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ENVIRONMENTAL ASSESSMENT OF FATTY ACIDS PRODUCTION FROM PALM OIL USING LIFE CYCLE APPROACH

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ABSTRACT

To date, no comprehensive life cycle assessment (LCA) study has been conducted on palm-based fatty acids, the powerhouse of the oleochemical industry. Thus, a cradle-to-gate LCA for the production of palm-based fatty acids in Malaysia was performed to assess their potential environmental impacts. The life cycle impact assessment (LCIA) findings showed that the significant impacts for palm-based fatty acids were mainly attributed to the production of the feedstocks used, which are crude palm kernel oil (CPKO) and refined, bleached and deodorised palm stearin (RBDPS). The greenhouse gas (GHG) emission for the fatty acids studied is in the range of 1.39-9.43 kg CO_2 eq. per kg fatty acid and dropped to a range of 0.07-0.18 kg CO_2 eq. per kg fatty acids by excluding contributions from the production of feedstock. For CPKO-based fatty acid production, the energy substitution using oil palm biomass led to a reduction of up to 13% in global warming potential compared to grid electricity. The findings from this study can be used to establish baseline information on the environmental profile of fatty acids and draw up policies pertaining to the carbon credit scheme or green labelling for the sustainable production of palm-based fatty acids in the future.

Keywords: environmental impact, greenhouse gases, LCA, palm-based fatty acids, sustainability.

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INTRODUCTION

Fatty acids, which are one of the basic oleochemicals, play an important role in the development of the oleochemical industry as well as other non-food industries. Intermediate chemicals such as fatty acid methyl esters, fatty alcohols and fatty amines can also be produced from fatty acids feedstock (Kiatkittipong *et al.*, 2022). *Figure 1* shows the processing routes for basic oleochemicals and their derivatives. The expansion of the global market and the diversification of the use of fatty acids in various applications are among the major factors increasing the demand for these fatty acid products. The availability of supplies of raw materials such as palm oil and coconut oil, along with good infrastructure and facilities, has made Southeast Asia as the hub for fatty acid manufacturing. Accordingly, several new oleochemical plants producing fatty acids have been built in Southeast Asia. Meanwhile, fatty acid manufacturers in Malaysia and Indonesia are also taking proactive steps to increase their production capacity to meet the growing demand.

Currently, there are 19 oleochemical plants operating in Malaysia (Parveez *et al.*, 2022), which exported about 2.86 million tonnes of oleochemicals in 2023 (Malaysian Palm Oil Board [MPOB], 2024). In 2023 alone, fatty acids represent approximately 36% of the total oleochemical products exported from Malaysia. *Figure 2* shows the volume of fatty acid exports from 2010 to 2023. Generally, fatty acids are carboxylic acids with hydrocarbon chains comprising four to 36 carbon atoms. They can be classified into short chains with two to four carbon atoms, medium chains with six to 10 carbon atoms and long chains consisting of 12-26 carbon atoms (Siram *et al.*, 2019). There are three types of fatty acids, namely saturated, mono-unsaturated and

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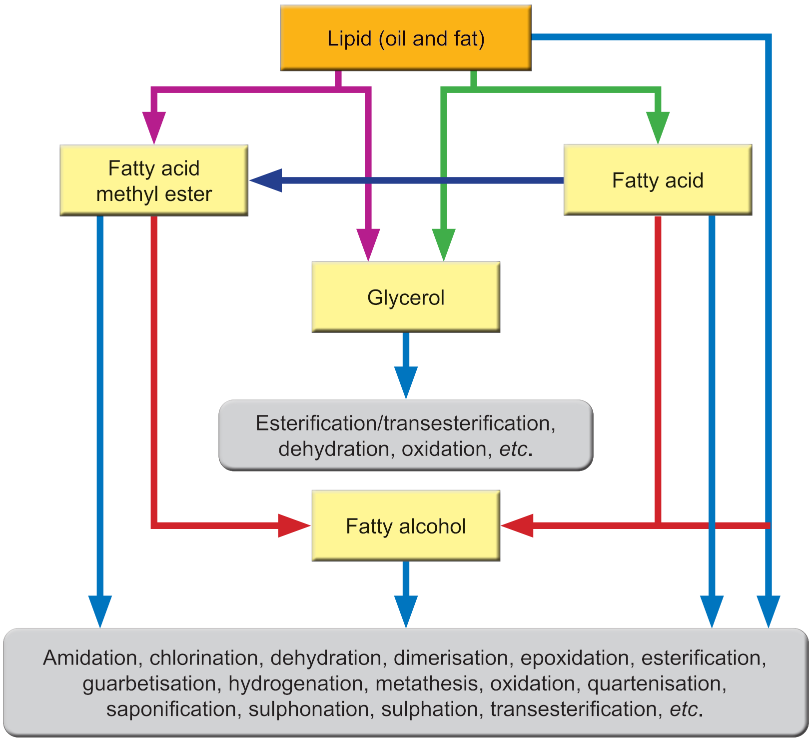
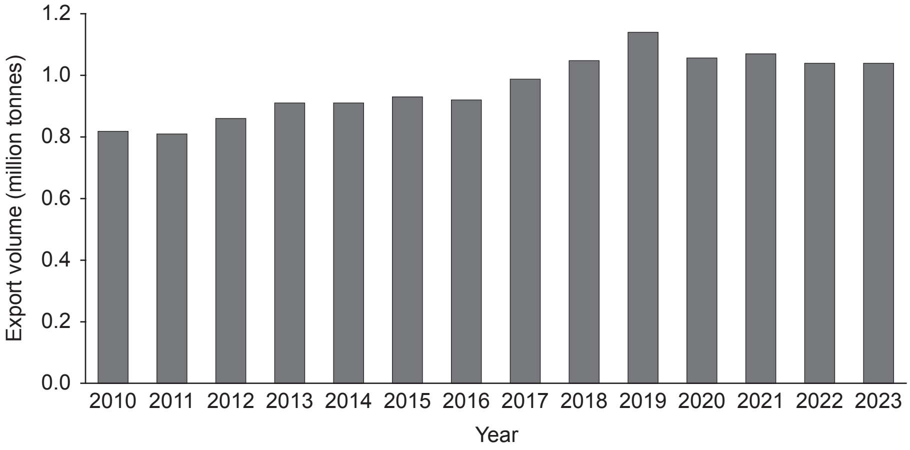
polyunsaturated, where saturated fatty acids do not contain any double bonds or other functional groups along the carbon chain. Monounsaturated fatty acids have only one double bond in their alkyl chain. Meanwhile, polyunsaturated fatty acids contain more than one double bond in their alkyl chain. A common method for the production of fatty acids is the separation or splitting process of fats at high temperatures and pressures. In addition, fractionation and distillation are common processes involved in the production of fatty acids. Apart from these processes, there are also other processes involved, such as hydrogenation, bleaching, and cooling separation. The number of fractionations used for fatty acid production may differ from one plant to another, depending on the plant's design and capacity. Several fatty acid manufacturers introduced the bleaching process before the splitting process to purify the feedstock used. The hydrogenation process is also carried out to increase the number of saturated alkyl carbon chains in the feedstock used.



