LIFE CYCLE ASSESSMENT FOR THE PRODUCTION OF REFINED PALM PRODUCTS AND PALM-BASED BIOFUELS

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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LIFE CYCLE ASSESSMENT FOR THE PRODUCTION OF REFINED PALM PRODUCTS AND PALM-BASED BIOFUELS

ABSTRACT

Palm oil is an important commodity for Malaysia which contributes 5-7% to the national gross domestic product. Being the second-largest producer in the world, crude palm oil (CPO) production in Malaysia has reached 19.858 million tonnes in 2019. Majority of the CPO produced are refined and fractionated in the local refineries before export or further downstream applications. The main objective of the study is to determine the environmental impacts of palm oil refining, fractionation and biofuels production in Malaysia. For palm oil refining and fractionation, the inventory data are derived from primary data supplied by six palm oil refineries for a period of five years operation. For biodiesel production, the inventory data are derived from primary data collected from six commercial biodiesel plants for a period of three years operation. The inventory data for hydroprocessing are referred to pilot plant operation data due to no commercial hydroprocessing activity in the country. Life cycle assessment (LCA) is conducted using SimaPro software version 9.1.1.1 and impact assessment is performed according to ReCiPe 2016 (Hierarchist) methodology. In the gate-to-gate LCA, bleaching earth, electricity and transportation of CPO are the main contributors to environmental impacts in the palm oil refining stage while RBD palm oil is the single major contributor to the palm oil fractionation stage. Improvement in the transportation of CPO can reduce the environmental impacts effectively in the refinery subsystem through sourcing of CPO from nearby palm oil mills and the use of modern Euro 5-compliant trucks. Methanol, acids and sodium methoxide (transesterification catalyst) are the three major contributors to the environmental impacts in the biodiesel subsystem. Hydrogen and electricity are the two important contributors to the hydroprocessing subsystem. Allocation based on economic value is suitable for LCA of palm oil refining, fractionation and biodiesel production due to different economic values of the products and co-products. Energy allocation based on lower heating values is suitable for the hydroprocessing subsystem since the products and co-products are energy-based. Sensitivity analysis on allocation procedures at refining and fractionation shows an insignificant difference between allocation based on mass and energy content simply due to the similar energy content of the refined and fractionated palm products. Sensitivity analysis on prices movement shows a negligible variation on the allocated environmental impacts for both the refinery and the biodiesel subsystems. The impact assessment of the palm biodiesel subsystem shows that the replacement of fossil-based methanol with biomethanol derived from biogas is the preferred mitigation option. 19% reduction in global warming impact and 60% saving of fossil resources are anticipated for the gate-to-gate impact assessment. The cradle-to-gate and cradle-to-grave LCA highlight the important contribution of biogas emissions from the palm oil mills subsystem to the overall global warming impact. Biogas capturing at palm oil mills and the replacement of fossil-based methanol are the two important strategies to reduce the potential environmental impacts.

Keywords: Allocation; life cycle assessment; RBD palm oil; palm biodiesel; palm biofuels

PENILAIAN KITARAN HAYAT PENGHASILAN PRODUK-PRODUK SAWIT TERTAPIS DAN BIOBAHAN API SAWIT

ABSTRAK

Minyak sawit merupakan komoditi utama Malaysia yang menyumbang kepada 5-7% keluaran dalam negeri kasar. Sebagai pengeluar kedua besar minyak sawit, sejumlah 19.858 juta tan minyak sawit mentah telah dihasilkan pada tahun 2019. Kebanyakan minyak sawit mentah tersebut ditapis dan diperingkat di kilang-kilang penapisan tempatan sebelum ia dieksport atau digunakan dalam sektor hiliran. Objektif utama kajian ini adalah untuk mengenalpasti impak persekitaran untuk proses penapisan dan pemeringkatan minyak sawit serta penghasilan biobahan api berasaskan sawit di Malaysia. Untuk penapisan dan pemeringkatan minyak sawit, data inventori dihasilkan melalui pengumpulan data primer daripada enam kilang penapisan minyak sawit berasaskan 5 tahun operasi. Manakala pengumpulan data primer dari enam kilang biodiesel telah dijalankan untuk menghasilkan data inventori yang berasaskan 3 tahun operasi. Data inventori untuk *hydroprocessing* pula merujuk kepada operasi loji rintis disebabkan tiada penghasilan secara komersil di Malaysia. Penilaian kitaran hayat dijalankan dengan perisian SimaPro 9.1.1.1 dan penilaian impak dilaksanakan berdasarkan metodologi *ReCiPe 2016 (Hierarchist)*. Penilaian kitaran hayat secara *gate-to-gate* menunjukkan bahawa bahan peluntur, bekalan elektrik dan pengangkutan minyak sawit mentah adalah penyumbang utama kepada impak persekitaran pada peringkat penapisan minyak sawit mentah manakala minyak sawit terproses merupakan penyumbang tunggal kepada impak persekitaran pada peringkat pemeringkatan minyak sawit terproses. Penambahbaikan pada proses pengangkutan melalui perolehan minyak sawit mentah dari kilang sawit yang terdekat serta penggunaan kenderaan diesel moden jenis Euro-5 dapat mengurangkan impak persekitaran secara berkesan. Metanol, asid-asid dan pemangkin merupakan tiga penyumbang utama kepada impak persekitaran pada sub-sistem biodiesel sawit. Hidrogen dan bekalan elektrik pula merupakan penyumbang utama impak persekitaran pada sub-sistem *hydroprocessing*. Peruntukan impak persekitaran berpandukan nilai-nilai ekonomi produk utama dan produk bersama didapati sesuai untuk penilaian kitaran hayat penapisan dan pemeringkatan minyak sawit serta penghasilan biodiesel sawit. Peruntukan impak persekitaran berpandukan kandungan tenaga iaitu *lower heating value* didapati sesuai untuk sub-sistem *hydroprocesing* kerana produk-produk tersebut adalah berasaskan tenaga. Analisa sensitiviti terhadap prosedur peruntukan pada peringkat penapisan dan pemeringkatan minyak sawit menunjukkan bahawa tiada perbezaan antara peruntukan berpandukan jisim dan kandungan tenaga disebabkan oleh kandungan tenaga produk-produk yang hampir sama. Analisa sensitiviti terhadap pergerakan harga tahunan tidak menunjukkan perbezaan yang ketara untuk sub-sistem kilang penapisan serta sub-sistem kilang biodiesel sawit. Penilaian impak pada sub-sistem biodiesel mendapati bahawa penggantian metanol berasaskan fosil oleh biometanol yang dihasilkan daripada biogas merupakan opsyen terbaik dengan 19% penurunan impak pemanasan global dan 60% penjimatan sumber fosil. Penilaian kitaran hayat secara *cradle-to-gate* dan *cradle-to-grave* memaparkan kepentingan pelepasan biogas pada sub-sistem kilang sawit terhadap impak pemanasan global secara keseluruhan. Pemerangkapan biogas dan penggantian metanol berasaskan fosil merupakan strategi utama pengurangkan impak-impak persekitaran.

Kata kunci: Peruntukan; penilaian kitaran hayat; minyak sawit terproses; biodiesel sawit; biobahan api sawit

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BOD	:	Biological oxygen demand
CED	:	Cumulative energy demand
CFC11 eq	:	Trichlorofluoromethane equivalent
CO_2	:	Carbon dioxide
CO_2 eq	:	Carbon dioxide equivalent
CONCAWE	:	Environmental Science for European Refining
COD	:	Chemical oxygen demand
CPO	:	Crude palm oil
Cu eq	:	Copper equivalent
DALY	:	Disability-adjusted life year
DOE	:	Department of Environment Malaysia
EFB	:	Empty fruit bunch
EMS	:	Environmental management system
FAME	:	Fatty acid methyl esters
FAO	:	Food and Agriculture Organisation of the United Nations
FEDIOL	:	European Union Vegetable Oil and Proteinmeal Industry Association
FELCRA	:	Federal Land Consolidation and Rehabilitation Authority
FELDA	:	Federal Land Development Authority
FFB	:	Fresh fruit bunch
g	:	Gram
GDP	:	Gross domestic product
GHG	:	Greenhouse gas

