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LIFE CYCLE ASSESSMENT FOR PALM OIL REFINING AND FRACTIONATION

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ABSTRACT

A gate-to-gate life cycle assessment (LCA) for production of refined palm products, i.e. *refined, bleached and deodourised (RBD) palm oil, palm olein and palm stearin was performed. Five years inventory data were obtained from six palm oil refineries located in Malaysia – three from Peninsular, two from Sabah and one from Sarawak. The LCA study was conducted using SimaPro software version 8.5 and the impact assessment was performed according to ReCiPe 2016 methodology. Allocation based on economic value was found suitable for the current study,* i.e. *allocating higher environmental burden to the more valuable main products - RBD palm oil from refining process and RBD palm olein from fractionation process. No difference was observed in the environmental impacts between allocation based on mass and energy content due to similar energy content of the products. Bleaching earth, electricity and transportation of crude palm oil (CPO) were identified as hotspots in palm oil refining whereas RBD palm oil was the single major hotspot in fractionation process. Improvement in transportation of CPO can significantly reduce the overall environmental impact, through sourcing of CPO from nearby mills and use of modern Euro 5-compliant trucks as mode of transportation.*

Keywords: fractionation, LCA, palm oil, refining.

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INTRODUCTION

Refining of crude palm oil (CPO) is an important process in the palm oil industry. In the refining process, CPO is purified by removal of undesired minor components such as gums, free fatty acids (FFA), heavy metals, colour pigments, *etc*. before it is used in downstream applications be it for edible or non-edible usages. In 2017, the total production of CPO in Malaysia was recorded at 19.92 million tonnes (MPOB, 2018). Of this, 81.2% or 16.18 million tonnes of CPO were processed locally to produce refined palm products either for local use or export (Kushairi *et al.*, 2018). Refined, bleached and deodourised (RBD) palm oil is the main product of the refining process whereas palm fatty acid distillate (PFAD) is the by-product. The refineries in Malaysia are also equipped with fractionation process that can fractionate RBD palm oil further into low melting liquid olein and high melting solid stearin. In 2017, 90.9% of the total RBD palm oil produced were fractionated into 10.68 million tonnes of RBD palm olein and 2.87 million tonnes of RBD palm stearin (MPOB, 2018). These refined palm products including PFAD were traded commercially as commodity.

CPO is the feedstock for palm oil refining. It is extracted from the mesocarp of palm fruits at palm oil mills which are typically located near to oil palm plantations (Khairudin *et al.*, 2012) and transported to palm oil refineries via road tankers. Palm oil refineries are typically located near to port area to facilitate export of refined palm products. In Malaysia, most of the refined palm products are produced for export market. The total export volume of RBD palm oil, palm olein, palm stearin and PFAD in 2017 was recorded at 11.04 million tonnes (MPOB, 2018).

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In the refining process, CPO is pre-treated with concentrated phosphoric acid, followed by bleaching with earth/clay, removal of spent bleaching earth and finally deodourisation. Generally, there are two methods for palm oil refining; chemical and physical refining. They differ in the way the FFA are removed. CPO typically consists of 3%-5% FFA. Chemical refining utilises caustic soda to neutralise the FFA, resulted in the formation of soapstock which is subsequently treated with diluted sulphuric acid to form palm acid oil as a by-product. In physical refining, FFA are removed from the oil at the deodourisation step as PFAD. Different terminology has been used to differentiate the products of chemical and physical refining. The refined palm oil obtained from chemical refining is called neutralised, bleached and deodourised (NBD) palm oil whereas RBD palm oil is the product of physical refining. Physical refining is preferred due to many advantages in particular lower operating cost and higher refining efficiency (Yusof, 1996). Hence, most of the CPO is physically refined in Malaysia. The total production of RBD palm oil in 2017 was recorded at 14.9 million tonnes compared to approximately 180 000 t for NBD palm oil (MPOB, 2018).

RBD palm oil is semi-solid at room temperature. Most of the RBD palm oil produced in the refineries will be fractionated in the same premises. RBD palm oil is first cooled in the crystallisers followed by filtration in the membrane filter press, to separate liquid from solid fraction. The liquid fraction, RBD palm olein is mainly used as cooking oil, in pure form or blended with other soft oil. No chemical is added during fractionation process.

Both refining and fractionation processes share the common utilities for daily operation. These include electricity from power grid, steam from boiler house and water. Wastewater discharged from both processes is treated prior to discharge. Spent bleaching earth generated from the refining process is usually collected by a third-party company for oil recovery and further downstream usages.

The first life cycle assessment (LCA) for production of CPO was based on data obtained from general references and SimaPro database with European normalisation and weighting factors (Sumiani and Hansen, 2007). Later, the production of rapeseed oil in Denmark was compared with the production of palm oil in Malaysia using consequential LCA approach (Schmidt, 2010). The system boundary for the study covered agriculture stage, extraction and refining of crude vegetable oils, and transportation of refined vegetable oil to Amsterdam. Relative to rapeseed oil production, Schmidt (2010) reported that the production of refined palm oil has less environmental impact related to ozone depletion, acidification, eutrophication, photochemical smog and land use. No obvious difference for global warming impact category was reported. Schmidt (2010) highlighted that oil palm cultivation and the wastewater treatment are the hotspots for the production of refined palm oil. It must be noted that the CPO refining process modelled in this study was based on chemical refining.

Complete cradle-to-gate LCA studies for production of palm oil (crude and refined) and palm biodiesel based on Malaysia scenario were reported (Halimah *et al.*, 2010; Puah *et al.*, 2010; Tan *et al.*, 2010; Vijaya *et al.*, 2010; Zulkifli *et al.*, 2010). These LCA studies segregated the supply chain of palm oil and palm biodiesel into five subsystems, namely production of oil palm seedlings at nursery stage, production of fresh fruit bunches in plantation, production of CPO in mills, production of refined palm products, *i.e.* RBD palm oil, olein and stearin in refinery and finally production of palm biodiesel from RBD palm oil in biodiesel plants. The overall greenhouse gas (GHG) emissions for these five subsystems were summarised and reported in Choo *et al.* (2011).

LCA studies reported thus far mainly focused on production of CPO and biodiesel (Yee *et al.*, 2009; Angarita *et al.*, 2009; De Souza *et al.*, 2010; Silalertruksa and Gheewala, 2012; Siregar *et al.*, 2015; Castanheira and Freire, 2017). The number of environmental studies on palm oil refining is low. As mentioned earlier, CPO refining and fractionation are important processes linking CPO produced from palm oil mills to further downstream applications, as evidenced by the total RBD palm oil produced and fractionated every year in the country. Hence, it is crucial to carry out an up-to-date study for production of refined palm products from palm oil refineries since the previous study by Tan *et al.* (2010) was carried out a decade ago.

MATERIALS AND METHODS

Goal and Scope Definition

The scope of the study covered two main activities in palm oil refinery, *i.e.* CPO refining (physical refining) and RBD palm oil fractionation. Production of steam from boilers for heating purpose in the refining and fractionation plants was included. Other common utilities such as electricity and water were modelled based on national data available in the Ecoinvent 3.4 database. The production and usage of chemicals and fuels included in this study were modelled from the databases available in the SimaPro software. The LCA was conducted using the SimaPro software version 8.5.

The goals of the study were to provide up-to-date life cycle inventory data for palm oil refining and fractionation, to perform a gate-to-gate life cycle impact assessment (LCIA) for palm oil refining and fractionation, to identify hotspots for palm oil refining and fractionation, and finally to propose options for environmental improvement, if any.

