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# Assessing the Environmental Performance of Palm Oil Biodiesel Production in Indonesia: A Life Cycle Assessment Approach

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**Abstract:** The production of palm oil biodiesel in Indonesia has the potential to negatively impact the environment if not managed properly. Therefore, we conducted a life cycle assessment (LCA) study on the production of palm oil biodiesel to assess the environmental performance in Indonesia. Using an LCA approach, we analyzed the environmental indicators, including the carbon footprint, as well as the harm to human health, ecosystem diversity, and resource availability in palm oil biodiesel production. The functional unit in this study was 1 ton of biodiesel. The life cycle of palm oil biodiesel production consists of three processing units, namely the oil palm plantation, palm oil production, and biodiesel production. The processing unit with the greatest impact on the environment was found to be the oil palm plantation. The environmental benefits, namely the use of phosphate, contributed 62.30% of the 73.40% environmental benefit of the CO<sub>2</sub> uptake from the oil palm plantation processing unit. The total human health damage of the life cycle of palm oil biodiesel production was 0.00563 DALY, while the total ecosystem's diversity damage was  $2.69 \times 10^{-5}$  species-yr. Finally, we concluded that the oil palm plantation processing unit was the primary contributor of the carbon footprint, human health damage, and ecosystem diversity damage, while the biodiesel production processing unit demonstrated the highest damage to resource availability.

**Keywords:** biodiesel; carbon footprint; ecosystems; human health; resources

## 1. Introduction

The total primary energy production in Indonesia in 2018, consisting of petroleum, natural gas, coal, and renewable energy, reached 411.6 million tons of oil equivalent (Mtoe). About 64% or 261.4 Mtoe of the total production was exported, and these exports were mainly dominated by coal and liquefied natural gas (LNG) [1]. However, Indonesia is still an importer of energy, especially in the form of crude oil and fuel products, amounting to 43.2 Mtoe, to meet the needs of its industrial sector. Indonesia's total energy consumption (without traditional biomass) in 2018 was approximately 114 Mtoe, with 40% going to the transportation sector, 36% to industry, 16% to households, 6% going to the commercial sector, and finally, 2% to other sectors. Petroleum production in Indonesia over the past 10 years has shown a downward trend, from 346 million barrels (949 thousand barrels of oil per day (BOPD) in 2009 to around 283 million barrels (778 thousand BOPD) in 2018 [1]. The decline in production was primarily caused by aging main oil wells and relatively limited new wells.

The reduced production of fossil energy, especially petroleum, as well as global commitments to the reduction of greenhouse gas emissions, encourage the government of Indonesia to continuously

support the role of new and renewable energy to help maintain energy security and independence [1]. According to the Indonesian Government Regulation No. 79 of 2014 concerning the National Energy Policy, the targets for new and renewable energy in 2025 are at least 23% and 31% in 2050 [2]. These targets are based on the sustainable and low carbon development scenarios in 2025 and 2050, respectively [1]. One of the policy's mandates is a 20% biofuel mixture-to-fuel ratio (B20) in the transportation sector. Indonesia has significant potential for the adoption of renewable energy sufficient to realize the energy mix targets.

The use of renewable energy in the transportation sector, especially biodiesel, began to develop rapidly in line with the implementations of the mandatory biofuel policy. In 2018, Indonesia's production, export, and domestic demand of biodiesel were, respectively, 4706, 1512, and 2618 kilo liters (kL). The Indonesian government continues to be optimistic about further developments in the use of biodiesel [1]. Biodiesel production in Indonesia mostly utilizes palm oil as the raw material. The potential of palm oils in supporting bioenergy development policies, in this case biodiesel, is significant. In 2016, approximately 3.4 million tons of crude palm oil (CPO) were used for biodiesel [3]. Indonesia is the largest palm oil producing country in the world, responsible for half the global CPO production [4]. The global production of palm oil (palm oil pulp) is 39 million tons per year. The largest producers are Indonesia (17.1 million t) and Malaysia (16.6 million t) [5]. The potential of palm oil as a source of food and as the main raw material for biodiesel in Indonesia is also very large [6].

Life cycle assessment (LCA) is a mechanism for analyzing and calculating the total environmental impact of a product in each stage of its life cycle, including the preparation of raw materials, the production process, sales and transportation, and product disposal [7]. Although biodiesel is claimed to be a renewable energy, the process of biodiesel production uses chemicals and non-renewable resources, which can be an environmental burden. The use of urea produces  $N_2O$  (a greenhouse gas) and will therefore have an impact on the environment [8].

The production of palm oil biodiesel in Indonesia still faces a level of uncertainty due to the expansion of oil palm plantations, stimulating debates on the environmental consequences. Changes in land use from the conversion of forest land and agricultural land to oil palm plantations can produce further environmental implications, such as greenhouse gas (GHG) emissions from changes in soil carbon stocks and biomass, forest fires, air pollutant emissions, losses of biodiversity, and losses of animals, plants, and species in forest ecosystems [9–13]. Therefore, an LCA study must be conducted to evaluate the potential environmental impact associated with the life cycle of palm oil biodiesel production.

There have already been a number of studies that reported on the life cycles of palm oil production [14–30]. However, the majority focused on GHG emissions and energy requirements [14–25], and only a few LCAs addressed a wider set of environmental impacts [25–30]. The life cycle studies that accounted for carbon emissions from land use change (LUC) [15,19,22,23,31,32] showed that this has a significant influence on the greenhouse gas (GHG) emission intensity of palm oil biodiesel production. However, other reported results on the estimation of the impacts of palm oil area expansion range widely, indicating that this remains an unclear topic [14,33]. The environmental impacts of palm oil biodiesel also depend on the land use practices, residue disposal practices, biogas management, and palm oil mill effluent (POME) treatments [16,18,19,21,28,34,35]. The calculation of nitrogen (nitrous oxide  $N_2O$ , nitrogen oxides  $NO_x$ , and ammonia  $NH_3$ ), and phosphorus field emissions from oil palm plantations are also a critical aspect of an LCA of palm oil biodiesel. These calculations influence the results of several environmental impacts, such as the GHG intensity, eutrophication, and acidification [19,21,24,28,36].

The majority of studies that perform an LCA of palm oil biodiesel production cover only a single issue, such as greenhouse gas emissions. An exception is Schmidt et al. [30], who carried out LCA studies on palm oil production and addressed multiple issues, including eight impact categories, namely global warming, ozone depletion, acidification, eutrophication, photochemical smog, land use, biodiversity, and land transformation. However, this study was still limited to the midpoint

level and the assessment was not carried out until the endpoint level. Other relevant studies are by Harsono et al., Siregar et al., and Soraya et al. [19,26,27], who looked at the potential impacts of greenhouse gas emissions and global warming by calculating the CO<sub>2</sub> emitted during the life cycle of biodiesel production.

Henson et al. [37] conducted a study aimed at estimating the carbon sequestration and emissions, associated with both the cultivation of palm oil and the initial processing of its products in the mill. However, they did not include the effects of transportation and processing of palm oils. A comprehensive study on the carbon footprint of palm oil biodiesel production that includes CO<sub>2</sub> sources and CO<sub>2</sub> sinks has not yet been performed. Specifically, none of the aforementioned studies provided a comprehensive account of the carbon footprint at the stage of palm oil production and biodiesel production. Therefore, our study aimed to assess the CO<sub>2</sub> uptake and emissions throughout the life cycle of palm oil biodiesel production in Indonesia, which consists of three processing units, namely the oil palm plantation, palm oil production, and biodiesel production.

Additionally, Harsono et al., Siregar et al., and Soraya et al. [19,26,27] did not consider the CO<sub>2</sub> uptake. They studied the greenhouse gas emissions and the global warming potential based on the CO<sub>2</sub> emitted during the production process. They did not consider CO<sub>2</sub> sinks. We are of the opinion that the CO<sub>2</sub> absorption by trees and plants is significant enough to be considered. Therefore, we calculated and analyzed the CO<sub>2</sub> emissions from the production process and compared this to the CO<sub>2</sub> that can be absorbed by trees and plants. Additionally, we considered the damage to human health, to ecosystem diversity, and to resource availability.

## 2. Materials and Methods

### 2.1. Life Cycle Inventory (LCI)

In this study, we used the SimaPro 9.0.0.49 faculty version software (the latest version at the time) and the Ecoinvent 3 database [38]. The main goal was to study the environmental performance and identify the main environmental hotspots of first-generation (palm oil) biodiesel produced in Indonesia. The environmental performance of biodiesel palm oil was estimated by employing the LCA methodology as set in ISO 14040: 2006 Environmental management—Life cycle assessment—Principles and framework [8]. The attributional LCA (ALCA) approach, which was chosen over the consequential LCA (CLCA) as the first inventory of inputs and outputs, typically reflecting the global or national averages and using normative allocation rules, was scaled linearly to the functional unit. Data on the palm oil mill production process were collected from a typical palm oil mill located in the Banyuasin Regency, South Sumatra Province, Indonesia, situated in close proximity to an oil palm plantation [27]. Data on the biodiesel production process were collected from a biodiesel pilot plant project in LEMIGAS (Research and Development Center of Oil and Gas Technology), Indonesia [27]. The functional unit used in this study was 1 ton of biodiesel from palm oil.

The boundary of this study was a cradle-to-gate system, where the assessment started from the production of raw materials (fresh fruit bunch) to the production of finished products (biodiesel). The life cycle of the cradle-to-gate biodiesel palm oil production consisted of three processing units, i.e., the oil palm plantation to produce the fresh fruit bunch (FFB), the crude palm oil production to produce the CPO, and the biodiesel production to produce the biodiesel [19,26,27] (Figure 1). The black dashed line indicates the boundary of this LCA study. The production processing unit is shown in a black-and light blue-striped box, while the material, fuel, and energy inputs are shown in the black-striped box. The product, end-product, and co-product outputs are shown in the black-striped box and the emission outputs are shown in red lines.

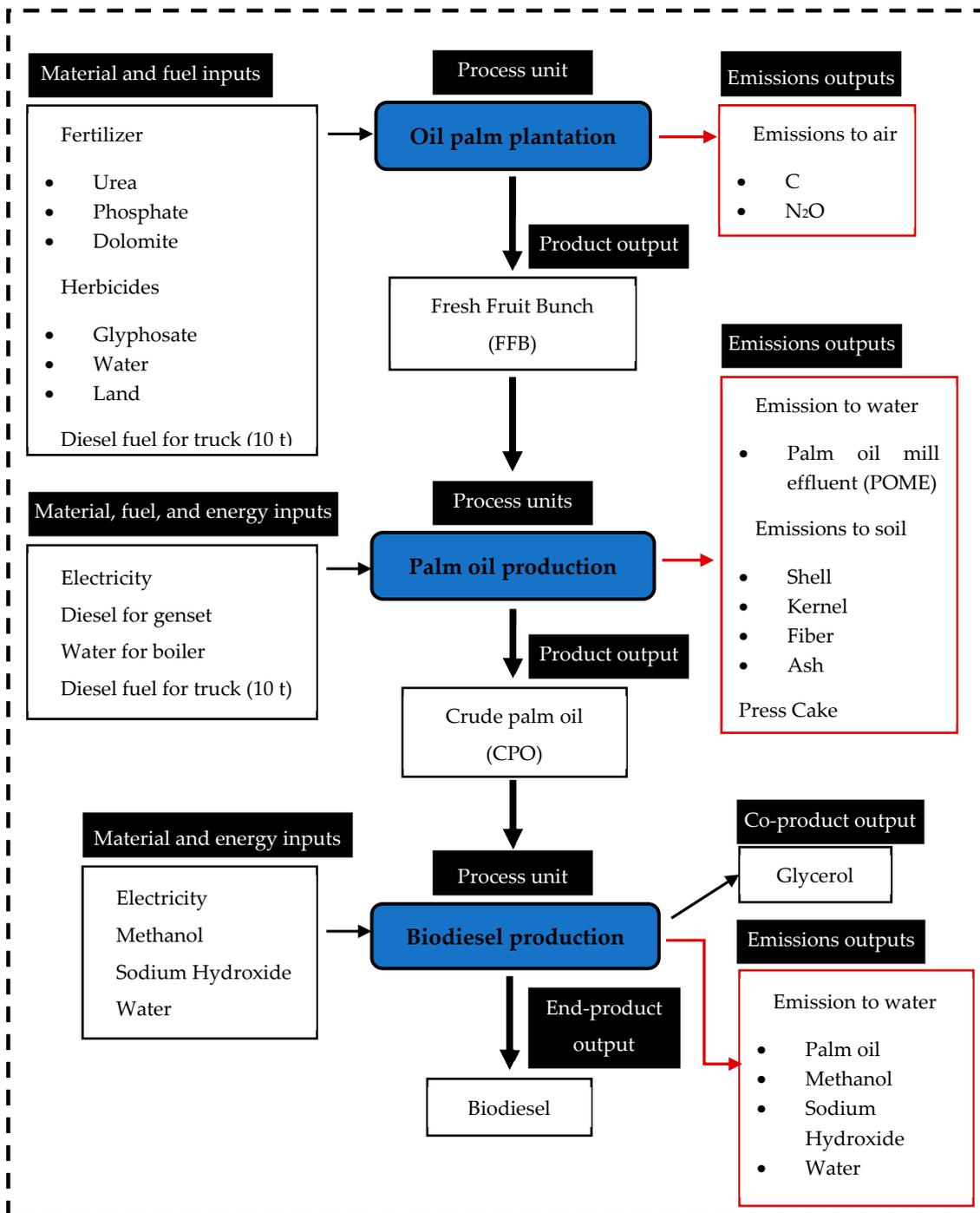


Figure 1. System boundary of palm oil biodiesel production.