GREET^{TM}	:	Greenhouse gases, Regulated Emissions, and Energy used in Transportation
GWP	:	Global warming potential
HRD	:	Hydroprocessed renewable diesel
HRJ	:	Hydroprocessed renewable jet fuel
HRN	:	Hydroprocessed renewable naphtha
HVO	:	Hydrotreated vegetable oil
IPCC	:	Intergovernmental Panel on Climate Change
ISCC	:	International Sustainability and Carbon Certification
ISO	:	International Organisation for Standardisation
ISPO	:	Indonesian Sustainable Palm Oil
JAMA	:	Japanese Automobile Manufacturers Association
kBq Co-60 eq	:	kilobecquerel of Cobalt-60 equivalent
kg	:	Kilogram
kWh	:	Kilowatt-hour
L	:	Litre
LCA	:	Life cycle assessment
LCI	:	Life cycle inventory
LCIA	:	Life cycle impact assessment
LHV	:	Lower heating value
m^3	:	Cubic metre
MJ	:	Megajoule
MPOB	:	Malaysian Palm Oil Board
MPOCC	:	Malaysian Palm Oil Certification Council
MSPO	:	Malaysian Sustainable Palm Oil
N eq	:	Nitrogen equivalent

NBD	:	Neutralised, bleached and deodourised
NO_x eq	:	Nitrogen oxides equivalent
Oil eq	:	Oil equivalent
P eq	:	Phosphorus equivalent
PFAD	:	Palm fatty acid distillate
PM2.5 eq	:	Fine particulate matter with a diameter of less than 2.5 µm equivalent
PME	:	Palm methyl esters
PNAS	:	Proceedings of the National Academy of Sciences of the United States of America
POME	:	Palm oil mill effluent
RBD	:	Refined, bleached and deodourised
RISDA	:	Rubber Industry Smallholder Development Authority
RM	:	Malaysian Ringgit
RSB	:	Roundtable on Sustainable Biomaterials
RSPO	:	Roundtable on Sustainable Palm Oil
SDGs	:	Sustainable Development Goals
SO_2 eq	:	Sulfur dioxide equivalent
t	:	Tonne
TC	:	Technical committee
tkm	:	Tonne-kilometre
TR	:	Technical report
TS	:	Technical specification
UN	:	United Nations
UNEP	:	United Nations Environment Programme
UP	:	United Plantations Berhad

US$	:	United States dollar
US DOE	:	United States Department of Energy
WCED	:	World Commission on Environment and Development
WHO	:	World Health Organisation

CHAPTER 1: INTRODUCTION

1.1 Introduction

Oils and fats are important commodities in the world. They are important sources of dietary fats for consumption in the daily human diet (FAO/WHO, 2001). There are a total of 17 major oils and fats in the world. In 2019, the total production of all 17 major oils and fats in the world was recorded at 234.485 million tonnes (MPOB, 2020a). 88.27% of the total oils and fats were vegetable oils while 11.73% were fats extracted from animals and fishes i.e. tallow, butter, lard and fish oil (Figure 1.1). Palm oil, soyabean oil and rapeseed oil are the three major oils that dominated more than two-thirds of the world production of oils and fats.

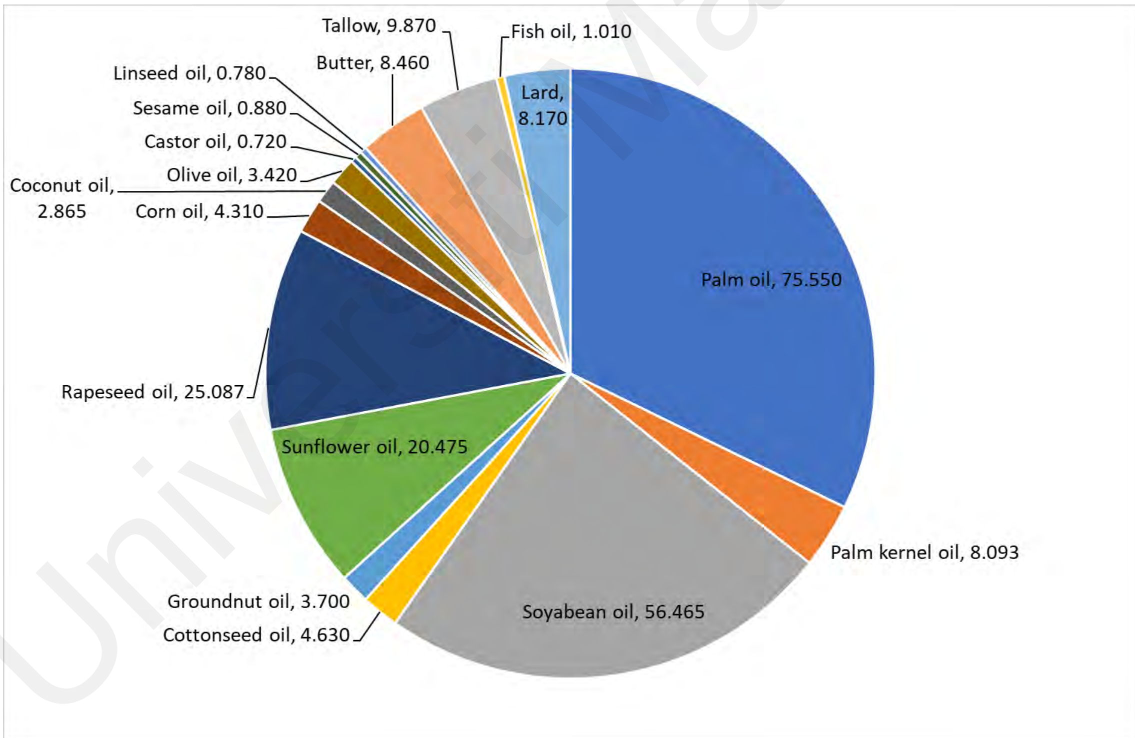


Figure 1.1: World production of 17 oils and fats (million tonnes) in 2019 (MPOB, 2020a)

Oil palm plays a very significant role in the production of oils and fats in the world. Typically, two types of oil can be obtained from palm fruits i.e. palm oil from the mesocarp and palm kernel oil from the seed or kernel (Figure 1.2). It is important to note that more than one-third of the total 17 oils and fats produced in the world at present days are contributed by palm oil and palm kernel oil.

Figure 1.2: Cross-section of a palm fruit

Palm oil emerged as the largest vegetable oil produced in the world since 2004 (MPOB, 2012). In 2019, the world production of palm oil has reached 75.55 million tonnes. Palm oil is mostly produced in the Southeast Asia region. Indonesia and Malaysia are the major palm oil producers in the world. The production of palm oil in Indonesia and Malaysia was recorded at 43.3 million tonnes and 19.858 million tonnes, respectively (Figure 1.3). 83.60% of the world palm oil production in 2019 were produced in these two countries. The remaining 16.40% or 12.392 million tonnes were produced from other countries such as Thailand, Colombia, Nigeria, Ecuador, Guatemala, Papua New Guinea etc. These countries individually contributed to less than 5% of the total palm oil production in the world.

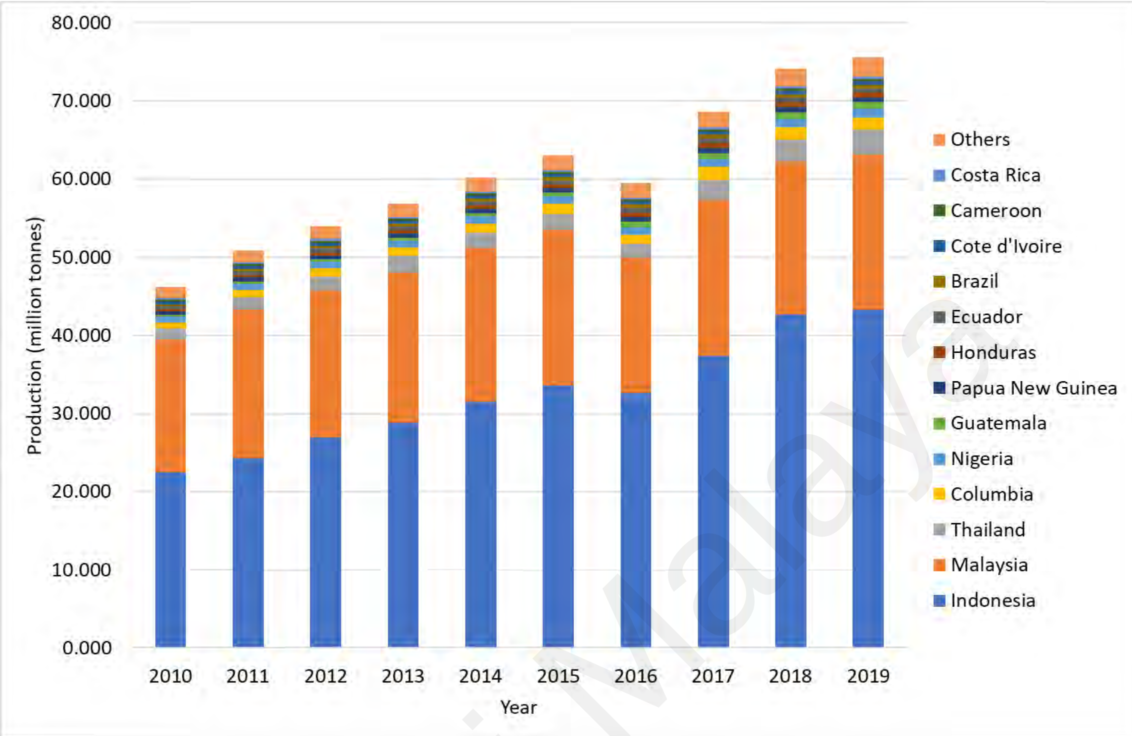


Figure 1.3: World major producers of palm oil in 2019 (MPOB, 2020a)

