An In-Depth Environmental Sustainability Analysis of Conventional and Advanced Bio-Based Diesels in Thailand

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Abstract: Thailand has been implementing its Alternative Energy Development Plan aiming to replace 20–25% of fossil fuels with locally produced biofuels by 2036. The partial substitution of fossil diesel with fatty acid methyl ester (FAME) derived from palm oil is one of the major options but blending beyond 20% of FAME is a concern for use in conventional diesel engines. This problem has led to the consideration of other bio-based diesels also derived from palm oil; namely, partially hydrogenated fatty acid methyl ester (H-FAME) and bio-hydrogenated diesel (BHD). This study performed a comparative life cycle assessment of various bio-based diesels using the ReCiPe life cycle impact assessment method. The results showed that in comparison to fossil diesel, bio-based diesels have superior performance for global warming and fossil resource scarcity, but an inferior performance for eutrophication, terrestrial acidification, human toxicity, and land use. Considering the collective environmental damages, BHD performed the worst for human health, and all the bio-based diesels showed poor performance for ecosystem quality, while diesel showed poor performance for resource availability. Among the bio-based diesel products, BHD has higher environmental burdens than FAME and H-FAME. Improvements have been suggested to enhance the environmental performance of the bio-based diesels.

Keywords: life cycle assessment; environmental impact; bio-based diesel; environmental sustainability; palm-based product

1. Introduction

Thailand’s energy demand has been increasing continuously due to population and economic growth. About 500 million barrels of crude oil was required to serve the national demand in 2019 [1]. More than 80% of this crude oil was imported from different countries, namely United Arab Emirates, Saudi Arabia, Malaysia, Russia, Australia, Qatar, and others. Crude oil was the top import product in Thailand costing about 24 billion euros in 2018 [2]. Use of crude oil in the country is about 1.3 million barrels per day and around 0.42 million barrels of diesel per day is used in the country. The crude oil demand increased by about 30% from the year 2009 to 2019 [1] Transportation is one of the major sectors using diesel and consequently contributes a significant share of the national greenhouse gas (GHG) emissions. In 2018, GHG emission from the transport sector was about 68 million tons CO2-equivalent sharing 26% of total GHG emissions in the country [3–5].

Thailand has high ambitions to meet the sustainable development goals (SDGs) of the United Nations [6,7]. Besides, being a middle-income country massively depending on imported fossil fuels,
sustainable consumption and production of national energy is being paid high attention. In this regard, the Alternative Energy Development Plan (2015–2036) is being implemented to reduce the dependence on fossil fuels, especially in the transport sector. Under this plan, the country is aiming to replace around 20–25% of fossil fuels by locally produced biofuels. One of the conventional biofuels is fatty acid methyl ester (FAME), also referred to as biodiesel, which is used to partially substitute fossil diesel. Although used extensively as a blend in Thailand, FAME has the limitation of high blending ratio with diesel which can cause adverse problems, for instance, poisoning of catalysts and filters in the conventional diesel engine due to fuel impurities. It also creates problems especially in diesel vehicles which are equipped with exhaust after-treatment devices [8]. Most of the diesel available at the pump is a 10% blend of FAME with fossil diesel (B10) though a maximum blend of 20% v/v (B20) has also been commercially launched in the country [9].

The blending wall of FAME has therefore led the attention to advanced alternative fuels for substituting fossil diesel, such as partially hydrogenated fatty acid methyl ester (H-FAME) and bio-hydrogenated diesel (BHD) [8,10,11]. These fuels are also produced from palm oil which is the most potential raw material for bio-based diesels in Thailand with several advantages; favorable yield, long-term cultivation (as a perennial crop), feedstock availability, techno-economic feasibility, and low environmental burdens [10,12–16]. This requires evaluating the whole life cycle of these biofuels to analyze their environmental sustainability.