Source: Kiatkittipong *et al.* (2022).

Figure 1. Processing route of basic oleochemicals and its derivatives reaction.



Source: MPOB (2011-2024).

Figure 2. Export of Malaysian fatty acids from 2010 to 2023.

Various fatty acids with different acid compositions (*Table 1*) have been produced in Malaysia using palm oil (PO) and palm kernel oil (PKO) products, including crude palm kernel oil (CPKO), crude palm oil (CPO), refined, bleached and deodorised palm oil (RBDPO), refined, bleached and deodorised palm kernel oil (RBDPKO) and refined, bleached and deodorised palm stearin (RBDPS). Caproic acid, caprylic acid, capric acid, lauric acid, myristic acid, palmitic acid, stearic acid and oleic acid are among the types of fatty acids that are often produced in Malaysia. With proper selection of carbon chain length with targeted properties, fatty acids can be used as starting materials to produce valuable oleochemical derivatives. These fatty acids can be used as feedstocks in the production of soaps, medium-chain triglycerides, polyol esters, detergents, emulsifiers, plastics, textiles, cosmetics, lubricants and many other products (Gervajio, 2005).

TABLE 1. FATTY ACID COMPOSITION IN PALM OIL AND PALM KERNEL OIL

Fatty acid	Composition (%)	
	Palm oil	Palm kernel oil
Caproic acid (6:0)	-	0.2
Caprylic acid (8:0)	-	3.3
Capric acid (10:0)	-	3.5
Lauric acid (12:0)	0.2	47.8
Myristic acid (14:0)	1.1	16.3
Palmitic acid (16:0)	44.0	8.5
Stearic acid (18:0)	4.5	2.4
Oleic acid (18:1)	39.2	15.4
Linoleic acid (18:2)	10.1	2.4
Linolenic acid (18:1)	0.4	-
Arachidic acid (18:2)	0.1	0.1

Source: Mancini *et al.* (2015).

The life cycle assessment (LCA) is highly recommended as a suitable tool for environmental evaluation of products or services that can be used to promote their sustainability (Salvador *et al.*, 2018). LCA provides a mechanism to evaluate the environmental impacts of products or processes by considering their entire life cycle. Currently, LCA on palm-based fatty acids produced by Malaysian fatty acid manufacturers is not available. However, the LCA approach is not new in the oil palm (OP) industry; in fact, several LCA studies on this industry have been conducted to address issues of sustainability and the environment. Hansen (2007) conducted the first LCA study on OP, which included a feasibility study of CPO performance in Malaysia. The most significant impact categories for CPO production were fossil fuels (FF) and respiratory inorganics, with minor impacts on global warming and acidification/eutrophication. On the other hand, continual environmental improvements were necessary for the OP industry in order to remain competitive in facing new challenges ahead. This fact was then proven by Subramaniam *et al.* (2010) through the LCA study on CPO production, where global warming was found to be the most significant impact caused by biogas from the anaerobic treatment of palm oil mill effluent (POME). Apart from that, an LCA study by Subramaniam *et al.* (2010) on the CPKO produced through a simple mechanical pressing method showed that the main impact contributors in the CPKO production were from OP upstream activities, *i.e.*, production and application of fertiliser and biogas emissions. It was suggested that integration between the palm kernel-crushing (PKC) plant and palm oil mill (POM) is the best approach in order to have the least environmental impacts for CPKO production.

There were also several LCA studies conducted on midstream PO products, *i.e.*, RBDPO, RBDPS, refined bleached and deodorised palm olein (RBDPOo) and biodiesel (Angarita *et al.*, 2009; Castanheira & Freira, 2017; Puah *et al.*, 2010; Silalertruksa & Gheewala, 2012; Siregar *et al.*, 2015; Tan *et al.*, 2010; Yee *et al.*, 2009; Yung *et al.*, 2020). In addition, a few LCA studies were also conducted on downstream (oleochemical) products, *i.e.*, polyol, methyl ester and methyl ester sulphonate (MES) as reported by Noorazah *et al.* (2015, 2016, 2017). All the LCA findings from these downstream studies showed that the major impact contributors in oleochemical production were from the production of feedstock used and/or utilities, which significantly contributed to climate change and FF depletion impact categories.