The oil palm planted area in Malaysia has reached 5.90 million hectares for the year 2019, a marginal increase from 5.85 million hectares in 2018 (Ahmad Parveez et al., 2020). Crude palm oil (CPO) production of 19.858 million tonnes in 2019 has again positioned Malaysia as the second-largest producer in the world after Indonesia. Due to its versatile usage, Malaysian palm oil and palm oil products are exported to more than 190 markets worldwide (Balu et al., 2018). As the second-largest exporter, the total export volume of palm oil, palm kernel oil and other palm oil products in 2019 was recorded at 27.98 million tonnes, 10.90% higher than the total export volume in 2018. However, a 3.97% lower export revenue or RM 64.84 billion was recorded for 2019 due to lower palm oil price in 2019 compared to 2018 (Ahmad Parveez et al., 2020). India strengthened its position as the number one export destination of Malaysian palm oil with an intake of 4.41 million tonnes in 2019, a drastic increase of 1.90 million tonnes or 75.40% compared to 2018 (Ahmad Parveez et al., 2020). This is followed by China, the European Union, Pakistan, Turkey, the Philippines, Vietnam, the United States, Iran and Japan. These ten countries accounted for 13.57 million tonnes or 73.49% of total Malaysian palm oil export in 2019. Palm oil is an important commodity contributing to the national gross domestic product (GDP). On average, 5% to 7% of the Malaysian GDP are contributed by the palm oil industry (Balu et al., 2018).

As a commodity, palm oil is facing continuous competition with other oils and fats produced in the world. Challenges from various angles such as safety and health concerns of palm oil for human consumption, processing technologies, deforestation, threats to animal habitats, loss of biodiversity, sustainable development etc, faced the industry for decades. Environmental concern for the planting of oil palm is often being discussed and criticised in the international arena. In recent years, consumers from importing countries, in particular, the developed nations, are demanding sustainable palm oil with minimal impacts on the environment. This has further driven the development of sustainability studies and certifications for palm oil and palm oil products. Roundtable on Sustainable Palm Oil (RSPO) is one of the renowned international sustainability schemes which was established in 2004 to promote the production and use of sustainable palm oil. A set of sustainability principles and criteria to govern sustainable palm oil production has been drawn under the RSPO scheme. There are also other sustainability schemes such as International Sustainability and Carbon Certification (ISCC) and Roundtable on Sustainable Biomaterials (RSB), to name a few. Being the major producing countries with a high commitment to the sustainable development of the palm industry, both Indonesia and Malaysia have also developed their own local sustainable certification schemes namely the Indonesian Sustainable Palm Oil (ISPO) and the Malaysian Sustainable Palm Oil (MSPO). Both ISPO and MSPO served as the national standards which govern the local palm oil production sustainably. Unlike the abovementioned voluntary schemes or certifications, MSPO is made mandatory for the growers and millers in Malaysia. As of July 2020, 84.74% of the total oil palm planted area and 89.38% of total palm oil mills in Malaysia have been certified under the MSPO scheme (MPOCC, 2020).

Life cycle assessment (LCA) is a tool to evaluate the environmental aspects and impacts of a product or a process. It helps to identify the environmental hotspots of the system evaluated and provide analysis on potential opportunities for environmental improvement. LCA has been used as a scientific approach to justify the actual environmental performance of the Malaysian oil palm industry for the past decades by presenting the potential environmental impacts of various subsystems in the palm oil supply chain. Besides, LCA has also been carried out by various parties around the globe on various products and product systems, not limited to agricultural products and processes.

1.2 Problem Statement

1.2.1 Filling of Data Gap

LCA for palm oil and palm biodiesel have been presented by various parties. However, most of the studies only focused on oil palm cultivation at plantations, production of CPO in palm oil mills and production of biodiesel from CPO. Palm oil refining is not considered or excluded in most of the studies. Only a handful of studies evaluated and reported the environmental performance of the refining activity as in Schmidt (2008), Tan et al. (2010), Choo et al. (2011) and Schneider and Finkbeiner (2013). Furthermore, the environmental performance of palm oil fractionation is only briefly evaluated in Tan et al. (2010), with no in-depth analysis. In reality, most of the palm oil produced in Malaysia are refined and fractionated in local palm oil refineries before being exported and/or used in further downstream applications. Hence, it is crucial to fill the missing data gap of LCA on palm oil refining and fractionation, an important refinery subsystem in the palm oil supply chain enabling further LCA evaluation of other palm products produced from these refined and fractionated palm oils.

1.2.2 Industry Practices and Credible Primary Data

LCA studies on palm oil and palm biodiesel reported thus far are mostly based on secondary data or general data available in the literature from public domains. A lack of effort in data collection from the industry players is observed, in particular for the LCA on Malaysian palm oil and palm biodiesel. The LCA results may not be representative if such important primary inventory data are not obtained from the relevant stakeholders in the country. Furthermore, some of the studies were conducted based on certain assumptions with a poor understanding of the industry practices. For example, some studies assumed that palm oil and palm kernel oil are processed together for biodiesel production. Some just simply assumed that the biodiesel is directly produced from CPO which refined, bleached and deodourised (RBD) palm oil in fact is the main feedstock use in the country. For palm oil refining, physical refining is the common practice in Malaysia and only a handful of refineries still practising the chemical refining approach at a relatively small scale based on special requests. Based on statistical data, the total production of RBD palm oil produced by physical refining versus neutralised, bleached and deodourised (NBD) palm oil produced by chemical refining for 2017 is in the ratio of 83:1 (MPOB, 2018). Hence, the LCA reported by Schmidt (2008) is considered site-specific results and only applicable for a relatively small volume of NBD palm oil, not the bulk RBD palm oil produced in Malaysia.

1.2.3 Environmental Performance and Possible Improvement Steps

Environmental improvements suggested thus far are mitigation steps at the plantations and the palm mills since very limited evaluation on the palm oil refineries have been conducted. Besides, reliable gate-to-gate LCA for palm oil refineries and biodiesel plants enable the refiners and biodiesel producers to understand their environmental performance based on current industry practices. With such information, environmental hotspots can be identified, suggestions for environmental impact mitigation for respective subsystems can be proposed and evaluated.

1.2.4 Value Choices

Evaluation of value choices for LCA e.g. allocation procedures, cut-off criteria and impact assessment methodologies were not described and elaborated comprehensively in most of the palm oil LCA studies. Mass allocation was chosen in some of the studies simply due to readily available production data without detailed analysis. Furthermore, the allocation was not applied or mentioned in some of the LCA studies. The concept of allocation was also misinterpreted. Hence, evaluation and further discussion on different allocation procedures conducted in the current study provides a clear picture of such important procedure, provides justification for such procedure and at the same time avoids wrong interpretation. Also, LCIA needs to be conducted based on the latest revised and/or improved impact assessment methodologies, avoiding the use of long-obsolete and/or superseded methodologies.