There is no commercial production yet of advanced bio-based diesels (i.e., H-FAME and BHD) in Thailand [17,18]. As it currently stands, palm oil is the most suitable option for producing bio-based diesels for diesel engines and it is already being used extensively for producing FAME in Thailand; it was thus the selected feedstock for the other alternative fuels as well. It should be noted that each alternative bio-based fuel has different energy content; the lower heating value (LHV) was applied for calculating the reference flows which amounted to 26.27, 25.51, 22.71 kg of FAME, H-FAME, and BHD per 1000 MJ of biofuels, respectively [19–21]. The inputs and outputs for each stage of production are provided in Figure 1.

Life cycle assessment (LCA) is a technique which is being used widely around the globe to evaluate the environmental sustainability of biofuels. It analyzes the product system considering all the inputs and outputs in a life cycle perspective [22]. So far, many studies have investigated life cycle GHG emissions of these biofuels. The GHG emissions of FAME have been reported to be between 16 to 24 gCO₂/MJ, H-FAME has been reported as 25 gCO₂/MJ, BHD ranging between −1.16 to 40.15 gCO₂/MJ [8,10,19,20,23]. However, not many studies have assessed the environmental sustainability of these alternative biofuels considering multiple impacts. Ensuring the environmental sustainability of biofuels is necessary to meet the Thailand’s ambitious environmental targets. This particular study aims at assessing the environmental sustainability of three promising liquid biofuels that can substitute fossil diesel, namely FAME, H-FAME, and BHD.

2. Methodology

This study followed the methodology of LCA according to ISO 14040/14044 [24,25]. LCA is an environmental impact assessment based on a systems approach. This tool includes four main steps, namely goal and scope, inventory analysis, impact assessment, and interpretation. Based on the life cycle approach, this study was carried out from ‘Well to Wheels’ for three selected bio-based diesels and the results compared to that of fossil diesel. The detailed steps are described in the sub-sections below. The SimaPro 8.5 software was used for the calculations [26].

2.1. Goal and Scope of the Study

This study was aimed at assessing the environmental impacts of three selected biofuels, namely FAME, H-FAME, and BHD. The environmental impact results of these biofuels were then compared with that of fossil diesel. The significant environmental stages and materials contributing to
The impacts were identified, and recommendations made to reduce the impacts of each alternative fuel. The results of this study are directed at providing insights to policy makers, and biofuel producers.

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Figure 1. Simplified system diagram for FAME, H-FAME, and BHD.

The functional unit was defined as the use of 1000 MJ fuel. The scope of this study for the bio-based diesels included cultivation and harvesting of oil palm fresh fruit bunch (FFB), transport of FFB to the palm oil mill, crude palm oil (CPO) production, transport of CPO to the refinery, refined bleached deodorized palm oil (RBDPO) production, transport of RBDPO, biofuel production, and the use of biofuel in pick-up trucks.

2.2. Life Cycle Inventory Analysis

The life cycle inventory data were collected from both primary and secondary sources. The inventory data for FFB production, transport of FFB, CPO production, RBDPO production, and FAME production were collected through interviews using the predesigned questionnaires [17,18]. The FFB production data were sourced from more than 800 oil palm growers throughout the country.
under the national project on life cycle environmental sustainability assessment of oil palm plantation in Thailand [17]. The process data for CPO were collected from 9 mills in Thailand which together account for more than 50% of the total production capacity of the country. The data for RBDPO production were obtained from 4 palm oil refineries in Thailand. The inventory data for FAME were based on 5 FAME production plants referred from the national report in Thailand.

The sources of secondary data included the national projects, literature review, and data inventories available in the SimaPro software. Most of the databases were selected from ecoinvent 3 with allocation based on the cut-off system model; this means that no credits from recyclable materials accrued to the system under consideration [27]. The inventory data for H-FAME production were referred from the national pilot plant in Thailand [28,29]. As well, data for BHD were sourced from Neste Oil’s NExBTL (trade name of synthetic BHD) production from Finland which is the biggest producer of BHD around the globe [20]. Wherever possible, the data were adapted to match the context of Thailand. The economic allocation procedure was applied to share the environmental burdens if more than one product was produced at any stage.