Functional Unit

The products of palm oil refining process are RBD palm oil and PFAD whereas the products of palm oil fractionation process are RBD palm olein and RBD palm stearin. All these products are commercially traded in tonne (mass) basis. Thus, the appropriate functional unit for palm oil refining and fractionation is the production of 1 t of products (RBD palm oil, PFAD, olein or stearin).

System Boundary

The inventory data obtained were based on a gate-to-gate basis, starting from transportation of CPO from palm oil mills to refineries, refining of CPO to produce RBD palm oil and PFAD, fractionation of RBD palm oil to produce RBD palm olein and stearin, and finally the storage of the refined palm products in bulk storage.

Inventory Data Collection

Inventory data for palm oil refining and fractionation were gathered from six refineries operated in Malaysia (three in Peninsular Malaysia, two in Sabah and one in Sarawak) through dissemination of survey questionnaires. A five year (2013-2017) data were collected. Data clarification and verification were carried out through e-mail and phone communications.

Besides site-specific foreground data, background data were also obtained from the Ecoinvent 3.4, Agri-footprint and US Life Cycle Inventory (USLCI) databases. The background process for the production of chemicals used in the refining process, *i.e.* bleaching earth and phosphoric acid, the electricity supply from the power grid, the production of fossil fuels and the water supply were obtained from Ecoinvent 3.4 database. The emissions of CPO transportation from mills to refineries and the combustion of fossil fuels for steam production were referred to Agri-footprint and USLCI databases, respectively.

Co-products Allocation

All the refined palm products are commodities traded commercially at different prices, so allocation based on economic value was used in the study. The 10-year average price of the refined palm products (*Table 1*) were used to derive the allocation ratios. Allocation ratios of 96.2:3.8 for RBD palm oil:PFAD and 81.6:18.4 for RBD palm olein:RBD palm stearin were used. Allocation methods based on mass and energy value were further analysed and discussed in the sensitivity analysis of the study.

TABLE 1. MPOB ANNUAL PRICES OF REFINED PALM PRODUCTS

Year	RBD palm oil (RM)	PFAD (RM)	RBD palm olein (RM)	RBD palm stearin (RM)
2008	2 699.00	1 674.00	3 054.50	2 551.00
2009	2 342.00	1 553.50	2 447.00	2 076.50
2010	2 801.50	2 310.00	2 852.50	2 701.00
2011	3 426.00	2 495.00	3 507.50	3 103.00
2012	2 970.50	2 522.50	2 963.00	2 786.00
2013	2 478.50	1 883.50	2 525.50	2 257.00
2014	2 502.00	2 269.50	2 494.50	2 446.00
2015	2 279.50	1 902.50	2 289.00	2 058.00
2016	2 710.50	2 462.50	2 769.50	2 650.50
2017	2 880.00	2 733.00	2 953.50	2 799.50
Average	2 708.95	2 180.60	2 785.65	2 542.85

Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Source: MPOB (2018).

LCIA

The LCIA was performed using ReCiPe 2016 (Hierarchist) methodology. A total of 18 midpoint impact categories were evaluated. The characterised LCIA was analysed and discussed in the results and discussion section.

Exclusion

The data for capital goods such as the building structures of refinery and fractionation plant, equipment and machinery used were excluded in the study because of difficulty in getting reliable data as the refineries were built many years ago. There are also no significant environmental impacts as reported in previous studies (Schmidt, 2010; Tan *et al.*, 2010; Schneider and Finkbeiner, 2013). Treatment of wastewater was also excluded in the current study because only a small amount of wastewater was produced from a physical refining plant and the environmental impacts was not significant (Schneider and Finkbeiner, 2013). However, the effects of wastewater treatment based on background data available in the Ecoinvent 3.4 database was assessed and discussed in the sensitivity analysis.

RESULTS AND DISCUSSION

Inventory Analysis

The inventory data for palm oil refining and fractionation processes were presented in *Tables 2* and *3*. These data were average data of six palm oil refineries collected over a period of five years, from 2013 to 2017. The data represented the input and output for production of 1 t of RBD palm oil (*Table 2*) and fractionation of 1 t of RBD palm oil (*Table 3*).

The inventory data in *Table 2* were similar to those reported by Tan *et al.* (2010). On average, 1.055 t of CPO was required to produce 1 t of RBD palm oil and 49 kg of PFAD. The use of chemicals in refining process was in accordance with the typical practice of a physical refining plant, *i.e.* 0.05%-0.2% phosphoric acid for degumming and 0.8%-2.0% of bleaching earth for absorption of any undesired contaminants (Yusof, 1996). Fuel used for steam production in boiler house and the characteristics of wastewater discharged in this study differed from Tan *et al.* (2010). Previously, the main fuel used for steam production was medium fuel oil, but shifted to natural gas for refineries in Peninsular Malaysia due to price changes. However, refineries in Sabah and Sarawak are still using fuel oil and petroleum diesel as boiler fuel as there is no gas piping facility in these areas. For the characteristics of wastewater discharged from palm oil refineries, biological oxygen demand (BOD) and chemical oxygen demand (COD) are the two important parameters determining the quality of wastewater. Much lower readings were reported in the present study, 15.08 mg litre^{-1} for BOD and 87.87 mg litre^{-1} for COD. These values were below the limits enforced by the Department of Environment, Malaysia (DOE, 2009).

In fractionation, 0.80 t of RBD palm olein and 0.20 t of RBD palm stearin were produced from fractionation of 1 t of RBD palm oil (*Table 3*). Besides electricity and water, fossil fuels were also needed to generate steam for heating the RBD palm oil prior to crystallisation in the fractionation process. The amount of wastewater produced per tonne of RBD palm oil fractionated and its quality were also reported in *Table 3*. No transportation was needed as the fractionation plant was just adjacent to the refining plant in the same premises.

TABLE 2. INVENTORY OF PALM OIL REFINING
(per tonne of RBD palm oil produced)

Item	Unit	Amount
Input		
Crude palm oil (CPO)	t	1.055
Phosphoric acid	kg	0.55
Bleaching earth	kg	11.05
Electricity	kWhr	10.17
Boiler fuel		
i. Natural gas	m^3	2.08
ii. Diesel	kg	0.24
iii. Fuel oil	kg	0.50
Water	litre	185.35
Weighted average distance from palm oil mill to refineries	km	172.07
Transport of CPO to refinery	tkm	181.57
Output		
Refined, bleached and deodourised (RBD) palm oil	t	1.00
Palm fatty acid distillate (PFAD)	kg	49.03
Wastewater	litre	26.65
Wastewater biological oxygen demand (BOD)	g	0.40
Wastewater chemical oxygen demand (COD)	g	2.34

TABLE 3. INVENTORY OF PALM OIL FRACTIONATION
(per tonne of RBD palm oil fractionated)

Item	Unit	Amount
Input		
Refined, bleached and deodourised (RBD) palm oil	t	1.00
Electricity	kWhr	13.12
Boiler fuel		
i. Natural gas	m^3	1.48
ii. Diesel	kg	0.09
iii. Fuel oil	kg	0.24
Water	litre	164.09
Output		
RBD palm olein	t	0.80
RBD palm stearin	t	0.20
Wastewater	litre	13.41
Wastewater biological oxygen demand (BOD)	g	0.16
Wastewater chemical oxygen demand (COD)	g	1.32