1.2.5 Continuous Improvement Exercise

LCA is a continuous improvement exercise. It is important to conduct an LCA using the latest inventory data whenever available. The previous comprehensive Malaysian LCA studies on palm oil and palm oil products were performed about a decade ago and the industry scenario may have changed. Furthermore, databases for background data have been continuously updated with more reliable industry data. More robust methodologies for environmental impact assessment have been developed, revised and updated. Hence, it is crucial to have the latest LCA study for palm oil refining, palm oil fractionation and palm biodiesel production which represent the actual performance of the industry in the country. Such a study is useful in providing the latest insight on environmental performance and providing solutions for the reduction of potential environmental impacts. The current study also provides a comparison for the production of conventional palm biodiesel with technology for the production of hydroprocessed renewable biofuels.

1.3 Objectives of the Study

The objectives of the study are:

1. To review the current practice of palm oil refining, palm oil fractionation and biodiesel/biofuel production in Malaysia.
2. To gather inventory data for palm oil refining, palm oil fractionation and biodiesel/biofuel production in Malaysia from relevant stakeholders.
3. To perform the environmental assessment for palm oil refining, palm oil fractionation and biodiesel/biofuel production in Malaysia.
4. To identify significant environmental impact contributors in palm oil refining, palm oil fractionation and biodiesel/biofuel production.
5. To recommend and evaluate ways and opportunities to minimise the potential environmental impacts.

1.4 Scope of the Study

The environmental performance for palm oil refining, palm oil fractionation and palm biodiesel/biofuel production are evaluated using the life cycle assessment (LCA) approach. The scope of this study is limited to activities in the palm oil refineries and biodiesel/biofuel plants, including the transportation of CPO from palm oil mills to palm oil refineries and the transportation of refined palm products from palm oil refineries to biodiesel plants.

CPO is the feedstock for the palm oil refining process. CPO is extracted in palm oil mills and transported to palm oil refineries for purification before it can be used in further downstream applications. Two main processes occur in palm oil refineries, namely the refining and fractionation processes. As mentioned earlier, there are two types of refining processes i.e. chemical refining and physical refining. The physical refining process is considered in the current study as it is the preferred process in local palm oil refineries due to higher refined oil yield and lower processing cost as compared to the chemical refining process (Yusof, 1996). RBD palm oil is the main product of physical refining while palm fatty acid distillate (PFAD) is the co-product. Most of the RBD palm oil produced is fractionated to produce liquid RBD palm olein and solid RBD palm stearin in the fractionation plant located in the refineries. RBD palm olein is typically used as cooking oil while RBD palm stearin is normally used as a blend with other oils to produced suitable functional products i.e. margarine fats, shortening, vanaspati and others (Noor Lida et al., 2017). Besides that, RBD palm stearin is also used for non-edible usage i.e. soap, animal feed and oleochemical feedstocks. All of the refined palm products mentioned above including PFAD are suitable feedstocks for biofuel production.

For biofuel production, two different technologies are evaluated in the current study namely transesterification and hydroprocessing technologies. Biodiesel produced from the transesterification of palm oil is the only biofuel commercially available in Malaysia. Biodiesel, or chemically known as fatty acid methyl esters (FAME), is the main product of the transesterification process while crude glycerol is the co-product. Biodiesel produced from palm oil and palm oil products is usually called palm methyl esters (PME) or palm biodiesel. Biodiesel is the only biofuel produced from the transesterification process. Typical starting materials for palm biodiesel production in Malaysia is RBD palm oil and methanol. Hydroprocessing technology is different from the transesterification process. In hydroprocessing, the fatty acids of the triglyceride molecules are cracked and followed by hydrogenation to produce hydrocarbon products. These hydrocarbon products are further isomerised and fractionated to produce various cuts of hydroprocessed biofuels, e.g. hydroprocessed renewable diesel (HRD), hydroprocessed renewable jet fuel (HRJ), hydroprocessed renewable naphtha (HRN) and propane mix gas. In other words, HRD and HRJ are the main products of the hydroprocessing process depending on process configurations and HRN and propane mix gas are the co-products. Unlike biodiesel, these hydroprocessed renewable biofuels are having similar chemical structures as their fossil counterparts. Hence, they are considered as drop-in biofuels by the industry.

1.5 Research Methodology

The LCA is conducted following ISO standards, namely ISO 14040 and ISO 14044 (ISO, 2006a & 2006b). Inventory data are obtained from palm oil refineries and palm biodiesel plants in operation in Malaysia. The inventory data for the production of hydroprocessed renewable biofuels are referred to pilot plant operation data and other published literature because there is no commercial plant available in Malaysia.

Refined palm oil products are commonly traded according to mass. Hence, the functional unit for the palm oil refining and fractionation processes is based on the production of one tonne of the refined palm products, i.e. RBD palm oil, RBD palm olein and RBD palm stearin. Palm biofuels in particular palm biodiesel, is also commonly traded according to mass. Hence, the suitable functional unit for palm biofuel production is one tonne of the biofuel produced.

ReCiPe 2016 is the chosen methodology for life cycle impact assessment (LCIA). A total of 12 midpoint impact categories are analysed. The LCIA results are further interpreted, and conclusions are deduced from the results. Detailed information on research methodology is presented in Chapter 3.

1.6 Significance of the Study

Palm oil is an important commodity for Malaysia. The palm oil industry plays a significant role in contributing to the development of the socio-economy in the country. On average, the palm oil industry has contributed 5% to 7% of Malaysia's GDP for the past years with annual export revenue of more than RM 60 billion (Balu et al., 2018). The palm oil industry has expanded significantly for the past few decades with the total planted area increased tremendously from 55 thousand hectares in 1960 to 5.90 million hectares in 2019. Nevertheless, Malaysia is keeping its promise made in the 1992 Rio Summit by maintaining more than 50% of its land as forest land (Vijaya et al., 2019). Malaysia is committed to sustainable development through various efforts such as good agriculture practices and the MSPO certification scheme.

This study will serve as a basis for comparison with the LCA studies conducted previously. The LCA is conducted based on the latest inventory data collected from relevant stakeholders and impact assessment is performed using the latest methodology. It provides possible solutions for further environmental improvement specifically at the refining and biofuel production subsystems. This study also provides information for policymaking to the government on the environmental benefits of biofuels produced from palm oil and palm products. For academic purpose, this study provides information for LCA practitioners on ways the LCA is carried out, discussion on impact assessment and interpretation of the LCA.

1.7 Thesis Outline

The thesis consists of five chapters as follows:

(a) Chapter One is the introduction section of the thesis. This section presents a brief description of the palm oil and palm oil industry in Malaysia. This section also presents the objectives, scope, methodology and significance of the current study.

(b) Chapter Two is the literature review section. This chapter illustrates in detail the palm oil refining and biofuel activities. It also summarises the LCA studies carried out for the palm oil industry with special emphasis on the refining and biofuel sectors.

(c) Chapter Three describes the research methodology that is used in conducting the research in the current study. It presents the methods, procedures, software and assumptions used.

(d) Chapter Four of the thesis describes the results of the study. Discussions on the results and scenarios are also presented in this chapter.

(e) Chapter Five is the last chapter of the thesis. It outlines the conclusion derived from the study. This section also presents some recommendations for future work.

The findings of the research work have been presented in conferences, seminars and published as journal papers. Details of the publication are listed in the List of Publications and Papers Presented.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Environmental issue has been the topic of discussion for the past decades. From just a local issue, it has emerged as an international agenda which was first discussed openly at the United Nations (UN) Conference on the Human Environment in 1972 and resulted in the establishment of the United Nations Environment Programme (UNEP) (Division of Sustainable Development Goals, 2020a). UNEP is the leading global environmental authority that sets the agenda, promotes the coherent implementation of sustainable development within the UN system and serves as an authoritative advocate for environmental related issues (UNEP, 2020).

At the 1983 UN General Assembly, a special commission i.e. World Commission on Environment and Development (WCED) was established to make available a report on environmental and global issues and to propose strategies for sustainable development. WCED published the report entitled "Our Common Future" or commonly known as Brundtland Report in 1987. Sustainable development is first defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (UNEP, 2007). The report highlighted the need for integration of economic development, natural resources management and protection and social equity and inclusion (Division of Sustainable Development Goals, 2020a). Sustainable development has been the main topic of discussion in the international arena since then.

The UN Conference on Environment and Development or Earth Summit which was held in Rio in 1992 has called for global partnership in addressing environmental problems and prepare for challenges of the 21st century (Division of Sustainable Development Goals, 2020a). A comprehensive plan of areas related to human impacts on the environment was adopted by more than 178 governments to improve human lives and protect the environment. Malaysia has also for the first time pledged to keep 50% of its land as forest cover (Embas, 2012).

