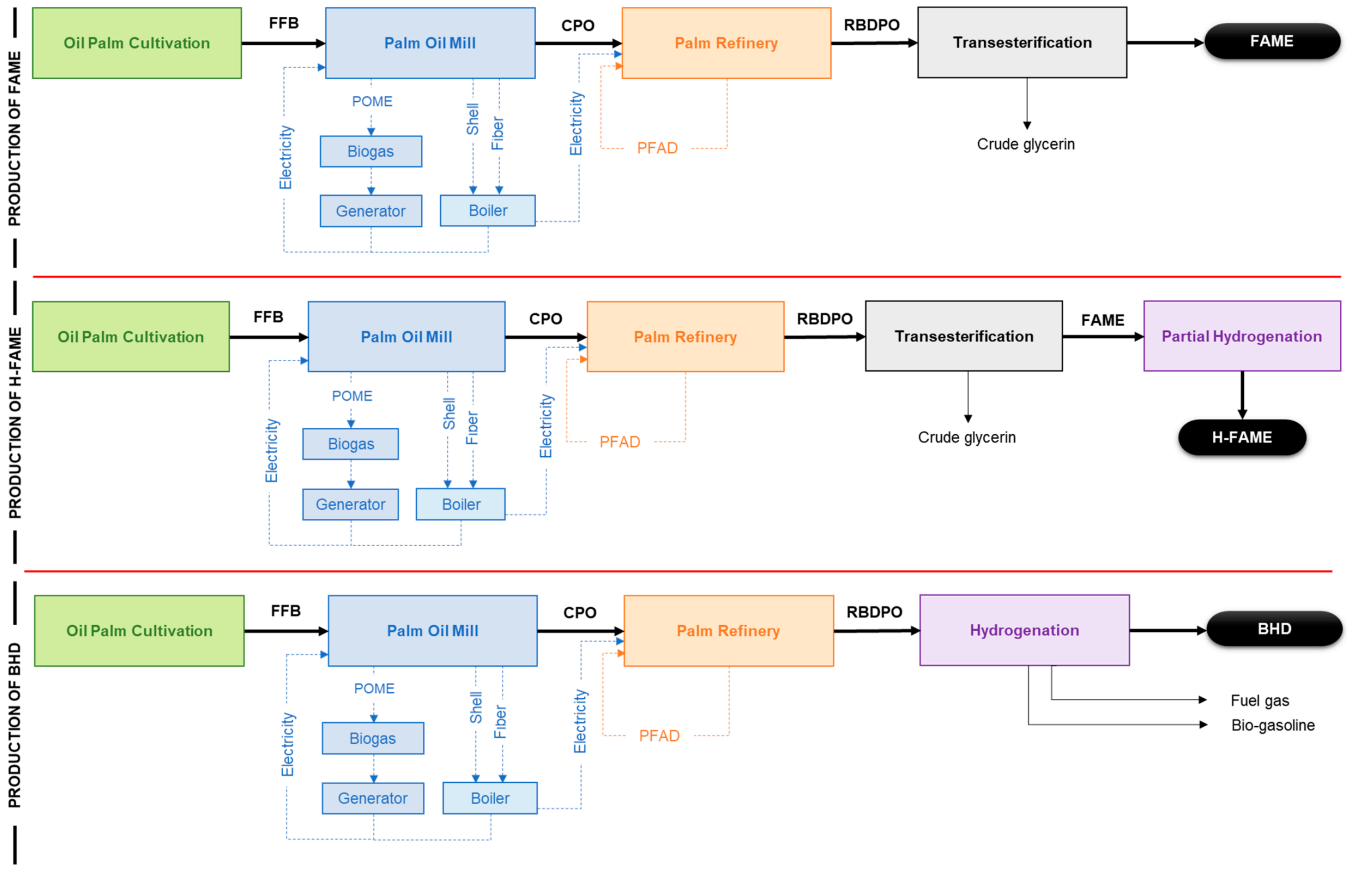

Figure 1. Bio-based diesel production systems (FFB: fresh fruit bunch, CPO: crude palm oil, RBDPO: refined bleached deodorized palm oil, PFAD: palm fatty acid distillate, POME: palm oil mill effluent).