2.3. Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) converts the life cycle inventory flows into potential impact categories. ReCiPe version 2016 was used as the impact assessment method in this study; both midpoint and endpoint indicators were considered in the analysis [30]. Many impact categories are characterized in the ReCiPe method; however, the most relevant environmental impact categories were selected to discuss in terms of the life cycle environmental impacts of the bio-based diesels and fossil diesel. For instance, a major concern of using fossil fuels is the emission of climate change-inducing greenhouse gases [8,12,23]. Thus, the impact category global warming was included to evaluate the potential of decarbonization induced by the bio-based diesels as compared to fossil diesel. Conversion of palm fruit bunch to refined palm oil as raw material for selected biofuels contributes particulate matter to the atmosphere from the burning of biomass (fiber and shells) for heat and power generation, so, fine particulate matter formation was taken into account. Cultivation of palm fresh fruit bunch and combustion of biofuels emit acidifying substances such as NOx, NH3, and SO2, therefore, terrestrial acidification was considered. Fertilizer application during cultivation stage discharges nutrients into the soil, freshwater, and marine bodies. Freshwater and marine eutrophication are thus considered in this analysis. Human carcinogenic toxicity is relevant to emissions of chemicals over the life cycle of the fuels, for example pesticides in the agriculture stage of the bio-based diesels or from energy use in the various stages of all fuels. Land use refers to species loss from land transformation, land occupation, and land relaxation. Oil palm is a perennial crop that occupies land in long term, thus, it is important to account the effects on land use. Producing biofuels does not rely only on biomass feedstock, fossil-based resources are also used over the life cycle. It is, therefore, important to address the significance of fossil depletion among the selected biofuels and fossil diesel. The endpoint impact indicators include final damage to human health, ecosystem quality, and resource availability, all of which are considered in the analysis.

3. Results and Discussion

3.1. Life Cycle Inventory Data Results

3.1.1. Fresh Fruit Bunch Production

Fresh fruit bunch (FFB) production refers to the agriculture and harvesting systems including seeding, oil palm nursery, oil palm cultivation, and harvesting. Oil palm is a perennial crop with a productive lifetime of 25 years. The yield of FFB varies with the age of the oil palm trees [8]; therefore, the data collection covered the entire life span of the oil palm which is divided into five
stages: (1) 0–3 years (2) 4–6 years (3) 7–10 years (4) 11–20 years (5) 21–25 years [17]. The data are shown in the Table 1 below.

Table 1. Life cycle inventory of 1000 kg FFB production.

| Input/Output          | Quantity | Unit   |
|-----------------------|----------|--------|
| Input                 |          |        |
| Land seeding          | 0.48     | kg     |
| Fertilisers/Chemicals used |        |        |
| N-Fertiliser          | 6.87     | kg     |
| P₂O₅ Fertiliser       | 4.42     | kg     |
| K₂O Fertiliser        | 11.7     | kg     |
| Cow manure            | 16.2     | kg     |
| Pig manure            | 7.4      | kg     |
| Chicken manure        | 25.6     | kg     |
| Other manure          | 0.03     | kg     |
| Agricultural machinery|          |        |
| Diesel                | 0.17     | L      |
| Gasoline              | 1.03     | L      |
| LPG                   | 2.08 × 10⁻⁴ | kg   |
| Electricity           | 0.02     | kWh    |
| Agrochemicals         |          |        |
| Glyphosate            | 2.28 × 10⁻² | kg   |
| Paraquat              | 1.85 × 10⁻¹ | kg   |
| Other herbicides      | 2.00 × 10⁻³ | kg   |
| Benomyl               | 5.46 × 10⁻⁵ | kg   |
| Cypermethrin          | 2.61 × 10⁻⁴ | kg   |
| Other insecticides    | 5.46 × 10⁻⁴ | kg   |
| Output                |          |        |
| FFB                   | 1000     | kg     |