RIO+20 conference was held 20 years after the Earth Summit. Once again, member states of the UN reiterated the importance of sustainable development for future generations. Member states also decided to develop a set of Sustainable Development Goals (SDGs) that converge with the post-2015 development agenda. As a result, 17 SDGs were announced and adopted by all member states at the 2015 UN General Assembly. Besides environmental efforts such as combating climate change, ocean and forests preservation, sustainable production and consumption, other humanitarian goals e.g. ending poverty and hunger, gender equality etc were also identified and adopted. Figure 2.1 depicted the 17 SDGs as identified and adopted by all member states.

Figure 2.1: 17 Sustainable Development Goals adopted by the United Nations (Division of Sustainable Development Goals, 2020b)

2.2 Environmental Management

Environmental management has undergone significant changes for the past decades along with the development of advanced technologies and environmental management principles (Mohd Nasir et al., 2006). The traditional laws and regulations which centred on the end-of-pipe treatment approach by controlling environmental load at the manufacturing stage were found not sufficient in mitigating the increasing environmental problems.

As driven by tightening of laws and regulations coupled with proliferation rising awareness by government authorities and stakeholders i.e. consumers, non-governmental organisations and the general public, industries and businesses realised the importance of environmental matters and their implications to business operation (Zilahy, 2017). Environment management was identified and adopted as an approach to improve productivity while minimising the production of waste which may potentially harm the environment, a paradigm shift from a defensive mode of problem-solving to a proactive mode of problems minimising and avoidance. Environmental management also enables industries and businesses to gain higher profits through the efficient consumption of limited natural resources.

As a result, the environmental management system (EMS) was introduced in company practice in the early 1990s (Zilahy, 2017). The establishment of the Technical Committee on Environmental Management (ISO/TC 207) in the early 1990s led to the development of an international standard on EMS which was published as ISO 14001 standard in 1996. EMS serves as a management tool enabling a corporation or organisation to evaluate its environmental performance for improvement. EMS integrates all organisation activities to environmental issues with an attempt to strive for continuous improvement.

2.3 Life Cycle Assessment

According to Finkbeiner et al. (1999), sustainable development can only be achieved if environmental management tools for both organisation i.e. EMS, and product/service i.e. life cycle assessment (LCA), are adopted.

LCA is defined as a compilation of inputs and outputs of a product system followed by an evaluation of environmental impacts of such a system throughout its life cycle (ISO, 2006a). In other words, LCA serves as a methodological tool to evaluate the environmental aspects and impacts of a product or a process. LCA helps to identify the environmental hotspots of the system evaluated and provide analysis on potential opportunities for environmental improvement. Besides, LCA also provides useful information to the industry for business decisions making, process improvement and product marketing and to the government on policy planning. Hence, LCA is a useful tool in environmental management.

Environmental management standards for LCA have been developed by the sub-committee on Life cycle assessment, ISO/TC 207/SC 5. The ISO standards listed in Table 2.1 are the international standards, technical specifications (TS) and technical reports (TR) developed for environmental management by ISO/TC 207 and its subcommittees. The ISO 14040 and 14070 series are dedicated to LCA (Finkbeiner, 2013). The ISO 14040 established the principles and framework of an LCA study while the requirements and guidelines are stipulated in ISO 14044 (ISO, 2006a; ISO, 2006b). ISO 14044 was published in 2006, combined and superseded the three standards of ISO 14041, 14042 and 14043 (Finkbeiner et al., 2006). For single impact category LCA, ISO 14046 and 14067 were established respectively for water footprint and carbon footprint.

Table 2.1: Selected ISO standards on environmental management system and life cycle assessment (ISO, 2020)

ISO Standard/document	Title
14001:2015	Environmental management systems - Requirements with guidance for use
14002-1:2019	Environmental management systems - Guidelines for using ISO 14001 to address environmental aspects and conditions within an environmental topic area – Part 1: General
14004:2016	Environmental management systems - General guidelines on implementation
14005:2019	Environmental management systems - Guidelines for a flexible approach to phased implementation
14006:2020	Environmental management systems – Guidelines for incorporating ecodesign
14040:2006	Environmental management - Life cycle assessment - Principles and framework
14044:2006	Environmental management - Life cycle assessment - Requirements and guidelines
14044:2006/AMD 1:2017	Environmental management - Life cycle assessment - Requirements and guidelines – Amendment 1
14045:2012	Environmental management - Eco-efficiency assessment of product systems - Principles, requirements and guidelines
14046:2014	Environmental management - Water footprint - Principles, requirements and guidelines
TR 14047:2012	Environmental management - Life cycle assessment – Illustrative examples on how to apply ISO 14044 to impact assessment situations
TS 14048:2002	Environmental management - Life cycle assessment – Data documentation format
TR 14049:2012	Environmental management - Life cycle assessment – Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
TS 14071:2014	Environmental management - Life cycle assessment – Critical review processes and reviewer competencies: Additional requirement and guidelines to ISO 14044:2006
TS 14072:2014	Environmental management - Life cycle assessment – Requirements and guidelines for organizational life cycle assessment
TR 14073:2017	Environmental management – Water footprint – Illustrative examples on how to apply ISO 14046
14067:2018	Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification

2.3.1 Life Cycle Assessment Framework

As stipulated in ISO 14040, there are four phases in an LCA study namely goal and scope definition, inventory analysis, impact assessment and interpretation. The relationship between these four phases is illustrated in Figure 2.2.

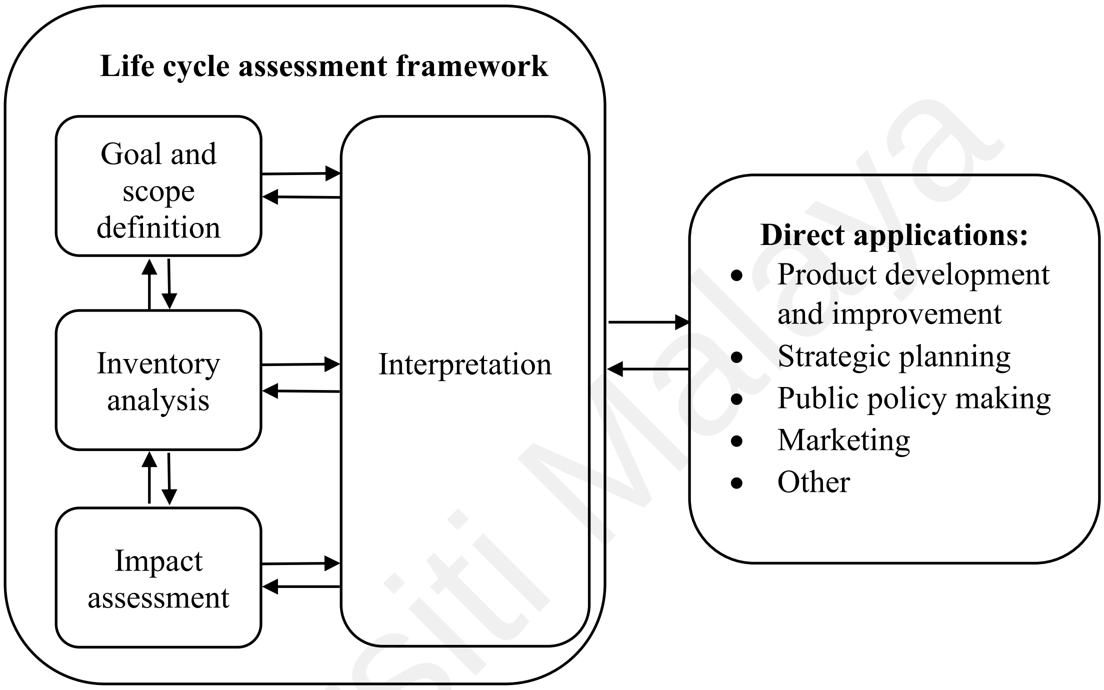


Figure 2.2: Stages of a life cycle assessment (ISO, 2006a)

2.3.2 Goal and Scope Definition

The first phase of an LCA study is to define the goal and the scope of the LCA study. The goal states the objectives and the reasons the study is conducted. It also discloses the targeted group to whom the results are to be communicated and whether the results are intended to be used in comparative assertions intended to be disclosed to the public. The scope covers the following items:

a) The product system to be studied

b) The functions of the product system

c) The functional unit

d) The system boundary

e) Allocation methods

f) Data requirements for the LCA study

g) Data quality requirements

h) Life cycle impact assessment (LCIA) methodology and impact categories

i) Interpretation of the results

j) Assumptions made

k) Limitations of the LCA study

2.3.3 Life Cycle Inventory Analysis

The life cycle inventory analysis involves the collection and calculation of inventory data in the product system within the defined system boundary. LCA is conducted by gathering the inventory data of the respective processes involved. The inventory data include the input to the process such as raw materials, chemicals, energy and utilities required and the product output including co-product and by-product if any. Other outputs such as emissions and waste materials associated with the activities within the scope and system boundary of the study are also included in the inventory list. The potential impact on the environment is generated using relevant impact assessment methodology.

