

Life Cycle Assessment of Biodiesel from Palm Oil

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Abstract Though the energy balance for the cultivation of oil palm biomass for biodiesel production is positive, current debate has been raised on its environmental sustainability due to the high consumption of fossil fuel, fertilizer, and pesticides. This chapter employs the well-to-wheel variant of life cycle analysis (LCA) to assess the various potential environmental impacts, energy and land use/conversion impacts associated with the production of biodiesel from palm oil. Eleven (11) main impact categories, namely land use, fossil fuel use, climate change, ozone layer depletion potential, minerals/heavy metals, acidification/eutrophication potential, ionizing radiation potential, ecotoxicity potentials, carcinogens, respiratory organics, and respiratory in organics based on Eco-Indicator 99, are analyzed and discussed. Excluding transportation impacts, the oil palm cultivation stage contributed the highest overall environmental impacts (44 % of the total impacts) compared to the other stages. On the other hand, fossil fuel consumption was highest (43 % of total impacts) in the transesterification unit exclusive of all impacts from transportation.

1 Introduction

The increasingly high cost, fast rate of exhaustion and negative impacts of fossil fuel's combustion on the environment have caused almost all economic sectors of the world to consider new lasting sources of energy to replace fossil fuels.

Biodiesel has recorded tremendous growth rate in its consumption and production over the past decade due to its positive environmental impacts (as well as other unique characteristics, e.g., biodegradability, non-toxicity, renewability) hence considered a feasible petro-diesel replacement (Vicente et al. 2004;

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Encinar et al. 2005). Moreover, biodiesel on combustion is reported to release insignificant amount of air emissions compared to fossil fuel (Antolin et al. 2002).

Biodiesel production processes utilize fossil-based fuels as main energy sources; thus, their emission effects add to the concentration of CO₂ in the atmosphere resulting in global warming. As reported by Roger et al. (2011), the production of 1 t of biodiesel from any feedstock averagely adds not less than 916 kg CO₂ to what is already in the atmosphere. Therefore, it can be inferred from these scenarios that energy use in biodiesel production processes is directly related to the emissions associated with its production thus needed to quantify these emissions and strategically allocate improvement measures. Life cycle assessment (LCA) presents a better assessment tool to quantify the environmental burdens associated with biodiesel over its life cycle. An LCA well-to-wheel assessment of palm oil biodiesel is discussed in this chapter.

LCA, also referred to as ecobalance analysis, is a technique used to quantify environmental impacts associated with the various stages of a product's life from raw material extraction through materials processing, distribution, use, repair, and maintenance, as well as waste management. The methodology of LCA brings out a wide outlook on the environmental burdens of a product because it considers a thorough inventory of energy, material inputs, and emissions; quantifies the potential environmental impacts associated with the specified inputs and emissions; and finally interprets the results which aid in policy making and implementation.

Currently, there has been a controversial debating issue on the environmental sustainability of biodiesel since its production makes use of great amount of fossil fuel which puts so much burden on the environment. The most important factor which affects the sustainability of biodiesel production is the choice of feedstock since each feedstock as well as its cultivation technology has its own specific ecological footprint. For instance, the environmental sustainability of palm oil production and subsequent conversion into biodiesel is characterized by land use, soil quality management, and genetic biodiversity (Parish et al. 2008). Biodiesel production from virgin feedstock such as palm oil is less sustainable than that from waste cooking oil (WCO) in terms of environmental impacts because the cultivation stage of WCO is eliminated from the life cycle assessment stage. Nonetheless, first generation biodiesel (FGB) feedstock, such as palm oil, soybean oil, rapeseed oil, has been pioneered and continued to saturate the biodiesel market until the commercial production of second and third generation feedstock become exceedingly sustainable over FGB feedstock.

1.1 Global Palm Oil Production Profile

Palm oil presents a better and attractive feedstock for biodiesel production compared to other first and second generation feedstock because of its high oil yield (averagely 8.6 t per hectare of land) which is almost three times more than that for

Table 1 Palm oil and palm biodiesel industries in major oil palm producing countries of the world

| Country | Oil palm plantation, million ha | Number of palm oil mills | Number of CPO refineries | Number of palm kernel oil crushing units | Number of palm oil biodiesel production plants |
|-----------|---------------------------------|--------------------------|--------------------------|--|--|
| Indonesia | 6.170 | 405 | 32 | 21 | – |
| Malaysia | 4.890 | 416 | 57 | 46 | 25 |
| Thailand | 0.512 | 70 | 12 | – | 15 |
| Nigeria | 0.385 | 21 | 9 | 4 | – |
| Colombia | 0.209 | 7 | – | – | 6 |
| Others | 0.754 | – | – | – | – |
| Total | 12.900 | – | – | – | 81 |

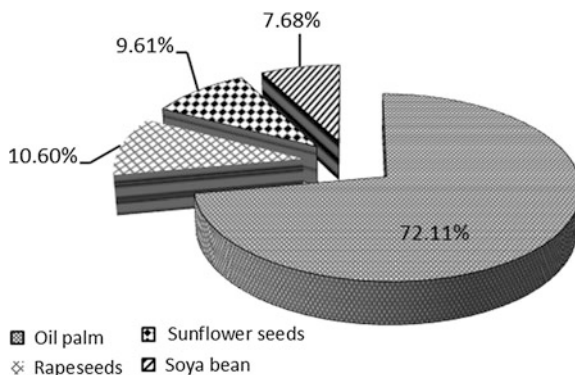
Source MPOB (2010)

coconut, 12 times more than soybean oil yield, and seven times more than that for rapeseed (Schmidt 2007; Bockish 1998). Also, the per-unit production cost of palm oil is much lower compared to soybean oil which is 20 % higher. This makes it a better vegetable oil for biodiesel production.

Palm oil currently is the second largest edible oil source (after soybean oil) which forms approximately 34 % of the global oil supply (Schmidt 2007). In 2009, both palm oil and palm kernel oil accounted for 5 % of the total cultivated land for vegetable oil production globally. In 2010, the global palm oil production was 47.9 million tonnes of which 11 % were used for biodiesel production. For the production in 2010, Malaysia and Indonesia together contributed about 87 % of the total palm oil produced in the world with about 19.5 and 22.5 million tonnes, respectively (MPOB 2010). Projections for 2012 palm oil production growth in Malaysia and Indonesia indicate expansion of about 3.5 million tonnes. Though Malaysia has only about 12.5 % of its total landmass (i.e., 32 million hectares) under oil palm plantation (GOFBM 2009), it has been recognized as the world's largest producer of certified sustainable palm oil (CSPO) contributing over 50 % of total CSPO production (RSPO report 2011). Nigeria (who was the largest exporter of palm oil in 1934 but overtaken by Malaysia in 1966) remains the largest producer of palm oil in Africa and the world's fourth leading producer in 2010 with a total oil palm landmass of about 385, 000 hectares (RSPO report 2011). Other palm oil-exporting countries include Thailand, Colombia, Ecuador, Papua New Guinea, Ivory Coast, Brazil. Table 1 shows the number of palm oil and biodiesel industries in 2010 in major palm oil-producing countries of the world. These figures keep increasing from year to year thus needed to assess their environmental impacts and suggest measures for improvement.

In 2007, global biodiesel produced from palm oil recorded the highest production capacity of about 38 million tonnes followed by soy oil biodiesel (36 million tonnes), rapeseed oil biodiesel (16 million tonnes), and sunflower oil biodiesel (10 million tonnes). Presently, these capacities have increased still with palm oil biodiesel leading at 44 million tonnes (Biodiesel 2020). Figure 1 shows the production of biodiesel from palm oil in comparison with other seed oils

Fig. 1 Biodiesel production from various feed stocks commonly used in the world in 2010



mainly used for biodiesel production in 2010. In 2010, Malaysia recorded the highest palm oil biodiesel installed capacity of 1.7 million tonnes. Between 2007 and 2008, Malaysia's biodiesel production gained a rise by 32 % from 129,715 to 171,700 t (Biodiesel 2020). The United States of America and the European Union were the main importers of biodiesel from Malaysia accounting for 39.2 and 38.6 % of the total biodiesel exports, respectively (Biodiesel 2020).

1.2 The Oil Palm

The oil palm is a perennial insect-pollinated plant which belongs to the family *Palmae* and genus *Elaeis* with many species including *guineensis*, *oleifera*, *kamerunicus*. *Elaeis guineensis* Jacq. has been the commonest species with an average generic life span of 150 years, an economic life of 20–25 years (11–16 months for nursery) and significantly high oil-to-bunch content (45–55 % oil) compared to the other species (Schmidt 2007). However, genus *oleifera* has been reported to have higher level of unsaturated fatty acids thus used for the production of interspecific hybrids with the genus *guineensis*.

The oil palm is cultivated in 45 countries in the world on a total land area of about 12.9 million hectares (GOFBM 2009). Oil palms are highly efficient producers of oil requiring less land than any other oil-producing crops. Only about 10 % of the oil palm produces the oil (which is extracted from the mesocarp or fleshy part of the fruits) and palm kernel oil (which is obtained from the kernel or seed in the fruit). The remaining 90 % is mainly the biomass comprising the empty fruit bunches (EFB), fibers, fronds, trunks, kernels, and mill effluent which are often disposed as wastes or used as mulch in the plantation.

After 24–30 months of planting a palm tree, it begins to bear fresh fruit bunches (FFB) and thus ready for harvest after some couple of months later. The normal frequency of harvesting is between 10 and 15 days (Xavier et al. 2008). The tree produces averagely 12 FFB annually with a bunch weighting 15–25 kg containing

1,000–1,300 fruitlets depending on the plantation management and establishment. On a per hectare basis, an oil palm plantation can yield averagely 35 t of FFB (from about 148 palm trees) and 8.6 t of palm oil (Henson 1990; Schmidt 2007). Generally, the extraction of 1 t of crude palm oil (CPO) requires 5 t of FFB which produces 1.15 t of EFB and 3.25 t of palm oil mill effluents (POME) as residues (Corley and Tinker 2003). The harvested FFB may contain around 20 % mesocarp oil, 25 % nuts (comprising 5 % kernels, 13 % fiber, and 7 % shell), and 23 % empty fruit bunches. The kernels also contain around 55 % oil and 8 % protein (Corley and Tinker 2003; Møller et al. 2000).