2.1. Defining the Functional Unit

To make a reasonable comparison for all the options, a proper functional unit (FU) is needed. Since this is a fuel-based study, producing a certain amount of energy was chosen as the functional unit. The functional unit is defined as producing 1000 MJ bio-based diesels, namely FAME, H-FAME, and BHD.

2.2. Identification of Products/Processes

The research is based on the entire life cycle, well-to-wheels (WTW), of the three bio-based diesels. The study considers oil palm cultivation, palm oil mill, palm refinery, production of fuels, and the use of fuels (cf. Figure 1).

2.3. Assessing the Life Cycle Environmental and Economic Impacts of the Products/Processes

2.3.1. Life Cycle Assessment

Life cycle assessment (LCA) was used to address the potential environmental impact of the selected bio-based diesels. The method followed the ISO 14040/14044 standards [31,32].

The scope of the study has already been shown in Figure 1. ReCiPe version 2016 was used as the impact assessment method considering the endpoint categories, viz., damage to human health, ecosystem quality, and resource availability [33]. The endpoint impact categories (i.e., human health, ecosystem quality, and resource availability) were defined in terms of disability adjusted life years (DALY), species.yr, and USD2013. The damage to human health is calculated as DALYs, which represents the years of life lost or lived disabled due to an accident or a disease. Furthermore, the damage to ecosystem quality is expressed by an aggregated unit, species.yr, which represents the local relative species loss or potentially disappeared fraction of species in terrestrial, freshwater, and marine ecosystems. Finally, the resource scarcity potential is represented by US dollars (USD2013), which represents the additional costs required for mineral or fossil resource extraction in the future. Life cycle inventory and life cycle impact assessment were based on a previous study by the authors [27].

2.3.2. Life Cycle Costing (LCC)

The economic examination of a manufacturing process by the life cycle cost approach is vital to the evaluation of the energy needs and material inputs. LCA enables us to quantify how much energy and raw materials are consumed, as well as how much by-products are generated at each stage of the production. Life cycle costing can be defined as an economic model for pricing products, equipment, and processes over the entire life span. Life cycle costing (LCC) was used to address costs occurring throughout the life cycle of the selected bio-based diesels in parallel with LCA. According to the code of practice for environmental life cycle costing, LCC is adaptable to the context of application [34,35]. This study carried out LCC for complementary LCA and eco-efficiency assessment. The scope of LCC is according to the scope of LCA in the previous study [27].

The calculation of LCC has been carried out based on material and energy input-output taken from the life cycle inventory used for the LCA.

The entire life cycle costs are estimated according to Equation (1) below, derived from [34] and expressed in terms of USD per functional unit ($/FU):

$$LCC_{\,Cradle\ to\ grave} = C_{RM} + C_{PC} + C_I + C_U - C_{BP} \quad (1)$$

where:

$LCC_{\,Cradle\ to\ grave}$—total life cycle cost of biofuel from "cradle to grave" ($/FU);
C_{RM}—costs of raw materials ($/FU);
C_{PC}—costs of product conversion ($/FU);
C_I—costs of investment ($/FU);
C_U—costs of product use ($/FU);
C_{BP}—costs of by-products ($/FU).

According to Ong et al. [36], capital investments have a negligible contribution to the production of biodiesel; therefore, they are not considered in this study. The calculations for life cycle costing have been based on a steady state cost model. Life cycle inventory and costs for selected bio-based diesels per functional unit are provided below in Table 1.

Table 1. Life cycle inventory and costs for the selected bio-based diesels per functional unit (1000 MJ).