3.1.2. Crude Palm Oil Production

Crude palm oil (CPO) is extracted from FFB at the palm oil mill. There are two types of processes for crude palm oil extraction, namely wet and dry extraction process. Since the wet process is the commercial process most often used in palm oil mills, hence this process was selected to represent CPO extraction in Thailand. The wet extraction process itself has five sub-processes: (1) Sterilization; (2) Threshing; (3) Pressing; (4) CPO clarification, and; (5) Nut/Fiber separation. The sterilization process weakens the FFB via pressurized steam. It also inhibits enzymatic decomposition to avoid the formation of high free fatty acids (FFA). The threshing process detaches the fruit from the bunch through a strong vibrator. The pressing process involves mashing and crushing the fruits by using a digester (mechanical stirring process). The output of this process is a mixture of CPO, water, and press cake (fiber and nut) which is purified at the clarification process involving filtration, settlement and drying.

The final process for CPO production is nut/fiber separation. The press cake from the previous process is dried to separate the nut from fiber. The nuts are then cracked to get kernel. This process hence has fiber, kernel, and shell as outputs. The process inventory for Crude palm oil (CPO) is presented in Table 2 [18]. The CPO production process has CPO and kernel as the two primary products. Some residues (fiber, shell, empty fruit bunch) can be sold and/or used as fuel for in-house steam and electricity generation.

Economic allocation was applied for dry kernel and excess shell. Empty fruit bunch and decanter cake were not considered as they have no market value. The palm oil mill effluent, shell, and fiber that were used internally for combined heat and power (also known as cogeneration) and thus not accounted for in the allocation. The economic allocation factors at the CPO production stage were derived as 92% for the CPO, 6% for the dry kernel, and 2% for the shell. This allocation was based on the local market price [18].
Table 2. Life cycle inventory of 1000 kg CPO production.

| Input/Output          | Quantity | Unit |
|-----------------------|----------|------|
| **Input**             |          |      |
| Steam                 | 3000     | kg   |
| Freshwater            | 2        | m³   |
| Electricity (CHP from biomass) | 84   | kWh  |
| Electricity (biogas)  | 8.2      | kWh  |
| Kaolin                | 290      | kg   |
| **Output**            |          |      |
| CPO                   | 1000     | kg   |
| Kernel                | 210      | kg   |
| Empty fruit bunch     | 1100     | kg   |
| Shell                 | 290      | kg   |
| Fibre                 | 39       | kg   |
| Palm oil mill effluent| 37       | m³   |
| Decanter cake         | 210      | kg   |

3.1.3. Refined Bleached Deodorized Palm Oil Production

In this process, the impurities such as triglycerides, vitamins E, carotenoids and phytosterols are removed from CPO to get refined bleached deodorized palm oil (RBDPO). There are two types of refining, namely physical and chemical refining. The physical refining process provides higher oil yield and uses fewer chemicals e.g., phosphoric acid, sulfuric acid, and caustic soda. Only the bleaching earth is consumed at higher quantities than the chemical refining process. Physical refining is more popular in commercial palm oil refining plants in Thailand; thus, this process is a representative for RBDPO production in this study. The refining process includes four main steps: (1) Degumming; (2) bleaching; (3) deodorization, and; (4) fractionation. Degumming is carried out by mixing CPO with concentrated phosphoric acid. This leads to decomposing magnesium and calcium complexes. After degumming, minor components are removed from crude palm oil through adsorptive bleaching. Bleaching clay is used to absorb pigments (carotenoids). Finally, RBDPO is the main product and palm fatty acid distillate (PFAD) is the co-product. All the PFAD is recirculated back into the refining process and hence not accounted for in the inventory. Table 3 presents the inventory data for RBDPO in Thailand [18].