The oil palm industry now focuses on genetic means of improving the oil yield, palm disease tolerance, and the height of the tree (breeding dwarf palms in order to prolong the economic cropping cycle). Corley and Lee (1992) and Pushparajah (2002) have reported the possibility of commercializing genetically bred oil palms for the next 15–40 years. However, currently, transgenically high oleic acid palms have been field tested and proven to give high yields (Ravigadevi et al. 2002).

2 Biodiesel Production from Palm Oil: Process Description

2.1 Oil Palm Cultivation and Harvesting

The production of FFB involves six (6) main processes which are summarized in Fig. 2. The planning stage involves the feasibility studies of the proposed area for plantation. Usually, environment impact assessment (EIA) forms part of the planning stage and the implementation of management measures to assuage the adverse effects of some social and environmental practices are also considered. Oil palm nursery proceeds after confirmation of the suitability of area for plantation which is normally endorsed by respective bodies for development. The seedlings are raised in polybags as nursery for about a year with adequate irrigation with manuring, etc. The land for the oil palm plantation is then cleared of vegetation. Creation of road or paths, water drainage systems, and other soil conservation measures are put in place before the actual transplant. Most often the vegetation is cleared by burning which affects the environment negatively. In order to control soil erosion after the seedlings transplant, leguminous crops are interspersed with the oil palm trees which further fix nitrogen into the soil. Other field maintenance practices include pruning, pest and disease control, and mulching. After 24–30 months of transplanting depending on the nutritious value of the soil, harvesting of FFB may be due (Corley and Tinker 2003). Normally, harvesting is done manually with chisels and sickles mounted on bamboo or aluminum poles. The FFB are then transported to the oil mill for oil extraction. In order to ensure minimal amount of free fatty acid (FFA) content of the oil, handling of FFB after harvesting must be done in a way to reduce bruises on the fruits. Also, since the quality of the oil produced depends on the time interval between harvesting and

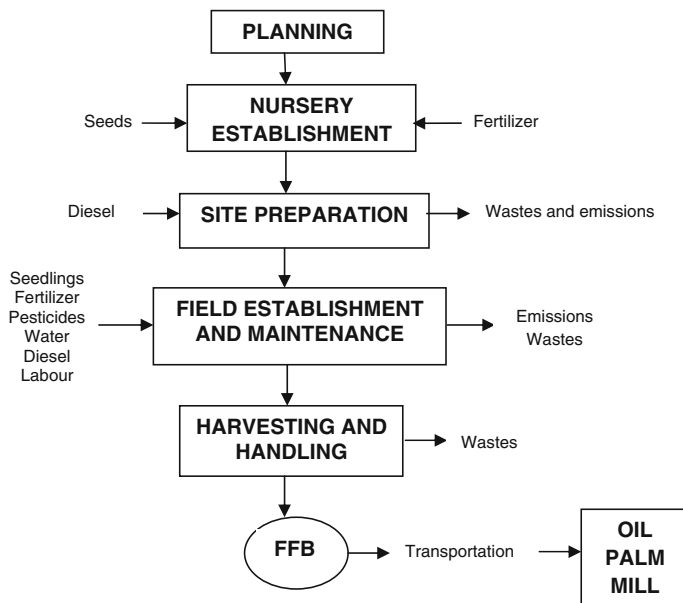


Fig. 2 Process flow diagram for oil palm cultivation

sterilization (the first stage of milling), FFB must be transported as soon as possible after harvesting and the distance from plantation to milling site must be close. Most oil mills are located near the plantation site to minimize the transportation distance and cost.

2.1.1 Environmental Interactions and Emissions from Palm Plantation

The cultivation and pretreatment of 1 tonne FFB emit approximately 285 kg of CO₂ eq. (Stichnothe and Schuchardt 2011). Oil palm cultivation has been reported as a major cause of substantial and irreversible damage to the natural environment (Schmidt 2007). Global warming potential (GWP) and eutrophication potential can be reduced by treating the palm oil mill effluents or co-composting the residues. In 2008, not less than 44 million tonnes of POME were generated in Malaysia which were and are still dumped in ponds releasing 5.5–9.0 kg of methane into the atmosphere for every tonne of FFB produced (Reijnders and Huijbregts 2008; Wu et al. 2010; Yacob et al. 2005).

Fertilizers applied to oil palm trees may be lost through volatilization and transformation to nitrous oxide (N₂O). Fertilizers may also contribute to nitrate and phosphate leakages to groundwater, hence causing water pollution. Paraquat (gramoxone) which is sprayed on the oil palm trees to kill herbs and weeds may

leave about 11 mg (per kg body weight) of its content on the sprayer's skin after some few minutes (DEQ 1990).

Oil palm plantation has resulted in rampant deforestation, burning of forests, peat land degradation, and habitat loss of critically endangered species, and this direct land use has brought about significant emission of CO₂ and N₂O into the atmosphere. Forest fires used to clear vegetation for oil palm plantations are one source of CO₂. The smoke produced through forest burning can contribute to GWP as well as posing serious health threats to plantation workers and close neighbors. For instance, in Malaysia and Indonesia, 1997 recorded the highest CO₂ emissions resulting from bush burning since 1957 (Román-Cuesta et al. 2011). An estimated 0.81–2.57 gigatons of carbon was released into the atmosphere by the fires: 13–40 % of the mean annual global carbon emissions from fossil fuels in that year alone (Clay 2004). Again, in Indonesia and Malaysia, over 140 and 47 land mammalian species are endangered, respectively, as a result of oil palm plantation. Over 45 % of the total peat land has been converted to oil palm plantation due to the increase demand of palm oil, and this has put the leading producers of palm oil on top of major emitters of greenhouse gas (GHG) in the world. Currently, the annual cropland for oil palm plantation in Indonesia and Malaysia contributes about 2.63 t CO₂ eq. and 2.44 t CO₂ eq. per tonne FFB processed, respectively (Clay 2004). The situation becomes aggravated during deforestation and bogs draining which releases the peat bogs that store great quantities of carbon. Hence, appropriate management of plantation and the use of the biomass from the plantation as well as the processing residues from palm oil production (fibers, kernel shells, POME) for biofuel can have an effect on reducing GHG emissions.

2.2 Palm Oil Milling (Oil Extraction)

Figure 3 summarizes the main processes involved in the milling or extraction of palm oil from FFB. Sterilization of FFB is done in a steamer (pressurized cages) at about 2–3 bars to ameliorate the content of FFA which could reduce the quality of the oil. A rotation drum stripper is used to thresh the fruitlets from the sterilized bunches and the fruitlets sent to the digester. The EFB are also used as mulch in the oil palm plantation.

The digester then removes the fruits' mesocarp from the nuts by continuously heating the fruits with steam which helps to open the oil cells in the mesocarp for effective oil extraction. The oil extraction is done with the help of screw press where the press cake and nuts are conveyed to the palm kernel crushing (PKC) plant and the pressed liquor also sent to a vibrating screen where it is diluted. The oil is then clarified and purified to remove dirt and moisture before it is dried. The sludge (comprising mainly water soluble parts of the palm fruits and suspended materials like palm fibers) from the clarifier is desilted and further sent to the centrifuge to recover the excess oil which is recycled into the clarifier. The water–sludge mixture (palm oil mill effluent, POME) is then sent to the effluent treatment

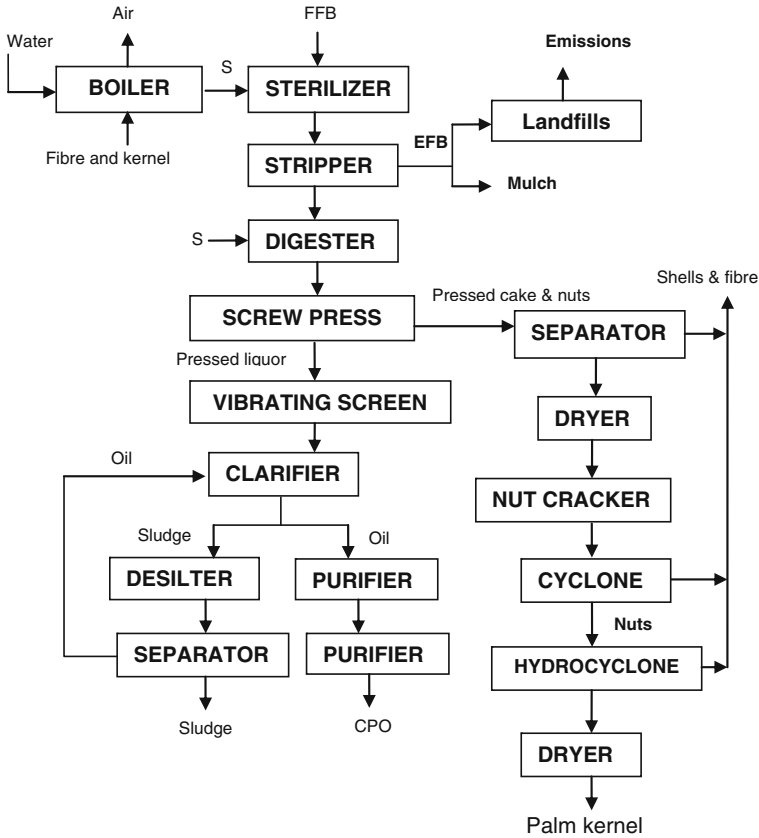


Fig. 3 Flow diagram of palm oil milling processes S represents steam

plant (ETP). The CPO produced is then stored and transported later to oil refinery. The palm kernel nuts are also cracked to separate the kernel from the shells. The oil palm fiber and kernel shells from the PKC plant are used as fuel in the boiler which generates steam for the oil milling processes.

2.2.1 Environmental Impacts Associated with CPO Production

The palm oil mill produces solid wastes such as palm pressed fiber (PPF), palm kernel shells (PKS), decanter cake, EFB, ash which are often damped without proper management or treatment. The EFB are also dumped in landfills or used as mulch in the oil palm plantation whose emissions also contribute to GWP. Due to some other problems associated with the use of EFB as mulch (including long decomposition period, high distribution and transportation cost), they can be used as fuel though it has a very small calorific value of 5 MJ/kg (Budiharjo 2010).

POME which are also a major liquid wastes from the palm oil mill are mostly mismanaged and disposed off wrongly. The direct rampant release of these effluents can cause water pollution which can affect downstream biodiversity and human beings. It has been reported that the average biochemical oxygen demand (BOD) of palm oil processing effluents is 25,000 ppm (Clay 2004). In Malaysia, for instance, effluents can legally be discarded into water bodies when their BOD levels are less than 100 ppm. However, the effluents also produce biogas mainly methane (Yusoff and Hansen 2007; Schmidt 2007) which can be tapped and used to generate electricity.