Inventory data can be either foreground or background data. Foreground data are related specifically to the product system evaluated and it is based on actual plant operation, measurements on-site and records. Foreground data are collected from the primary source. Background data are generally not specifically related to the product system and may be obtained on average or ranges from published literature and/or statistics. Data calculation includes validation of the data collected, relating the data to a unit process and with reference to the functional unit as set previously. For a product system that involves more than one product, a proper allocation must be conducted to distribute the burden among the products according to suitable allocation procedures. Commonly, an allocation is made according to the material balance of the system based on the mass ratio among the products and co-products. Allocation based on energy content and economic value are the alternative options.

2.3.4 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is the third phase of an LCA study. It is aimed to evaluate the inventory data collected and calculated in the inventory analysis phase, by linking the inventory data to their environmental impacts (ISO, 2006b). Different steps involved in this phase are classification of various emissions into different impact categories, characterization of midpoint impacts or endpoint impacts by multiplying emission with predefined midpoint or endpoint characterization factors. This is to facilitate the comparison of impacts contributed by different emissions in which the emission units can be very different from each other. LCIA shall be carefully conducted to meet the goal and scope of the study (ISO, 2006b). The environmental impacts can be presented in midpoint impact or endpoint damages, depending on the methodology used. Some examples of the LCIA methodologies are listed below:

a) CML92
b) Eco-indicator 99
c) TRACI
d) IMPACT 2002+
e) IMPACT World+
f) LIME
g) ReCiPe 2016
h) ILCD
i) USEtox

2.3.4.1 Eco-indicator 99

Eco-indicator 99 is one of the methods to consistently measure damage to human health, ecosystem quality and resources. Damage to human health is expressed in equivalent years of life lost as disability-adjusted life year (DALY). It includes respiratory and carcinogenic effects, global warming, destruction of ozone and ionising radiation. Damage to ecosystem quality is expressed as a percentage of extinct species in a certain area due to the environmental burden. This includes the effects of ecotoxicity, acidification, eutrophication and land use. The extraction of mineral and fossil resources is characterised by the excess energy required for future extractions. Eco-indicator 99 was developed based on European scenarios. It is now de-facto replaced by the ReCiPe methods (Jolliet et al., 2015).

2.3.4.2 ReCiPe 2016

ReCiPe 2008 was developed in the effort to combine the midpoint approach of the CML method with the damage approach of the Eco-indicator 99 method (Goedkoop et al., 2009). ReCiPe 2008 was upgraded to ReCiPe 2016 which comprises three damage categories and 18 midpoint impact categories. The three damage categories are similar to those described in Eco-indicator 99. Similar to Eco-indicator 99, the ReCiPe 2008 method focus on a European scale. However, characterisation factors for the global scale are introduced in the latest ReCiPe 2016 method (Huijbregts et al., 2017). The general structure of ReCiPe 2016 is illustrated in Figure 2.3.

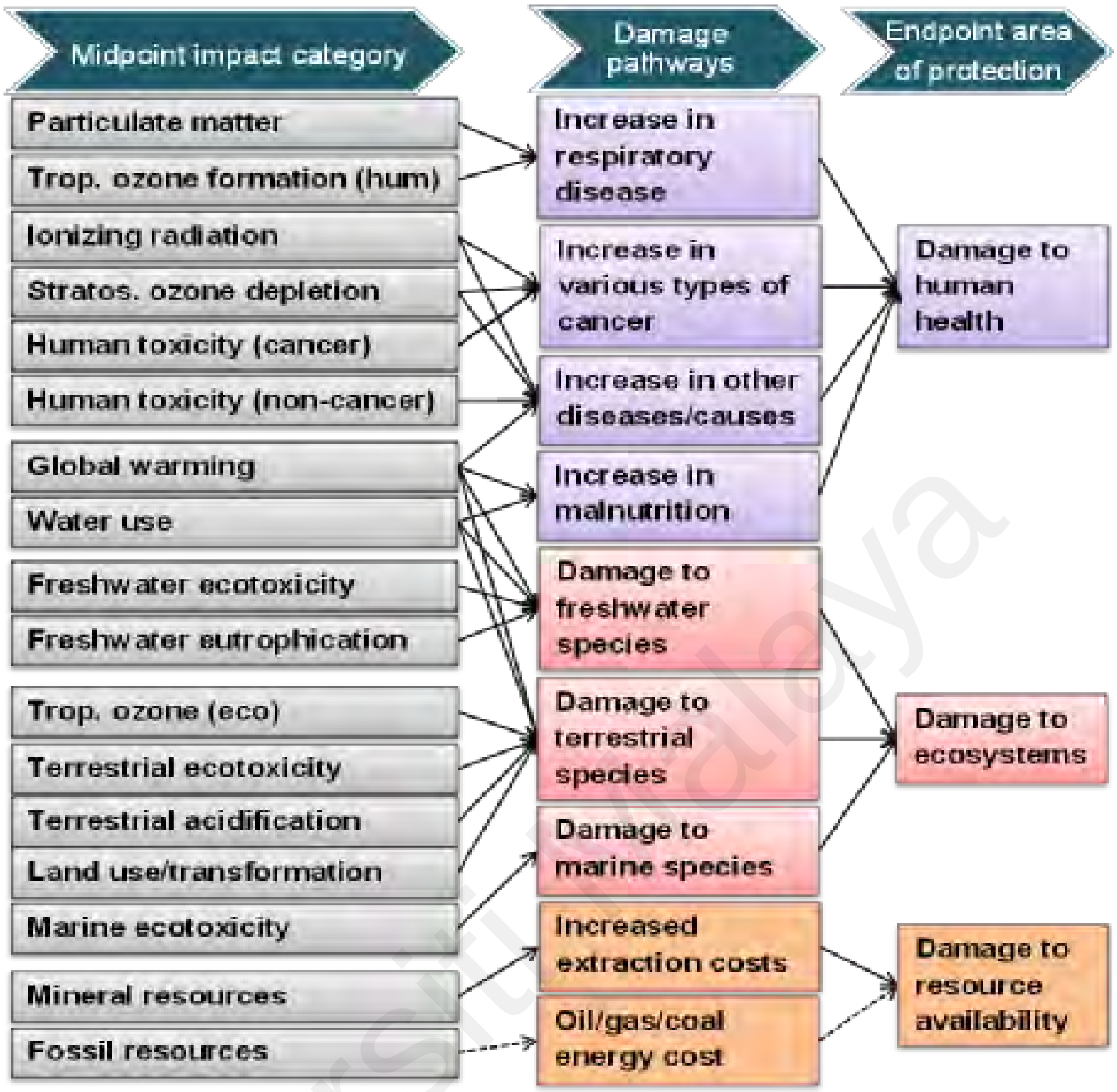


Figure 2.3: Overview of the impact categories in ReCiPe 2016 (Huijbregts et al., 2017)

2.3.5 Life Cycle Interpretation

The findings from the inventory analysis and the impact assessment are considered together in the interpretation phase (ISO, 2006a). Based on the results of the preceding inventory analysis and impact assessment phases, the interpretation phase aimed at identifying the significant environmental impact category of a process or product at the life cycle stage. Also, the quality and robustness of the results are assessed using a series of checks e.g. sensitivity analysis and uncertainty analysis. The interpretation phase should deliver results that are consistent with the goal and scope defined earlier enabling the LCA practitioner to conclude the LCA study, explain the limitations of the study and provide recommendations for future study.