Table 3. Life cycle inventory of 1000 kg RBDPO production.

| Input/Output         | Quantity | Unit |
|----------------------|----------|------|
| **Input**            |          |      |
| CPO                  | 1100     | kg   |
| Phosphoric acid      | 1.1      | kg   |
| Bleaching earth      | 11       | kg   |
| Silica               | 0.27     | kg   |
| Activated carbon     | 0.34     | g    |
| Sodium hydroxide (NaOH) | 0.18  | kg   |
| Steam                | 190      | kg   |
| Electricity (from grid) | 12    | kWh  |
| LPG                  | 2.5      | kg   |
| Water                | 0.11     | kg   |
| **Output**           |          |      |
| RBDPO                | 1000     | kg   |
3.1.4. Biofuel Production

(i) Fatty acid methyl ester production

Fatty acid methyl ester (FAME) or “biodiesel” is derived from the transesterification of palm oil and methanol using NaOH as a catalyst [8,18,23]. The details of LCI for FAME production has been shown in Table 4. The transesterification process not only provides FAME but also crude glycerine as co-product. For FAME production, economic allocation was considered resulting in the environmental burdens being shared 70% for FAME and 30% for crude glycerine [18].

![Table 4. Life cycle inventory of 1000 MJ fuel.](image)

(ii) Partially hydrogenated fatty acid methyl ester

Partially hydrogenated fatty acid methyl ester (H-FAME) is made by upgrading FAME to enable increasing the FAME-fossil diesel blending ratio [28]. It is produced by adding high pressure hydrogen gas to FAME in the presence of catalyst to facilitate the reaction, so called ‘partial hydrogenation process’ [10,31]. Palladium with activated carbon was used as the catalyst. The inventory data for H-FAME production in Thailand is presented in Table 4 [29].

(iii) Bio-hydrogenated diesel production

There are two main processes to produce BHD, namely pre-treatment of vegetable oil, and hydrogenation process. Pre-treatment process refers to the production of RBDPO and Hydrogenation refers to the addition of hydrogen to RBDPO using a catalyst. The suitable catalyst for the hydrogenation process is palladium with activated carbon [32–34]. The hydrogenation process produces fuel gas and bio-gasoline as the co-products of BHD, which is the main product (Table 4). Economic allocation applied to the co-products to estimate the share of environmental burdens between them yielded a factor of 97% for BHD, 2% for fuel gas, and 1% for bio-gasoline [35].

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\[ a \text{ Calculated from the power supply for a semi-batch reactor.} \]
3.2. Life Cycle Environmental Impacts

The results of the midpoint impact assessment are presented in Table 5. Based on the functional unit, bio-based diesel products give better environmental performance than fossil diesel for global warming, and fossil resource scarcity impacts. This is anticipated since the bio-based diesels have a biomass (non-fossil) origin and uptake carbon dioxide during the growth stage. However, fossil diesel had lesser impacts than bio-based diesels for eutrophication (freshwater and marine), terrestrial acidification, human carcinogenic toxicity, and land use impact categories. Once again, this can be explained by the fact that bio-based diesels use land as well as fertilizers and other agrochemicals during cultivation which account for the higher impacts in impact categories relevant to land and chemical use. Among the three bio-based diesels, BHD gives higher environmental burdens for all the selected impact categories than FAME and H-FAME. This is due to the higher requirement of palm fruit bunch from cultivation which account for the higher impacts in impact categories relevant to land and chemical use.

These results support the findings of Lecksiwilai and Gheewala that bio-based diesels may have advantages in terms of global warming and energy security, but they pose serious threats considering their higher impacts for other environmental issues and competing use of limited natural resources [36]. Therefore, considering only some of the environmental aspects like global warming or energy security may result in misleading conclusions for decision makers. A thorough and comprehensive analysis of all the environmental aspects by the policy makers, such as shown in this study, is essential for the sustainable use of bio-based diesels in the country.