The biomass (mostly palm oil mills fruit fiber and kernel shells) powered combined heat and power (CHP) plants of the palm oil mills mostly operate without flue gas cleaning devices, hence causing the emissions of heavy metals and particulate matter which accounts for about 93 and 79 % of the human toxicity potential and heavy metals emissions to the air, respectively (Yusoff and Hansen 2007). Therefore, exhaust gas cleaning may help to reduce some of these environmental impacts drastically.

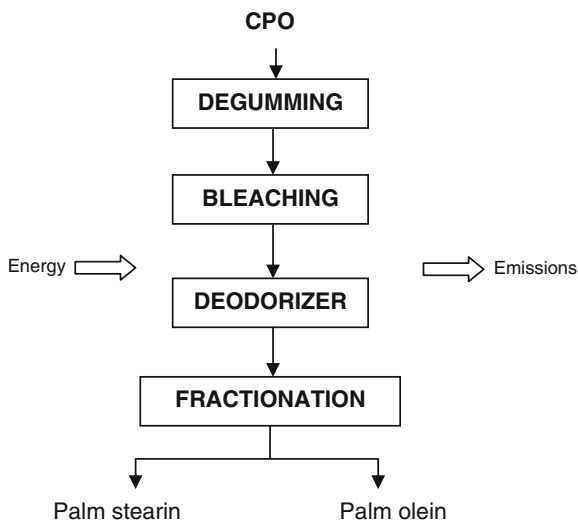
2.3 CPO Refinery

The refining of CPO helps to remove much FFA, odoriferous materials, phosphatides, waxes dirt, metal traces, etc., from the CPO. This process is achieved either through chemical or physical means. However, the physical process of CPO refining is the most commonly applied technology because of its simplicity, low capital cost, and high efficiency. Steam or physical refining involves degumming, bleaching, deodorizing, and fractionation into liquid olein and solid stearin fractions. CPO is acid treated in the degumming process to precipitate and separated out the gums or phosphatides. The oil is then bleached with activated clay or carbon under vacuum pressure to remove coloring pigment and metal ions. Deodorizing is carried out at high temperatures from 240 to 260 °C and pressure of 2–6 mmHg by injecting open steam which distills off the odoriferous matter present in the oil (Bockish 1998; Kheok and Lim 1982). The deodorized oil is then fractionated into palm olein and stearin by allowing the oil to crystalize under controlled temperature where the slurry passes through a filter press to obtain the stearin and olein fractions. The simple flow diagram of CPO treatment into refined palm oil (RPO) is shown in Fig. 4.

2.4 Transesterification of Palm Oil into Biodiesel

Biodiesel production from vegetable oil can be achieved through various means including pyrolysis, micro-emulsion, thermal cracking, transesterification. Transesterification of vegetable oil into biodiesel has been the most commonly

Fig. 4 Flow diagram of CPO refining processes



used technology due to its simplicity and environment-friendly processing. The catalyst (either sodium hydroxide, NaOH, or potassium hydroxide, KOH) is mixed with methanol in an agitator and the mixture made to react with the vegetable oil in a reactor at a temperature from 50 to 70 °C for 1–6 h. The resulting phases, i.e., glycerin and biodiesel phases usually containing some amount of methanol, are neutralized and then separated. Methanol is then recovered from the two phases with the help of distillation columns. The biodiesel is then purified by washing with warm water to remove soaps or excess catalysts, then dried and stored. Figure 5 shows the summary of flow diagram of transesterification processes of palm oil into biodiesel using alkaline catalyst.

2.4.1 Environmental Impacts Associated with the Transesterification of RPO into Biodiesel

In this chapter, homogenous base catalyst (NaOH) is used as the catalyst for transesterification thus there are bound to be the formation of soap together with the biodiesel, especially if the oil contains high amount of free fatty acids (FFA). The wastewater resulting from the washing of these soap stocks from the biodiesel is mostly released into water bodies untreated. Also, air emissions are released during the combustion of fossil fuel to produce energy to power the various unit operations within the plant. The transesterification unit is reported to contribute greatly to fossil fuel use compared to the other unit processes in the palm methyl ester (PME) production (Novizar and Dwi 2010).

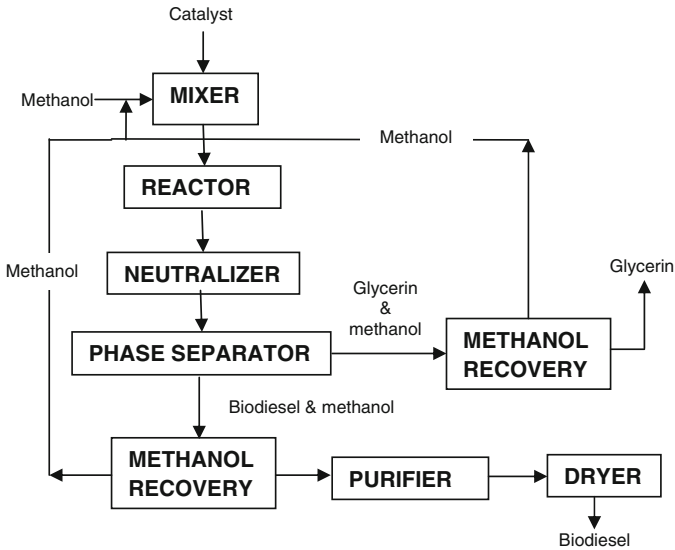


Fig. 5 Flow diagram of transesterification of palm oil into biodiesel

3 Tailpipe Emissions from Vehicles Using Biodiesel

Biodiesel is found to reduce tailpipe emissions from most vehicles compared to the conventional fuel such as petro-diesel. Tailpipe emissions such as hydrocarbon (HC), particulate matter (PM), carbon dioxide (CO₂), carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen oxide (NO_x) are low with biodiesel use irrespective of the type of feedstock used.

Previous studies (Hitchcock et al. 1998; Turrio-Baldassarri et al. 2004) have carried out various investigations to compare the tailpipe emissions from conventional diesel and biodiesel. Figure 6 shows a summary of the contribution of tailpipe emissions from different vehicles that run on biodiesel and petro-diesel. It can be seen from Figure 6 that the emissions from biodiesel combustion are significantly lower than those for petroleum diesel. Nitrogen oxide emissions from biodiesel combustion, however, are slightly higher. Emissions of NO_x from biodiesel combustion can be reduced substantially by advancing the injection time. CO₂ emissions were also insignificant from almost all the vehicles running on biodiesel since CO₂ emitted during biodiesel combustion is recycled into the photosynthesis process in plants which is not so with CO₂ produced by fossil fuel combustion. Tailpipe emissions also differ in amount with different vehicles. The graph also shows that new buses (NB) and heavy goods vehicles (HG) running on biodiesel recorded a higher NO_x emissions compared to smaller cars and old cars.

Turrio-Baldassarri et al. (2004) reported the tailpipe emissions from buses which ran on biodiesel. Their results indicated that emissions of CO were 20 % lower than those for conventional diesel. SO₂ tailpipe emissions were also reduced

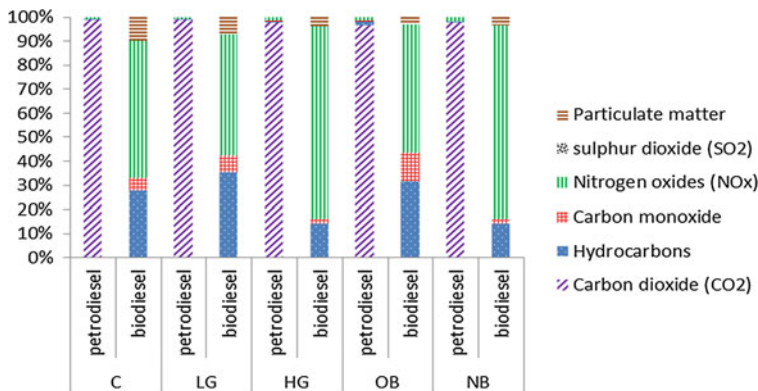
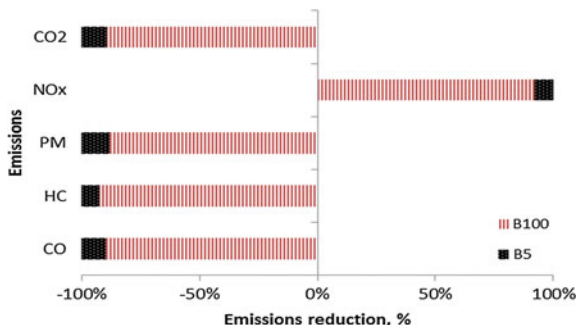


Fig. 6 Tailpipe emissions from vehicles using biodiesel and conventional diesel data source: Hitchcock et al. 1998. *C* Car, *LG* light goods vehicle, *HG* heavy goods vehicle, *OB* old bus, *NB* new bus

Fig. 7 Potential emission reduction from Tailpipe emissions from vehicles using biodiesel



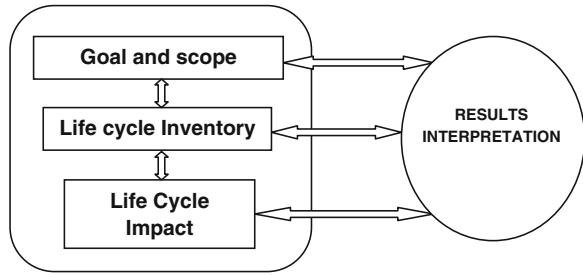
by almost 100 %, while particulate matter was reduced by about 40 %. Figure 7 shows the potential reduction in tailpipe emissions from pure biodiesel (B100) and a diesel with 5 % biodiesel and 95 % petro-diesel (B5).

Engine modifications, efficient designs, and PM filters can also help to reduce tailpipe emissions from the use of biodiesel. Also, efficient recirculation of exhaust gas can help to reduce combustion temperature and pressure which leads to NO_x emissions reduction.

4 Life Cycle Assessment Methodology

LCA methodology used in this study followed the principles and framework of the International Organization for Standardization, ISO 14040 and 14044, which comprises four major steps that are summarized in Fig. 8. Some inventory data

Fig. 8 Life cycle assessment methodology framework



were taken from GABi database and Ecoinvent 99 database version 2.1. GaBi 4.2 LCA software was used for the data analyses.