The overall greenhouse gas (GHG) emissions for each OP supply chain conducted in Malaysia were reported by Choo *et al.* (2011). The sustainability of the OP supply chain was proven through the complete cradle-to-gate LCA studies, where the best scenario practices and approaches were used. As concern for environmental issues increases, it is deemed necessary to evaluate the environmental performance of palm-based fatty acids, which are the major basic oleochemicals exported and commonly used in many consumer products. As of now, there have not been any LCA studies carried out for the production of palm-based fatty acids in Malaysia and this study is the first of its kind. Therefore, this article aims to evaluate the potential environmental impacts of fatty acid production in Malaysia using PO products as feedstock and different energy sources, which include electricity from the power grid and energy substitution using biomass from PO. As an outcome, the findings of this study can be used as a benchmark for sustainable production of palm-based fatty acids in the future.

MATERIALS AND METHODS

Goal and Scope Definition

This LCA aims to develop baseline information for the production of fatty acids in Malaysia using CPKO and RBDPS as feedstocks, specifically to identify the impacts contributed by the production of fatty acids. The scope of this study covers the assessment of the production of the main fatty acids, *i.e.,* lauric acid, myristic acid, palmitic acid and stearic acid, at commercial fatty acid plants in Malaysia. The environmental impacts of fatty acid production were evaluated for a cradle-to-gate system boundary, covering OP nursery, OP plantation, POM and PO refinery up to the fatty acid plant with the exclusion of its use and distribution.

Functional Unit

The functional unit of this study is 1 kg of lauric acid, myristic acid, palmitic acid and stearic acid produced.

Inventory Data Source and Allocation

The original production data were obtained from fatty acid manufacturers based in Malaysia through actual on-site quantification of the raw materials, water, electricity, energy, chemicals, products and wastes. The inventory data were collected, verified and then back-calculated according to the functional units. The source of data used in this study is listed in *Table 2*. Other established background data were also used in order to support the site-specific foreground data, including from the Ecoinvent 3.4 and Agri-footprint databases. In this study, mass allocation was used as the main allocation for the baseline assessment, which was based on the yield of the product from fat splitting process, *i.e.,* 95.0% fatty acids (main product) and 12.0% glycerol (co-product). In this case, the mass allocation used for utilities and chemical among the fatty acid was the same based on the percentage yield of the fatty acids production in Malaysia, which made mass allocation as 88.7% (fatty acids) and 11.3% (glycerol). Besides, the economic values were volatile, fluctuated based on time, and required data to be updated frequently. However, the economic allocation was conducted through a sensitivity analysis, as described in the scenario of the study in *Table 2*.

TABLE 2. SOURCES AND SCENARIOS OF THE OIL PALM SUPPLY CHAIN USED IN THIS STUDY

Stage	Source
OP nursery	Muhamad *et al.* (2014) • Seedling cultivated for 10-12 months
OP plantation	Hashim *et al.* (2014) • Land use change from OP to OP • Cultivated on mineral soils • OP tree life cycle: 25 years
POM	Subramaniam *et al.* (2020) • Biogas capture scenario at 90% capture efficiency • Mass allocation: CPO (58%), palm kernel (24%), palm kernel shell (18%)
PKC plant	Subramaniam *et al.* (2020) • Plant operating in the proximity of ports
PO refinery plant	Yung *et al.* (2020)
Fatty acids plant	• Data obtained from fatty acids manufacturers in Malaysia • Scenarios for LCA study: 1) Scenario 1: Production of fatty acids using continued land use (OP to OP) with biogas capture, energy source from electricity grid - using cradle-to-gate system boundary 2) Scenario 2: Production of fatty acids using continued land use (OP to OP) with biogas capture, energy source from OP biogas capture - using cradle-to-gate system boundary 3) Sensitivity analysis: Production of fatty acids as in Scenario 1 based on economic allocation

Note: OP - oil palm; PO - palm oil; PKC - palm kernel-crushing; CPO - crude palm oil; LCA - life cycle assessment; POM - palm oil mill.

System Boundary

Figure 3 shows a system boundary for the life cycle impact assessment (LCIA) of fatty acid production. In the OP nursery, the growth and development of OP seedlings for the first 10-12 months are closely monitored before transporting the seedlings to the OP plantation (Haryati *et al.*, 2022; Muhammad *et al.*, 2010). The OP seedlings are field-planted on mineral soils at the OP plantation when they reach 12-15 months old. The OP is first harvested within two to three years after being planted in the plantation and this is a continuous process for the next 20-25 years, where one fresh fruit bunches (FFB) is produced every 10-21 days (Zulkifli *et al.*, 2010). Both the nursery and plantation activities involve the use of pesticides and fertiliser for OP growth. Then, the harvested FFB is immediately delivered to POMs to ensure the production of high-quality CPO (Foong *et al.*, 2019).

At this stage, the extracted CPO is clarified in order to remove any water, dirt and impurities, before being transferred into the storage tank. Later, the CPO is sent for refining or export purposes (Subramaniam *et al.*, 2010). Meanwhile, the palm kernel (PK) is transported to the kernel crushing plants for CPKO extraction, while the PK shell is used as a boiler fuel. Apart from CPO, PK and PK shell, other main by-products produced at the POMs are empty fruit bunches (EFB), pressed mesocarp fibre and POME or sludge. At the kernel crushing plant, the cleaned PK is processed using a continuous screw press (expeller) and PK cake is discharged from this process as a by-product (Subramaniam *et al.*, 2010). The CPO from POM is then sent to the refining plant for the production of refined PO products. At this refining stage, the CPO undergoes a purification process to remove any undesired minor components, *e.g.*, gums, free fatty acids (FFA), heavy metals, colour pigments and others before the products, *i.e.*, RBDPO and palm fatty acid distillate (PFAD), are obtained (Yung *et al.*, 2020). The RBDPO is then fractionated into RBDPS and RBDPOo products.