The collective results of final damages per functional unit are shown in Table 6 for the three damage categories, i.e., human health, ecosystem quality, and resource availability. Considering damages to human health and ecosystem quality, all bio-based diesels show an inferior performance than fossil diesel. Fossil diesel represents higher damages only for resource availability which is understandable considering its fossil origin. BHD resulted in the highest damages for human health and ecosystem quality. Among the bio-based diesel products, the environmental performance of BHD remained the worst for all the three damage categories. The detailed analysis of the endpoint results is presented in Section 3.3.

### Table 5. Environmental impacts (Midpoint impact categories) of 1000 MJ FAME, H-FAME, BHD, and fossil diesel.

| Impact Categories                  | Unit     | FAME     | H-FAME   | BHD      | Diesel    |
|-----------------------------------|----------|----------|----------|----------|-----------|
| Global warming                    | kg CO₂ eq| 1.07 × 10⁴| 1.23 × 10⁴| 3.96 × 10⁴| 2.19 × 10²|
| Fine particulate matter formation | kg PM2.5 eq| 1.60 × 10⁻¹| 1.66 × 10⁻¹| 2.07 × 10⁰| 3.96 × 10⁻¹|
| Terrestrial acidification         | kg SO₂ eq| 6.54 × 10⁻¹| 6.73 × 10⁻¹| 7.21 × 10⁰| 9.42 × 10⁻¹|
| Freshwater eutrophication         | kg P eq  | 2.55 × 10⁻¹| 2.48 × 10⁻¹| 2.88 × 10⁻¹| 6.54 × 10⁻⁴|
| Marine eutrophication             | kg N eq  | 9.45 × 10⁻²| 9.17 × 10⁻²| 9.03 × 10⁻²| 4.97 × 10⁻⁴|
| Human carcinogenic toxicity       | kg 1.4-DCB| 3.32 × 10⁻¹| 3.43 × 10⁻¹| 2.79 × 10⁰| 9.57 × 10⁻²|
| Land use                          | m² a crop eq| 4.83 × 10⁻¹| 4.75 × 10⁻¹| 8.42 × 10⁻¹| 2.44 × 10⁻²|
| Fossil resource scarcity          | kg oil eq| 4.82 × 10⁰| 5.09 × 10⁰| 9.74 × 10⁰| 4.96 × 10¹|

### Table 6. Environmental impacts (Endpoint impact categories) for FAME, H-FAME, BHD, and diesel.

| Impact Category            | Unit       | FAME     | H-FAME   | BHD      | Diesel    |
|----------------------------|------------|----------|----------|----------|-----------|
| Human health               | DALY       | 1.06 × 10⁻⁴| 2.94 × 10⁻⁴| 1.33 × 10⁻³| 2.57 × 10⁻⁴|
| Ecosystem quality          | species.yr | 9.77 × 10⁻⁷| 1.17 × 10⁻⁶| 2.54 × 10⁻⁶| 3.69 × 10⁻⁷|
| Resource availability      | USD2013    | 1.76 × 10⁰| 1.87 × 10⁰| 2.31 × 10⁰| 2.49 × 10¹|
3.3. Contribution Analysis

(i) Midpoint impacts

The contribution of different life cycle stages of FAME (i.e., the production of palm fresh fruit bunches, transportation, CPO production and conversion to FAME, and the final utilization) to the selected midpoint impact categories is presented in Figure 2.

In general, from the final impact results, it has been revealed that most of the impacts to the environment were contributed by the agricultural phase (i.e., oil palm cultivation). The stages of transportation and tailpipe emissions (due to the burning of FAME in automobile engine) proved to be the least contributing stages in the entire life cycle.

In particular, most of the global warming was contributed by the agricultural phase from the cultivation of palm fruit bunches. This was followed by FAME conversion and crude palm oil production, respectively. The production and application of nitrogen fertilizers, and use of fossil-based energy, were the major sources of GHG emissions at the agriculture stage.