Oil palm plantations have material and fuel inputs, including fertilizer (urea, phosphate, and dolomite), herbicides (glyphosate, water, and land), and diesel fuel for trucks (10 t). Additionally, they have a product output, namely FFB. Finally, oil palm plantations have emission outputs, including air emissions, namely C and N<sub>2</sub>O. The inputs for palm oil production are materials, fuel, and energy in the form of electricity, diesel for generators, water for boilers, and diesel fuel for trucks (10 t). The outputs for palm oil production are CPO and emission outputs, including water emissions, namely palm oil mill effluent (POME), and soil emissions, namely shell, kernel, fiber, ash, and press cake. Biodiesel production has material and energy inputs, namely electricity, methanol, sodium hydroxide, and water, as well as an end-product output (biodiesel), and a co-product output (glycerol).

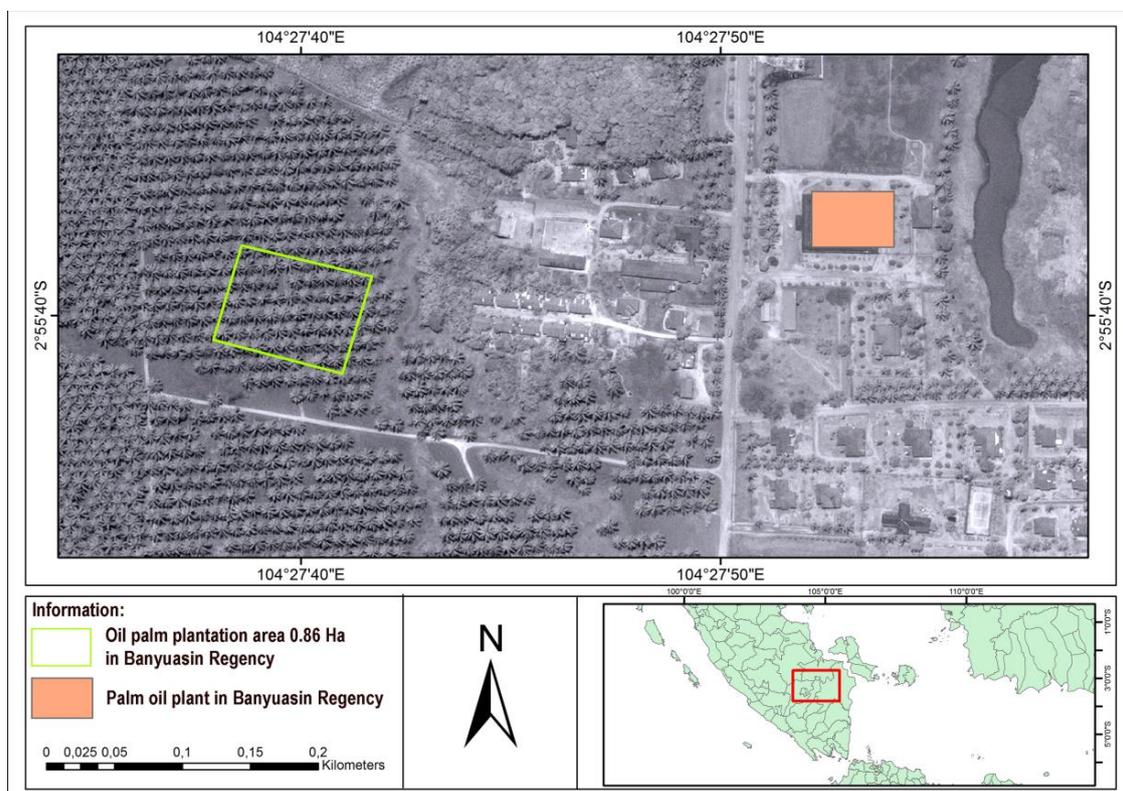
Biodiesel production also has emission outputs, including water emissions (palm oil, methanol, and sodium hydroxide). The assumptions in this study were:

- (1) Oil palm plantations used peat lands;
- (2) Water used by the oil palm plantation was river water;
- (3) Water used in the boiler was ultrapure water;
- (4) POME was liquid waste that was directly emitted to the waters;
- (5) Shell, kernel, fiber, ash, and press cake were solid waste that was directly emitted to the ground surface;
- (6) Water used for biodiesel washing was ultrapure water; and
- (7) The remaining methanol, sodium hydroxide, water, and palm oil were liquid waste that was directly emitted into the waters.

The data on the life cycle inventory (LCI) were taken from several sources in order to obtain a complete and comprehensive picture. The following is an overview of the LCI data in the context of the oil palm plantation, palm oil production, and biodiesel production processing units.

### 2.1.1. Oil Palm Plantation

An oil palm plantation has three types of inputs, namely fertilizer, herbicides, and diesel fuel. The fertilizer consists of urea (104.37 kg), phosphate (109.73 kg), and dolomite (97.92 kg) [27]. The nitrogen content in urea helps plants develop additional green leaf matter, called chlorophyll. With abundant green leaves, plants will find it easier to carry out photosynthesis [39]. Phosphate is useful for stimulating the growth of palm oil roots [40]. The herbicide input consists of glyphosate (3 kg) [27]. Diesel fuel input consists of 5.03 L for a 10-t truck [26]. Oil palm plantations have air emissions in the form of carbon (C) (10.7 t) and dinitrogen monoxide ( $N_2O$ ) (8 kg), both from the drained peatland [41]. A high productivity of palm oil is achieved by good management of palm oil cultivation, including the provision of fertilizers and herbicides. Figure 2 is a map of the oil palm plantation in the Banyuasin Regency.



**Figure 2.** Map of the oil palm plantation in the Banyuasin Regency (source: Google Earth).

The map of the oil palm plantation was taken from satellite imagery using Google Earth software. The selected imagery was taken in 2014, which is the same year as when an inventory was done of the oil palm plantations. The map results from Google Earth were then processed with ArcGIS software to digitize the area covering the oil palm plantation. The plantation land area of 0.86 ha is indicated with a green box. The oil palm plantation is located in the Banyuasin Regency, South Sumatra Province, Indonesia. The oil palm plantation is located near the palm oil plant. The production of 1 ton of palm oil biodiesel requires a plantation of 0.86 ha in size. The plantation area of 0.86 ha is capable of producing 6.39 tons of fresh fruit bunches (Figure 2).

### 2.1.2. Palm Oil Production

The production of palm oil requires electricity, diesel fuel, and water. The electricity input is equal to 95.81 kWh [27]. The diesel fuel supports a 4.9-L generator (genset) and 2.54 L of diesel fuel goes to the 10-t truck [26]. The boiler unit uses 5.75 m<sup>3</sup> of water [27]. The emissions from palm oil production affect the water and soil. The emissions into water consist of 3.83 m<sup>3</sup> of POME discharge [27], while the emissions into soil consist of 0.22 of shell, 0.35 of kernel, 0.83 of fiber, 0.032 of ash, and 1.66 t of press cake [27]. Palm oil production has a CPO output of 1.28 t [27], whereas the palm oil mill is capable of producing 1.28 t of CPO from an FFB input of 6.39 t.

### 2.1.3. Biodiesel Production

Biodiesel production requires several inputs, namely electricity, methanol, sodium hydroxide, and water. The electricity input is 256.5 kWh [27]. The input of methanol and sodium hydroxide amount to 0.64 t and 0.03 t, respectively [27]. The production of biodiesel involves a transesterification reaction process. Palm oil reacts with methanol (input) with the addition of a sodium hydroxide catalyst (input) to accelerate the reaction for the formation of methyl ester (biodiesel) and glycerol. Biodiesel production involves emissions into water in the form of palm oil, methanol, and sodium hydroxide. The output of the entire biodiesel production process is 1 t of biodiesel as the end-product and 0.22 t of glycerol as the co-product [27]. The LCI data are displayed in Table 1.

**Table 1.** The life cycle inventory of palm oil biodiesel production.

|     | Activity   | Materials Input  | Reference |
|-----|--|--|-----------|
| (1) | Oil palm plantation processing unit<br>0.86 ha to produce FFB 6.39 t | <ul style="list-style-type: none"> <li>• Chemical 315.02 kg</li> <li>• Water 2959.51 L</li> <li>• Fuel 5.03 L</li> </ul>                 | [26,27]   |
| (2) | Palm oil production processing unit to<br>produce CPO 1.28 t         | <ul style="list-style-type: none"> <li>• Electricity 95.81 kWh</li> <li>• Diesel 7.44 L</li> <li>• Water 5.75 m<sup>3</sup></li> </ul>   | [26,27]   |
| (3) | Biodiesel production processing unit<br>to produce biodiesel 1 t     | <ul style="list-style-type: none"> <li>• Electricity 256.5 kWh,</li> <li>• Chemical 0.67 t</li> <li>• Water 1.5 m<sup>3</sup></li> </ul> | [27]      |

Soraya et al. [27] reported that 0.134 ha of land can produce 1 t of FFB, whereas 4.99 t of FFB can produce 1 t of CPO, and 1.28 t of CPO can produce 1 t of biodiesel. Based on this information, 6.39 t of FFB and 0.86 ha of land would be required to produce 1 t of biodiesel. Further details on the life cycle inventory are provided in the supporting information.

## 2.2. Life Cycle Impact Assessment (LCIA)

This study aimed to assess the environmental performance of palm oil biodiesel production in Indonesia. The LCIA was used to analyze the carbon footprint, midpoint impact, and endpoint damage

on biodiesel palm oil production in Indonesia. This study utilized the Greenhouse Gas Protocol and ReCiPe Endpoint (H) for the impact assessment. Four categories of carbon footprint impacts were analyzed in this study, namely the fossil CO<sub>2</sub> eq, biogenic CO<sub>2</sub> eq, CO<sub>2</sub> from land transformation, and CO<sub>2</sub> uptake. Fossil CO<sub>2</sub> eq are carbons originating from fossil fuels, while biogenic CO<sub>2</sub> eq is carbon originating from biomass sources, such as trees and plants. Biogenic CO<sub>2</sub> comes from biomass combustion which is part of the natural carbon cycle. For biomass burning, the carbon stored in organic material will be released into the atmosphere and captured back into the natural carbon cycle as the biomass regrows. This cycle helps maintain a constant level of carbon in the environment and plays an important role in balancing Earth's natural carbon cycle. CO<sub>2</sub> from land transformation has a direct impact, and CO<sub>2</sub> uptake is CO<sub>2</sub> that is stored in trees and plants as they grow [42]. The impact categories grouped into damage categories are shown in Table 2.