4.1 Goal and Scope Definitions

The goals of this chapter are (1) to come up with an inventory of resources associated with the production of palm oil biodiesel over its entire life cycle (from cradle to grave), (2) to identify and compare the major environmental impacts (damages) associated with each life cycle stage of the production of biodiesel from palm oil, (3) to identify the most important environmental loads on the production systems and suggest improvement measures. The focus of this chapter is geared toward the energy balance of biodiesel production from palm oil and its effect on the emissions of greenhouse gases, air, water, and solid waste pollutants on the environment. The assessment of the domestic economic importance of using the palm oil biodiesel does not fall within the scope of this chapter.

The scope according to ISO 14040 and 14044 includes the system boundary definition, the functional unit, allocation steps, temporal and geographical boundaries, data quality requirement, technology coverage, etc. This chapter dwells on palm oil production and conversion into biodiesel based on Malaysia's conditions (including plant location, feedstock origin, sources of electricity, and end-uses). Thus, geographical boundaries are not considered in this chapter as there are no assumptions of imports of biodiesel into the country.

4.1.1 System Boundary and Functional Unit

Figure 9 shows the system boundary for the production of biodiesel from palm oil considering the stages from cultivation of palm fruits to transesterification of palm oil into biodiesel. However, Figs. 2, 3, 4, and 5 detail the process flows of oil palm cultivation, palm oil milling, palm oil refining, and transesterification of palm oil into biodiesel, respectively. The major considerations within the system boundary for this chapter include the production of FFB (which comprises nursery stage and

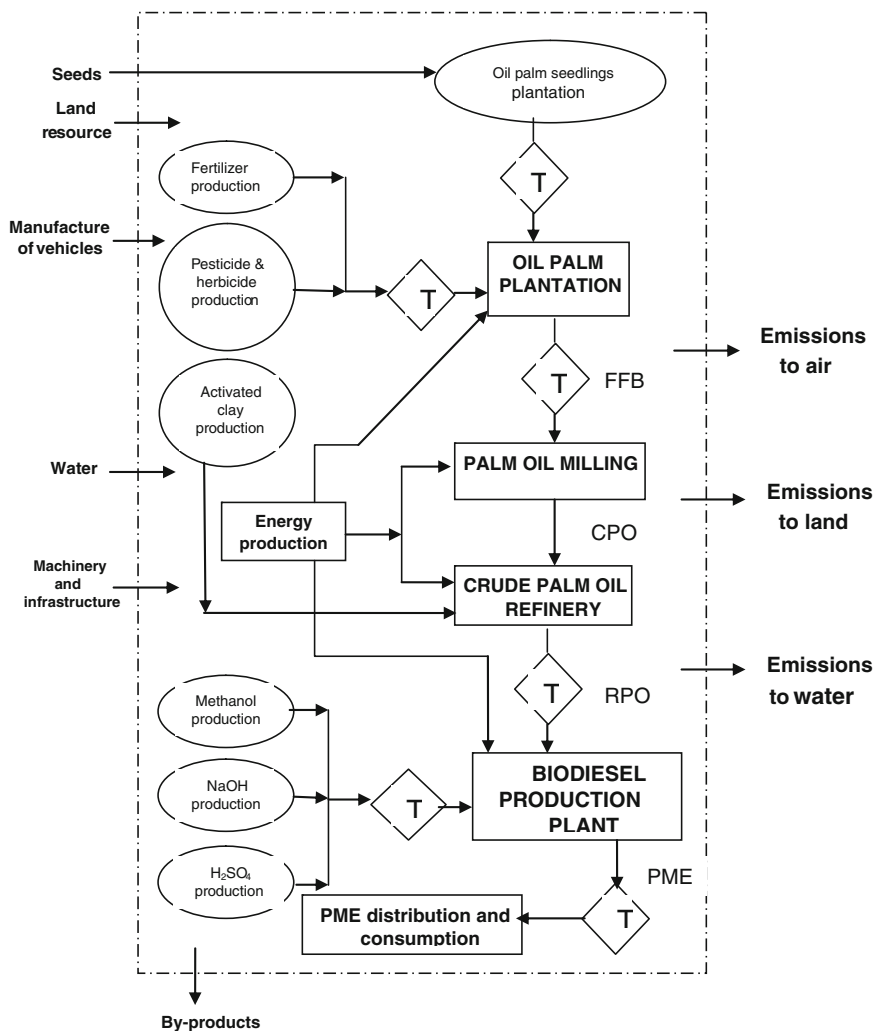


Fig. 9 LCA system boundary of biodiesel production from palm oil

oil palm plantation), transportation of FFB to crushing or milling facility, recovery of crude palm oil from the mill and refining of CPO, transportation of refined palm oil to biodiesel production plant and transesterification of RPO, transportation of palm oil methyl ester (PME) to consumers and finally the use of PME in diesel engines. Each of these stages has various substages which are detailed in Sect. 2.

Energy (such as electricity, fossil-based diesel) as well as the environmental inputs of the supply chain for the production of the raw materials used in each stage is also included in the system boundary. The life cycle environmental impacts associated with the production of machinery, infrastructure and land for

the cultivation of FFB, palm oil milling and conversion into biodiesel are excluded from the system boundary for this chapter. This assumption is based on the results from previous studies (Schmidt 2007; Novizar and Dwi 2010) which report negligible contributions because on a basis of per kilogram inputs, small amount of energy is accounted for when the energy embodied in the machinery is distributed over the amount of outputs from the machine over its entire life cycle.

Again, the energy for constructing the biodiesel plant as well as the energy production facilities, such as hydropower plants, thermal plants, has equally negligible contributions of less than 1 % hence neglected in the system boundary for this chapter. This is because, on per kilogram basis of biodiesel, the plant would have very low energy and emission contributions since the energy embedded in fixed inputs would have to be distributed over the total biodiesel production during the lifespan of the plant (Schmidt 2007; Novizar and Dwi 2010). The production of seeds (for nursery) and organic fertilizer is also excluded from the system boundary. Organic fertilizers are assumed to be residues that are not produced specifically for oil palm cultivation.

The functional unit (FU) in LCA appends a reference to which the input and output resources are related. An FU of 1 kg of PME in Malaysia is chosen as the reference unit for all the input and output streams as well as the potential environmental effects.

4.1.2 Allocation Procedures

The choice of LCA allocation methods for multi-input/output process like biodiesel from palm oil is critical in quantifying the environmental burdens of the coproducts generated by the various unit operations (Tillman 2000) because they may have a significant impact on the final results (Bernesson et al. 2006). Since biodiesel production from palm oil generates many kinds of coproducts (by-products or wastes) such as oil palm fronds, empty fruit bunches, glycerin (depending on the raw material inputs and production processes employed), realistically the main product (biodiesel) should not carry all the environmental burdens. Allocations of such environmental burdens to the different coproducts are made based on ISO 14041 LCA allocation procedures. In this chapter, the main LCA allocation method used is the system expansion where no allocation is made ('avoiding allocation'). By this method, all the major unit processes to be allocated are divided into sub-unit processes. The PME is thus expanded to involve the other functions related to the coproducts, but PME is allocated the most share of the energy consumption within the process chain. This method has the advantage of modeling the indirect effects of the environmental burdens on the coproducts (Ekvall and Finnveden 2001). As reported by Bernesson et al. (2006) for systems whose coproducts can replace other products in later processes, the expansion method of LCA allocation is suitable for application in this chapter.

4.2 Life Cycle Inventory Analysis

4.2.1 Data Collection

Life cycle inventory (LIC) is a methodology for estimating the utilization and consumption of resources and the amount of waste streams and environmental emissions ascribed to a product's life cycle. The LCI analysis used in this chapter focused on materials and energy resource use, air emission, water emission, soil emissions, land use, and other wastes involved in the life cycle of biodiesel production based on 1 kg of 100 % PME. Data used for the LCI analysis in this chapter were obtained from plant reports, literature reviews (Yusoff and Hansen, 2005; Schmidt 2007), Ecoinvent database (GaBi Software and database for life cycle Engineering 4 2003), experimental results (Novizar and Dwi 2010; Choosak et al. 2009), and estimations based on Malaysia's oil palm industry (MPOB 2006). Table 2 shows the summary of materials and energy resources as inputs and outputs for producing 1 kg biodiesel from palm oil. The most important parameters associated with the key environmental impacts of biofuels were estimated for each impact category as detailed in Sect. 4.3 of this chapter.

4.2.2 Assumption and Limitations

For 1 ha of land, the oil palm plantation produces averagely 20 t of FFB annually which yields about 4.6 t of mesocarp oil (crude palm oil), and 0.750 t PKS which produces about 0.250 t of PKO, 0.500 t of kernel meal, and 300 t of POME. For the same size of oil palm plantation, about 18 t of oil palm fronds (OPF), 3 t of oil palm trunks (OPT), 15 t of EFB, and 3 t of palm pressed fiber are produced annually. In this chapter, methane from POME is assumed to be emitted into the air. However, efforts are currently being made to trap the methane as biogas for energy production. OPF and OPT are also assumed to be used as mulch in the oil palm plantation.