One the other hand, more than half of the fine particulate matter formation impact was contributed by crude palm oil production followed by palm fresh fruit bunch production. The use of biomass fuel for heat and power generation in the palm oil mill was one of the major contributors to particulate matter formation. Freshwater eutrophication and marine eutrophication were mainly from the emissions of the macronutrients (i.e., nitrogen and phosphorous) from fertilizer application in the agricultural phase. However, for human toxicity and land use categories, the main contributor was the palm fruit production (i.e., agriculture) which was followed by refined and crude palm oil production. The use of agrochemicals (fertilizers, pesticides, and insecticides) was the major source of human toxicity at the agricultural stage. Fossil resource scarcity was contributed mainly by FAME conversion and cultivation of palm fruit bunch. The use of fossil-based materials (i.e., fossil-based fuels and fertilizers) at the agricultural stage contributed the major share of fossil scarcity.

Figure 3 presents the contribution of various life cycle stages to the environmental impacts due to the production and utilization of the H-FAME. The life cycle stages of FAME and H-FAME show similar contribution trends: The production of the palm fruit was one of the phases contributing to almost all the impact categories, and the transportation and burning of H-FAME (i.e., tailpipe emissions) were the two least contributing stages in the life cycle of H-FAME.
Figure 3. Contribution of the life cycle stages to the impacts of H-FAME.

Fine particulate matter formation and terrestrial acidification were mainly contributed by crude palm oil production followed by palm fresh fruit bunch production and H-FAME conversion. Freshwater and marine eutrophication were from the emissions of the macronutrients in the agricultural phase. On the other hand, human toxicity and land use were mainly contributed by palm fresh fruit bunch production followed by refined palm oil production, crude palm oil production and FAME conversion. Fossil resource scarcity was mainly contributed by FAME conversion and palm fresh fruit bunch production.

In the production and utilization of BHD, the contribution of the different life cycle stages is presented in Figure 4. The obtained results show that the BHD conversion phase was one of the most significant stages contributing to the several midpoint impacts. On the other hand, palm fruit production was also one of the important stages. However, transportation and tailpipe emissions proved to be the least significant stages as in the case of FAME and H-FAME.
Palladium catalyst at the BHD conversion stage contributed the most to global warming, particulate matter formation, terrestrial acidification, human toxicity, and fossil resource depletion. Likewise, the production of the palm fruit bunches was one of the most significant stages in terms of freshwater eutrophication and marine eutrophication.

The life cycle stage contribution analysis of fossil diesel is shown in Figure 5. The fuel production stage is cradle-to-gate; it is presented in a more aggregated form than for the bio-based diesels because the environmental profile of diesel is mainly used as a benchmark for comparison.
(ii) Endpoint impacts

Contemplating the relation of midpoint impacts and environmental damages (i.e., endpoint categories) to find the most significant midpoint categories, it was revealed that for FAME, H-FAME, and BHD, damage to human health was mainly from fine particulate matter formation (Figure 6). For fossil diesel, the major share to human health damage (i.e., 67%) was from fine particulate matter formation, with global warming contributing the remaining. Considering the category of ecosystem quality, for FAME and H-FAME, the major share was from land use followed by terrestrial acidification and freshwater eutrophication (Figure 7). Interestingly, for BHD, the major share to ecosystem impact category was from terrestrial acidification (i.e., 60%) followed by land use. Global warming followed by terrestrial acidification were the main contributors towards ecosystem damage from diesel fuel. The resource availability damage from each product was only being caused by fossil resource category for all the products. Nevertheless, the material and process contribution remained much the same as observed for midpoint categories and discussed in detail above. A graphical representation of midpoint categories contribution towards the resource availability was not shown because it was being caused only by fossil resource scarcity.