LCIA

Contribution analysis of palm oil refining and fractionation. The characterised LCIA for the production of RBD palm oil at the midpoint level is shown in *Figure 1*. For all impact categories, significant contributors were in the following descending order: bleaching earth > electricity > transportation of CPO > phosphoric acid > combustion of fossil fuels to produce steam > fossil fuels > water. Bleaching earth contributed significantly to all the 18 impact categories, in particular, the mineral resource scarcity, ionising radiation, human non-carcinogen toxicity, eutrophication (freshwater and marine) and ecotoxicity (terrestrial, freshwater and marine). It was followed by electricity consumption from power grid and transportation of CPO from palm oil mills to refineries. Electricity consumption contributed to ecotoxicity (freshwater and marine) and eutrophication (freshwater and marine) while transportation contributed to ozone formation for both effects on terrestrial and human health. Phosphoric acid used for degumming, fossil fuels and combustion of fossil fuels in the boiler for steam generation were significant in impact categories such as toxicity, fossil resource scarcity, terrestrial acidification, global warming and fine particulate matter formation. Water required for steam generation and cooling only impacted the water consumption impact category.

RBD palm oil was the single major contributor (60%-96%) to all impact categories evaluated for the fractionation process (*Figure 2*). Electricity consumption from power grid was the second important contributor, which has an important impact on ecotoxicity, eutrophication, toxicity, fine particulate matter formation, stratospheric ozone depletion and global warming. Fossil fuels and combustion of fossil fuels in boiler only played a very minimal impact to terrestrial acidification, fossil resource scarcity, global warming and fine particulate matter formation. Similar to refining, water use in the fractionation plant for steam generation and cooling was significant in the water consumption impact category.

Global warming. Global warming is the impact of GHG emissions to the atmosphere. Carbon dioxide, methane and nitrous oxide are the common GHG among the 207 GHG identified by the Intergovernmental Panel on Climate Change (IPCC). Global warming is expressed in kg CO_2 eq by summing up the normalised values calculated according to the global warming potential factors published in the IPCC report (IPCC, 2013). In palm oil refining stage, the main source for GHG emissions was transportation of CPO from palm oil mills to refineries, combustion of fossil fuels in boiler for steam production, electricity from power grid and the background process for production of bleaching earth (*Figure 3*). These four contributors accounted for 95.2% of the total GHG emitted. In the fractionation stage, the main contributor is feed material, *i.e*. RBD palm oil, 69.5% of the total GHG emitted. The remaining were due to electricity from the grid (20.6%) and combustion of fossil fuels for steam production (8.7%).

Ionising radiation. Ionising radiation is measured by emission of the reference substance Cobalt-60 to air (Steinmann and Huijbregts, 2017). In *Figure 4*, it was noticed that the major contributor was the background process for production of bleaching earth used (76.2%). The other less significant contributors were phosphoric acid (9.1%) and fossil fuels (7.1%). The contribution in the refining process was further passed down to the fractionation process as 91.8% of the ionising radiation were inherited from RBD palm oil.

Photochemical ozone formation. Ozone is formed as a result of photochemical reaction of nitrogen oxide (NO_X) and non-methane volatile organic compounds (Van Zelm and Huijbregts, 2017b). Ozone is harmful to both human health and the ecosystem. It can inflame human airway and cause damage to lungs resulted in various respiratory sickness, *e.g*. asthma chronic obstructive pulmonary diseases. Ozone also has a negative impact on vegetation. It affects seed production and growth of a plant. The impact of ozone on both human health and terrestrial ecosystem is measured by kg NO_X eq. In the refining stage, photochemical ozone formation was mainly due to transportation of CPO from mills to refineries, 77% (*Figure 5*). Similar to ionising radiation, 89.3% of the ozone formation in the fractionation process was inherited from RBD palm oil. Other factors barely contributed the remaining 10%.

Fine particulate matter formation. Fine particulate matter (PM2.5) is referred to particles with a diameter of less than 2.5 mm. It is a complex mixture of organic and inorganic substances which can cause respiratory problems to human health (Van Zelm and Huijbregts, 2017a). Four major contributors to fine particulate matter formation in the palm oil refining were transportation of CPO, electricity from power grid, production of bleaching earth and combustion of fossil fuels for steam production (*Figure 6*). In the fractionation stage, 67% of the PM2.5 were contributed by RBD palm oil and the remaining contributors were electricity (23.2%) and combustion of fossil fuels (8.9%).

Terrestrial acidification. The emission of inorganic substances, *i.e.* sulphates, nitrates and phosphates can cause changes in soil acidity (Van Zelm and

Huijbregts, 2017c). For every plant, there is a suitable acidity range for it to grow. Deviation in soil acidity is harmful to plant species and may cause a shift in species in the affected ecosystem. In the refining stage, the acidification was mainly caused by the transportation of CPO and combustion of fossil fuels for steam production (*Figure 7*). This was followed by production of bleaching earth and electricity from grid. In the fractionation stage, it was noticed that 72.5% of the acidification was due to RBD palm oil. Combustion of fossil fuels for steam production and electricity from grid contributed 12.8% and 13.5%, respectively.

Ecotoxicity and human toxicity. Among the five impact categories related to ecotoxicity and toxicity, palm oil refining has prominent impacts to the terrestrial ecotoxicity and human non-carcinogen toxicity compared to human carcinogen toxicity, freshwater and marine ecotoxicity (*Figure 8*). The main contributors to terrestrial ecotoxicity were bleaching earth used as adsorbent and transportation of CPO from mills to refineries, 74.2% in total. The electricity from power grid and background process of phosphoric acid were the third and fourth contributors in this impact category, 23% in total. For human non-carcinogen impact category, the major contributor was the background process for production of bleaching earth, 48.8% of the total contribution. Electricity, phosphoric acid and combustion of fossil fuels for steam production contributed to the remaining 44.8%. For the fractionation process, the major contribution was once again due to RBD palm oil (72.1%). Electricity from grid contributed to 24.5% of human non-carcinogen toxicity potential.

Sensitivity Analyses

Allocation of co-products. Evaluation of the impacts of different allocation methods, *i.e.* allocation based on economic value, energy content and mass value, were conducted. RBD palm oil was the main product in the refining process, 95.3% of total output. PFAD was traded at 19.5% discount to RBD palm oil based on average 10 years data (*Table 1*). Although higher environmental load was attributed to RBD palm oil due to its higher commercial value compared to PFAD, insignificant effects to all impact categories were observed as shown in *Figure 9a*. However, this was not the case for the production of PFAD. Lower environmental impacts for all impact categories were observed for PFAD with allocation based on economic value compared to that based on energy content or mass. As the lower commercial value coupled with the relatively small production volume, obvious 20% reduction of environmental impact was observed for all impact categories. No significant difference between allocation based on energy content and mass value was recorded for RBD palm oil and PFAD. This was mainly because of the similar calorific value for both products.

Unlike the refining stage, different allocation methods in the fractionation stage showed a less significant difference. Less than 10% difference was observed (*Figure 9b*). This was mainly due to the smaller difference between the trading prices and production volume of RBD palm olein and stearin.