In Malaysia, the cultivation of 1 hectare land of oil palm requires about 191 kg nitrogen/year, 62 kg phosphorus oxide/year, 318 kg potassium oxide/year, and 98 kg magnesium oxide/year (Ng and Thamboo 1967). Comparing these fertilizer quantities to those applied in Nigeria, Malaysia's conditions require quite higher fertilizer quantities for the same hectare of land use in Nigeria. In Nigeria, 1 hectare of oil palm plantation requires about 149, 48, 236, and 93 kg nitrogen, phosphorus oxide, potassium oxide, and magnesium oxide per year, respectively (Tinker and Smilde 1963). Before field planting, the nursery also receives some amount of fertilizer in the form of nitrogen, phosphorus oxide, potassium oxide, and magnesium oxide. The first few weeks (from 8 to 24 weeks) may require little fertilizer (from 3.5–10 g fertilizer per seedling) bi-weekly. From the first year to the time of transplanting, in every 3 weeks, a seedling of oil palm may require about 12 kg nitrogen (from ammonium sulfate), 12 kg of phosphorus oxide (from

Table 2 Life cycle inventory of biodiesel production from palm oil

| | Unit | Quantity | Energy coefficient (MJ/kg) | Total energy (MJ) |
|--|------|----------|-------------------------------|----------------------|
| <i>Nursery</i> | | | | |
| <i>Input</i> | | | | |
| Seeds | No. | 0.001336 | 33.6400 | 0.044943 |
| Water | kg | 0.698280 | 0.0042 | 0.002933 |
| <i>Fertilizer</i> | | | | |
| Nitrogen (N) | kg | 9.259E-6 | 48.9000 | 0.004528 |
| Urea | kg | 1.346E-5 | 22.5000 | 3.029E-4 |
| Phosphate (P ₂ O ₅) | kg | 2.934E-6 | 17.4300 | 5.114E-5 |
| Potassium (K ₂ O) | kg | 2.094E-5 | 10.3800 | 2.174E-4 |
| Magnesium (MgO) | kg | 5.011E-6 | 2.3200 | 1.163E-5 |
| Boron (Borate) | kg | 1.179E-6 | 32.2700 | 3.804E-5 |
| <i>Pesticides and herbicides</i> | | | | |
| Glyphosate | kg | 0.000282 | 18.6200 | 0.005251 |
| Paraquat | kg | 0.000141 | 130.0000 | 0.018330 |
| Furadan | kg | 0.000211 | 13.1580 | 0.002776 |
| Human energy | MJ | | | 0.000037 |
| <i>Transportation of chemicals</i> | | | | |
| Diesel | kg | 0.000604 | 48.1000 | 0.029052 |
| <i>Total energy input</i> | MJ | | | 1.08E-1 |
| <i>Output</i> | | | | |
| Oil palm seedlings | No. | 0.001336 | 36.0400 | 0.048149 |
| <i>Emissions to soil</i> | | | | |
| Nitrogen (N) | kg | 1.474E-6 | 48.9000 | 7.208E-5 |
| Phosphate (P ₂ O ₅) | kg | 5.890E-7 | 17.4300 | 1.027E-5 |
| Glyphosate | kg | 0.000115 | 18.6200 | 0.002141 |
| Paraquat | kg | 0.000096 | 130.0000 | 0.012480 |
| Furadan | kg | 0.000104 | 13.1580 | 0.001368 |
| <i>Emissions to air</i> | | | | |
| NO _x | kg | 1.474E-7 | 296.0000 | 4.363E-5 |
| CO ₂ | kg | 0.001657 | 32.1200 | 0.053222 |
| SO ₂ | kg | 5.895E-8 | 29.5000 | 1.739E-6 |
| <i>Total energy output</i> | MJ | | | 0.048149 |
| <i>Transportation of seedlings (T1)</i> | | | | |
| Diesel | kg | 0.004692 | 48.1000 | 0.225685 |
| <i>Emissions to air</i> | | | | |
| CO | kg | 0.014683 | 10.1100 | 0.148445 |
| NO _x | kg | 0.000054 | 296.0000 | 0.015984 |
| Particulate matter | kg | 0.000027 | - | - |
| SO ₂ | kg | 2.165E-5 | 29.5000 | 0.000639 |
| TOC | kg | 0.001457 | - | - |
| <i>Transplanting</i> | | | | |
| <i>Input</i> | | | | |
| Seedlings | No. | 0.001336 | - | - |

(continued)

Table 2 (continued)

| | Unit | Quantity | Energy coefficient (MJ/kg) | Total energy (MJ) |
|--|------|----------|-------------------------------|----------------------|
| Water | kg | 2179.511 | 4.2E-3 | 9.153950 |
| Fertilizer | | | | |
| Nitrogen (N) | kg | 0.02890 | 48.90 | 1.413210 |
| Urea | kg | 0.04200 | 22.50 | 0.945000 |
| Phosphate (P ₂ O ₅) | kg | 0.00916 | 17.43 | 0.159659 |
| Magnesium (MgO) | kg | 0.01564 | 2.32 | 0.036285 |
| Borate | kg | 0.00368 | 32.27 | 0.118754 |
| Potassium (K ₂ O) | kg | 0.06536 | 10.38 | 0.678437 |
| Pesticides | | | | |
| Glyphosate | kg | 0.00184 | 18.72 | 0.034445 |
| Paraquat | kg | 0.00070 | 130.00 | 0.091000 |
| Furadan | kg | 0.00299 | 13.16 | 0.039340 |
| Herbicides | kg | 0.00015 | 184.71 | 0.027707 |
| Wood chippings | kg | 3.54311 | 19.00 | 67.31909 |
| Field establishment | kg | 0.02659 | 48.1 | 1.278883 |
| Diesel | | | | |
| Field maintenance | | | | |
| Diesel | kg | 0.01329 | 48.1 | 0.639441 |
| Electricity | MJ | 1.23924 | – | 1.239240 |
| Labor (harvest) | MJ | 0.00600 | – | 0.006000 |
| <i>Total energy input</i> | MJ | | | 83.18044 |
| <i>Output</i> | | | | |
| FFB | kg | 4.17000 | 43.33 | 180.6861 |
| OPF | kg | 1.50120 | 20.51 | 30.78961 |
| OPT | kg | 0.03336 | 16.88 | 0.563117 |
| Emissions to soil/water | | | | |
| Nitrogen (N) | kg | 0.00460 | 48.90 | 0.224940 |
| Phosphate (P ₂ O ₅) | kg | 0.00184 | 17.43 | 0.032071 |
| Pesticides | kg | 0.00037 | 245.57 | 0.090861 |
| Emissions to air | | | | |
| NO _x | kg | 0.00046 | 296.00 | 0.136160 |
| SO ₂ | kg | 0.00018 | 29.50 | 0.005310 |
| Pesticides/herbicides | kg | 0.00009 | 245.57 | 0.022592 |
| CO ₂ | kg | 0.01092 | 32.12 | 0.350706 |
| <i>Total energy output</i> | MJ | | | 212.9018 |
| Transportation of raw materials to mill (T2) | kg | 0.02346 | 48.10 | 1.12843 |
| Diesel | | | | |
| Emissions to air | | | | |
| CO | kg | 0.07342 | 10.11 | 0.74228 |
| NO _x | kg | 0.00027 | 296.00 | 0.07992 |
| Particulate matter | kg | 0.00014 | – | – |
| SO ₂ | kg | 0.00011 | 29.50 | 0.00325 |
| TOC | kg | 0.00729 | – | – |

(continued)

Table 2 (continued)

| | Unit | Quantity | Energy coefficient (MJ/kg) | Total energy (MJ) |
|------------------------------------|------|----------|-------------------------------|----------------------|
| Palm oil mill | | | | |
| <i>Inputs</i> | | | | |
| FFB | kg | 4.17 | 43.33 | 180.686 |
| Water | kg | 6.58076 | 4.2E-3 | 0.02764 |
| <i>Energy consumption</i> | | | | |
| Electricity | MJ | – | – | 0.29440 |
| Diesel | MJ | 0.00012 | 48.10 | 0.00578 |
| Steam | MJ | 5.47941 | 1.36 | 7.45200 |
| <i>Total energy input</i> | MJ | | | 188.4658 |
| <i>Output</i> | | | | |
| CPO | kg | 0.94 | 31.40 | 29.5160 |
| POME | kg | 2.3 | – | – |
| EFB | kg | 1.0764 | 20.47 | 22.13391 |
| PPF | kg | 0.7176 | 19.22 | 13.79227 |
| PKS | kg | 0.6532 | 21.44 | 14.00461 |
| <i>Emissions to soil/air/water</i> | | | | |
| Steam | kg | 5.479411 | 1.36 | 7.45200 |
| NO _x | kg | 0.000588 | 296.00 | 0.17405 |
| CO | kg | 0.005188 | 10.11 | 0.05245 |
| CO ₂ | kg | 1.199897 | 32.12 | 38.5407 |
| Particulate matter | kg | 0.001269 | – | – |
| SO ₂ | kg | 0.000018 | 29.50 | 0.00053 |
| TOC | kg | 0.000046 | – | – |
| VOC | kg | 0.003607 | – | – |
| Biogas from POME storage | MJ | 0.0644 | – | 2.31800 |
| BOD | kg | – | – | – |
| COD | kg | – | – | – |
| Nitrates | kg | 0.000759 | 22.5 | 0.01708 |
| Ash | kg | 0.045 | 19.61 | 0.88245 |
| <i>Total energy output</i> | | | | 128.884 |
| <i>CPO refining</i> | | | | |
| <i>Inputs</i> | | | | |
| CPO | kg | 0.94 | 41.86 | 39.3484 |
| Activated clay | kg | 0.00846 | 34.54 | 0.29222 |
| Electricity | MJ | – | – | 0.31505 |
| Steam | MJ | – | – | 4.96871 |
| <i>Total energy input</i> | MJ | – | – | 44.9244 |
| <i>Outputs</i> | | | | |
| RPO | kg | 0.92500 | 31.40 | 29.0450 |
| <i>Emissions to air</i> | | | | |
| CO ₂ | kg | 4.97541 | 32.12 | 159.810 |
| SO ₂ | kg | 0.00012 | 29.50 | 0.00345 |
| NO _x | kg | 0.00029 | 296.00 | 0.08622 |

(continued)

Table 2 (continued)

| | Unit | Quantity | Energy coefficient (MJ/kg) | Total energy (MJ) |
|---|------|----------|-------------------------------|----------------------|
| <i>Total energy output</i> | MJ | | | 188.945 |
| Transportation of RPO to biodiesel plant (T3) | | | | |
| Diesel | kg | 0.02531 | 48.10 | 1.22029 |
| Emissions to air | | | | |
| CO | kg | 0.07920 | 10.11 | 0.80076 |
| NO _x | kg | 0.00038 | 296.00 | 0.11248 |
| Particulate matter | kg | 0.00015 | – | – |
| SO ₂ | kg | 0.00017 | 29.50 | 0.00502 |
| Transesterification | | | | |
| <i>Input</i> | | | | |
| RPO | kg | 0.92500 | 31.40 | 29.04500 |
| Methanol | kg | 0.12278 | 19.70 | 2.418766 |
| Sodium hydroxide (NaOH) | kg | 0.01031 | 19.87 | 0.204879 |
| Water | kg | 0.29576 | 0.0042 | 0.001242 |
| Phosphoric acid (H ₃ PO ₄) | kg | 0.00959 | 32.62 | 0.312826 |
| Energy consumption | | | | |
| Steam | MJ | 0.21600 | 1.36 | 0.293760 |
| Electricity | MJ | 0.04214 | – | 0.042140 |
| <i>Total energy input</i> | MJ | | | 32.31861 |
| <i>Outputs</i> | | | | |
| Biodiesel | kg | 1.00000 | 39.84 | 39.84000 |
| Glycerol | kg | 0.23860 | 18.05 | 4.306730 |
| Wastewater | kg | 0.05359 | 45.93 | 2.461388 |
| Na ₃ PO ₄ | kg | 0.00146 | 1.421 | 0.002075 |
| Emissions to air | | | | |
| CO ₂ | kg | 2.55281 | 32.12 | 81.99626 |
| <i>Total energy output</i> | MJ | | | 128.6065 |
| Transportation of biodiesel to consumer (T4) | | | | |
| Diesel | kg | 0.02490 | 48.10 | 1.1978 |
| Emissions to air | | | | |
| CO ₂ | kg | 0.07792 | 32.12 | 2.5027 |
| NO _x | kg | 0.00028 | 296.00 | 0.0829 |
| Particulate matter | kg | 0.00014 | – | – |
| SO ₂ | kg | 0.00011 | 29.50 | 0.0032 |
| TOC | kg | 0.07732 | – | – |
| Biodiesel use in diesel engine | | | | |
| Biodiesel | kg | 1.00000 | 39.84 | 39.840 |
| Emissions to air | | | | |
| CO ₂ | kg | –16.0890 | 32.12 | –516.78 |
| NO _x | kg | 0.01360 | 296.00 | 4.0256 |
| Particulate matter | kg | –0.00454 | – | – |