2.4 Life Cycle Assessment Software

As mentioned previously, a large amount of data is needed for an LCA study thus making manual calculation very tedious and time-consuming. To simplify the calculation and to minimise human errors in mathematic calculation, LCA software is developed. The modern LCA software is equipped with databases enabling fast and easy impact assessment and interpretation. Some of the LCA software programmes available in the market are listed below:

a) SimaPro
b) GaBi
c) Quantis suite
d) openLCA
e) Brightway2
f) Chain management by life cycle assessment (CMLCA)

SimaPro is one of the well-accepted and well-recognised software specially developed for LCA study. It simplified the presentation and interpretation of inventory and impact assessment results (PRé Consultants, 2017). The contribution of each unit process is reviewed in detail by the SimaPro software. GaBi is particularly relevant for industrial applications in the automotive and electronic sectors. It is based on the fundamental work on LCA at the University of Stuttgart (GaBi, 2003). Both SimaPro and GaBi are commercial software and subscription fees are needed. However, there is also some free software available in the market such as openLCA, Brightway2 and CMLCA.

2.5 The Malaysian Palm Oil Industry

The oil palm tree was first introduced to Malaysia as an ornamental plant in 1870 (Tang, 2009). The palm species, *Elaeis guineensis* is originated from West Africa. In 1917, the first commercial planting of oil palm was undertaken in Tennamaran, Selangor (Anuar, 2015). However, large scale commercial cultivation of oil palm was only started in the 1960s due to crops diversification programme and an effort to avoid over-dependence on natural rubber which was the major commodity then. The palm oil industry has grown by leaps and bounds for the past six decades and presently it has emerged as the most remunerative agricultural commodity in Malaysia.

Oil palm grows well in the tropical climate within 5° north and south of the equator (Yusof, 1996). The ideal growing conditions of oil palm trees include rainfall of over 2000 mm per year spread evenly throughout the year and more than 2000 hours of sunshine per annum with a moderately high temperature of 25 to 33°C. The current oil palm planted in Malaysia is *Tenera*, a crossbred of *Dura* and *Pisifera,* which yields about four tonnes of palm oil and 0.5 tonnes of palm kernel oil per hectare per year (Tang, 2009).

The oil palm tree is a perennial crop with an economic life of about 25 years. Harvesting of palm fruits in the form of a fresh fruit bunch (FFB) begins 30 months after field planting (Tang, 2009). FFB weighs approximately 10 to 50 kg and consists of up to

2000 fruits per bunch. The palm fruit is about the size of a plum. Each fruit comprises exocarp (skin), mesocarp, endocarp (shell) and kernel (seed). The mesocarp contains about 49% palm oil and the kernel contains about 50% palm kernel oil.

The total oil palm planted area in Malaysia was only recorded at about 55 thousand hectares in the early days of commercial planting in 1960 (Anuar, 2015). The cultivation area expanded more than 11 folds to 642 thousand hectares in 1975, the year which the official figure was captured and published annually (Figure 2.4). Subsequently, the oil palm cultivated area in Malaysia has expanded rapidly to one million, two million and four million hectares in 1980, 1990 and 2005. With the significant expansion mainly in Sabah and Sarawak for the past 20 years, the total oil palm cultivated area has reached 5.90 million hectares in 2019. Sarawak is currently the largest oil palm planted state with 1.59 million hectares, closely followed by Sabah with 1.54 million hectares. The remaining 2.77 million hectares or 46.93% are spread across 11 states in Peninsular Malaysia.

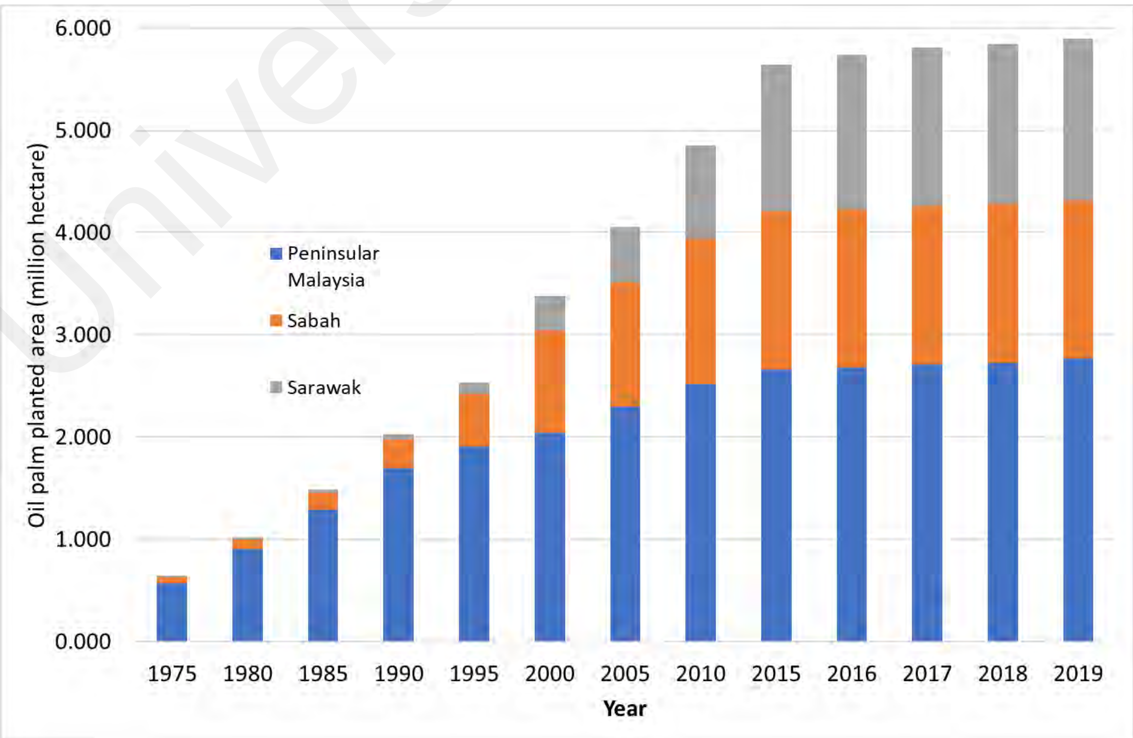


Figure 2.4: Expansion of oil palm planted area in Malaysia (MPOB, 2020a)

In terms of ownership, 61.11% of the total planted area or 3.61 million hectares of oil palm cultivation land are owned by private estates (Figure 2.5). It is followed by the independent smallholders, 0.99 million hectares or 16.72%. Government agencies such as the Federal Land Development Authority (FELDA), the Federal Land Consolidation and Rehabilitation Authority (FELCRA) and the Rubber Industry Smallholder Development Authority (RISDA) collectively owned 16.63% of the total cultivated area. The remaining 5.55% are owned through state schemes i.e. the Sabah Land Development Board, the Sarawak Land Development Board and the Sarawak Land Consolidation and Rehabilitation Authority.

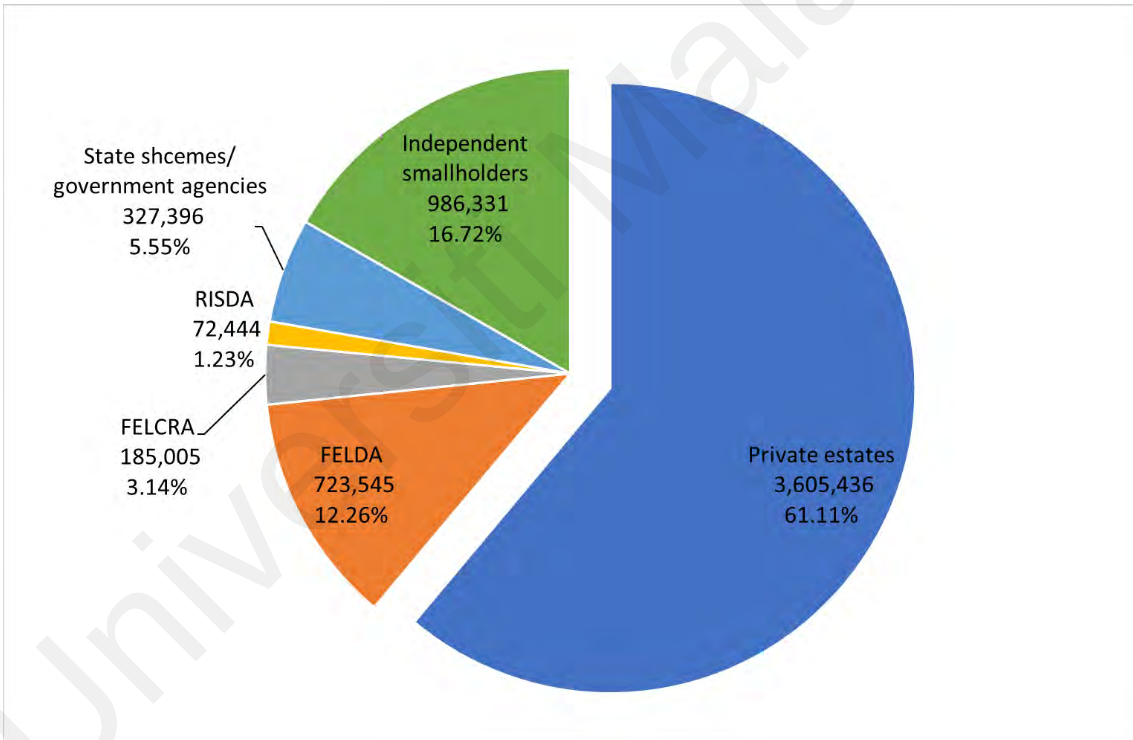


Figure 2.5: Distribution of oil palm cultivation by category (hectare) (MPOB, 2019)