Input/Output	FAME	H-FAME	BHD	Material Cost	Cost Data Sources
		Input			
RBDPO	24.6 kg		21 kg	1.35 $/kg	[37]
FAME		26 kg		1.33 $/kg	This study
		FAME conversion			
Methanol	3.47 kg			0.27 $/kg	[38]
Steam	1.84 kg				
Electricity (grid)	0.52 kWh			0.15 $/kWh	[39]
Phosphoric acid	0.11 kg			1.52 $/kg	[40]
Potassium hydroxide	0.27 kg			2.0 $/kg	[41]
		Hydrogenation			
Palladium		0.76 mg	5 mg	0.10 $/mg	[42]
Activated carbon		37.2 mg	89 mg	0.006 $/g	[43]
Hydrogen		0.019 kg	0.95 kg	2.27 $/kg	[44]
Electricity		0.08 kWh	1 kWh	0.15 $/kWh	[39]
		Output			
Product	26.3 kg	25.5 kg	22.7 kg		

2.3.3. Allocation Procedure

Since several coproducts are being produced at different life cycle stages of biodiesel products, the economic allocation was therefore employed to share the environmental and economic burdens among these coproducts. The allocation factors for different stages were derived from Permpool et al. [27]; at the CPO production stage, the allocation factors were obtained as 0.92, 0.06, and 0.02, for the CPO, dry kernel, and shell, respectively; at the FAME production stage, the allocation was considered as 0.7 and 0.3 for FAME and crude glycerin, respectively; at the BHD production stage, allocation factor values were 0.97, 0.02, and 0.01 for BHD, fuel gas, and bio-gasoline, respectively. However, at the RBDPO production stage, the PFAD coproduct was internally used in the refining stage; therefore, all the impacts were given to only RBDPO.

2.4. Eco-Efficiency Calculation

According to ISO 14045, eco-efficiency is a tool to optimize the overall system, considering both environmental and economic dimensions [30]. However, the method to quantify eco-efficiency is adaptable to the goal of the individual study [6,10,45–48]. This study carried out the eco-efficiency calculation based on environmental impact reduction compared to fossil diesel and life cycle costing. The calculation of eco-efficiency is shown in Equation (2) below [6].

$$Eco - efficiency = \frac{Environmental\ value_{aggregated}}{Economic\ value_{aggregated}} \quad (2)$$

For the aggregated environmental value, the environmental impact reduction potential of the selected bio-based diesels was used for the eco-efficiency analysis. Three endpoint impact categories (i.e., damage to human health, ecosystem quality, and resource availability) were selected as the environmental impact indicators. Then, reduction potential was obtained by subtracting the impact of bio-based diesels from the impact of fossil diesel, considering it as a baseline. The life cycle impact assessment results were obtained from the previous study by the authors [27]. On the other hand, for the aggregated economic value, the life cycle cost of the bio-based diesels is directly used as the economic indicator for the eco-efficiency analysis.

The previous study showed that for BHD, the catalyst contributes a significant share towards environmental impacts [27]. If this impact could be reduced, then the environmental profile of BHD could be significantly improved. In the last decade, much attention has been paid to the advancement of the catalyst used to produce BHD, focusing on several

groups of catalysts under different oil feedstocks and hydrotreating conditions [49–51]. However, this is still in the development stage and, optimistically, it can be presumed that in the near future, cheaper and greener catalyst alternatives will be available in the market. Therefore, a sensitivity analysis was conducted in this study by considering two different scenarios (i.e., eco-efficiency of BHD with and without the catalyst). For the scenario without the catalyst, the impacts of the catalyst (i.e., used in the production of BHD) are assumed to be zero.

Furthermore, the obtained eco-efficiency values are normalized separately in the range of 0 to 1 using the normalization method (see Equation (3)) so that the different values can be conveniently compared on the same scale.

$$\text{Eco} - \text{efficiency}_{\text{normalized}} = \frac{x_i - Min(x)}{Max(x) - Min(x)} \quad (3)$$

where:

x_i = the value of eco-efficiency;
$Min(x)$ = the minimum value of x (in the respective range);
$Max(x)$ = the maximum value of x (in the respective range);
$\text{Eco-efficiency}_{\text{normalized}}$ = normalized value of eco-efficiency.