(continued)

Table 2 (continued)

| | Unit | Quantity | Energy coefficient (MJ/kg) | Total energy (MJ) |
|-------------------|------|----------|-------------------------------|----------------------|
| SO ₂ | kg | -0.00454 | 29.50 | -0.1339 |
| Hydrocarbons (HC) | kg | -0.00454 | - | |
| CO | kg | -0.05543 | 10.11 | -0.5604 |

All quantities are wet weight averages from (MPOB 2010; Felda 2010; Schmidt 2007; Subramaniam et al. 2008; Yusoff 2006; Wicke et al. 2008)

Net energy value (NEV) = energy content of PME – net energy inputs = 20.28 MJ

NRnEV = energy content of PME – fossil energy inputs = 24.63 MJ

Net energy ratio (NER) = net energy outputs/net energy inputs = 1.4893

rock phosphate), 17 kg of potassium oxide, and 2 kg of magnesium oxide or kieserite (Von Uexkull and fairhurst 1991; Hartley 1988). At the early stage after transplanting, urea and limestone may be applied to the young palms at a rate of 6–8 kg/palm tree (Von Uexkull and fairhurst 1991). Borate is currently applied to oil palms up to the age of 6 years. Paraquat and glyphosate as herbicides are also applied twice or thrice a year at a rate of 0.625–1.25 kg/ha/time and 1.875–3.125 kg/ha/time, respectively (Von Uexkull and fairhurst 1991). Water requirement for the oil palm cultivation is assumed to be from rain water and irrigation at early stages of transplanting. The CHP system of the mill is assumed to utilize the PPF and palm kernel shells as fuel to produce heat for steam and electricity generation.

4.2.3 Transportation

The nursery field is assumed to be about 1.7 km away from the oil palm plantation field. The oil mill is assumed to be situated closer to the oil palm plantation; hence, the distance is negligible. CPO transportation to CPO refinery is assumed to be part of the biodiesel production plant which is estimated to be 296 km away from the oil mill.

4.2.4 Energy Analysis

For the production of 1 kg PME with energy content of 39.84 MJ, the NEV and NER of the whole life cycle of PME production are 20.28 MJ per kg of PME and 1.489 (without energy production from EFB, PPF, etc.), respectively. The NER would have been 4.81 if all EFB, PPF, PKS, etc., were considered as energy source (which is considered in this chapter). This clearly shows an energy profit for the PME production system. The total life cycle energy consumption of the PME product system is shown to be 20.28 MJ per kg PME.

The main energy supply to the palm oil mill includes diesel, electricity, and steam. PPF and PKS which are regarded as wastes from the palm oil mill are normally used to produce energy. Figures 10 and 11 summarize the energy contributions of various inputs into the various production stages excluding the transportation stages. Figure 12 shows the contribution of the total energy inputs by the four main transportation stages associated with the production of biodiesel from palm oil. Due to the conversion of solar radiation to biomass by means of photosynthesis, the chemical energy content of the harvested FFB and other biomass exceeds the energy input through the farming system. Oil palm is therefore regarded as a net source of useful energy (Corley and Tinker 2003). From Fig. 10, the consumption of water, fertilizer, pesticides, and chemicals as well as human work was highly recorded in the oil plantation stage. For chemical (including major input materials such as FFB for oil mill, wood chips for plantation) consumption, the energy inputs between FFB and wood chips were high which triggered the high values for the oil milling (57 % of total chemicals) and plantation (21 % of total chemicals) stages, respectively. The PPF and EFB (as part of chemical inputs in this chapter) from the mill with dry calorific values of 19.22 MJ/kg and 20.47 MJ/kg, respectively (Yusoff 2006), are used as fuel to produce steam and electricity for use within the mill.

Though the transesterification stage consumes many chemicals, the energy contents of these chemicals are quite low (10 % of total input chemicals), hence reducing the total energy consumption from chemicals in that stage. On the other hand, CPO refinery stage consumes activated clay with high heating value, hence increasing the energy contents of the chemical use (12 % of total energy of chemicals used) within that stage.

The oil mill, however, recorded the second highest (13 % of total input fuel excluding transportation) consumption of energy (including fossil and non-fossil fuel from EFB, PPF) compared to all the other stages. Since it was assumed in this chapter that 1 kg biodiesel was used in the “end use” or combustion stage, the

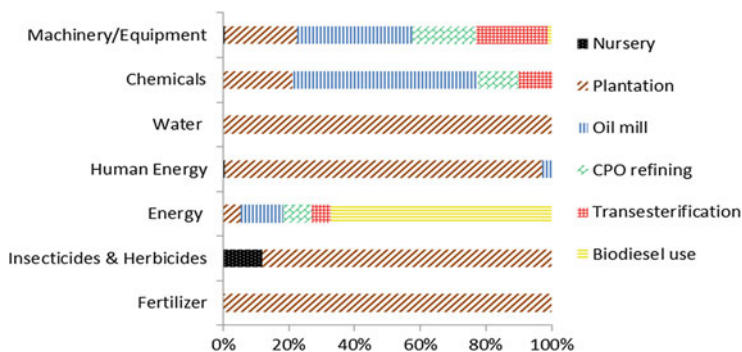


Fig. 10 Percent energy contribution of inputs into PME production by the various production stages (without transportation stages). Chemicals include catalyst, methanol, H₃PO₄, RPO, FFB, activated clay, etc. Energy includes diesel fuel, electricity, steam

highest energy consumption (67 % of total input fuel) was recorded in this stage. This shows positive environmental impacts because it releases insignificant air emissions upon combustion.

Plantation stage recorded highly significant human energy input (97 % of total human energy input) compared to other energy inputs (5 % of total energy input) such as diesel.

According to Henson (2004), palm oil mills are self-sufficient for electricity and heat. It has been reported (Husain et al. 2003) that the total heat and power generation for every tonne of FFB is about 1181 MJ (approximately 0.7 t steam). Within the mill, energy could be released as emissions into the atmosphere which is estimated to be 16 MJ per tonne FFB (Subramaniam 2006). It is assumed that the energy produced is more than the energy required by the mill; hence, the surplus is released into the atmosphere.

The highest water requirement for the whole production came from the oil palm plantation stage (contributing 99.6 % of the total water requirement).

Generally, according to Fig. 11, the highest energy consumption within the whole production cycle excluding transportations was obtained from the input chemicals/materials (which included EFB, PPF, etc.) with contribution of 81 % of total energy of inputs. Energy inputs from fossil and non-fossil fuel contributed about 16 % of the total energy inputs. Herbicide and pesticide use within both the nursery and plantation stages carried the least energy content of about 0.06 % of the total energy of inputs into the PME production.

The production of 1 kg of PME requires approximately 63.17 MJ of energy in the form of fuel (fossil and non-fossil fuel) and 396.67 MJ energy in the form of other raw materials, machinery, etc., including diesel consumption from transportation stages. The transportation of PME from biodiesel production plant to the consumer recorded the highest diesel consumption (32 %) compared to all the other transportation stages. This is attributed to the total distance covered by the truck delivering the raw materials.

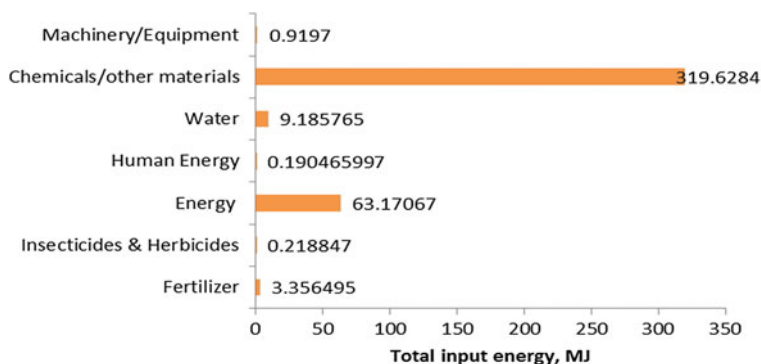


Fig. 11 Total energy inputs into PME production by all the stages within the system boundary

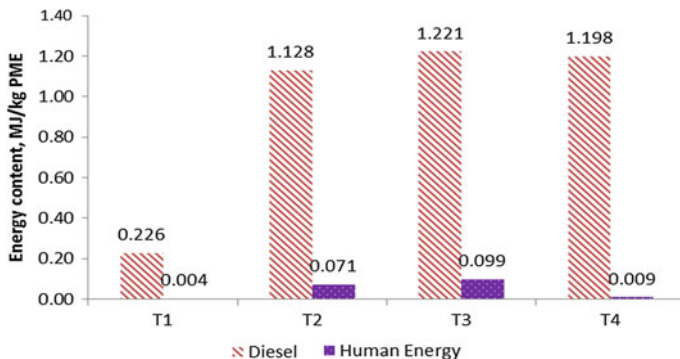


Fig. 12 Total energy inputs into PME production by the transportation stages. *T1* Transportation of seedlings to plantation site, *T2* transportation of FFB from plantation site after harvest to oil mill, *T3* transportation of RPO to biodiesel production plant, *T4* transportation of PME to consumer

4.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is a major step in LCA which provides basic indicators for analyzing the potential environmental contributions of all the resource extractions including wastes and emissions. Eco-Indicator 99 (EI 99, Agalitarian Approach [AH]) was used to assess the environmental impacts associated with the life cycle of palm oil biodiesel. Standard LCIA comprises (1) impact categories selection and classification, (2) characterization, and (3) valuation steps.