![Figure 6. Contribution of midpoint categories towards environmental damages (Human health) of fossil and bio-based diesels.](image-url)
3.4. Insights for Policy Makers and Biofuel Producers

As mentioned in Section 1, Thailand, like many other developing nations, is keen to replace its imported fossil diesel with bio-based diesels which, in addition to being produced from local feedstocks, may also have GHG emissions benefits. For this purpose, FAME (conventionally known as biodiesel) is commonly being used in Thailand as B10 (10% blend of FAME with fossil diesel). However, these efforts face a big hurdle of blending wall which restricts the use of FAME percentage to no more than 20%. Employing a higher percentage of FAME in the vehicle requires special modifications to the engine. This has raised the quest for alternative bio-based diesel products which can overcome the blending percentage limitation associated with FAME. H-FAME and BHD are such alternative products which can serve as a replacement to FAME.

- The best environmental performance among the bio-based diesels is shown by the FAME which is quite understandable considering the extra processes involved for the alternatives.
- H-FAME has slightly higher impacts than FAME; however, it still presents a benefit in terms of solving the issue of blending wall and keeping most of the benefits of FAME in comparison to fossil diesel. This tradeoff situation suggests that H-FAME can be considered where it is needed to overcome the limitations associated with FAME.
- Based on the environmental performance, BHD is the least favorable among the three bio-based diesels being compared; in fact, it is also worse than fossil diesel for some impact categories. These results do not support the use of BHD.
- Palladium is a major contributor to the environmental impacts of both H-FAME and BHD, but especially so for BHD. The damage assessment of BHD shows that palladium could contribute damages of 90% to human health, 81% to ecosystem quality, and 73% to resource availability. This means minimizing the palladium application to the conversion of H-FAME and BHD or changing it to other catalysts (e.g., Nickel-Molybdenum) could be options to reduce the
environmental burdens associated with catalyst. Simply removing palladium used in BHD conversion could result in a massive decrease in damage to human health making it almost equal to FAME.

- Anyhow, the environmental performance of all bio-based diesels could be improved greatly by reducing the environmental impacts at the agricultural stage, for instance, by optimizing the use of agrochemicals (fertilizers, pesticides, and insecticides) and improving the yield. Among those agrochemicals, the production and application of N-fertilizers and P-fertilizers lead to high environmental impacts so their optimum use might be the key to improve environmental performance for all bio-based diesels.

4. Conclusions

The study presented environmental sustainability for three promising bio-based diesels in Thailand, namely FAME, H-FAME, and BHD, and their performance was compared with fossil diesel. As anticipated, the bio-based diesels present considerable environmental benefits as compared to fossil diesel for global warming, and fossil resource scarcity. However, it was at the expense of higher impacts on eutrophication (freshwater and marine), human carcinogenic toxicity, and land use categories. For terrestrial acidification impacts, BHD showed the worst performance while the other two bio-based diesels performed better than fossil diesel. When comparing the collective performance of all the products based on damage categories; BHD performed the worst for human health, all bio-based diesels performed worse than fossil diesel for ecosystem quality, but better for resource availability. A careful evaluation of all these aspects should be considered when making a decision. Considering only some of the aspects, for example, global warming or fossil resource scarcity, which are no doubt very important and usually included in policies, may provide misleading results. Accordingly, a comprehensive analysis of tradeoffs is necessary before the promotion of bio-based diesel products.

Anyhow, the environmental performance of bio-based diesels could be improved further. For instance, considerable benefits could be obtained for bio-based diesels by optimizing the use of materials and chemicals and controlling the emissions to the environment. As most of the impacts for bio-based products are coming from the agricultural stage, therefore, reducing the environmental impacts in agricultural activities through improving the yield, optimizing the use of fertilizer (especially nitrogen fertilizers), and reducing the use of pesticide and herbicide chemicals could enhance the environmental performance of the bio-based diesels considerably. The life cycle assessment of the three selected bio-based diesels showed that BHD has the highest environmental burdens. The main contributor is from the palladium used in its conversion. Increasing the regeneration of catalyst and/or changing the catalyst type would lead to significant improvement in environmental performance and sustainable energy production.

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