**Table 2.** Impact categories grouped into damage categories.

| No | Impact Category                 | Damage Category | Unit       |
|----|---------------------------------|-----------------|------------|
| 1  | Climate change—human health     | Human health    | DALY       |
| 2  | Ozone depletion                 |                 |            |
| 3  | Human toxicity                  |                 |            |
| 4  | Photochemical oxidant formation |                 |            |
| 5  | Particulate matter formation    |                 |            |
| 6  | Ionizing radiation              |                 |            |
| 7  | Climate change—ecosystems       | Ecosystems      | species·yr |
| 8  | Terrestrial acidification       |                 |            |
| 9  | Freshwater eutrophication       |                 |            |
| 10 | Terrestrial ecotoxicity         |                 |            |
| 11 | Freshwater ecotoxicity          |                 |            |
| 12 | Marine ecotoxicity              |                 |            |
| 13 | Agricultural land occupation    | Resources       | \$         |
| 14 | Urban land occupation           |                 |            |
| 15 | Natural land transformation     |                 |            |
| 16 | Metal depletion                 | Resources       | \$         |
| 17 | Fossil depletion                |                 |            |

### 3. Results and Discussion

#### 3.1. Carbon Footprint of Oil Palm Plantation

The carbon footprint of oil palm plantation is split into four impact categories, namely fossil CO<sub>2</sub> eq, biogenic CO<sub>2</sub> eq, CO<sub>2</sub> eq from land transformation, and CO<sub>2</sub> uptake. The resulting figures for these four categories are shown in Table 3.

**Table 3.** Characterization of the carbon footprint of the oil palm plantation.

| Impact Category                             | Unit                  | Total    | FFB-Oil Palm Plantation | Urea, as N | Phosphate Fertilizer, as P <sub>2</sub> O <sub>5</sub> | Dolomite | Glyphosate | Diesel |
|---|-----------------------|----------|-------------------------|------------|--|----------|------------|--------|
| Fossil CO <sub>2</sub> eq                   | kg CO <sub>2</sub> eq | 2743.777 | 2120                    | 347.779    | 234.537  | 4.303    | 34.786     | 2.371  |
| Biogenic CO <sub>2</sub> eq                 | kg CO <sub>2</sub> eq | 18.575   | 0                       | 3.559      | 13.275   | 0.247    | 1.469      | 0.025  |
| CO <sub>2</sub> eq from land transformation | kg CO <sub>2</sub> eq | 7.940    | 0                       | 0.185      | 7.633  | 0.007    | 0.113      | 0.001  |
| CO <sub>2</sub> uptake                      | kg CO <sub>2</sub> eq | 43.134   | 0                       | 4.780      | 36.582   | 0.221    | 1.529      | 0.022  |

The largest contribution of the carbon footprint from the oil palm plantation came from the FFB-oil palm plantation, with 2120 kg CO<sub>2</sub> eq in the category of impact of fossil CO<sub>2</sub> eq caused by air emissions (Table 3). Fossil CO<sub>2</sub> eq and biogenic CO<sub>2</sub> eq came from different sources. Fossil CO<sub>2</sub> eq came from burning fossil fuels and N<sub>2</sub>O gas from drained peatland. Biogenic CO<sub>2</sub> eq came from burning biomass

fuels [22]. The global warming potential (GWP) 100 years relative to the fossil CO<sub>2</sub> eq for N<sub>2</sub>O gas emissions was 298 kg of fossil CO<sub>2</sub> eq, compared to 1 kg of N<sub>2</sub>O [22,23,41]. Therefore, the contribution of fossil CO<sub>2</sub> eq was greater than the biogenic CO<sub>2</sub> eq. There were two forms of air emissions, namely carbon and dinitrogen monoxide (N<sub>2</sub>O) from drained peatland. Carbon has a smaller global warming effect potential than that of N<sub>2</sub>O. The pollution effect caused by N<sub>2</sub>O gas is 298 times larger than that of CO<sub>2</sub>. In Indonesia, peatlands are being drained and cleared for facilitating oil palm plantations [24]. The lowland peatlands of Southeast Asia represent an immense reservoir of fossil carbon and are reportedly responsible for 30% of the global carbon dioxide (CO<sub>2</sub>) emissions from land use, land use change, and forestry [43]. The largest contributor in the impact category of biogenic CO<sub>2</sub> eq, CO<sub>2</sub> eq from land transformation, and CO<sub>2</sub> uptake is phosphate fertilizer. The reason for this is that biomass fuel is used in the phosphate fertilizer production process. Phosphate production produces large amounts of biogenic CO<sub>2</sub> eq. We consider CO<sub>2</sub> uptake to be CO<sub>2</sub> that is easily absorbed by trees and plants, and this is considered a biogenic CO<sub>2</sub> [42].

The total carbon footprint of the oil palm plantation in this study was 2727 kg CO<sub>2</sub> eq. This is a larger carbon footprint than those reported by Castanheira et al., Harsono et al., Choo et al., Souza et al., Siregar et al., and Soraya et al. [14,19,21,24,26,27], who respectively reported 1800, 1440, 119, 1220, 1380, and 400 kg CO<sub>2</sub> eq. The reason for the carbon footprint being larger in this study is that the inventory data include N<sub>2</sub>O gas air emissions. Choo et al., Siregar et al., and Soraya et al. [21,26,27] excluded N<sub>2</sub>O gas air emissions, whereas Castanheira et al. and Harsono et al. [14,19] included N<sub>2</sub>O gas air emissions, resulting in a larger carbon footprint [21,26,27].

### 3.2. Carbon Footprint of Palm Oil Production

The carbon footprint of palm oil production includes FFB-oil palm plantations as an input. The carbon footprint of palm oil production is shown in Table 4.

**Table 4.** Characterization of the carbon footprint of palm oil production.

| Impact Category                             | Unit                  | Total    | CPO-Palm Oil Production | Diesel for a Genset | Water, Ultrapure | Diesel for a Truck | FFB-Oil Palm Plantation | Electricity, Low Voltage |
|---|-----------------------|----------|-------------------------|---------------------|------------------|--------------------|-------------------------|--------------------------|
| Fossil CO <sub>2</sub> eq                   | kg CO <sub>2</sub> eq | 2825.536 | 0                       | 2.314               | 0.262            | 1.197              | 2743.777                | 77.985                   |
| Biogenic CO <sub>2</sub> eq                 | kg CO <sub>2</sub> eq | 21.517   | 0                       | 0.024               | 0.004            | 0.013              | 18.575                  | 2.902                    |
| CO <sub>2</sub> eq from land transformation | kg CO <sub>2</sub> eq | 8.153    | 0                       | 0.001               | 0.0002           | 0.0006             | 7.940                   | 0.211                    |
| CO <sub>2</sub> uptake                      | kg CO <sub>2</sub> eq | 45.895   | 0                       | 0.029               | 0.004            | 0.011              | 43.134                  | 2.724                    |

In fossil CO<sub>2</sub> eq, the contributions of FFB-oil palm plantations and electricity were, respectively, 2743.77 and 77.98 kg CO<sub>2</sub> eq. In biogenic CO<sub>2</sub> eq, the contributions of FFB-oil palm plantations and electricity were, respectively, 18.57 and 2902 kg CO<sub>2</sub> eq. In the CO<sub>2</sub> eq from land transformation, the contributions of FFB-oil palm plantations and electricity were, respectively, 7940 and 0.211 kg CO<sub>2</sub> eq. In the CO<sub>2</sub> uptake, the contributions of FFB-oil palm plantations and electricity were, respectively, 43.134 and 2724 kg CO<sub>2</sub> eq (Table 4).

The results showed that, in fossil CO<sub>2</sub> eq, biogenic CO<sub>2</sub> eq, CO<sub>2</sub> eq from land transformation, and CO<sub>2</sub> uptake, the largest contributor was FFB-oil palm plantations, followed by electricity. The carbon footprint of palm oil production in this study totaled 2809 kg CO<sub>2</sub> eq. This included the total carbon footprint of the oil palm plantation, and this result is greater than the results of other studies (Bessou et al., Castanheira et al., Rodrigues et al., Kaewmai et al., Hansen et al., Harsono et al., Choo et al., Souza et al., Siregar et al., Soraya et al., and Schmidt [9,14,15,17–19,21,24,26,27,44]). The results of these studies are smaller as the LCA calculation did not include the N<sub>2</sub>O gas from drained peatlands. The results of this study are less than the results of Reijnders and Huijbregts [45], who reported 19,700 kg CO<sub>2</sub> eq.

### 3.3. Carbon Footprint of Biodiesel Production

The carbon footprint of biodiesel production included CPO-palm oil production as an input. Therefore, CPO-palm oil production emerged as one of the largest contributors out of the four impact categories. The carbon footprint of biodiesel production is shown in Table 5.

**Table 5.** Characterization of the carbon footprint of biodiesel production.

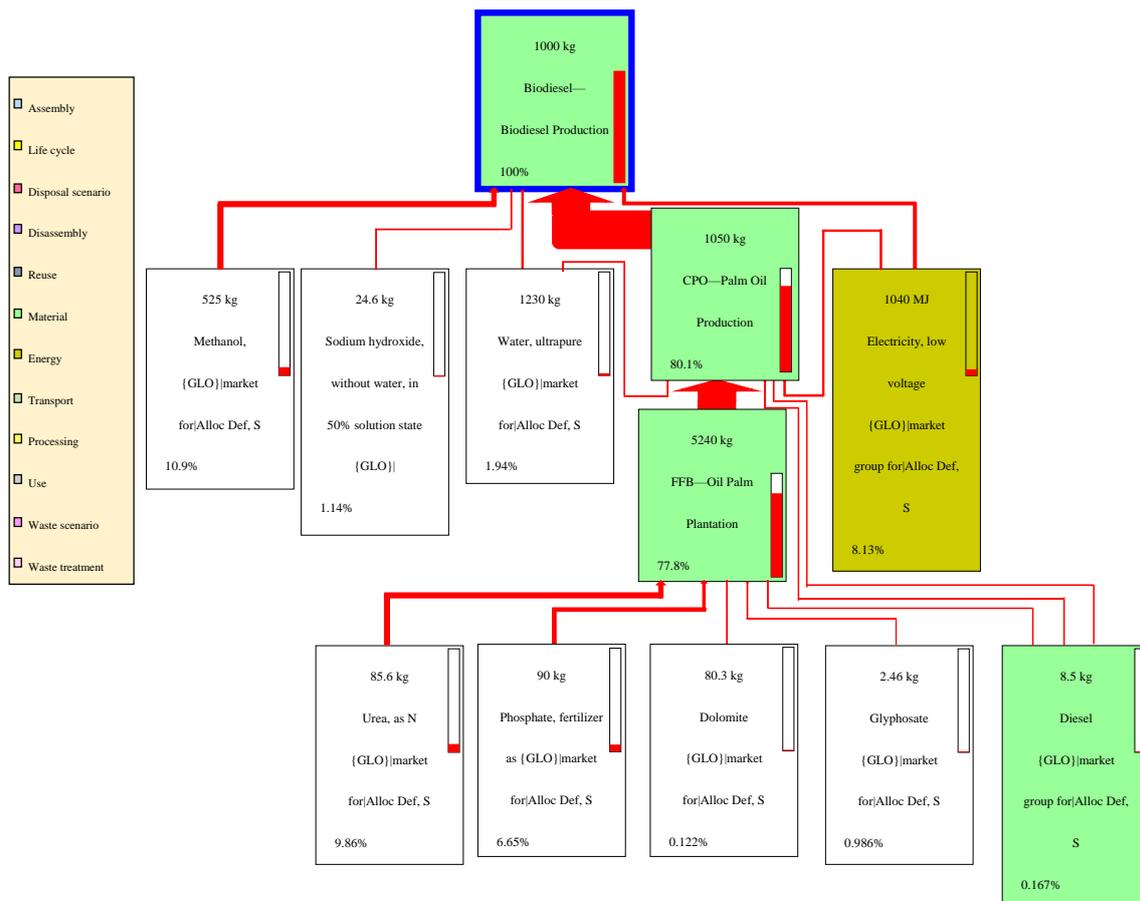
| Impact Category                             | Unit                  | Total    | Biodiesel—<br>Biodiesel<br>Production | Methanol | Sodium<br>Hydroxide | Water,<br>Ultrapure | CPO-Palm<br>Oil<br>Production | Electricity,<br>Low<br>Voltage |
|---|-----------------------|----------|---------------------------------------|----------|---------------------|---------------------|-------------------------------|--------------------------------|
| Fossil CO <sub>2</sub> eq                   | kg CO <sub>2</sub> eq | 2893.613 | 0                                     | 316.583  | 32.922              | 55.968              | 2316.939                      | 171.200                        |
| Biogenic CO <sub>2</sub> eq                 | kg CO <sub>2</sub> eq | 28.777   | 0                                     | 2.612    | 1.332               | 0.818               | 17.644                        | 6.370                          |
| CO <sub>2</sub> eq from land transformation | kg CO <sub>2</sub> eq | 7.451    | 0                                     | 0.177    | 0.080               | 0.045               | 6.685                         | 0.463                          |
| CO <sub>2</sub> uptake                      | kg CO <sub>2</sub> eq | 48.184   | 0                                     | 2.388    | 1.337               | 0.846               | 37.634                        | 5.980                          |

The three largest contributors to both the non-biogenic CO<sub>2</sub> (fossil) and biogenic CO<sub>2</sub> (biomass) carbon footprint were CPO-palm oil production, methanol, and electricity, as presented in Table 5. Biogenic CO<sub>2</sub> came from the utilization of biomass in the life cycle of these processes. In addition, the three largest contributors to biogenic CO<sub>2</sub> eq were CPO-palm oil production (17,644), electricity (6370), and methanol (2612 kg CO<sub>2</sub> eq).