4.3.1 Impact Category Selection and Classification

The potential environmental impact categories selected for this chapter according to EI99, AH method of LCIA, include land use/conversion ($\text{PDF} \cdot \text{m}^2 \cdot \text{a}$)^{1,2} acidification/nitrification potential ($\text{PDF} \cdot \text{m}^2 \cdot \text{a}$), ecotoxicity potentials ($\text{PDF} \cdot \text{m}^2 \cdot \text{a}$), fossil fuel use (MJ surplus energy), mineral resources (MJ surplus energy), climate change (DALY),³ ozone layer depletion potential (DALY), radiation potential (DALY), carcinogenic effects (DALY), respiratory organics (DALY), and respiratory inorganics (DALY). The complete human health impact is obtained by adding up all the DALY values, while the ecosystem impacts and resource depletion are obtained by adding up the PDF and surplus energy, respectively. These categories were selected based on their relevance for assessing the

¹ PDF: Potentially disappeared fraction (plant species disappeared as a result of the impacts).

² a: year (annually).

³ DALY: Disability adjusted life years (years of life lost due to the impacts).

environmental emissions associated with biofuel systems and those suggested by previous researches (Guinée et al. 2001; Edwards et al. 2007; Buchholz et al. 2009). These impact categories are evaluated using LCA software such as Simapro (developed by PRÉ Consultants), Gabi 4.2 (developed by PE International), Umberto (developed by IFU Hamburg GmbH), while the databases from Eco-Indicator 99 or 95, CML 2001 or 1996, Environmental Design of Industrial Products (EDIP 1997) or EDIP 2003, etc., are used to evaluate the final environmental impacts. Other LCIA methods that are implemented in Ecoinvent database include cumulative energy demand, ecological scarcity 1997, environmental priority strategies in product development (EPS 2000), IMPACT 2002, IPCC 2001 (climate change).

The main regulated pollutants evaluated in this chapter include CO, particulate matter, non-methane hydrocarbons, nitrogen oxides (NO_x), etc. Solid wastes, water, and CO₂ emissions as well as overall energy requirements are also evaluated. Each of these emissions and pollutants are classified into their main environmental impact category. For instance, CO₂ and CH₄ emissions were classified under climate change, NO₂ and SO₂, on the other hand, contribute to acid rain formation and some degree of direct effect on human health hence classified accordingly.

4.3.2 LCIA Characterization

This step involves the quantification of the extent to which each pollutant or emission contributes to different environmental impacts. Standard characterization factors conforming to Eco-Indicator 99 (EE99, EA) evaluation procedures are used in this stage. In this method, human health category is measured in DALY/kg FU, while ecosystem impacts and resource depletion are also measured in PDF*m²*a/kg FU and surplus energy/kg FU. These are available in Gabi 4.2. On the other hand, using CML 2001 database for the impacts evaluation generate different impact categories units. For instance, acidification potentials of NO_x and SO₂ are based on proton formation potentials (PFP) (i.e., 0.7 for NO_x and 1 for SO₂) expressed as SO₂ equivalent per FU. Thus, the total acidification potentials of 10 g NO₂ and 5 g SO₂ are given by $(10 \times 0.7) + (5 \times 1) = 12$ g SO₂ equivalent per FU. This is estimated by multiplying the amounts of the emissions by their proton formation factors and aggregating the results of these multiplications for each impact category.

Again, global warming potentials are based on CO₂ equivalent, while ozone layer depletion potentials are measured in CFC-11 equivalent. These characterization factors can be extended through normalization, grouping, and weighting. In normalization, the results of the impact categories are usually compared with the total impacts in the area of interest, for instance, in this chapter, Malaysia. Grouping also involves the sorting and ranking of the impact categories. In weighting, the different environmental impacts are weighted relative to each other,

Table 3 Characterization of air and water emissions in PME production

| Type of emission | LCIA category |
|---|---|
| <i>Emissions to air</i> | <i>GWP (CO₂ eq./g)^a – 100 years</i> |
| Carbon dioxide (CO ₂) | 1 |
| Nitrous oxide (N ₂ O) | 310 |
| Carbon monoxide (CO) | 3 |
| Methane (CH ₄) | 21 |
| Carbon tetra-fluoride (CF ₄) | 6,300 |
| Sulfur hexafluoride (SF ₆) | 23,900 |
| Hydro fluorocarbon (HFC) | 140–12,100 |
| Per-fluorocarbons (PFC) | 6,500–9,200 |
| | <i>AP (SO₂ eq./g)^b</i> |
| Sulfur dioxide (SO ₂) | 1 |
| Oxides of nitrogen (NO _x) | 0.7 |
| Hydrochloride acid (HCl) | 0.88 |
| Hydrogen fluoride (HF) | 1.6 |
| Nitrogen monoxide (NO) | 1.07 |
| Nitrogen dioxide (NO ₂) | 0.7 |
| Ammonia (NH ₃) | 1.8 |
| <i>Emissions to water</i> | <i>EP (PO₄ eq./g)^c</i> |
| Phosphates (PO ₄ ³⁻) | 1 |
| Nitrates (NO ₃) | 0.42 |
| Nitrogen oxides (NO _x) | 0.13 |
| Ammonia (NH ₃) | 0.33 |

^a U.S. DOE/EIA (1997)

^b Heijungs (1992)

^c Mark et al. (2001)

summed up to obtain a single number for the total environmental impact. Table 3 shows a summary of LCIA classification and characterization estimations associated with PME production.

4.3.3 Valuation

This step uses results from the LCIA to evaluate each process for improvements in the performance of every stage associated with the life cycle of palm oil biodiesel.

5 LCA Results and Interpretation

The major objective of this chapter's LCA interpretation is to detect or assess the points of potential environmental impacts which can lead to overall improvement of the performance of the palm oil biodiesel production industries in the world, especially in Malaysia. Figure 13 summarizes the environmental impact associated with each life cycle stage of PME production. Figure 14 shows the environmental

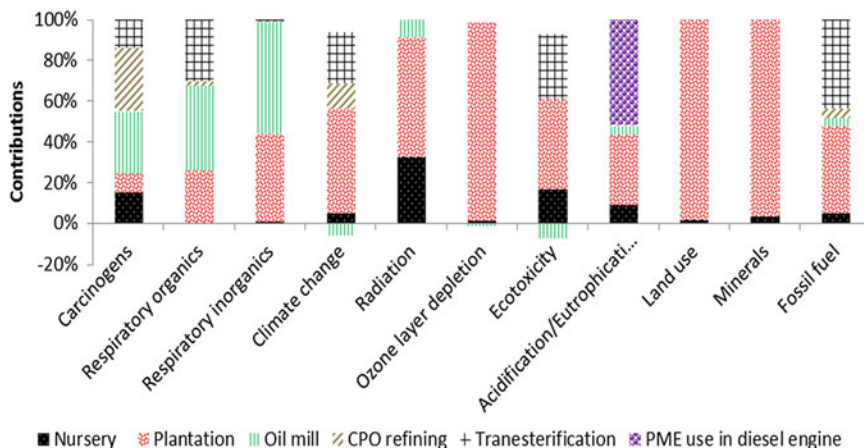


Fig. 13 Environmental impact potentials for 1 kg PME (excluding impacts from transportation)

impacts associated with the four main transportation stages within the PME production. Figure 15 summarizes the total environmental impacts (including transportation stages) within each of the production processes within the life cycle of palm oil biodiesel.

5.1 Emissions Associated with Oil Palm Nursery System

Out of the eleven impact categories, six of them, namely radiation (32.57 % of total radiation potentials), carcinogens (14.79 % of total carcinogens), ecotoxicity (19.11 % of total ecotoxicity), climate change (5.18 % of total climate change), land use (1.49 % of total land use), and acidification/eutrophication (8.81 % of total acidification) potentials, were highly significant (Fig. 13) excluding the impacts from transportation stages. The main emissions associated with these impacts include the use of herbicides and pesticides (radiation, ecotoxicity, carcinogens, etc.) and fertilizers (ecotoxicity, acidification, radiation). N-fertilizers emit N_2O into the air which contributes to the climate change effects. The use or spraying of herbicides and insecticides also emits particulate matter into the air.

Combining the effects on all impact categories as a single score, it can be seen that the nursery stage contributed only 1 % environmental impacts for 1 kg production of PME (Fig. 15). On the basis of human health, ecosystem depletion, and resource use, the nursery stage contributed 0.358, 0.192, and 0.188 %, respectively, for 1 kg PME.

In order to further reduce these impacts, the use of organic fertilizers can replace inorganic ones. Glyphosate and paraquat as pesticides and herbicides must

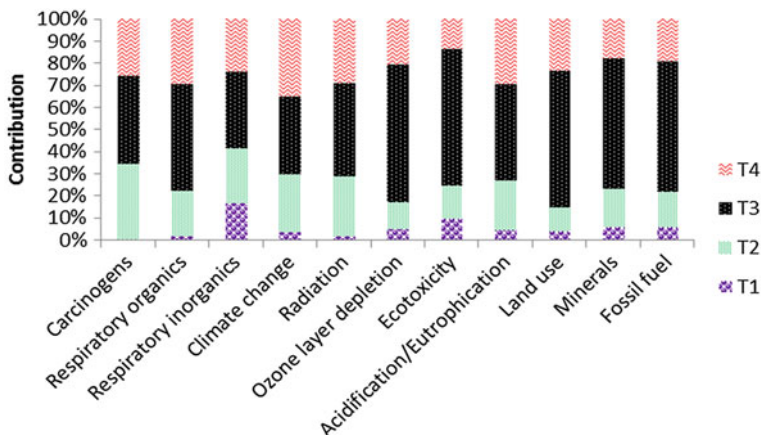


Fig. 14 Environmental impacts associated with transportation stages in the life cycle of PME. *T1* Transportation of oil palm seedlings to plantation site, *T2* transportation of FFB from palm plantation site to oil mill, *T3* transportation of RPO to transesterification unit, *T4* transportation of biodiesel from transesterification unit to consumer

be used in a minimal quantities, while efficient treatment of oil palm seeds are used for nursery.