Generally, a common method employed for fatty acid production is fat splitting, which is carried out at high temperatures between 240°C and 260°C and at high pressure. The CPKO or RBDPS, which are used as feedstock, will hydrolyse at high temperatures and high pressures to become fatty acids and sweet water, also known as crude glycerol. The raw fatty acids are then fractionated or distilled based on different boiling points to produce the desired fatty acid chain length composition. The fatty acids obtained through this process are referred to as light-cut (consists mainly of caproic acid, caprylic acid, and capric acid), mid-cut (mixtures of lauric acid and myristic acid), and heavy-cut (from palmitic acid upwards). Sometimes, the hydrogenation process will also be introduced to harden the fatty acids by modifying their unsaturation level.

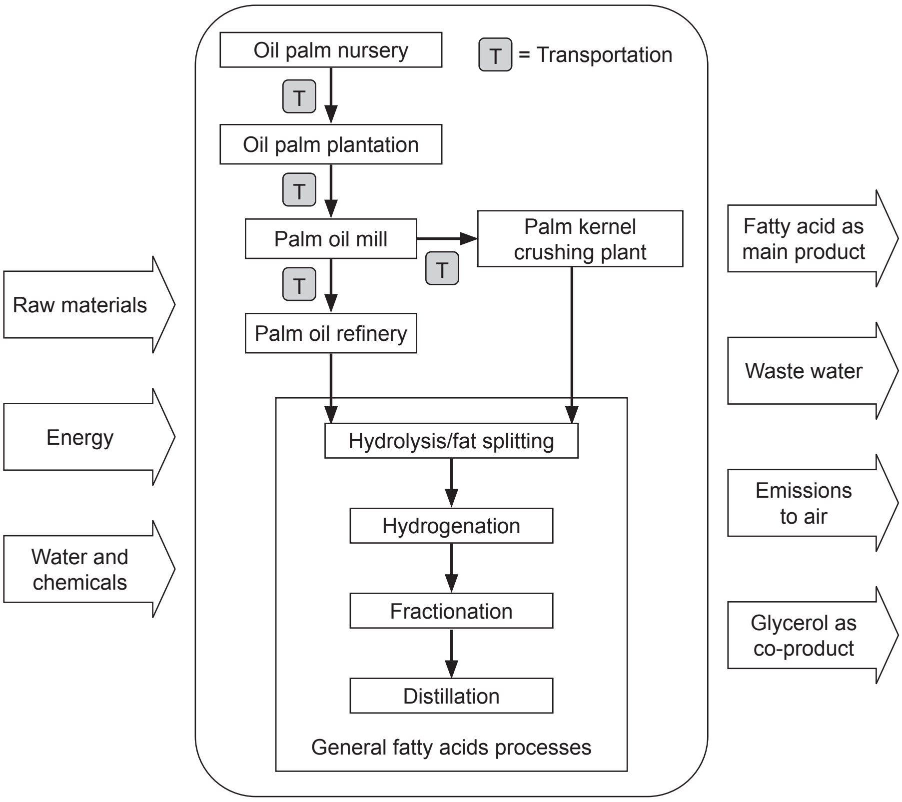


Figure 3. System boundary for fatty acid production using palm oil products as feedstock.

Life Cycle Impact Assessment

The LCA study was performed based on International Organization for Standardization (ISO) 14040:2006 and 14044:2006 standards (ISO, 2006a; 2006b), while SimaPro 9.1.1.1 software was chosen to assess the LCIA of this study. The LCIA aims to describe the environmental impacts of the process. The ReCiPe 2016 midpoint methodology was applied using the 'hierarchist' perspective to estimate the potential environmental impacts from fatty acid production. The environmental impacts of the study were analysed and discussed.

Sensitivity Analysis

The sensitivity analysis is performed in order to investigate the changes in the calculation of the final LCA results by setting different parameters or values for the most significant contributors in the study, with any assumptions unchanged throughout the study. In accordance with the ISO 14044:2006 standard (ISO, 2006b), sensitivity analysis is a procedure to check if changes in data affect the results of the LCIA. In this study, sensitivity analysis on economic allocation was conducted using the average prices of fatty acids and glycerol.

RESULTS AND DISCUSSION

Life Cycle Inventory (LCI)

Table 3 shows the consolidated average data for fatty acid production, encompassing OP nursery, plantation, POM, PO refinery and fatty acid plants. These data are the average data of six fatty acid manufacturers (for lauric acid, myristic acid and palmitic acid) and five fatty acid manufacturers (for stearic acid). In this study, weight allocation was carried out for the input and output flows of each product stage. The transportation in the consolidated data is for all product stages except for the fatty acid production boundary. Natural gas was used only at the PO refinery and fatty acid plants. The power supply for the whole supply chain was obtained from a non-renewable energy source where FF was consumed and wastes were generated along the process. The electricity data were taken from the Malaysian electricity profile generated at power stations as national grid source. For the electricity process flow, the input data was collected, including the mining process and extraction of FF (natural gas, coal, *etc.*), the production of electricity, and its distribution to the grid at the points of use. In this case, the power consumption from electricity using the national grid per kg of fatty acids produced varies, depending on the processes involved in each fatty acid production. Some of the fatty acid manufacturers used a combination of biomass (about 13% in total) and natural gas to produce heat for their boiler systems. Furthermore, the number of fractionation processes also varies for all fatty acids, from single fractionation up to triple fractionations, depending on the plant design and its capacity. The use of triple fractionations with hydrogenation processes elucidated why natural gas consumption somehow was higher in some fatty acid production.