The total carbon footprint of biodiesel production was 2882 kg CO<sub>2</sub> eq, which includes that of the FFB-oil palm plantation and CPO-palm oil production. This is a larger carbon footprint than reported by Hansen et al. (875), Choo et al. (1113), Souza et al. (1901), Siregar et al. (2570), and Soraya et al. (690 kg CO<sub>2</sub> eq) [18,21,24,26,27]. The results of these studies are smaller as the LCA calculation does not include the N<sub>2</sub>O gas from drained peatlands. The carbon footprint environmental hotspot from biodiesel production is shown in Figure 3, which shows the network analysis for the fossil CO<sub>2</sub> eq impact category. The CO<sub>2</sub> eq network from fossils is highlighted in the discussion as it generated a higher carbon footprint compared to the biogenic CO<sub>2</sub> from biomass utilization and the CO<sub>2</sub> from land transformation.

The results from the network analysis of fossil CO<sub>2</sub> eq showed that 80.10% of the environmental hotspots from biodiesel production were primarily coming from the palm oil production. The environmental hotspots are shown with a wide red arrow in Figure 3. The primary contributor to environmental hotspots in the palm oil production unit was the oil palm plantation, contributing 77.80%. Other contributors were diesel (0.11%), water (0.97%), and electricity (2.03%). This makes the oil palm plantation in itself an environmental hotspot due to contributing 77.80% of 80.10% to the environmental hotspots in palm oil production. The palm oil production processing unit itself contributed 3.3% (Figure 3).

The environmental hotspot of fossil CO<sub>2</sub> eq from biodiesel production was the oil palm plantation, which contributed 77.80% of the total environmental hotspot of fossil CO<sub>2</sub> eq in the life cycle of palm oil biodiesel production. This result is in line with Harsono et al., Siregar et al., and Soraya et al. [19,26,27]. The material and fuel inputs in oil palm plantations, namely urea, phosphate fertilizer, dolomite, glyphosate, and diesel contributed, respectively, 9.86%, 6.65%, 0.122%, 0.986%, and 0.056%, totaling 17.62%. Therefore, 60.18% of the contributions came from emissions. The inventory data of this study included air emissions, namely dinitrogen monoxide (N<sub>2</sub>O) from drained peatlands. From this, it is clear that the N<sub>2</sub>O gas from drained peatlands contributed 60.18% of the 77.80% to the oil palm plantation. This also indicates that 60.18% of the 100% environmental hotspot of fossil CO<sub>2</sub> eq of biodiesel production was caused by N<sub>2</sub>O gas from drained peatlands.



**Figure 3.** Environmental hotspots from the network analysis of fossil CO<sub>2</sub> eq.

The results of the environmental hotspot of fossil CO<sub>2</sub> eq were the first findings in this study. They indicate that the life cycle of biodiesel production from palm oil and the oil palm plantation unit contributed majorly (81.10%) toward forming an environmental hotspot of fossil CO<sub>2</sub> eq of biodiesel production. This was the same for N<sub>2</sub>O gas from drained peatlands (77.80%), which is the main contributor of the palm oil processing unit, and the remaining 22.2% of contributions came from the palm oil production and biodiesel production units at 3.3% and 18.9%, respectively.

The environmental benefit of the carbon footprint of biodiesel production is shown in Figure 4. The network analysis in Figure 4 is a network of the impact categories for the CO<sub>2</sub> uptake.

The data in Figure 4 are the percentage contributions of the CO<sub>2</sub> uptake impact categories. The percentage contributions of the CO<sub>2</sub> uptake impact categories on the life cycle of palm oil biodiesel production were taken from the chemical inputs, fuel, electricity, and emissions outputs.

The CO<sub>2</sub> uptake network analysis showed that the environmental benefits of biodiesel production stemmed for 78.10% from palm oil production, as further detailed in Figure 4. In Figure 4, the environmental benefits are illustrated with a wide green arrow. The primary contributor to the environmental benefits of the palm oil production unit was the oil palm plantation with 73.40%, followed by electricity (3.4%), water (0.88%), and diesel (0.06%). Figure 4 also shows that the contribution of phosphate to the oil palm plantation processing unit's contribution was a considerable 62.3%. We therefore conclude that the environmental benefits are due to the use of phosphate. The palm oil processing unit itself contributed 4.7% to the total environmental benefit (Figure 4).

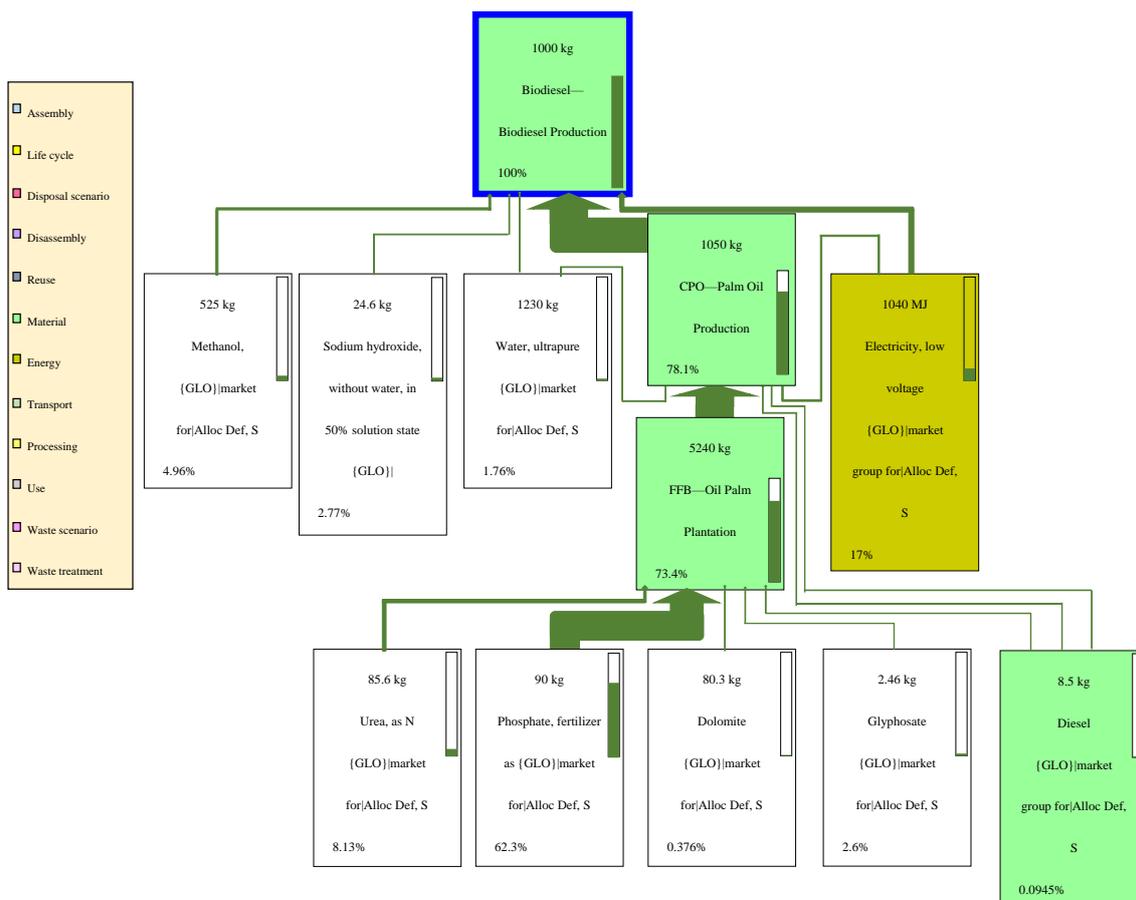


Figure 4. Environmental benefits from the network analysis of the CO<sub>2</sub> uptake.

This research included environmental benefits, which is a unique aspect compared to the research of Harsono et al., Siregar et al., and Soraya et al. [19,26,27]. The results on the environmental benefits of CO<sub>2</sub> uptake were the second finding in this study. These findings show the life cycle of biodiesel production from palm oil. CO<sub>2</sub> uptake is CO<sub>2</sub> that can be absorbed by trees and plants, and thus provide benefits to the environment. The total CO<sub>2</sub> uptake by plants in the life cycle of producing 1 ton of palm oil biodiesel is 48.184 kg CO<sub>2</sub> eq (Table 5).

One hectare (ha) of oil palm plantations can absorb CO<sub>2</sub> equivalent to 97.1% [46]. CO<sub>2</sub> emissions from oil palm plantations and CO<sub>2</sub> absorption can balance out 25 years after planting palm oils [46]. Fossil fuels in nature are formed through a long process of millions of years under conditions of high pressure and temperature deep in the earth. The carbon chains contained in fossil fuels are complex C chains which are not easily decomposed in the atmosphere. This type of fossil fuel CO<sub>2</sub> is not easily absorbed by trees and plants. [47].

Biogenic CO<sub>2</sub> is produced from the burning of plant biomass and takes a short time to form as the plant grows from bud to maturity (less than 5 years). Oil palms produce fruit and biomass that may be harvested after only 4 years [48]. Burning biomass emits carbon that is part of the biogenic carbon cycle. Biomass combustion simply returns to the atmosphere the carbon that was absorbed as the plants grew [47].

The CO<sub>2</sub> uptake in this study came from the biogenic CO<sub>2</sub> sink of plants. A biogenic CO<sub>2</sub> sink is the absorption of CO<sub>2</sub> by plants through the process of photosynthesis. Photosynthesis produces energy that is useful for plants to grow. Through photosynthesis, plants convert atmospheric CO<sub>2</sub> into biomass [49]. At night, the plants perform respiration to produce biogenic CO<sub>2</sub> [50]. Thus, the biogenic CO<sub>2</sub> in this study came from the burning of biomass fuel and plant respiration. The CO<sub>2</sub> eq from land transformation came from CO<sub>2</sub> emissions in the process of converting forests to oil palm plantations

through forest fires. Fossil fuel CO<sub>2</sub> eq came from N<sub>2</sub>O gas from drained peatlands (the main source), the use of urea, electricity, and the use of diesel fuel in gensets and trucks. In the LCA calculation results, N<sub>2</sub>O gas from drained peatlands was included in the impact category of fossil CO<sub>2</sub> eq. Finally, in the results of this study, the production of 1 ton of biodiesel required 0.86 ha of land plantation and produced 2893.61 kg fossil fuel CO<sub>2</sub> eq, 28.77 kg biogenic CO<sub>2</sub> eq, 7.451 kg CO<sub>2</sub> eq from land transformation, and the uptake of 48.18 kg CO<sub>2</sub> eq (Table 5).