Effect of wastewater treatment. Choo *et al.* (2011) reported that wastewater played a substantial role contributing to the total GHG emissions in the palm oil refining stage, 18% of the total GHG emissions. However, this was not the case for the current study. The impact of wastewater treatment was evaluated based on five years wastewater data supplied by the refineries participated in the current study and background data on wastewater treatment available in the Ecoinvent 3.4 database. The impact of wastewater treatment was found to be insignificant to all the 18 impact categories as evaluated using ReCiPe 2016 methodology (*Figure 10*). This result concurred with the findings reported by Schneider and Finkbeiner (2013).

Transportation of CPO. In the refinery stage, transportation of CPO from palm oil mills to refineries was identified as one of the major hotspots to the potential environmental impacts. For example, 37% of the total GHG emissions were contributed by the transportation. To reduce the impact, two areas of improvement were proposed and evaluated. The first approach was sourcing of CPO from nearby palm oil mills. Based on the inventory data obtained, the average distance between palm oil mills and refineries was 172 km, higher than the 120 km reported by Tan *et al.* (2010). The shorter the distance, the lower the diesel consumption and ultimately contributed to lower environmental impacts on global warming, stratospheric ozone depletion, ozone formation, fine particulate matter formation, terrestrial acidification, terrestrial ecotoxicity and fossil depletion (*Figure 11*).

The second approach was the replacement from Euro 2 to Euro 5 emissions compliant trucks. Euro 5 diesel was introduced to the Malaysian market as an optional diesel since 2014. However, such diesel is only available in selected retail stations and most of the trucks currently used in the transportation sector is still Euro 2 emissions compliance. The replacement with Euro 5 trucks and Euro 5 diesel will lead to better exhaust emissions from vehicle tailpipe and give overall significant reduction in ozone formation (-30%) (*Figure 12*). Only mild improvement in the terrestrial acidification (-11%), fine particulate matter formation (-9%) and stratospheric ozone depletion (-7.6%) were anticipated.

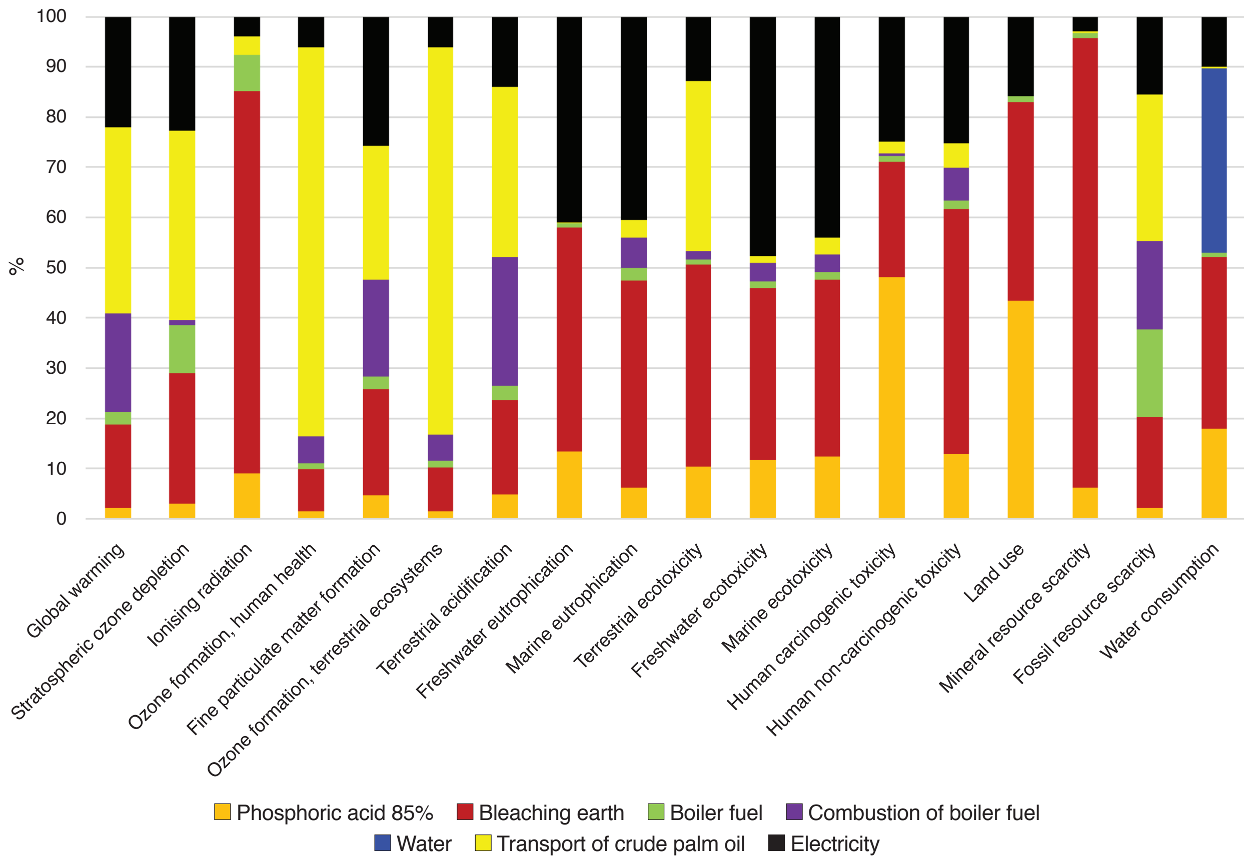


Figure 1. Characterised life cycle impact assessment (LCIA) for the production of refined, bleached and deodourised (RBD) palm oil.