3. Results and Discussion

This study considered environmental impact reduction using the three environmental impacts (i.e., human health, ecosystem quality, and resource availability) and life cycle costing for the eco-efficiency analysis. The results for environmental impact reduction, life cycle costing, eco-efficiency, and normalized eco-efficiency are presented in Table 2. The environmental impact reduction potential was chosen as the environmental indicator; therefore, negative values were obtained in some cases where the impact of the bio-based diesel was higher than that of fossil diesel. The overall eco-efficiency results show that FAME was the most preferable among all the potential substitutes with regard to human health and ecosystem quality. This was mainly because of the higher environmental impact reduction obtained by FAME for these impact categories. However, in the case of resource availability, H-FAME showed the minimum eco-efficiency. On the other hand, despite the fact that BHD is beneficial in terms of the economic indicator (i.e., LCC), it is still the least preferable in terms of eco-efficiency when considering human health and ecosystem quality, though it performs the best for resource availability. The results for H-FAME are also promising, in line with FAME. This is understandable since H-FAME is produced from FAME with just one additional process, which is not very burdensome.

Table 2. The eco-efficiency of the selected bio-based diesels (with catalyst) per 1000 MJ.

Indicator	Units	FAME	H-FAME	BHD
Economic indicator				
LCC	$	34.85	34.98	31.08
Environmental indicator				
Human health	DALY	1.51×10^{-4}	-3.70×10^{-5}	-1.07×10^{-3}
Eco-efficiency	DALY/$	4.33×10^{-6}	-1.06×10^{-6}	-3.45×10^{-5}
$\text{Eco-efficiency}_{\text{normalized}}$		1.00	0.86	0.00
Ecosystem quality	species.yr	-6.08×10^{-7}	-8.01×10^{-7}	-2.17×10^{-6}
Eco-efficiency	species.yr/$	-1.74×10^{-8}	-2.29×10^{-8}	-6.99×10^{-8}
$\text{Eco-efficiency}_{\text{normalized}}$		1.00	0.90	0.00
Resource availability	USD2013	23.1	23	22.6
Eco-efficiency	USD2013/$	6.64×10^{-1}	6.58×10^{-1}	7.27×10^{-1}
$\text{Eco-efficiency}_{\text{normalized}}$		0.08	0.00	1.00

As discussed earlier, BHD production is still in the development stage but is being promoted as one of the advanced biofuels to be used as a diesel substitute in the future. It would be interesting to see what technical improvements might be possible and how much the eco-efficiency could be improved. Thus, a sensitivity analysis was conducted to check the influence of the significant stage on the eco-efficiency results. The eco-efficiency results and the normalized ranking of the bio-based diesels (without catalyst for BHD) are presented in Table 3. The results show that the catalyst plays a significant role in the ranking of the potential substitutes of the bio-based diesels in terms of eco-efficiency. The BHD would be the most suitable option among all the selected bio-based diesels if the catalyst impacts are reduced by some means, e.g., (1) multiple regenerations of the catalyst may reduce the impacts up to a negligible level, or (2) the replacement of the catalyst with a cheaper and greener catalyst having insignificant impacts on the economics and environment. On the other hand, in this case, H-FAME is proven as the least preferable option, performing inadequately in terms of eco-efficiency. Contrary to this, the FAME performed very well in the case of ecosystem quality as an environmental indicator; meanwhile, it showed moderately good results if human health is considered as an environmental indicator. In short, by the advent of an improved catalyst, the BHD production will be more feasible than at present—as presented in Table 3 (i.e., eco-efficiency analysis without catalyst).

Table 3. The eco-efficiency of the selected bio-based diesels (without catalyst for BHD) per 1000 MJ.

Indicator	Units	FAME	H-FAME	BHD
Economic indicator				
LCC	$	34.85	34.98	30.58
Environmental indicator				
Human health	DALY	1.51×10^{-4}	-3.70×10^{-5}	1.57×10^{-4}
Eco-efficiency	DALY/$	4.33×10^{-6}	-1.06×10^{-6}	5.13×10^{-6}
$\text{Eco-efficiency}_{\text{normalized}}$		0.87	0.00	1.00
Ecosystem quality	species.yr	-6.08×10^{-7}	-8.01×10^{-7}	-6.71×10^{-7}
Eco-efficiency	species.yr/$	-1.74×10^{-8}	-2.28×10^{-8}	-2.19×10^{-8}
$\text{Eco-efficiency}_{\text{normalized}}$		1.00	0.00	0.15
Resource availability	USD2013	23.1	23	23.8
Eco-efficiency	USD2013/$	6.64×10^{-1}	6.54×10^{-1}	7.79×10^{-1}
$\text{Eco-efficiency}_{\text{normalized}}$		0.08	0.00	1.00