Three types of water were used in the overall process, *i.e.,* deionised water (for high-pressure steam), softened water (for boiler feed water and low-pressure steam) and tap water (mainly for cleaning and cooling water). During the oil

TABLE 3. CONSOLIDATED AVERAGE DATA ON FATTY ACID PRODUCTION

Input (nursery-plantation-mill-refinery-fatty acids)	Average per t fatty acids			
	Lauric acid	Myristic acid	Palmitic acid	Stearic acid
Seedlings	5.02	14.87	17.93	27.77
FFB (t)	15.22	45.05	54.32	84.15
Palm kernel (t)	5.23	15.48	-	-
CPO (t)	-	-	10.65	16.50
RBDPO (t)	-	-	10.09	15.64
Pesticides (kg)	20.58	60.91	73.44	113.78
Fertilisers (kg)	737.42	2,182.69	2,631.82	4,077.10
Fuels, total (kg)	32.74	96.96	121.12	187.64
Water, total (m^3)	12.44	36.78	97.92	151.22
Electricity, total (kWh)	635.08	1,813.14	430.45	573.80
Natural gas (m^3)	66.40	162.00	96.92	182.97
Chemicals (kg)	25.3	9.60	148.06	207.16
Hydrogen (m^3)	-	-	51.2	90.3
Transportation, total (tkm)	586.68	586.68	654.08	654.08

Note: FFB - fresh fruit bunches; PK - palm kernel; CPO - crude palm oil; RBDPO - refined, bleached and deodorised palm oil.

splitting process in fatty acid production, crude glycerol or sweet water was also produced as a co-product. In most oleochemical plants, this crude glycerol will be purified up to 99.5% for high-end applications. Overall, there were many differences in fatty acid processes between the manufacturers, which include the number of steps in the process, utilities, and source of energy. The different ranges in energy consumption might be due to the plant design requirements, fractionator efficiency, boiler efficiency and the number of steps in the processes in each fatty acid production.

Life Cycle Impact Assessment (LCIA)

The characterised LCIA for all fatty acid production at midpoint level is shown in *Figure 3*. CPKO production was found to be the single major contributor in all impact categories evaluated for lauric acid and myristic acid productions (*Figure 4a* and *4b*), whereas RBDPS, which is produced from RBDPO, was the largest contributor in palmitic acid and stearic acid productions (*Figure 4c* and *4d*). Other than that, there were also contributions from the production and consumption of natural gas and electricity in almost all impact categories for all fatty acid production. The intensity of energy for the production of CPKO-fatty acids is higher compared to RBDPS-fatty acids due to the processes involved, mainly at the milling stage.

Scenario 1: Cradle-to-gate of fatty acid production using continued land use (OP to OP) and biogas capture, with energy sources from the electricity grid. The environmental impacts for 1 kg of each fatty acid studied were quantified for all impact categories, as shown in *Table 4*. Among these impact categories, only six contribute significantly to fatty acid production, with more than 0.5 units (cut-off criteria) of their respective impact categories is elaborated in detail, which are global warming, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity.

Global warming. Global warming is known as one of the most applied environmental impact indicators in any LCA study and is expressed in kg CO_2 eq. Consequently, this study measured how much GHG was emitted from fatty acid production and trapped in the atmosphere and was calculated using the global warming potential factors published in the Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2013; Yung *et al.*, 2020). The results indicated that the production of myristic acid had the highest impact on global warming compared to other fatty acids (*Table 4*) due to the contribution from the production of CPKO used as feedstock, *i.e.*, the amount of CPKO required to produce 1 kg of myristic acid is almost three times higher than lauric acid on average. This could be caused by the different fatty acid composition in PKO as described in *Table 1*, where a huge amount of CPKO is required to produce 1 kg of myristic acid compared to lauric acid. Meanwhile, palmitic acid, which is produced from RBDPS, had the lowest impact on global warming, 36% lower than the impact generated by stearic acid. The significant contributors to GHG emissions from CPKO production are POME, N-based fertiliser and the production of electricity. Both POME from the POM and fertiliser used in the plantations are burdens carried by the feedstock from upstream activities.

It was observed that the higher the amount of feedstock and energy used, the higher the GHG emitted. The GHG emissions for all fatty acid productions vary due to the different types and amounts of feedstock used for each production. The GHG emission for myristic acid was higher among all fatty acids in this study due to the higher amount of feedstock used, *i.e.*, PK to produce CPKO with 9.43 kg CO_2 eq. per kg myristic acid, followed by lauric acid with 3.22 kg CO_2 eq. per kg lauric acid. However, the GHG values for RBDPS-based fatty acids, *i.e.*, palmitic acid and stearic acid, were slightly lower than those for CPKO-based fatty acids (lauric acid and myristic acid), which are 1.39 and 2.39 kg CO_2 eq. per kg of fatty acid, respectively. This is because the RBDPS process had a lower impact than the CPKO process due to the allocation made along the RBDPS supply chain. Nevertheless, through this study, the GHG emissions for all fatty acid production were reduced up to >90% when gate-to-gate system boundary analysis was performed, where the GHG dropped to a range of 0.07-0.18 kg CO_2 eq. per kg of fatty acids. This finding is consistent with most LCA studies conducted for the downstream product, in which the possible impacts are primarily driven by the feedstock used, which bears the burdens of upstream processes.

Ecotoxicity and human toxicity. The toxicity was assessed using the maximum tolerable concentrations of substances that exist in the water and is expressed as kg 1,4-dichlorobenzene (1,4-DCB) equivalent. The ecotoxicity impact analysed in this study is a combination of impacts on terrestrial, freshwater, and marine ecotoxicity. In all fatty acid production, the ecotoxicity impact on the terrestrial ecosystem was found to be 93 times higher compared to the freshwater ecosystem. Meanwhile, the ecotoxicity impact on the marine ecosystem is less than 0.5 kg 1,4-DCB eq. for all fatty acids produced. The impact on ecotoxicity is mainly caused by the manufacturing of fertilisers and the consumption of pesticides