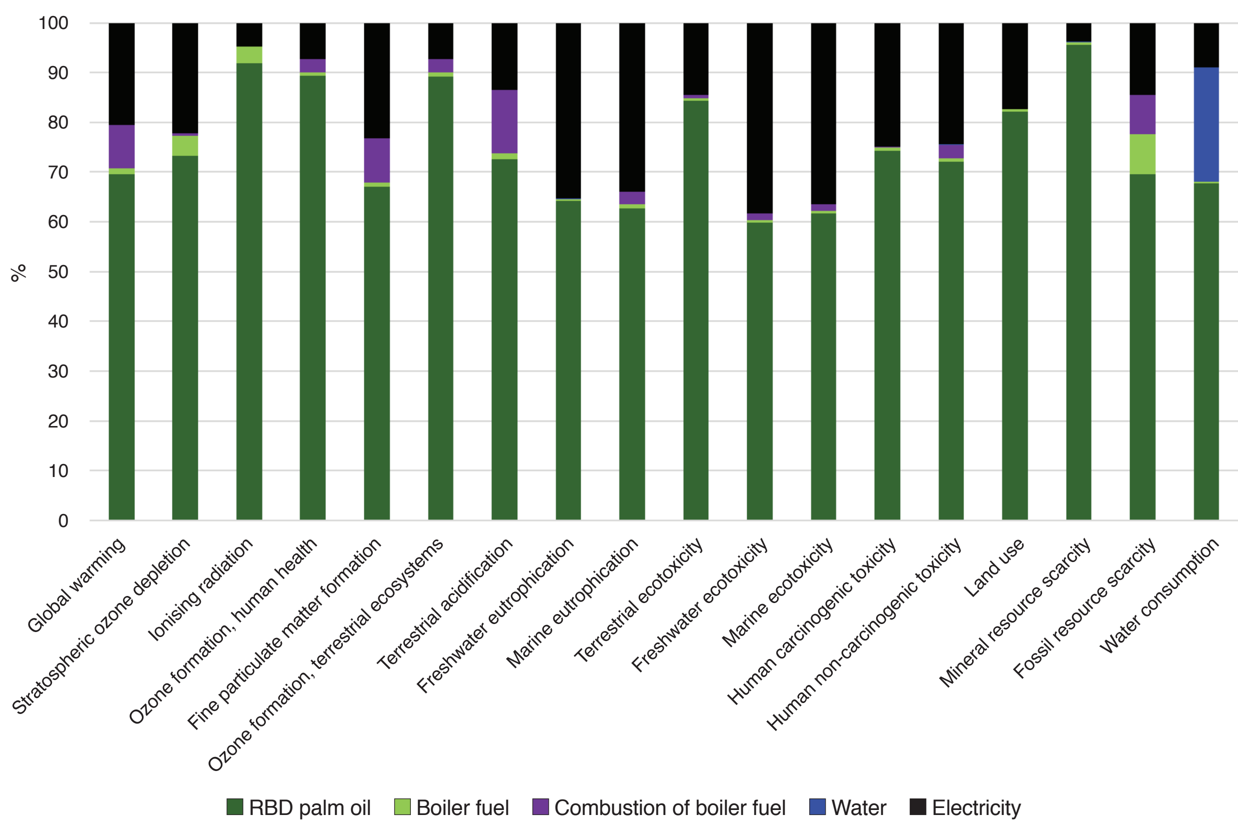
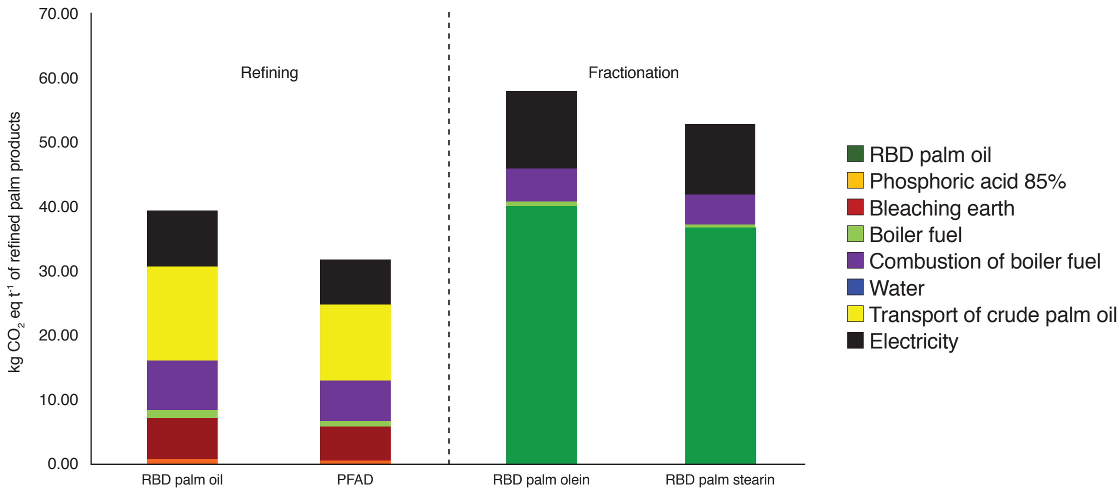
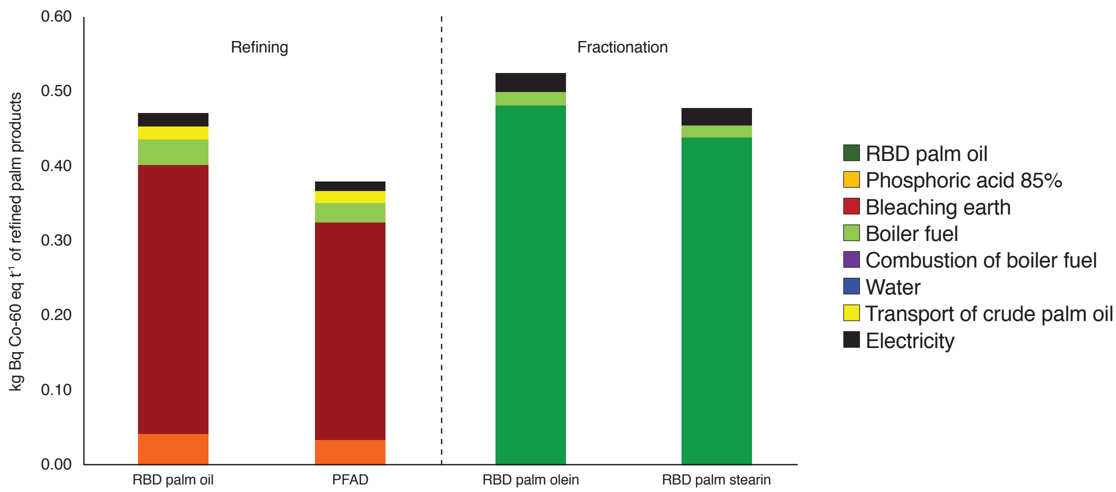


Figure 2. Characterised life cycle impact assessment (LCIA) for the fractionation of refined, bleached and deodourised (RBD) palm oil.



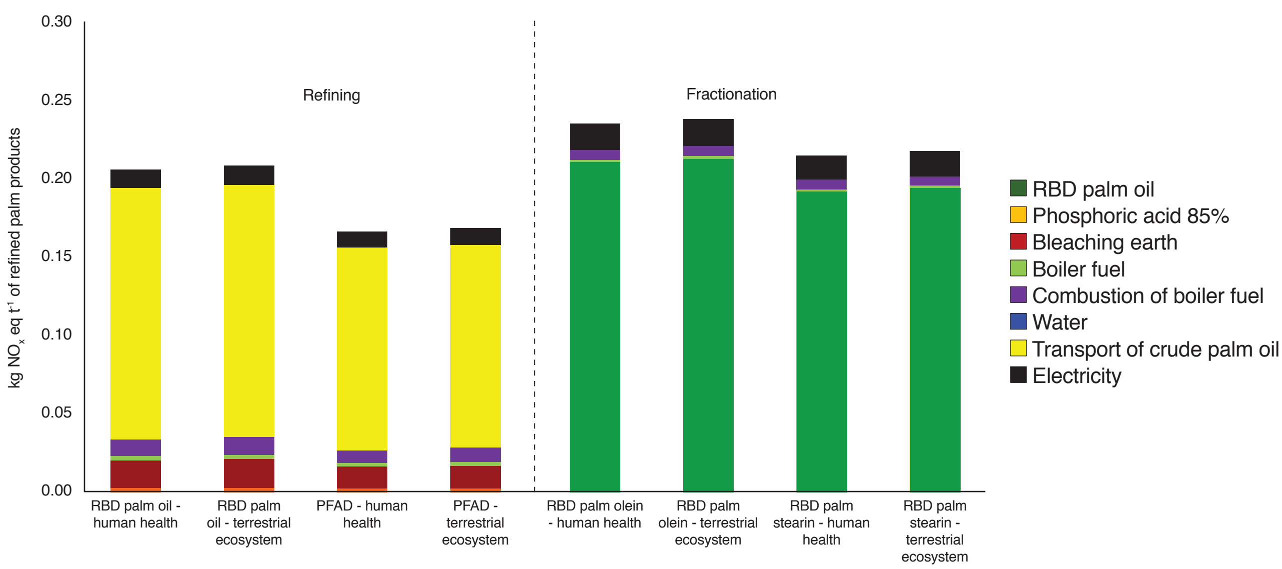
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 3. Global warming potential for the production of 1 t of refined palm products.