Overall, the eco-efficiency results of these biodiesel products indicate a trade-off situation for the decision-makers. Careful consideration of all opportunities and obstacles associated with respective biodiesel products is suggested before making a decision. For instance, considering the human health and ecosystem quality indicators, FAME shows the best performance while BHD is the least favorable option. On the other hand, for the resource availability indicator, BHD performs the best while H-FAME is the worst. The performance of H-FAME is similar to FAME, which is understandable considering that FAME is the raw material for its production. The better performance of FAME for human health and ecosystem quality is mainly because of the additional processing steps involved in the production of the other two products (i.e., H-FAME and BHD), while the higher requirements of RBDPO raw material for FAME are responsible for its poor performance while considering the resource availability indicator. This situation suggests that it would be preferable to use FAME until the blending wall percentage (20% blend with fossil diesel) is reached, and should be followed by the use of H-FAME (30% blend with fossil diesel). In the current situation, the use of BHD is recommended only for overcoming the limitations of the blending wall posed by the other two products (i.e., FAME and H-FAME). Nevertheless, the technical improvement of catalyst application (type and performance of catalyst) for BHD can also enhance its eco-efficiency performance. As the agricultural stage contributes a significant share towards both the environmental and economic indicators for

all the bio-based products, improving the performance of oil palm cultivation is suggested (optimizing the use of agrochemicals and fuels, improving the yield, etc.).

4. Conclusions and Recommendations

Eco-efficiency is a tool to optimize the overall system, considering both environmental and economic dimensions. This study evaluated the eco-efficiency of bio-based diesels to address the perspective of producers as well as policymakers for launching advanced diesel alternatives. The quantified eco-efficiency of the selected bio-based diesels showed that FAME demonstrates the best performance among the three with regard to human health and ecosystem quality, but the worst for resource availability. It has a higher life cycle cost compared to the other bio-based diesels.

Even though BHD is beneficial considering life cycle costing, it is still the least preferable in terms of eco-efficiency when considering human health and ecosystem quality. This is the result of using the palladium catalyst, the production of which has a significant contribution to environmental impacts. However, it performs the best for resource availability. Currently, BHD production is still in the development stage but it is being promoted as one of the advanced biofuels to be used as a diesel substitute in the future. Reducing the impact of the catalyst in BHD conversion could lead to significant improvement in the eco-efficiency value, making it the most suitable option among all the selected bio-based diesels.

It is suggested that the technologies for BHD production should be improved, especially the catalyst used, which contributes greatly to the environmental impacts and costs. It is can be presumed that in the near future, cheaper and greener catalyst alternatives will be available on the market. This could make BHD production more feasible than at present.

Author Contributions: Conceptualization, N.P. and S.H.G.; methodology, N.P., S.H.G., and A.M.; software, N.P. and A.M.; validation, S.H.G.; formal analysis, N.P., A.M., H.U.G., and S.H.G.; writing—original draft preparation, N.P.; writing—review and editing, S.H.G.; visualization, A.M. and H.U.G.; supervision, S.H.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Thailand Research Fund under the Royal Golden Jubilee Ph.D. program (Grant PHD.0147.2558) and the APC was funded by The Joint Graduate School of Energy and Environment (JGSEE).

Acknowledgments: The authors would like to express their gratitude to Thailand Research Fund under the Royal Golden Jubilee Ph.D. programme (Grant PHD.0147.2558) and the Newton Fund PhD Placement Grant for Scholars (2016/2017), for providing financial support. The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi and the Center of Excellence on Energy Technology and Environment (CEE), PERDO, Ministry of Higher Education, Science, Research and Innovation are also acknowledged for their support.

Conflicts of Interest: The authors declare no conflict of interest.

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