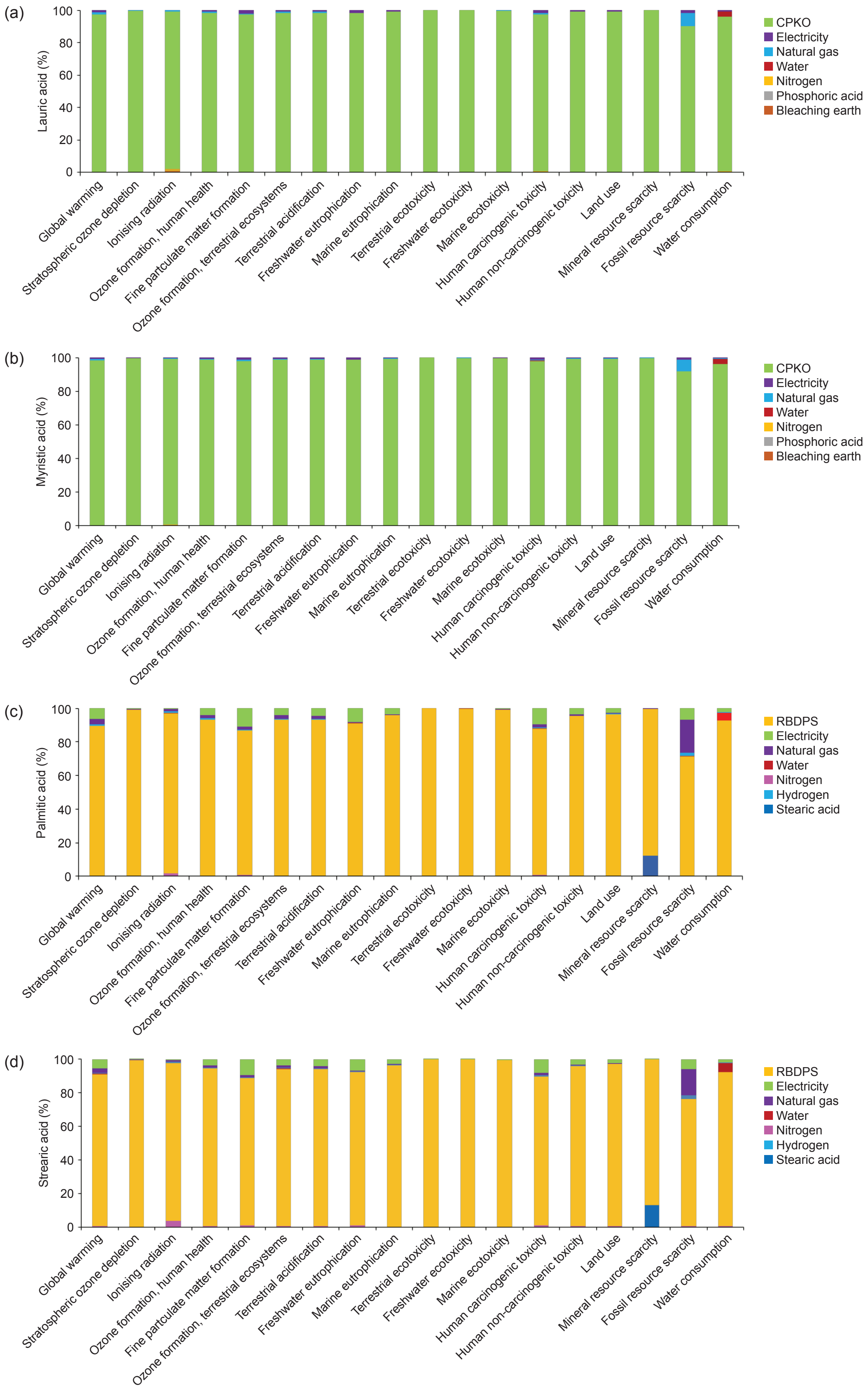


Figure 4. Characterised life cycle impact assessment (LCIA) to produce 1 kg of: (a) Lauric acid, (b) myristic acid, (c) palmitic acid and (d) stearic acid.

during agricultural activities, in this case at the OP plantation and nursery. Panichelli *et al.* (2009) reported that cypermethrin, used as a pesticide in the supply chain, is also responsible for the impact on ecotoxicity. Results show that the production of myristic acid had the highest impact on the terrestrial ecotoxicity impact category compared to other fatty acids (*Table 4*).

Human non-carcinogenic toxicity. For this impact category, the production of feedstock used, *i.e.*, CPKO and RBDPS, has a prominent impact with a contribution of 99% and 95% of the total contribution, respectively. Meanwhile, the main contributors were the background process for the production of electricity and also activities during FFB production itself, including pesticide usage.

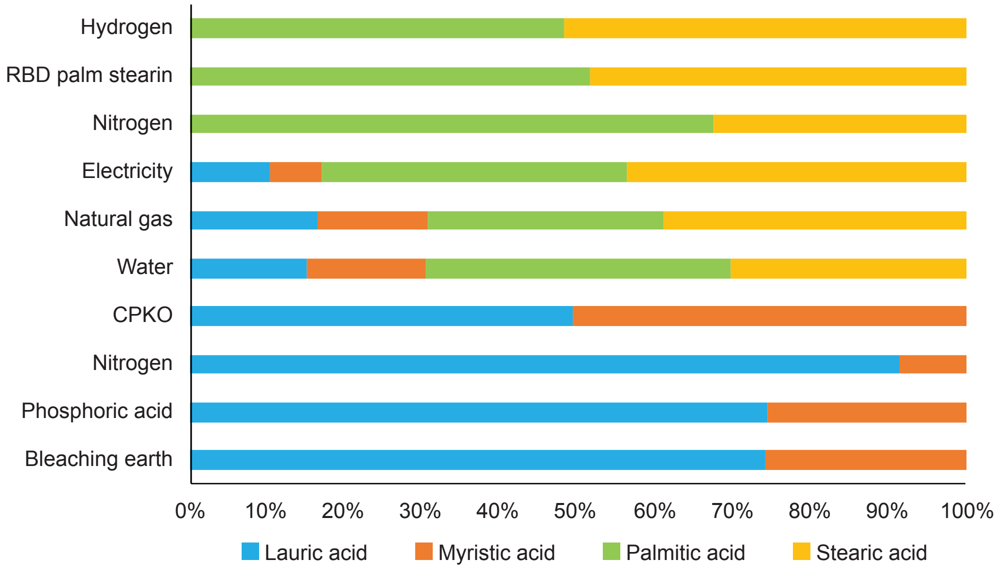
Fossil resource scarcity. This impact category is related to the use of FF as a source of energy and feedstock for production; in this case, the production of electricity and also natural gas, which were measured in a kg of oil equivalent (addressed as the fossil resource scarcity category). *Figure 5* shows the major impact contributors to the fossil resource scarcity impact category, where the production of raw materials (CPKO and RBDPS) was identified as the major contributor to this impact category due to the accumulation of FF used along their supply chain.