### 3.4. Impact and Damage Assessment of Oil Palm Plantation

The results from the impact assessment of the oil palm plantation are divided into 17 impact categories. These 17 impact categories are further divided into six impact categories with DALY units, nine impact categories with species-yr units, and two impact categories with \$ units. The results from the impact assessment of the oil palm plantation are shown in Table 6.

The three largest contributors out of the 17 impact categories were the FFB-oil palm plantations, urea, and phosphate. FFB-oil palm plantations contribute to climate change—Human health and climate change—Ecosystems with 0.00334 DALY and  $1.89 \times 10^{-5}$  species-yr, respectively. Urea had eight major contributors, namely ozone depletion ( $1.27 \times 10^{-7}$  DALY), photochemical oxidant formation ( $2.92 \times 10^{-8}$  DALY), particulate matter formation (0.000213 DALY), terrestrial acidification ( $1.39 \times 10^{-8}$  species-yr), marine ecotoxicity ( $4.73 \times 10^{-10}$  species-yr), natural land transformation ( $1.71 \times 10^{-7}$  species-yr), metal depletion (1.503 \$), and fossil depletion (22.451 \$). Phosphate also had eight major contributors, namely human toxicity (0.000138 DALY), particulate matter formation (0.000311 DALY), ionizing radiation ( $5.48 \times 10^{-7}$  DALY), terrestrial ecotoxicity ( $2.7 \times 10^{-7}$  species-yr), agricultural land occupation ( $6.99 \times 10^{-7}$  species-yr), urban land occupation ( $3.82 \times 10^{-7}$  species-yr), metal depletion (2.307 \$), and fossil depletion (12.565 \$) (Table 6).

The FFB-oil palm plantation processing unit contributed to climate change—human health and climate change—ecosystems at 0.00334 DALY and  $1.89 \times 10^{-5}$  species-yr, respectively. A study by Bessou et al. [51] reported N<sub>2</sub>O emissions related to nitrogen associated with the decomposition of soil organic carbon (SOC). Accounting for N<sub>2</sub>O emissions related to carbon losses through the C:N ratio resulted in increased land use and land use change (LULUC) climate change impacts. Peatlands play an important role in the emissions of the greenhouse gases CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, which are produced during the mineralization of peat organic matter [52]. In the atmosphere, nitrogen oxides (NO<sub>x</sub>) can react with volatile organic compounds (VOCs) when exposed to sunlight radiation, resulting in the formation of photochemical oxidants [53,54].

Nitrates produced from the nitrification process can cause terrestrial acidification [55]. Foth [55] suggested that nitrogen-containing fertilizers, in the form of ammonium, can be turned into nitrates, which, in turn, decrease the soil pH. Nitrification, on the other hand, results in the formation of hydrogen ions (H<sup>+</sup>) and has the potential to increase the soil pH. Nitrates released into the water can cause freshwater eutrophication, which is a direct result of algae growth [56]. Nitrite and ammonium are compounds that can cause human toxicity, freshwater ecotoxicity, and marine ecotoxicity. According to Wantasen et al. [57], abiotic environments can be polluted by the transformation of nitrogen, including nitrates, nitrites, and ammonium. Nitrate is a nutrient that plays a role in the growth of aquatic plants and algae, causing uncontrolled growth of aquatic flora, while killing other aquatic organisms. According to Rustadi [58], a high nitrogen concentration can cause excessive phytoplankton growth, or eutrophication, and can cause reservoir water pollution. In addition to the abiotic environment, the results of the transformation of nitrogen can also hurt humans. Nitrites and nitrates in soil can pollute the surrounding water sources, such as rivers.

**Table 6.** Characterization of the impact assessment of the oil palm plantation.

| Impact Category                 | Unit       | Total                 | FFB-Oil Palm Plantation | Urea, as N             | Phosphate Fertilizer, as P <sub>2</sub> O <sub>5</sub> | Dolomite               | Glyphosate             | Diesel                 |
|---------------------------------|------------|-----------------------|-------------------------|------------------------|--|------------------------|------------------------|------------------------|
| Climate change—Human health     | DALY       | 0.00420               | 0.00334                 | 0.000481               | 0.000327   | $5.95 \times 10^{-6}$  | $4.79 \times 10^{-5}$  | $3.26 \times 10^{-6}$  |
| Ozone depletion                 | DALY       | $2.28 \times 10^{-7}$ | 0                       | $1.27 \times 10^{-7}$  | $6.85 \times 10^{-8}$                                  | $8.42 \times 10^{-10}$ | $2.37 \times 10^{-8}$  | $7.61 \times 10^{-9}$  |
| Human toxicity                  | DALY       | 0.000234              | 0                       | $8.17 \times 10^{-5}$  | 0.000138   | $1.01 \times 10^{-6}$  | $1.27 \times 10^{-5}$  | $2.6 \times 10^{-7}$   |
| Photochemical oxidant formation | DALY       | $7.3 \times 10^{-8}$  | 0                       | $2.92 \times 10^{-8}$  | $3.82 \times 10^{-8}$                                  | $7.61 \times 10^{-10}$ | $4.31 \times 10^{-9}$  | $5.66 \times 10^{-7}$  |
| Particulate matter formation    | DALY       | 0.000557              | 0                       | 0.000213               | 0.000311   | $4.72 \times 10^{-6}$  | $2.56 \times 10^{-5}$  | $1.73 \times 10^{-6}$  |
| Ionizing radiation              | DALY       | $9.58 \times 10^{-7}$ | 0                       | $3.13 \times 10^{-7}$  | $5.48 \times 10^{-7}$                                  | $8.73 \times 10^{-9}$  | $7.16 \times 10^{-8}$  | $1.71 \times 10^{-8}$  |
| Climate change—Ecosystems       | species·yr | $2.38 \times 10^{-5}$ | $1.89 \times 10^{-5}$   | $2.73 \times 10^{-6}$  | $1.85 \times 10^{-6}$                                  | $3.37 \times 10^{-8}$  | $2.71 \times 10^{-7}$  | $1.84 \times 10^{-8}$  |
| Terrestrial acidification       | species·yr | $2.92 \times 10^{-8}$ | 0                       | $1.39 \times 10^{-8}$  | $1.4 \times 10^{-8}$                                   | $1.49 \times 10^{-10}$ | $9.94 \times 10^{-10}$ | $1.24 \times 10^{-10}$ |
| Freshwater eutrophication       | species·yr | $1.62 \times 10^{-8}$ | 0                       | $2.87 \times 10^{-9}$  | $1.11 \times 10^{-8}$                                  | $7.83 \times 10^{-11}$ | $2.19 \times 10^{-9}$  | $1.24 \times 10^{-11}$ |
| Terrestrial ecotoxicity         | species·yr | $2.81 \times 10^{-7}$ | 0                       | $8.45 \times 10^{-9}$  | $2.7 \times 10^{-7}$                                   | $6.76 \times 10^{-11}$ | $2.32 \times 10^{-9}$  | $4.22 \times 10^{-11}$ |
| Freshwater ecotoxicity          | species·yr | $7.03 \times 10^{-9}$ | 0                       | $2.31 \times 10^{-9}$  | $4.27 \times 10^{-9}$                                  | $3.5 \times 10^{-11}$  | $4.07 \times 10^{-10}$ | $1.18 \times 10^{-11}$ |
| Marine ecotoxicity              | species·yr | $1.37 \times 10^{-9}$ | 0                       | $4.73 \times 10^{-10}$ | $8.13 \times 10^{-10}$                                 | $7.01 \times 10^{-12}$ | $7.93 \times 10^{-11}$ | $1.94 \times 10^{-12}$ |
| Agricultural land occupation    | species·yr | $8.35 \times 10^{-7}$ | 0                       | $1.04 \times 10^{-7}$  | $6.99 \times 10^{-7}$                                  | $3.91 \times 10^{-9}$  | $2.72 \times 10^{-8}$  | $4.03 \times 10^{-10}$ |
| Urban land occupation           | species·yr | $4.32 \times 10^{-7}$ | 0                       | $3.81 \times 10^{-8}$  | $3.82 \times 10^{-7}$                                  | $1.44 \times 10^{-9}$  | $1.02 \times 10^{-8}$  | $5.69 \times 10^{-10}$ |
| Natural land transformation     | species·yr | $3.92 \times 10^{-7}$ | 0                       | $1.71 \times 10^{-7}$  | $1.97 \times 10^{-7}$                                  | $1.23 \times 10^{-9}$  | $1.24 \times 10^{-8}$  | $1.03 \times 10^{-8}$  |
| Metal depletion                 | \$         | 3.967                 | 0                       | 1.503                  | 2.307  | 0.0126                 | 0.139423               | 0.00462                |
| Fossil depletion                | \$         | 37.889                | 0                       | 22.451                 | 12.565   | 0.183                  | 1.798                  | 0.892                  |

Phosphate contributes to the three largest impact categories, namely terrestrial ecotoxicity ( $2.7 \times 10^{-7}$  species-yr), agricultural land occupation ( $6.99 \times 10^{-7}$  species-yr), and urban land occupation ( $3.82 \times 10^{-7}$  species-yr). The manufacturing process of phosphate uses the raw materials of natural phosphate rock, which may contain heavy metals, such as cadmium (Cd), and may cause terrestrial ecotoxicity [56,59]. Therefore, natural phosphate fertilizer and its derivatives have the potential to transfer heavy metals into soil. While part of the heavy metals in fertilizer will move into the plant tissue, some remains in the soil. A study by Syers et al. [60] suggested a high content of Zn (57–1010), arsenic (2–23), cadmium (2–100), and uranium (64–153 mg/kg) in various types of natural phosphate. The production of phosphate fertilizers whose raw materials are taken from nature can lead to agricultural land occupation and urban land occupation.

The damage assessment results of the oil palm plantation are displayed in three impact categories, namely human health (DALY), ecosystems (species-yr), and resources (\$). These are shown in Table 7.

**Table 7.** Damage assessment of the oil palm plantation.

| Damage Category | Unit       | Total                 | FFB-Oil Palm Plantation | Urea, as N            | Phosphate Fertilizer, as P <sub>2</sub> O <sub>5</sub> | Dolomite              | Glyphosate            | Diesel                |
|-----------------|------------|-----------------------|-------------------------|-----------------------|--|-----------------------|-----------------------|-----------------------|
| Human health    | DALY       | 0.00499               | 0.00334                 | 0.000777              | 0.000777   | $1.17 \times 10^{-5}$ | $8.63 \times 10^{-5}$ | $5.27 \times 10^{-6}$ |
| Ecosystems      | species-yr | $2.58 \times 10^{-5}$ | $1.89 \times 10^{-5}$   | $3.07 \times 10^{-6}$ | $3.43 \times 10^{-6}$                                  | $4.06 \times 10^{-8}$ | $3.27 \times 10^{-7}$ | $2.99 \times 10^{-8}$ |
| Resources       | \$         | 41.856                | 0                       | 23.954                | 14.872   | 0.196                 | 1.938                 | 0.896                 |

Table 7 shows that FFB-oil plantations are the primary contributor of damages to human health and ecosystems. The results of the midpoint characterization will continue until the endpoint. The midpoint results affect the results at the endpoint. Thus, the endpoint results of the damage assessment of palm plantations showed that the largest contributions were from oil palm plantations, urea, and phosphate in human health, ecosystems, and resource damage. The major contributors to damages to resources were urea and phosphate.

### 3.5. Impact and Damage Assessment of Palm Oil Production

The impact assessment of palm oil production included FFB-oil palm plantations as an input. This emerged as one of the largest contributions out of the 17 impact categories. The results of the impact assessment are shown in Table 8.

The data in Table 8 shows an assessment of the impact on the environment in the palm oil production unit that comes from chemical inputs, fuel, electricity, and emissions outputs. Table 8 is the result of LCA calculations utilizing the ReCiPe method.