5.2 Emissions Associated with Oil Palm Plantation

Emissions from the plantation are determined from material balance of the major substances such as N_2O , CO , CO_2 , particulate matter into and out of the production stage. Since oil palm is a perennial crop, during the life cycle for the generation of FFB and uptake of nutrients, the harvesting and decomposition of biomass residues varies, hence making emissions data unavailable at early stages.

In the plantation stage, all the impact categories were significant compared to the other production stages but were higher for land use (98.51 % of total land use), minerals (96.75 % of total minerals), radiation (58.62 % of total radiation), climate change (58.42 % of total climate change), ecotoxicity (51.79 % of total ecotoxicity), respiratory inorganics (43.46 % of total respiratory inorganics), fossil fuel use (46.62 % of total fossil fuel use), and acidification (34.58 % of total acidification) (Fig. 13) excluding impacts from transportation stages. The use of fertilizers, herbicides, pesticides, and diesel use were the main sources of these emissions. Organic fertilizers could be used in place of inorganic ones in order to reduce some of these emissions. The commonly used herbicide, paraquat dichloride, is found to also emit quite substantial amount of minerals and metals into the soil. Table 4 shows the emissions of heavy metals/minerals associated with the production of 1 kg FFB from the plantation stage.

Table 4 Emissions of heavy metals from the production of 1 kg FFB

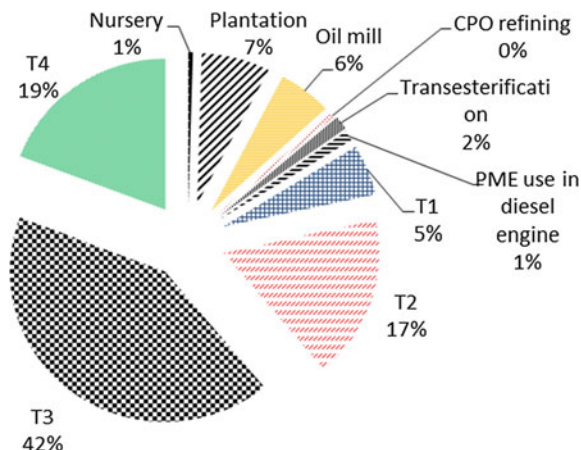
| Heavy metal type | Emissions, mg/kg FFB |
|------------------|----------------------|
| Arsenic | 0.0285 |
| Cadmium | 0.05429 |
| Chromium | 1.26857 |
| Cobalt | 0.00571 |
| Copper | 0.0331429 |
| Mercury | 0.000857 |
| Molybdenum | 0.002857 |
| Nickel | 0.145714 |
| Lead | 0.057143 |
| Selenium | 0.011429 |
| Zinc | 1.96286 |

The harvests of FFB, irrigation, etc., are done manually, some requiring the use of trucks and other machinery which utilizes fossil fuel. This can also result in greenhouse gas emissions contributing to high climate change effect. Land use/conversion effect was highest (98.51 %) for the plantation stage due to heavy land use. It is recommended that, new oil palm plantations should be cultivation on degraded land in order to reduce land conversion/use effects. On a percentage score with transportations impacts inclusive, the plantation stage alone contributed approximately 7 % of the total environmental impacts from the whole production stages (Fig. 15). On the basis of human health, ecosystem depletion, and resource use, the plantation stage had a percent contribution of 13.10, 7.26, and 1.70 %, respectively.

5.3 Emissions Associated with the Palm Oil Mill

The most significant impact categories in the oil milling stage are carcinogens, respiratory organics, respiratory inorganics, and ozone layer depletion with percent shares of 30.83, 41.44, 55.02, and 55.51 % with transportations excluded (Fig. 13). The major parameters resulting in high potentials of these impact categories are the POME and the boiler ash. POME is the wastewater generated from the clarification and other processing steps in the mill. This is normally treated in open ponds in order to reduce its biological oxygen demand. The EFB in this chapter is considered to be used for fuel production within the mill hence no emissions from dumping sites resulting in climate change effect. Climate change potential is insignificant due to the use of renewable fuels from PPF to EFB in the mill. The boiler ash also contributes to emissions into the soil. In this chapter, most of the wastes within the mill were considered to be recycled or treated before they were released into the environment.

Fig. 15 Total environmental impacts associated with the production of PME



The oil milling stage contributed approximately 6 % of the total environmental impacts (Fig. 15). Human health, ecosystem depletion, and resource use for the oil milling stage recorded a percent environmental impact share of 13.01, 0.56, and 0.16 %, respectively.

5.4 Emissions Associated with CPO Refinery

The most dominant impact categories within the CPO refinery are carcinogens, climate change, fossil fuel use, and respiratory organics with contribution of 31.48, 14.34, 4.92, and 2.34 % of the total impacts for the PME production system, respectively (Fig. 13). The emissions from this stage come from the use of fossil fuel emitting N_2O , CO_2 , CO, particulate matter, respiratory gases, etc., which result in these significant impact categories.

On a single score, the CPO refinery contributed approximately 0.002 % of the total impacts associated with PME production (Fig. 14). Human health, ecosystem depletion, and resource use were 0.84, 0.15, and 0.20 % of the total impacts, respectively.

5.5 Emissions Associated with Transesterification Stage

The significant impact potentials within the transesterification stage are carcinogens, respiratory organics, climate change effect, ecotoxicity, and fossil fuel use with contributions of 13.64, 30.31, 28.77, 37.19, and 43.59 %, respectively (Fig. 13). These are due to the emissions resulting from the use of fossil fuel, sodium hydroxide, phosphoric acid as well as wastewater containing soap stocks

which are not transformed into any useful products. Emissions such as CO_2 , N_2O , particulate matter are predominant in the transesterification stage.

On the whole, 2 % (Fig. 15) of the total environmental impacts were associated with the transesterification stage with 1.36, 0.80, and 1.73 % of the total impacts being assigned to human health, ecosystem depletion, and resource use, respectively.

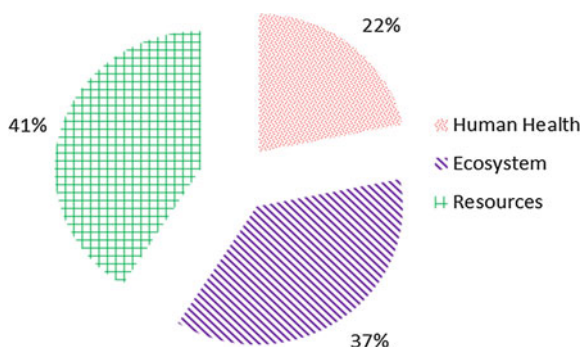
PME uses in diesel engine showed significance in acidification/eutrophication potential due to the emission of CO_2 , N_2O , CO, and other particulate matter into the environment. This stage offsets some of the environmental impacts by negating them. Hence, the use of biodiesel contributed to the reduction of most of the environmental impacts.

5.6 Emissions Associated with Transportation

Four main transportation stages were considered in this chapter, namely transportation of oil palm seedlings to plantation site (T1), transportation of FFB from plantation site to oil mill (T2), transportation of RPO to transesterification unit (T3), and transportation of biodiesel to the consumer (T4). These stages contributed the most impacts (83 %) (Fig. 15) due to the use of fossil fuel which emitted greenhouse gases and other particulate matter into the environment upon combustion. The most significant impacts category associated with transportation is climate change (Fig. 14). T1, T2, T3, and T4 contributed 5, 17, 43, and 19 % of the total impacts associated with PME production, respectively. On the whole, all the transportation stages contributed 71.33, 80.45, and 96.02 % to human health, ecosystem depletion, and resource use, respectively.

From Fig. 16, resource use was the major environmental concern (41 %) followed by ecosystem depletion. This means that fossil fuel use and mineral/metal emissions were high in the PME production. Ecotoxicity, acidification, and land use potentials (ecosystem depletion) were high at 37 % of the total impacts

Fig. 16 Environmental impacts associated with the life cycle of biodiesel from palm oil



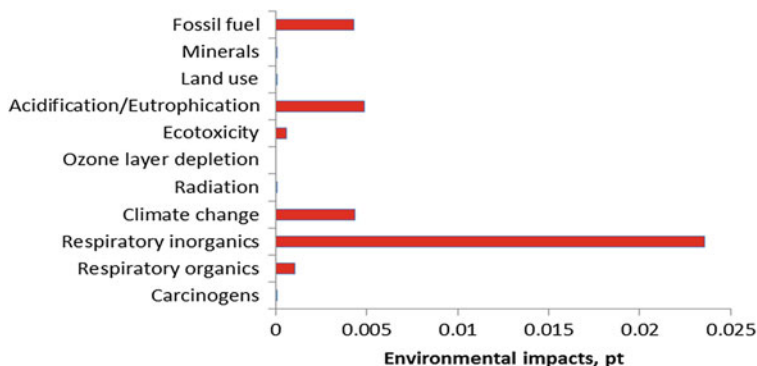


Fig. 17 Environmental impacts associated with biodiesel from palm oil. Pt: Eco-Indicator 99 (EI99, EA) points. 1 pt ~ impacts from one-thousandth person per year

associated with PME production. Figure 17 summarizes the total environmental impacts associated with the production of PME over its life cycle.

The most significant environmental damage or impacts were caused by respiratory inorganics which are caused by emissions from fossil fuel combustion and other chemical use such as sodium hydroxide. Fossil fuel, acidification/eutrophication, ecotoxicity, climate change, respiratory organics, and respiratory inorganics were also significant at 11.07, 12.58, 1.49, 11.17, 3.08, and 60.61 % of the total environmental impacts associated with 1 kg PME production, respectively.

6 Conclusion

Environmental impacts associated with the life cycle of palm oil biodiesel were assessed in this chapter using the well-to-wheel variant. The potentials of eleven main impact categories were considered for oil palm nursery, plantation, oil mill, CPO refinery, transesterification, biodiesel use as well as four transportation stages. Results from the analysis indicated that fossil fuel use was high in the plantation, transesterification, and transportation stages which further led to increase in climate change, respiratory organics, and acidification potentials. Fossil fuel consumption was highest (43 % of total impacts) in the transesterification unit exclusive of all impacts from transportation. Emissions from diesel use and transportation throughout the life cycle of palm biodiesel were more than 90 % of the total impacts. The use of fertilizers and herbicides also increased the overall impacts in the nursery and plantation stages.

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