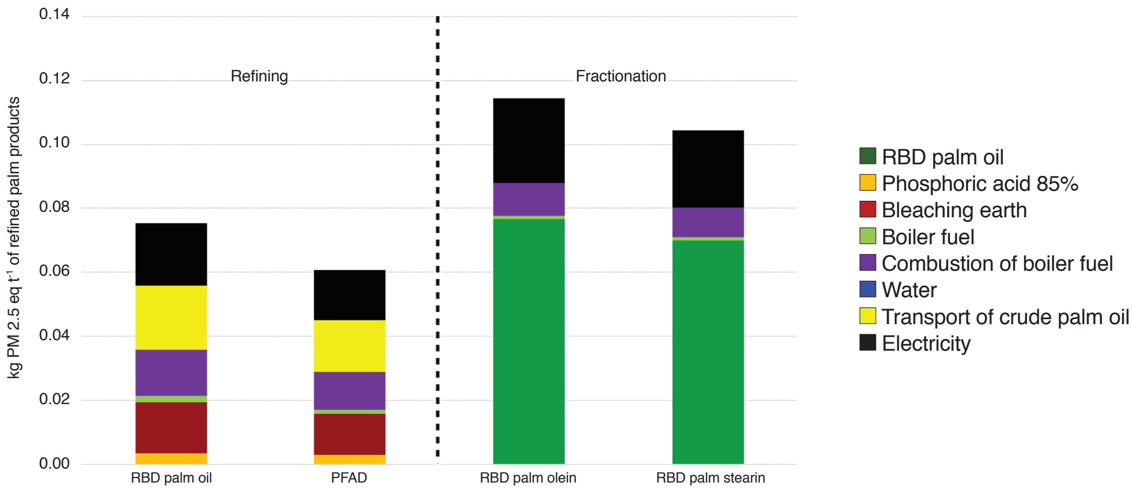
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 4. Ionising radiation potential for the production of 1 t of refined palm products.



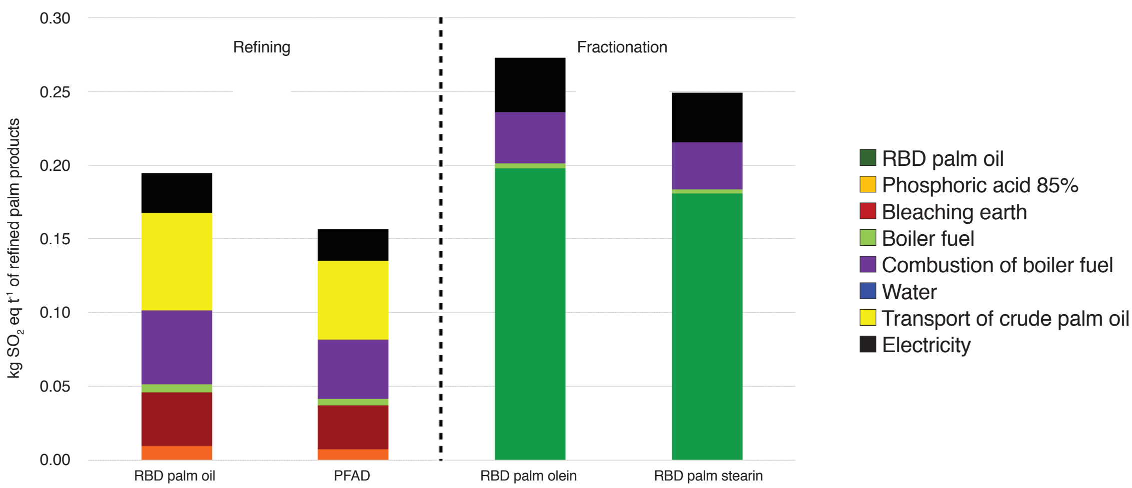
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 5. Ozone formation potential (human health and terrestrial ecosystem) for the production of 1 t of refined palm products.



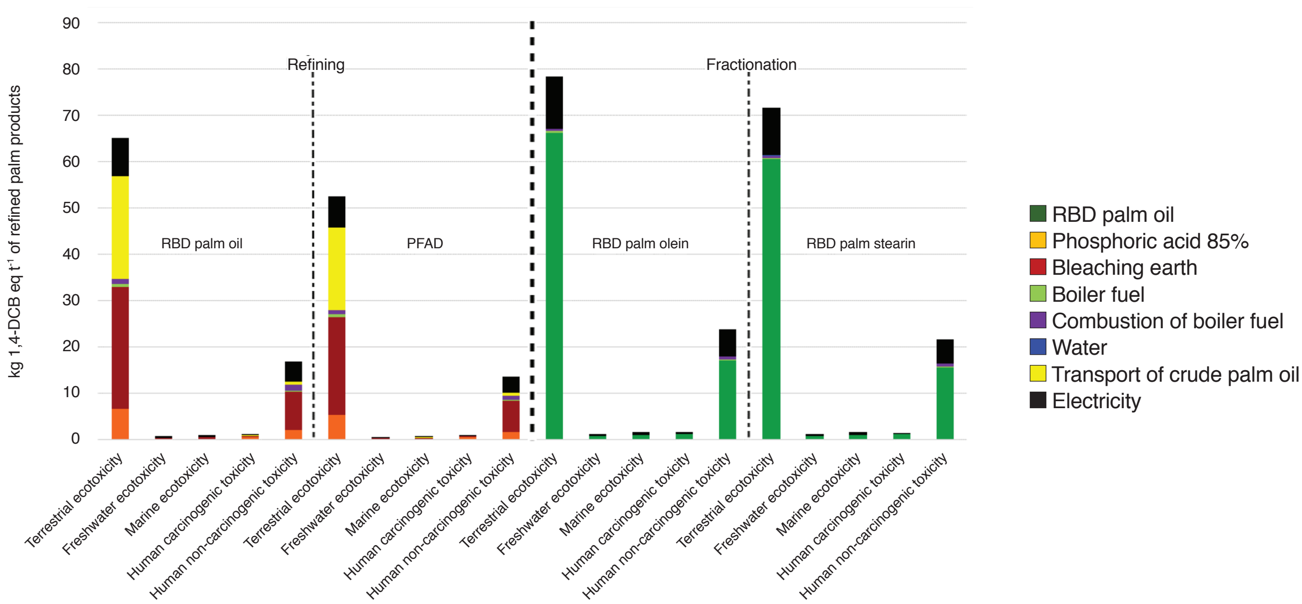
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 6. Fine particulate matter formation potential for the production of 1 t of refined palm products.