The findings showed that the higher the amount of natural gas used to produce steam at the plant's boiler and electricity used during fatty acid production, the higher the depletion of FF. In these fatty acid productions, there were differences in energy source and consumption, which were mainly due to the number of fractionation processes involved and also the efficiency of the plant since there were newer and older fatty acid plants evaluated in this study. The higher the number of fractionations required, the higher the energy consumption. Generally, the production of RBDPS-based fatty acids (palmitic acid and stearic acid) only involved a single-step fractionation process, while the production of CPKO-based fatty acids could be single, or double, or may go up to a maximum of triple fractionations, depending on the plant design and also its capacity. Eventually, the impact it has depends heavily on the nature of the feedstock itself.

Overall, the LCIA results indicated that the impacts of fatty acid production from CPKO were greater than those from RBDPS, mainly because of the allocation and upstream burdens from each process, *i.e.*, plantation, milling and refinery, besides the energy usage during the fatty acid production itself, *i.e.*, number of fractionations involved. Clearly, the main contributor to environmental impacts in fatty acid production was dominated by the production of CPKO and RBDPS, with more

TABLE 4. ENVIRONMENTAL IMPACTS OF 1 KG OF LAURIC ACID, MYRISTIC ACID, PALMITIC ACID AND STEARIC ACID (SCENARIO 1)

Input category	Unit	Impact per kg fatty acid			
		Lauric acid	Myristic acid	Palmitic acid	Stearic acid
Global warming	kg CO_2 eq.	3.22	9.43	1.39	2.19
Stratospheric ozone depletion	kg CFC_{11} eq.	1.80E-05	5.33E-05	7.40E-06	1.15E-05
Ionising radiation	kBq Co-60 eq.	0.05	0.15	0.03	0.04
Ozone formation, human health	kg NO_x eq.	0.01	0.02	3.43E-03	0.01
Fine partculate matter formation	kg PM2.5 eq.	4.73E-03	0.01	2.03E-03	3.19E-03
Ozone formation, terrestrial ecosystems	kg NO_x eq.	0.01	0.02	3.50E-03	0.01
Terrestrial acidification	kg SO_2 eq.	0.01	0.04	0.01	0.01
Freshwater eutrophication	kg P eq.	1.15E-03	3.38E-03	4.63E-04	7.24E-04
Marine eutrophication	kg N eq.	1.87E-04	5.51E-04	7.63E-05	1.19E-04
Terrestrial ecotoxicity	kg 1,4-DCB	261.87	774.65	109.20	169.26
Freshwater ecotoxicity	kg 1,4-DCB	2.85	8.42	1.17	1.81
Marine ecotoxicity	kg 1,4-DCB	0.78	2.30	0.32	0.50
Human carcinogenic toxicity	kg 1,4-DCB	0.15	0.44	0.07	0.11
Human non-carcinogenic toxicity	kg 1,4-DCB	3.37	9.91	1.45	2.27
Land use	m^2a crop eq.	0.06	0.18	0.03	0.05
Mineral resource scarcity	kg Cu eq.	0.02	0.06	0.01	0.02
Fossil resource scarcity	kg oil eq.	0.69	1.98	0.34	0.56
Water consumption	m^3	0.04	0.12	0.03	0.05



Note: RBD - refined, bleached and deodorised; CPKO - crude palm kernel oil.

Figure 5. Percentage of the major contributors to the fossil resource scarcity impact category for the production of 1 kg of lauric acid, myristic acid, palmitic acid and stearic acid.

than 90% contribution in all impact categories. Along with that, the consumption of natural gas and electricity, which were used as energy and heat sources in fatty acid production, also had significant impacts on the environment. All these contributors were similar for all fatty acid productions assessed.

Scenario 2: Cradle-to-gate of fatty acid production using continued land use (OP to OP) and biogas capture, with replacement of energy sources with OP biomass. In this study, the utilisation of OP biomass, *i.e.*, shell and mesocarp fibre, as an alternative to replace the current energy source from FF is proposed. The purpose of this scenario is to find out how much environmental impact or burden associated with fatty acid production can be reduced by replacing the energy source at all stages without any change to other parameters or processes. At the POM, the OP biomass is directly burned to be used as a fuel for boiler plants in order to produce heat to convert water into steam (Noorazah *et al.*, 2015). In this fatty acid production, the total non-renewable primary energy demand is in the range of 0.86-6.53 MJ per kg fatty acid. Overall, for the CPKO-based fatty acid production, the utilisation of OP biomass managed to reduce about 13% and 16% of impacts in the global warming and fossil resource scarcity impact categories, respectively, as compared to using energy from the electricity grid in Scenario 1 according to the ReCiPe methodology (*Figure 6*). Meanwhile, for RBDPS-based fatty acid production, only 1.4% of the impact can be reduced for both impact categories as compared to Scenario 1 studied.