Two impact categories were determined to be major contributors, namely FFB-oil palm plantations and electricity. FFB-oil palm plantations were the largest contributor to eight impacts. These were climate change—Human health ( $0.00420$  DALY), ozone depletion ( $2.28 \times 10^{-7}$  DALY), human toxicity ( $0.000234$  DALY), climate change—Ecosystems ( $2.38 \times 10^{-5}$  species-yr), terrestrial ecotoxicity ( $2.81 \times 10^{-7}$  species-yr), urban land occupation ( $4.32 \times 10^{-7}$  species-yr), metal depletion ( $3.967$  \$), and fossil depletion ( $37.889$  \$). Electricity was the largest contributor to seven impacts, namely photochemical oxidant formation ( $7.6 \times 10^{-9}$  DALY), particulate matter formation ( $6.53 \times 10^{-5}$  DALY), ionizing radiation ( $1.85 \times 10^{-7}$  DALY), freshwater eutrophication ( $1.89 \times 10^{-9}$  species-yr), freshwater ecotoxicity ( $8.38 \times 10^{-10}$  species-yr), marine ecotoxicity ( $1.59 \times 10^{-10}$  species-yr), and fossil depletion ( $3.191$  \$) (Table 8).

**Table 8.** Characterization of the impact assessment of palm oil production.

| Impact Category                 | Unit       | Total                 | CPO-Palm Oil Production | Diesel                 | Water, Ultrapure       | Diesel                 | FFB-Oil Palm Plantation | Electricity, Low Voltage |
|---------------------------------|------------|-----------------------|-------------------------|------------------------|------------------------|------------------------|-------------------------|--------------------------|
| Climate change—Human health     | DALY       | 0.00431               | 0                       | $3.18 \times 10^{-6}$  | $3.64 \times 10^{-7}$  | $1.64 \times 10^{-6}$  | 0.00420                 | 0.000108                 |
| Ozone depletion                 | DALY       | $2.49 \times 10^{-7}$ | 0                       | $7.43 \times 10^{-9}$  | $1.1 \times 10^{-10}$  | $3.84 \times 10^{-9}$  | $2.28 \times 10^{-7}$   | $9.89 \times 10^{-9}$    |
| Human toxicity                  | DALY       | 0.000256              | 0                       | $2.53 \times 10^{-7}$  | $5.48 \times 10^{-8}$  | $1.31 \times 10^{-7}$  | 0.000234                | $2.11 \times 10^{-5}$    |
| Photochemical oxidant formation | DALY       | $8.15 \times 10^{-8}$ | 0                       | $5.52 \times 10^{-10}$ | $7.2 \times 10^{-11}$  | $2.86 \times 10^{-10}$ | $7.3 \times 10^{-8}$    | $7.6 \times 10^{-9}$     |
| Particulate matter formation    | DALY       | 0.000625              | 0                       | $1.69 \times 10^{-6}$  | $1.93 \times 10^{-7}$  | $8.73 \times 10^{-7}$  | 0.000557                | $6.53 \times 10^{-5}$    |
| Ionizing radiation              | DALY       | $1.17 \times 10^{-6}$ | 0                       | $1.67 \times 10^{-8}$  | $3.74 \times 10^{-10}$ | $8.64 \times 10^{-9}$  | $9.58 \times 10^{-7}$   | $1.85 \times 10^{-7}$    |
| Climate change—Ecosystems       | species-yr | $2.44 \times 10^{-5}$ | 0                       | $1.8 \times 10^{-8}$   | $2.06 \times 10^{-9}$  | $9.31 \times 10^{-9}$  | $2.38 \times 10^{-5}$   | $6.09 \times 10^{-7}$    |
| Terrestrial acidification       | species-yr | $3.15 \times 10^{-8}$ | 0                       | $1.21 \times 10^{-10}$ | $8.02 \times 10^{-12}$ | $6.27 \times 10^{-11}$ | $2.92 \times 10^{-8}$   | $2.12 \times 10^{-9}$    |
| Freshwater eutrophication       | species-yr | $1.82 \times 10^{-8}$ | 0                       | $1.21 \times 10^{-11}$ | $9.63 \times 10^{-12}$ | $6.25 \times 10^{-12}$ | $1.62 \times 10^{-8}$   | $1.89 \times 10^{-9}$    |
| Terrestrial ecotoxicity         | species-yr | $2.81 \times 10^{-7}$ | $2.28 \times 10^{-12}$  | $4.12 \times 10^{-11}$ | $1.28 \times 10^{-11}$ | $2.13 \times 10^{-11}$ | $2.81 \times 10^{-7}$   | $6.21 \times 10^{-10}$   |
| Freshwater ecotoxicity          | species-yr | $7.89 \times 10^{-9}$ | $3.04 \times 10^{-15}$  | $1.15 \times 10^{-11}$ | $1.24 \times 10^{-12}$ | $5.93 \times 10^{-12}$ | $7.03 \times 10^{-9}$   | $8.38 \times 10^{-10}$   |
| Marine ecotoxicity              | species-yr | $1.54 \times 10^{-9}$ | $1.75 \times 10^{-15}$  | $1.9 \times 10^{-12}$  | $3.29 \times 10^{-13}$ | $9.82 \times 10^{-13}$ | $1.37 \times 10^{-9}$   | $1.59 \times 10^{-10}$   |
| Agricultural land occupation    | species-yr | $8.84 \times 10^{-7}$ | 0                       | $3.94 \times 10^{-10}$ | $7.45 \times 10^{-11}$ | $2.04 \times 10^{-10}$ | $8.35 \times 10^{-7}$   | $4.77 \times 10^{-8}$    |
| Urban land occupation           | species-yr | $4.43 \times 10^{-7}$ | 0                       | $5.56 \times 10^{-10}$ | $3.3 \times 10^{-10}$  | $2.87 \times 10^{-10}$ | $4.32 \times 10^{-7}$   | $9.6 \times 10^{-9}$     |
| Natural land transformation     | species-yr | $4.24 \times 10^{-7}$ | 0                       | $1.01 \times 10^{-8}$  | $1.65 \times 10^{-10}$ | $5.21 \times 10^{-9}$  | $3.92 \times 10^{-7}$   | $1.67 \times 10^{-8}$    |
| Metal depletion                 | \$         | 4.080                 | 0                       | 0.00451                | 0.00118                | 0.00233                | 3.967                   | 0.105                    |
| Fossil depletion                | \$         | 42.415                | 0                       | 0.870                  | 0.0143                 | 0.450                  | 37.889                  | 3.191                    |

These results show that FFB-oil palm plantations were the largest contributor in four impact categories, namely climate change—Human health (0.00420 DALY), climate change—Ecosystems ( $2.38 \times 10^{-5}$  species-yr), terrestrial ecotoxicity ( $2.81 \times 10^{-7}$  species-yr), and urban land occupation ( $4.32 \times 10^{-7}$  species-yr). The cause of the large contribution to this impact category was explained prior.

The results of the damage assessment of palm oil production included FFB-oil palm plantations as an input. FFB-oil palm plantations emerged as the largest contributor in three damage categories. The results are shown in Table 9.

**Table 9.** Damage assessment of palm oil production.

| Damage Category | Unit       | Total                 | CPO-Palm Oil Production | Diesel for Genset     | Water, Ultrapure      | Diesel for Truck      | FFB-Oil Palm Plantation | Electricity, Low Voltage |
|-----------------|------------|-----------------------|-------------------------|-----------------------|-----------------------|-----------------------|-------------------------|--------------------------|
| Human health    | DALY       | 0.00520               | 0                       | $5.14 \times 10^{-6}$ | $6.12 \times 10^{-7}$ | $2.66 \times 10^{-6}$ | 0.00499                 | 0.000194                 |
| Ecosystems      | species-yr | $2.65 \times 10^{-5}$ | $2.28 \times 10^{-12}$  | $2.92 \times 10^{-8}$ | $2.66 \times 10^{-9}$ | $1.51 \times 10^{-8}$ | $2.58 \times 10^{-5}$   | $6.89 \times 10^{-7}$    |
| Resources       | \$         | 46.494                | 0                       | 0.874852              | 0.0155                | 0.452                 | 41.856                  | 3.296                    |

Table 9 shows that the FFB-oil palm plantation was the primary contributor in damage assessment for human health, ecosystems, and resources. Electricity demonstrated the second largest contribution to human health, ecosystems, and resources. Diesel for gensets and trucks did not contribute greatly to human health, ecosystems, and resources as the capacity of using diesel for gensets and trucks was small.

### 3.6. Impact and Damage Assessment of Biodiesel Production

The damage assessment of biodiesel production also included CPO-palm oil production as an input. This emerged as one of the largest contributors to the 17 impact categories. The results are shown in Table 10.

Table 10 shows that, out 17 impact categories, there were six that provided the largest contribution. They were biodiesel—Biodiesel production, methanol, sodium hydroxide, water, CPO-palm oil production, and electricity. Biodiesel—biodiesel production contributed to freshwater ecotoxicity ( $8.01 \times 10^{-10}$  species-yr). Methanol was the largest contributor in eight impact categories, namely ozone depletion ( $2.35 \times 10^{-7}$  E-07 DALY), human toxicity (DALY), photochemical oxidant formation ( $5.1 \times 10^{-8}$  DALY), terrestrial acidification ( $1.67 \times 10^{-8}$  species-yr), freshwater ecotoxicity ( $4.09 \times 10^{-9}$  species-yr), natural land transformation ( $2.9 \times 10^{-7}$  species-yr), metal depletion (1.221 \$), and fossil depletion (61.422 \$). Sodium hydroxide contributed to ozone depletion ( $5.95 \times 10^{-8}$  DALY). Water was the major contributor in three categories, namely photochemical oxidant formation ( $1.54 \times 10^{-8}$  DALY), freshwater eutrophication ( $2.06 \times 10^{-9}$  species-yr), and urban land occupation ( $7.06 \times 10^{-8}$  species-yr).

CPO-palm oil production was the largest contributor in eight categories, namely climate change—Human health (0.003537 DALY), human toxicity (0.00021 DALY), ionizing radiation ( $9.59 \times 10^{-7}$  DALY), climate change—Ecosystems ( $2 \times 10^{-5}$  species-yr), terrestrial ecotoxicity ( $2.31 \times 10^{-7}$  species-yr), agricultural land occupation ( $7.25 \times 10^{-7}$  species-yr), metal depletion (3.345 \$), and fossil depletion (34.780 \$). Electricity was the largest contributor in seven categories, namely human toxicity ( $4.64 \times 10^{-5}$  DALY), particulate matter formation (0.000143 DALY), ionizing radiation ( $4.07 \times 10^{-7}$  DALY), freshwater eutrophication ( $4.15 \times 10^{-9}$  species-yr), freshwater ecotoxicity ( $1.84 \times 10^{-9}$  species-yr), marine ecotoxicity ( $3.48 \times 10^{-10}$  species-yr), and fossil depletion (7.005 \$) (Table 10).