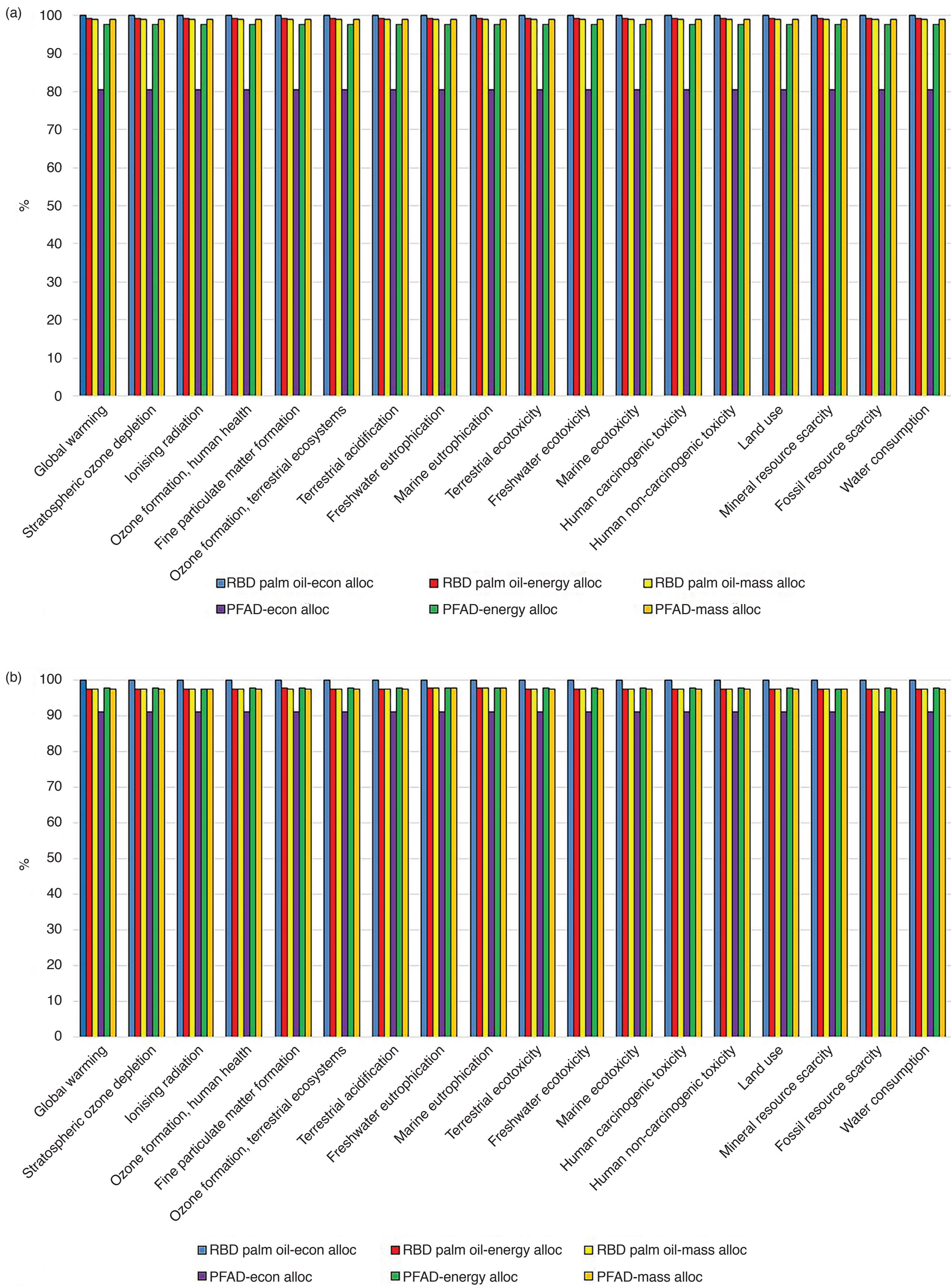
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 7. Terrestrial acidification potential for the production of 1 t of refined palm products.



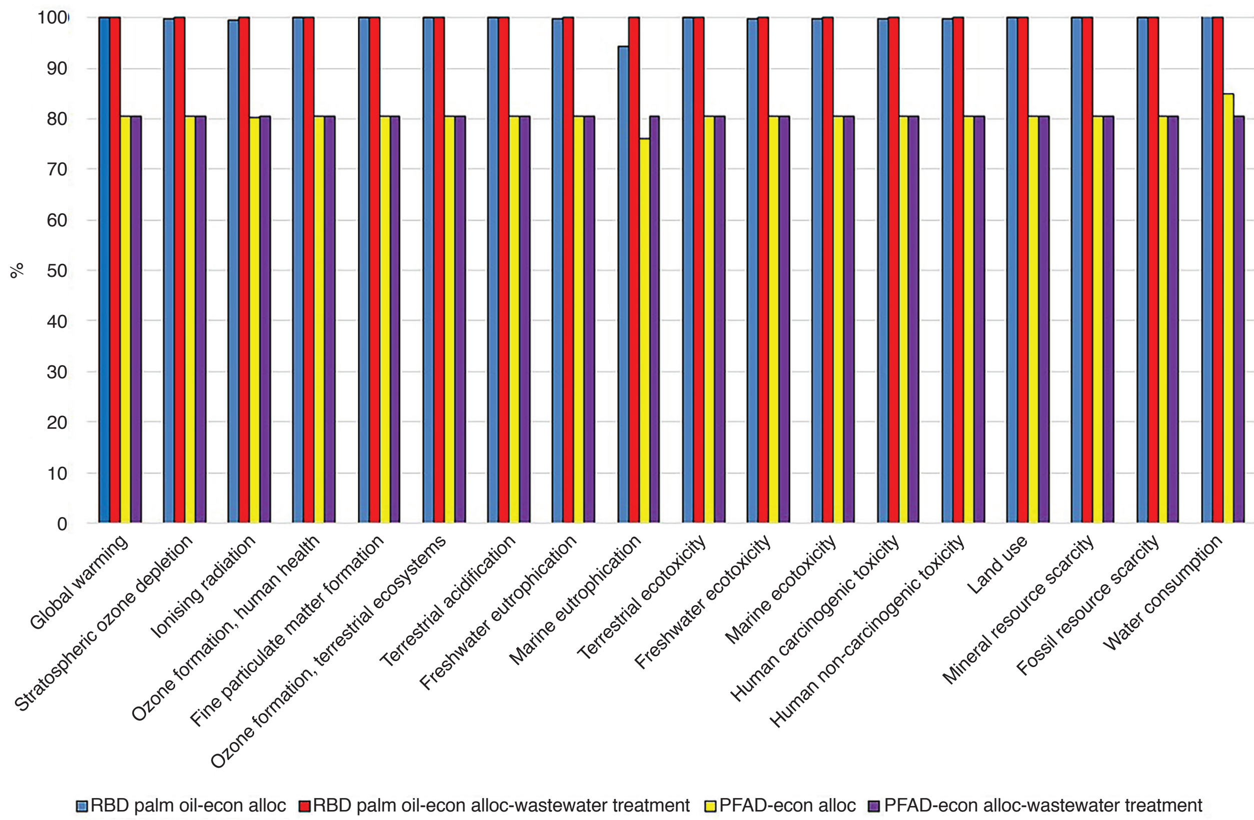
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 8. Ecotoxicity and human toxicity potential for the production of 1 t of refined palm products.