This shows that the CPKO-based fatty acid production process is most energy-intensive as compared to RBDPS-based fatty acid production. The replacement of fossil-based energy from grid electricity with OP biomass-based renewable energy, even at a small amount, can definitely help to reduce the climate change impact and the industry's dependency on FF (Subramaniam *et al.*, 2021). Indirectly, these initiatives will help to lessen the related impacts generated from fatty acid production through better energy substitution and also improve the sustainability performance of the OP supply chain by maximising the use of by-products from their industry itself.

Sensitivity analysis (Production of fatty acids as described in Scenario 1 based on economic allocation). The initial allocation in this study was weight allocation. A sensitivity analysis was conducted via economic allocation based on price between fatty acid and glycerol as a co-product with a ratio of 61:39. The economic evaluation was difficult to conduct due to the daily price fluctuation, and in this case, the value of fatty acids was higher than glycerol (prices based on MPOB). In this study, the allocation went from 88.7% (mass allocation) to 61.0% (economic allocation). As a result, the impacts decreased by about 31.0% in selected impact categories when economic allocation was used, which is more favourable for fatty acid production compared to mass allocation (*Table 5*). This also shows that allocation choice can change the results significantly. Additionally, Yung *et al.* (2021) suggested that economic allocation seems more beneficial for palm biodiesel production than allocation by mass or energy content.

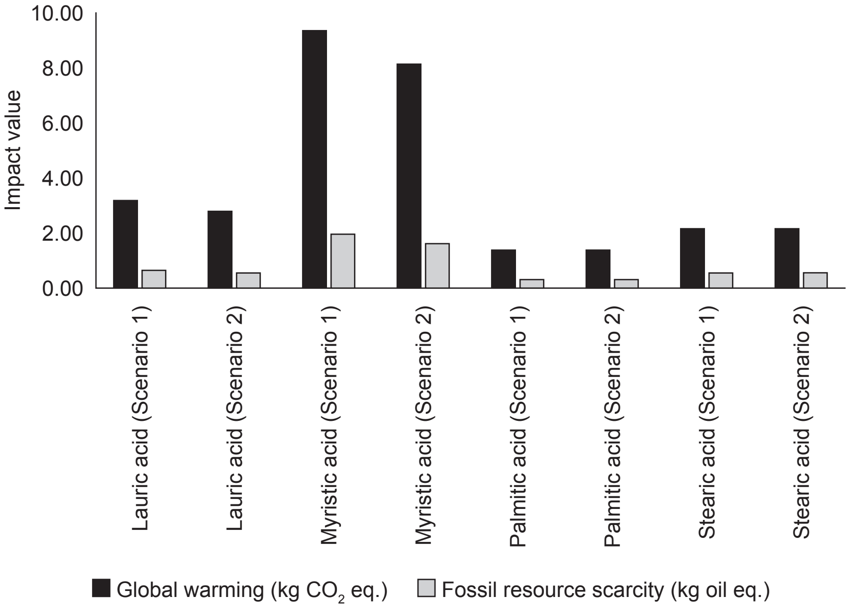


Figure 6. Comparison of impacts from all fatty acid productions for Scenario 1 and 2.

TABLE 5. SELECTED ENVIRONMENTAL IMPACTS OF 1 KG OF LAURIC ACID, MYRISTIC ACID, PALMITIC ACID AND STEARIC ACID (MASS ALLOCATION *vs.* ECONOMIC ALLOCATION)

Fatty acid	Impact category					
	Global warming (kg CO_2 eq.)		Terrestrial ecotoxicity (kg 1,4-DCB)		Fossil resource scarcity (kg oil eq.)	
	Mass allocation	Economic allocation	Mass allocation	Economic allocation	Mass allocation	Economic allocation
Lauric acid	3.22	2.25	261.87	183.04	0.69	0.48
Myristic acid	9.43	6.59	774.65	541.47	1.98	1.38
Palmitic acid	1.39	0.97	109.20	76.33	0.34	0.24
Stearic acid	2.19	1.53	169.26	118.31	0.56	0.39

CONCLUSION

This study specifically evaluates the environmental performance of palm-based fatty acid manufacturers in Malaysia, who are also part of the OP industry supply chain. The environmental hotspots identified in this LCA will help the manufacturers identify the environmental impacts of their production and the industry can take steps to mitigate this by improving their processes. Overall, the GHG emissions for this study demonstrated that the selected impacts generally for CPKO-based fatty acid production are reduced by about 16% by replacing the energy source from the electricity grid with OP biomass. The LCA results based on economic allocation also showed that the impact can be reduced by up to 31% in all impact categories, which gives more benefits to all fatty acid production as compared to weight allocation.

In general, the downstream process, as in the production of fatty acids, will carry the burdens and impacts of the upstream processes. As a recommendation, the manufacturers can consider looking into other potential sources for energy generation. It is suggested that the manufacturer explore other alternative energy sources and heat-producing techniques for their current and future plant operations, such as energy efficiency technology, biogas utilisation, solar system, cogeneration system and heat integration system in order to reduce their dependency on fossil fuels such as coal, natural gas, *etc.* By implementing these approaches, it could help reduce the total impact generated from the production of feedstock and the production of fatty acids. Better and greener technologies for energy efficiency are suggested to be implemented and introduced to the oleochemical industry, which is believed to reduce environmental impacts, especially the global warming potential and fossil resource scarcity impact categories.

On the other hand, it is also essential for the respective manufacturer to maintain and continuously use feedstock from certified sources, *i.e.,* with RSPO or MSPO certification, the implementation of good agriculture practices (GAP) at the OP plantation, the application of biogas capture facility at POM, a good wastewater treatment system, *etc.* In the end, the findings from this study, which are GHG emissions, can also be used by manufacturers to determine the level of carbon footprint of their products and this information is also required in the product market.

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