**Table 10.** Characterization of the impact assessment of biodiesel production.

| Impact Category                 | Unit       | Total                 | Biodiesel—Biodiesel Production | Methanol               | Sodium Hydroxide       | Water, Ultrapure       | CPO-Palm Oil Production | Electricity, Low Voltage |
|---------------------------------|------------|-----------------------|--------------------------------|------------------------|------------------------|------------------------|-------------------------|--------------------------|
| Climate change—human Health     | DALY       | 0.00432               | 0                              | 0.000422               | $4.54 \times 10^{-5}$  | $7.78 \times 10^{-5}$  | 0.003537                | 0.000236                 |
| Ozone depletion                 | DALY       | $5.44 \times 10^{-7}$ | 0                              | $2.35 \times 10^{-7}$  | $5.95 \times 10^{-8}$  | $2.35 \times 10^{-8}$  | $2.04 \times 10^{-7}$   | $2.17 \times 10^{-8}$    |
| Human toxicity                  | DALY       | 0.000368              | $1.59 \times 10^{-6}$          | $8.66 \times 10^{-5}$  | $1.26 \times 10^{-5}$  | $1.17 \times 10^{-5}$  | 0.00021                 | $4.64 \times 10^{-5}$    |
| Photochemical oxidant formation | DALY       | $1.54 \times 10^{-7}$ | 0                              | $5.1 \times 10^{-8}$   | $3.75 \times 10^{-9}$  | $1.54 \times 10^{-8}$  | $6.68 \times 10^{-8}$   | $1.67 \times 10^{-8}$    |
| Particulate matter formation    | DALY       | 0.000936              | 0                              | 0.000213               | $2.69 \times 10^{-5}$  | $4.13 \times 10^{-5}$  | 0.000512                | 0.000143                 |
| Ionizing radiation              | DALY       | $1.74 \times 10^{-6}$ | 0                              | $2.18 \times 10^{-7}$  | $7.57 \times 10^{-8}$  | $8 \times 10^{-8}$     | $9.59 \times 10^{-7}$   | $4.07 \times 10^{-7}$    |
| Climate change—ecosystems       | species·yr | $2.44 \times 10^{-5}$ | 0                              | $2.39 \times 10^{-6}$  | $2.57 \times 10^{-7}$  | $4.41 \times 10^{-7}$  | $2 \times 10^{-5}$      | $1.34 \times 10^{-6}$    |
| Terrestrial acidification       | species·yr | $4.98 \times 10^{-8}$ | 0                              | $1.67 \times 10^{-8}$  | $9.56 \times 10^{-10}$ | $1.72 \times 10^{-9}$  | $2.58 \times 10^{-8}$   | $4.65 \times 10^{-9}$    |
| Freshwater eutrophication       | species·yr | $2.52 \times 10^{-8}$ | 0                              | $3.28 \times 10^{-9}$  | $8.24 \times 10^{-10}$ | $2.06 \times 10^{-9}$  | $1.49 \times 10^{-8}$   | $4.15 \times 10^{-9}$    |
| Terrestrial ecotoxicity         | species·yr | $2.44 \times 10^{-7}$ | $9.49 \times 10^{-10}$         | $8.12 \times 10^{-9}$  | $4.56 \times 10^{-10}$ | $2.74 \times 10^{-9}$  | $2.31 \times 10^{-7}$   | $1.36 \times 10^{-9}$    |
| Freshwater ecotoxicity          | species·yr | $1.39 \times 10^{-8}$ | $8.01 \times 10^{-10}$         | $4.09 \times 10^{-9}$  | $3.95 \times 10^{-10}$ | $2.66 \times 10^{-10}$ | $6.47 \times 10^{-9}$   | $1.84 \times 10^{-9}$    |
| Marine ecotoxicity              | species·yr | $2.24 \times 10^{-9}$ | $1.71 \times 10^{-12}$         | $4.84 \times 10^{-10}$ | $7.76 \times 10^{-11}$ | $7.04 \times 10^{-11}$ | $1.26 \times 10^{-9}$   | $3.48 \times 10^{-10}$   |
| Agricultural land occupation    | species·yr | $9.13 \times 10^{-7}$ | 0                              | $4.29 \times 10^{-8}$  | $2.5 \times 10^{-8}$   | $1.59 \times 10^{-8}$  | $7.25 \times 10^{-7}$   | $1.05 \times 10^{-10}$   |
| Urban land occupation           | species·yr | $5.15 \times 10^{-7}$ | 0                              | $5.32 \times 10^{-8}$  | $7.29 \times 10^{-9}$  | $7.06 \times 10^{-8}$  | $3.63 \times 10^{-7}$   | $2.11 \times 10^{-8}$    |
| Natural land transformation     | species·yr | $7.18 \times 10^{-7}$ | 0                              | $2.9 \times 10^{-7}$   | $8.35 \times 10^{-9}$  | $3.54 \times 10^{-8}$  | $3.48 \times 10^{-7}$   | $3.67 \times 10^{-8}$    |
| Metal depletion                 | \$         | 5.180802              | 0                              | 1.221                  | 0.131                  | 0.253                  | 3.345                   | 0.230                    |
| Fossil depletion                | \$         | 107.6268              | 0                              | 61.422                 | 1.364                  | 3.056                  | 34.780                  | 7.005                    |

Biodiesel production emits oleic acid compounds into water ( $8.01 \times 10^{-10}$  species-yr), which cause it to be the largest contributor in the freshwater ecotoxicity impact category. Methanol was the major contributor in two categories, namely ozone depletion ( $2.35 \times 10^{-7}$  DALY) and fossil fuel depletion (61.422 \$). The process of producing methanol uses coal as a fossil fuel, which causes fossil fuel depletion. The use of methanol may cause photochemical oxidant formation as methanol is a VOC. Methanol evaporates into the atmosphere and reacts with NO<sub>x</sub>, water vapor, and sunlight radiation, resulting in photochemical oxidant formation.

The combustion of coal fuel in the process of producing electricity also produces particulate matter in the form of PM<sub>10</sub>, CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>2</sub> emissions [61]. PM<sub>10</sub> contributes to particulate matter formation (0.000143 DALY). CO<sub>2</sub>, which reflects infrared radiation back to Earth, contributes to global warming. Global warming, in the form of climate change, negatively impacts human health (climate change—Human health) (0.000236 DALY) and climate change—Ecosystems ( $1.34 \times 10^{-6}$  species-yr). SO<sub>2</sub> in the atmosphere can oxidize into H<sub>2</sub>SO<sub>4</sub> compounds, which, in turn, produce acid rain [62]. Acid rain contributes to terrestrial acidification ( $4.65 \times 10^{-9}$  species-yr) (Table 10). Water has one of the largest contributions in urban land occupation ( $7.06 \times 10^{-8}$  species-yr). CPO-palm oil production primarily contributes to climate change—human health (0.003537 DALY), climate change ecosystems ( $2 \times 10^{-5}$  species-yr), and terrestrial ecotoxicity ( $2.31 \times 10^{-7}$  species-yr). Lastly, electricity has three potential contributions, namely toward ionizing radiation ( $4.07 \times 10^{-7}$  DALY), freshwater eutrophication ( $4.15 \times 10^{-9}$  species-yr), and marine ecotoxicity ( $3.48 \times 10^{-10}$ ).

Soraya et al. [27] reported that the highest contribution of photochemical oxidation (57.64%) was caused by biodiesel production. Our results indicated that the highest contribution of photochemical oxidant formation was from biodiesel production (55.60%). The studies of Soraya et al. and Siregar et al. [26,27] suggested that 59% and 54.42%, respectively, of eutrophication's highest contributions came from cultivation. In this study, we found that freshwater eutrophication's highest contribution came from the oil palm plantations (59.07%). The studies of Soraya et al. and Siregar et al. [26,27] reported that acidification's highest contribution was due to cultivation, namely 50% and 52.22%, respectively. In this study, terrestrial acidification's highest contribution was due to oil palm plantations (51.84%). This study is in line with Soraya et al. and Siregar et al. [26,27], as the largest contribution of terrestrial acidification was due to the oil palm plantations. Soraya et al. [27] suggested that the highest contribution of abiotic resource depletion came from cultivation (55%). In this study, the highest contribution of metal depletion was due to the oil palm plantations (64.57%). This is supported by Soraya et al. [27], who stated that metal depletion's largest contribution was due to the oil palm plantations.

Results of the damage assessment of biodiesel production also included CPO-palm oil production as an input. CPO-palm oil production emerged as the largest contributor to all three damage categories. The results are shown in Table 11.

**Table 11.** Damage assessment of biodiesel production.

| Damage Category | Unit       | Total                 | Biodiesel—<br>Biodiesel<br>Production | Methanol              | Sodium<br>Hydroxide   | Water,<br>Ultrapure  | CPO-Palm<br>Oil<br>Production | Electricity,<br>Low<br>Voltage |
|-----------------|------------|-----------------------|---------------------------------------|-----------------------|-----------------------|----------------------|-------------------------------|--------------------------------|
| Human health    | DALY       | 0.00563               | $1.59 \times 10^{-6}$                 | 0.000721              | $8.51 \times 10^{-5}$ | 0.000131             | 0.00426                       | 0.000426                       |
| Ecosystems      | species-yr | $2.69 \times 10^{-5}$ | $1.75 \times 10^{-9}$                 | $2.81 \times 10^{-6}$ | $3.01 \times 10^{-7}$ | $5.7 \times 10^{-7}$ | $2.17 \times 10^{-5}$         | $1.51 \times 10^{-6}$          |
| Resources       | \$         | 112.808               | 0                                     | 62.644                | 1.494                 | 3.309                | 38.125                        | 7.235                          |

The damage assessment of biodiesel production showed that, for human health, the three largest contributions came from methanol (0.000721 DALY), CPO-palm oil production (0.00426 DALY), and electricity (0.000426 DALY). The three largest contributions to the ecosystems came from methanol ( $2.81 \times 10^{-6}$  species-yr), CPO-palm oil production ( $2.17 \times 10^{-5}$  species-yr), and electricity ( $1.51 \times 10^{-6}$  species-yr). Methanol was the largest contributor for damage to resources (62.644 \$) compared to CPO-palm oil production (38.125 \$) and electricity (7.235 \$) (Table 11).

The environmental hotspots of damage assessment in biodiesel production are shown in Figures 5–7. The network analyses in Figures 5–7 are for human health damage, ecosystem diversity damage, and resource availability damage, respectively. The environmental hotspots of human health damage, ecosystem diversity damage, and resource availability damage are shown with a wide red arrow.

The results of the network analysis of damage to human health (DALY) showed that the environmental hotspot for biodiesel production was with the palm oil production processing unit at 75.70% and, to a lesser extent, with methanol at 12.80%. The environmental hotspots are indicated in Figure 4 by wide red arrows. Contributors to environmental hotspots in the palm oil production processing unit were primarily the oil palm plantations (72.80%), followed by electricity (1.73%), water (1.17%), and diesel (0.13%). The oil palm plantation was demonstrated again to be an environmental hotspot contributing 72.80% of 75.70% to the environmental hotspots in palm oil production. While the palm oil production processing unit itself contributed only 2.90%, the biodiesel production processing unit contributed 24.30% (Figure 5).