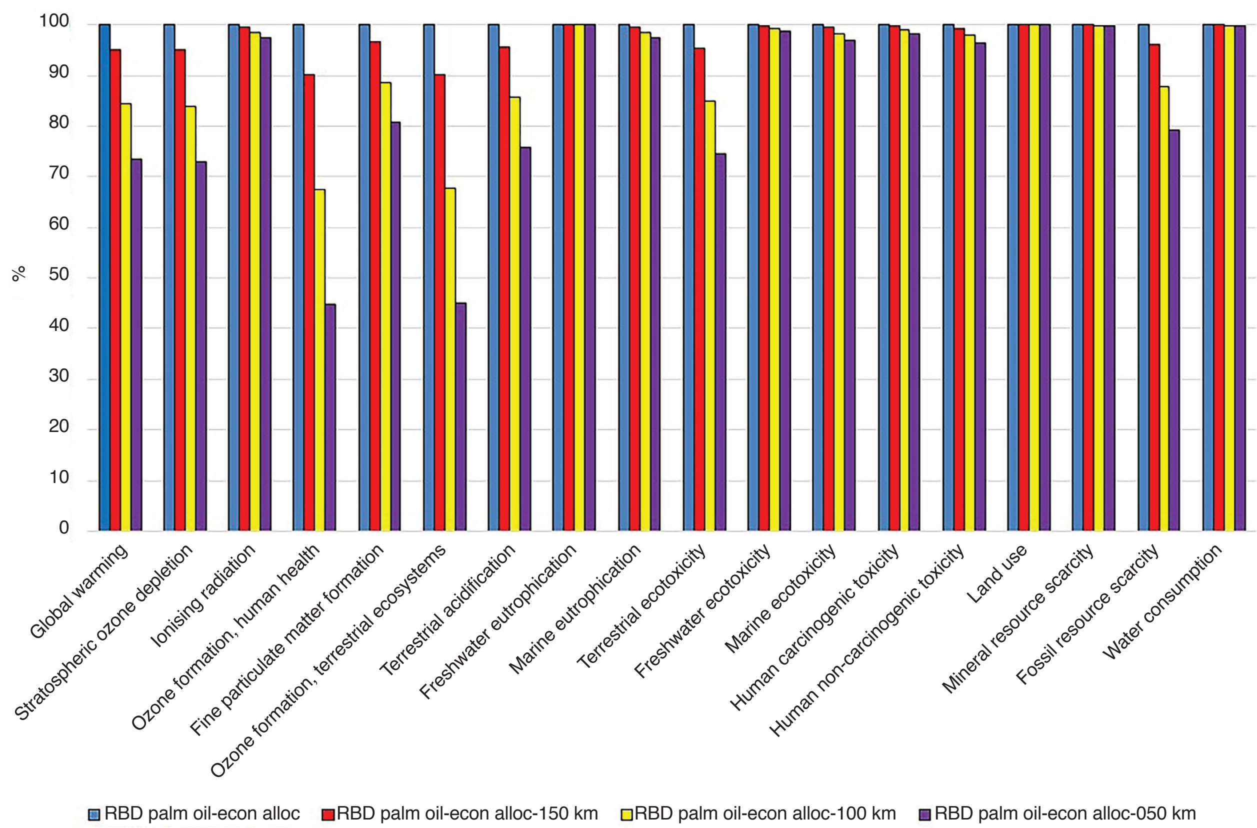
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 9. Comparison of different allocation methodologies in (a) crude palm oil refining, and (b) RBD palm oil fractionation.



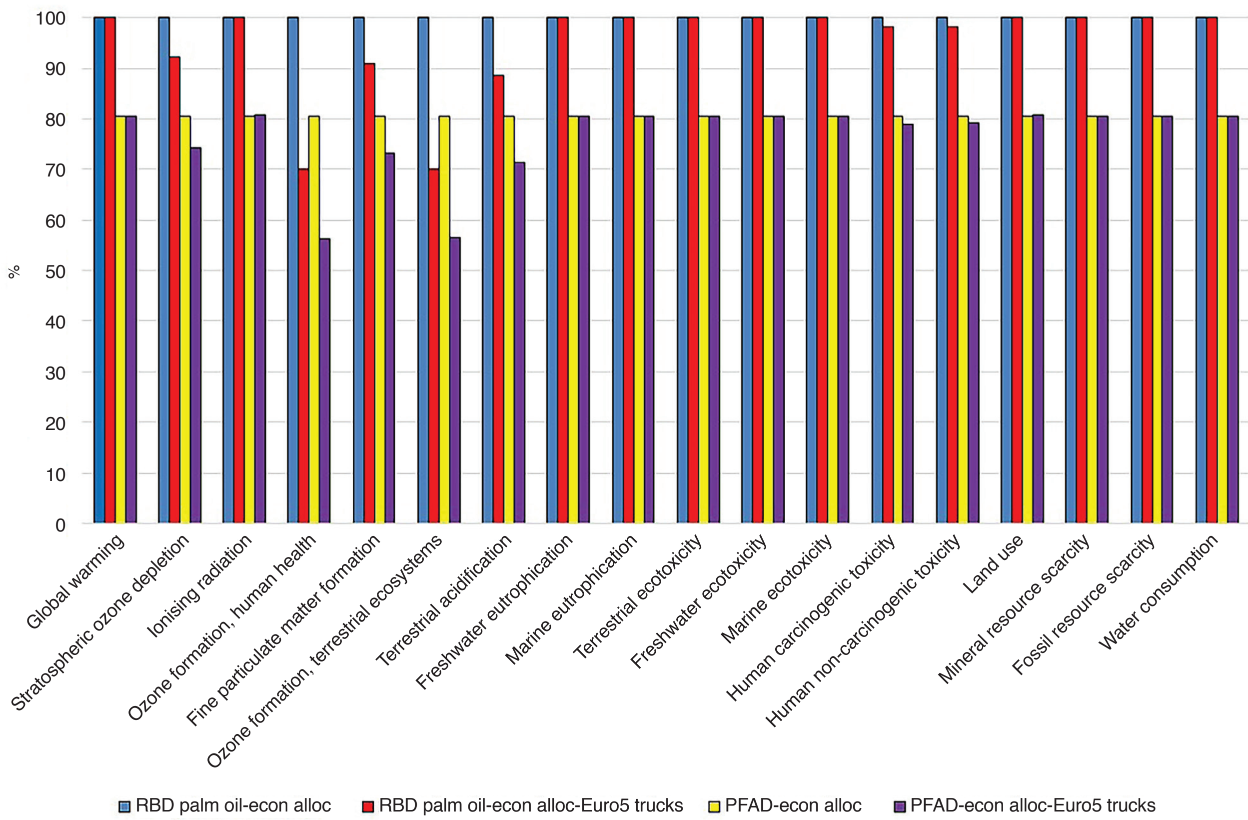
Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 10. The effects of wastewater treatment to the characterised life cycle impact assessment (LCIA) for the crude palm oil refining.



Note: RBD - refined, bleached and deodourised.

Figure 11. The effects of distance between palm oil mills and refineries to the characterised life cycle impact assessment (LCIA) for crude palm oil refining.



Note: RBD - refined, bleached and deodourised, PFAD - palm fatty acid distillate.

Figure 12. The difference of the use of Euro 2 and Euro 5 emissions compliant trucks in the characterised life cycle impact assessment (LCIA) for crude palm oil refining.

CONCLUSION

Bleaching earth and transportation of CPO played significant roles in contributing to the environmental impacts of palm oil refining and fractionation. The amount of bleaching earth used was found within the recommended minimum requirement, 1.05% of the amount of CPO refined; hence no further improvement was proposed. On the other hand, refineries should source CPO from nearby palm oil mills to significantly reduce environmental impact caused due to longer distance between mills and refineries. Also, improving the transport vehicles to a better emission standard had a noticeable improvement in dedicated impact categories, *i.e*. ozone formation, terrestrial acidification, fine particulate matter formation and stratospheric ozone depletion. No significant contribution from wastewater treatment in the refining unlike in palm oil milling stage due to comparatively lesser water consumption and better wastewater quality. Allocation should be based on economic value to the various products from the refining and fractionation processes since they are traded commercially at different prices, in particular for RBD palm oil and PFAD.

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