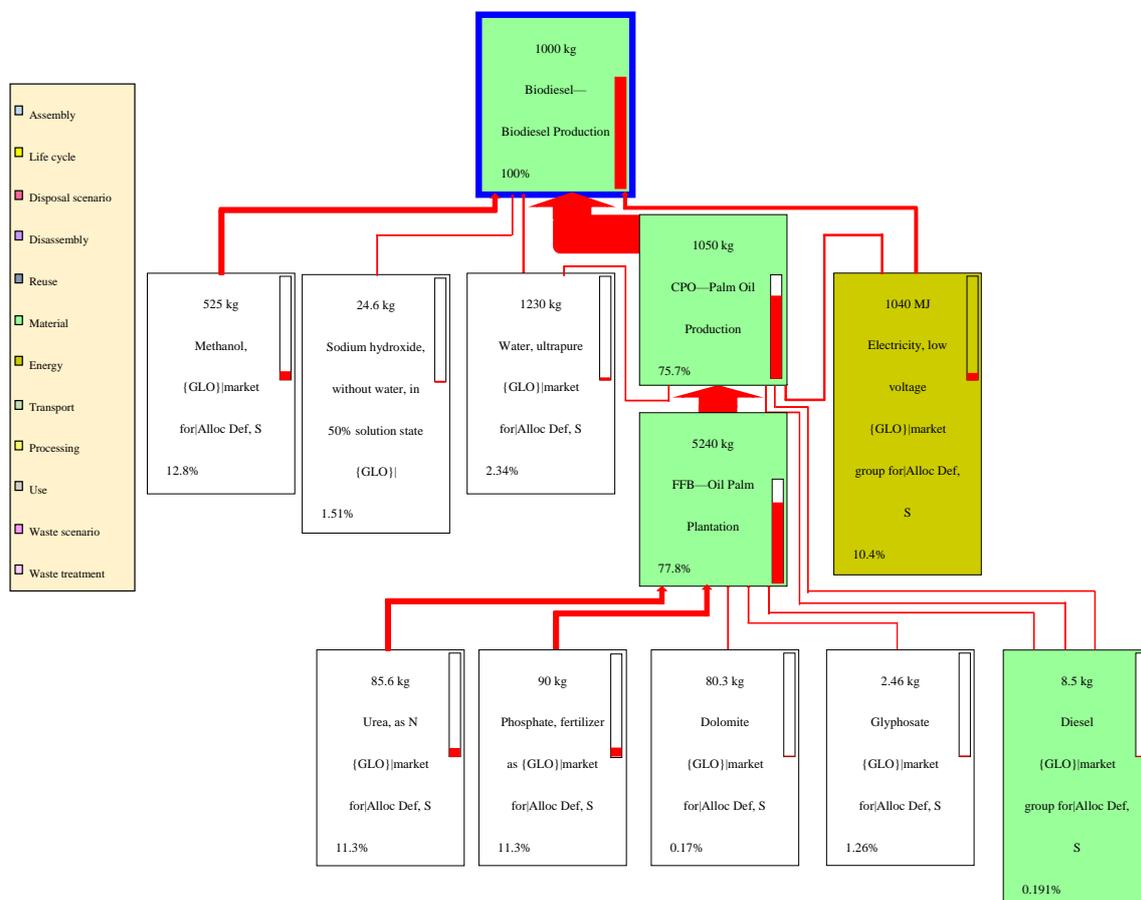
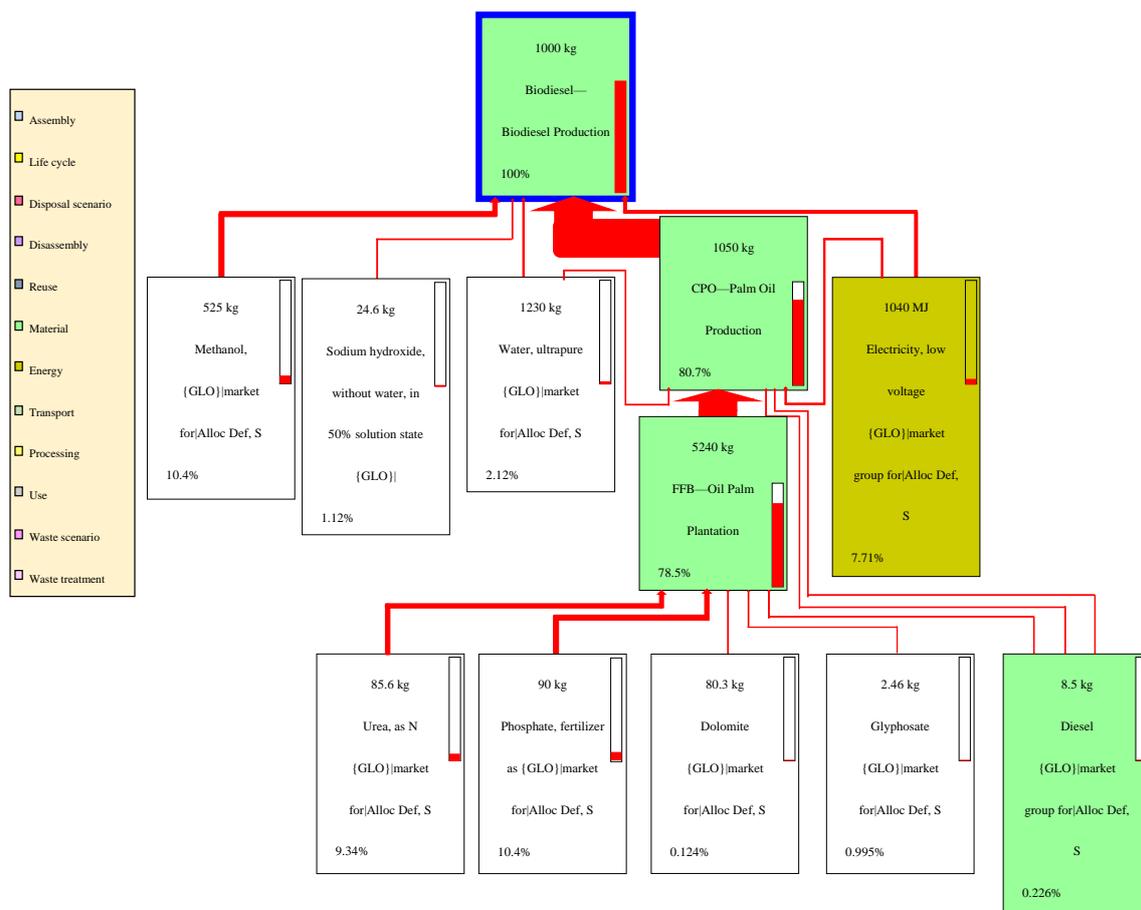


Figure 5. The environmental hotspot from the network analysis of human health damage (DALY).

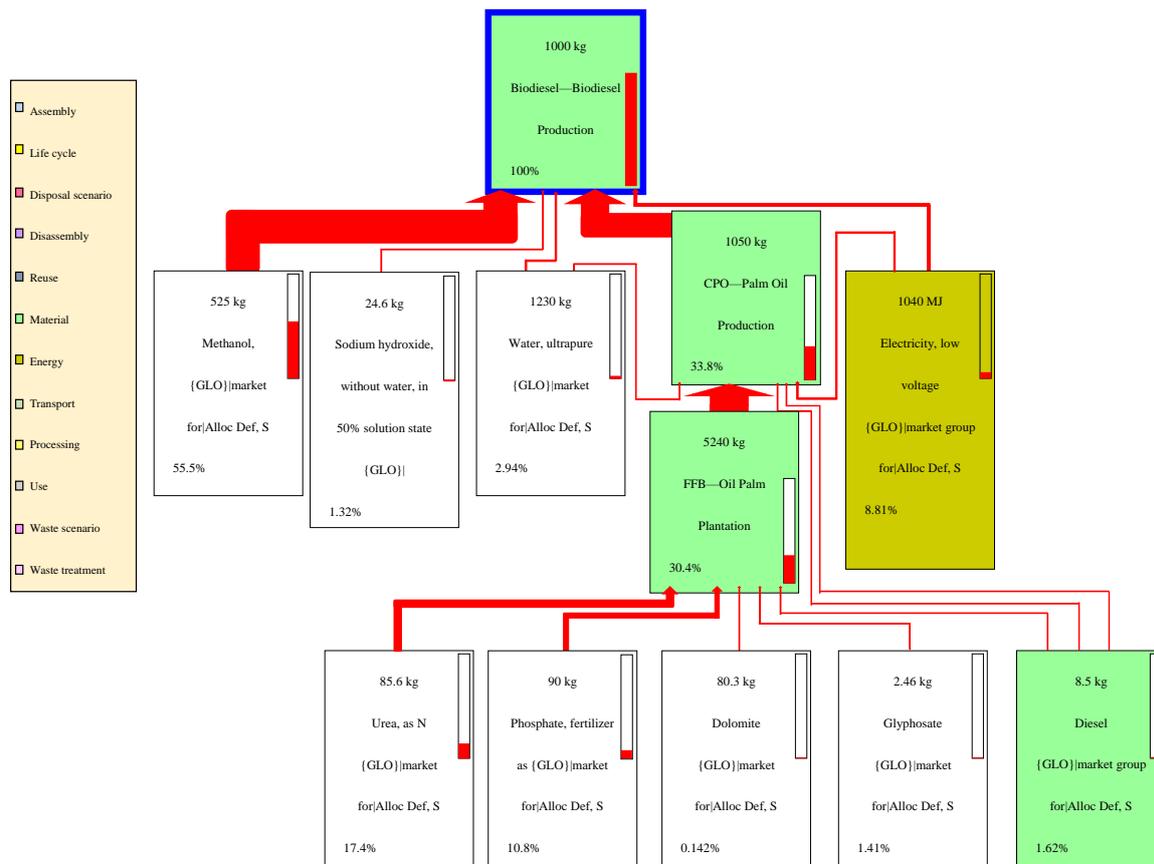
The biodiesel production environmental hotspot was in the palm oil production processing unit at 80.70%, and, to a lesser extent, with methanol at 10.40%. The primary contributors to the palm oil production processing unit were the oil palm plantations (78.50%), followed by electricity (1.29%), water (1.06%), and diesel (0.15%). This showed the oil palm plantations, once again, as an environmental hotspot contributing 78.50% of 80.70%. The palm oil production processing unit contributed 2.20% and the biodiesel production processing unit contributed 19.30% (Figure 6).



**Figure 6.** The environmental hotspot from the network analysis of ecosystem diversity damage (species-yr).

The network analysis on resource availability damage (\$) showed that the biodiesel production environmental hotspot was in the use of methanol, which contributed 55.50%, and with the palm oil production processing unit, which contributed 33.80%. Environmental hotspots are indicated by the wide red arrows. Figure 7 shows that the main contributors to environmental hotspots in the palm oil production processing unit were the oil palm plantations (30.40%), followed by water (1.47%), electricity (1.47%), and diesel (1.08%). The oil palm plantation was again an environmental hotspot due to contributing 30.40% of 33.80% to the environmental hotspots in palm oil production. The palm oil production processing unit contributed 3.40%, while the biodiesel production processing unit contributed 66.20% (Figure 7).

Based on the environmental hotspot from a network analysis of human health damage (DALY), the contribution of oil palm plantations, palm oil production, and the biodiesel production processing unit, respectively, amounted to 72.80%, 2.90%, and 24.30% (Figure 5). The network analysis of the ecosystem diversity damage (species-yr) contribution of oil palm plantations showed palm oil production and the biodiesel production processing unit, respectively, at 78.50%, 2.20%, and 19.30% (Figure 6). The same analysis, but for resource availability damage (\$), showed that the contributions of oil palm plantations, palm oil production, and the biodiesel production processing unit amounted to 30.40%, 3.40%, and 66.20%, respectively (Figure 7).



**Figure 7.** The environmental hotspot from the network analysis of resource availability damage (\$).

The third finding in this study was the total human health damage of biodiesel production, which was 0.00563 DALY. This comprised 0.0041 DALY from the oil palm plantation unit (72.80%), 0.00016 DALY from the palm oil production processing unit (2.9%), and 0.0014 DALY from the biodiesel production processing unit. This study also revealed that the total ecosystem diversity damage of biodiesel production was  $2.69 \times 10^{-5}$  species-yr (Table 11), with the main contributor being the CPO production processing unit. The total damage from biodiesel production to resource availability was 112.808 \$ (Table 11), which was mainly contributed to by the biodiesel production unit.

The life cycle of biodiesel production can be made more environmentally friendly if the activities in the oil palm plantation processing unit are carried out more wisely. That is, if it does not damage the peat forests and is more frugal in the use of urea fertilizer. Additionally, in the biodiesel production processing unit, the use of methanol and electricity should be minimized. This finding is a contribution to the development of science in the endpoint analysis on three damage categories (human health damage, ecosystem diversity damage, and resource availability damage) in the process of palm oil biodiesel production in Indonesia. This result may be valuable as a reference for further similar research and may be influential in the determining of policies by companies and governments.

#### 4. Conclusions

In this study on carbon footprint analysis, human health damage, ecosystem diversity damage, and resource availability damage caused by biodiesel production from palm oil in Indonesia, we concluded that, within the life cycle of palm oil biodiesel production, the environmental hotspot can be found in the oil palm plantation processing unit.  $N_2O$  gas was, by far, the main culprit for the high numbers in the fossil  $CO_2$  eq impact category and this came from the oil palm plantation processing unit.

The damage to human health was shown to be significant in the LCA analysis. As a result of the peatland damage and excessive use of urea, the oil palm plantation processing unit resulted in the largest carbon footprint, and the most significant damages to human health and ecosystem diversity. The biodiesel production processing unit dealt the most damage to resource availability, due to the excessive use of methanol and electricity.

The life cycle of biodiesel production can be made more environmentally friendly if activities in the oil palm plantation processing unit are carried out more consciously. That is, a focus on not damaging peatlands and limiting the use of urea fertilizers, as well as limiting the use of methanol and electricity in the biodiesel production processing unit.

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