The harvested FFBs are transported to nearby palm oil mills for processing and oil extraction (Khairudin *et al.*, 2012). In 2019, a total of 452 palm oil mills were in operation in the country with a total processing capacity of 112.91 million tonnes of FFB per annum (Ahmad Parveez et al., 2020). 241 of the mills are located in Peninsular Malaysia while 130 and 81 palm oil mills are located in Sabah and Sarawak, respectively. The production of CPO in 2019 was recorded at 19.86 million tonnes. Sabah is the largest CPO producing state with 5.04 million tonnes and it is followed by Sarawak with 4.24 million tonnes. The remaining 10.58 million tonnes of CPO were produced in Peninsular Malaysia.

2.6 Palm Oil Refining and Fractionation in Malaysia

CPO extracted from the mesocarp of palm fruit contains a small number of impurities and undesirable components such as gums, free fatty acids, heavy metals, colour pigments, etc. (Yusof, 1996). Palm oil refining is a process to remove these impurities to produce a clean, palatable and attractive looking refined oil suitable for both edible and non-edible usages. CPO is typically transported from palm oil mills to palm oil refineries via road tankers. Palm oil refineries are typically located near to port area to facilitate the export of refined palm products.

In 2019, 51 palm oil refineries were in operation in Malaysia with a total refining capacity of 26.63 million tonnes of CPO and crude palm kernel oil (Ahmad Parveez, 2020). 34 of the refineries with a total capacity of 15.33 million tonnes are located in Peninsular Malaysia while 10 and 7 refineries are located in Sabah and Sarawak, respectively. Most of the CPO produced in Malaysia are processed in these refineries before they are used locally or exported overseas. In 2019, 17.66 million tonnes of CPO were processed in these refineries to produce various refined palm products i.e. RBD palm oil, RBD palm olein, RBD palm stearin and PFAD. Most of these refined palm products are produced for the export market. The total export volume of RBD palm oil, RBD palm olein, RBD palm stearin and PFAD in 2019 was recorded at 12.08 million tonnes (MPOB, 2020a).

There are two types of CPO refining processes, namely chemical refining and physical refining. These two processes differed in the way free fatty acids are removed from the oil. CPO typically consists of 3-5% free fatty acids. Chemical refining utilises caustic soda to neutralise the free fatty acids, resulting 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, free fatty acids are removed from the oil at the deodorisation step as PFAD. It is estimated that the cost of chemical refining is two to three times higher than physical refining (Yusof, 1996). Hence, physical refining is the preferred choice due to the advantages of low processing cost and high refining efficiency. Also, different terminology is used to differentiate the products of the chemical and the physical refining. The refined palm oil obtained from chemical refining is called neutralised, bleached and deodorised (NBD) palm oil while RBD palm oil is the product of physical refining. Most of the CPO is physically refined in Malaysia. For example, the production of RBD palm oil and NBD palm oil in 2017 was recorded at 14.9 million tonnes and 180 thousand tonnes, respectively (MPOB, 2018).

Figure 2.6 shows the steps involved in a physical refining process. The first step is a degumming process. CPO is heated to 90-110 °C before food grade phosphoric acid is added. The mixture is allowed to react for 15-30 minutes before the removal of gum in the subsequent step. Bleaching is carried out in a stainless-steel vessel at 95 °C under vacuum for 30 minutes. Bleaching earth or activated clay is then added to the degummed oil to absorb the phospholipids precipitated by the phosphoric acid added in the previous step. Bleaching earth also helps to absorb other undesirable impurities such as trace metals and colour pigments. The level of oxidation products is reduced in the bleaching step. Sufficient agitation is needed to ensure good contact between the oil and the bleaching earth or clay. The quantity of bleaching earth used ranges from 1 to 2%, depending on the quality of the CPO. The degummed and bleached oil is then cooled to 60-70 °C and spent bleaching earth is removed through filtration. Spent bleaching earth usually contains about 20% of oil and this is the only oil loss in the refining process. Deodorisation is the final step. It is a distillation process carried out at 240-270 °C under vacuum pressure of 2-5 mm Hg. Free fatty acids are removed from oil as PFAD. The oil produced is generally known as RBD palm oil.

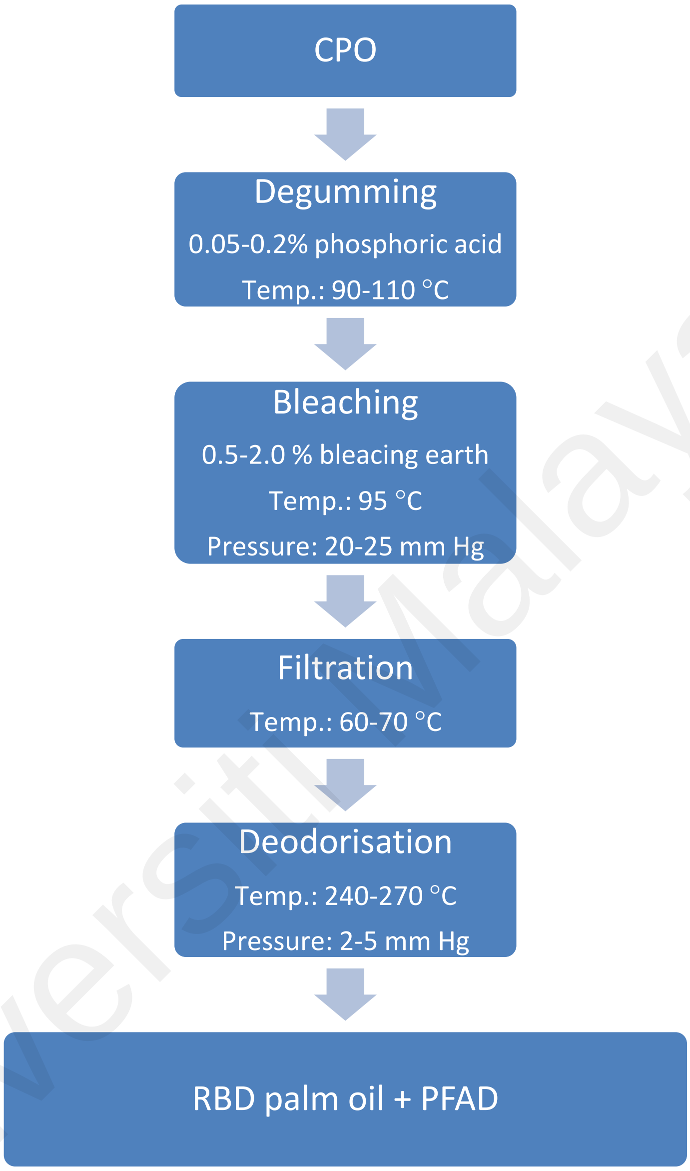


Figure 2.6: Process flow diagram of the physical refining process

The physical appearance of RBD palm oil is in semi-solid form at room temperature. Most of the RBD palm oil produced in the refineries is fractionated in the same premises. In the fractionation process, RBD palm oil is first cooled in crystallisers followed by filtration in a membrane filter press, to separate the liquid from a solid fraction (Figure 2.7). The liquid fraction, RBD palm olein is mainly used as cooking oil, in pure form or blended with other soft oil. The palm oil fractionation process is a physical separation process and no chemical is consumed. In 2019, 89.55% of the total RBD palm oil produced were fractionated to produce 11.460 million tonnes of RBD palm olein and 3.217 million tonnes of RBD palm stearin (MPOB, 2020a). These refined palm products including RBD palm oil and PFAD are commodity products commercially traded in the open market.

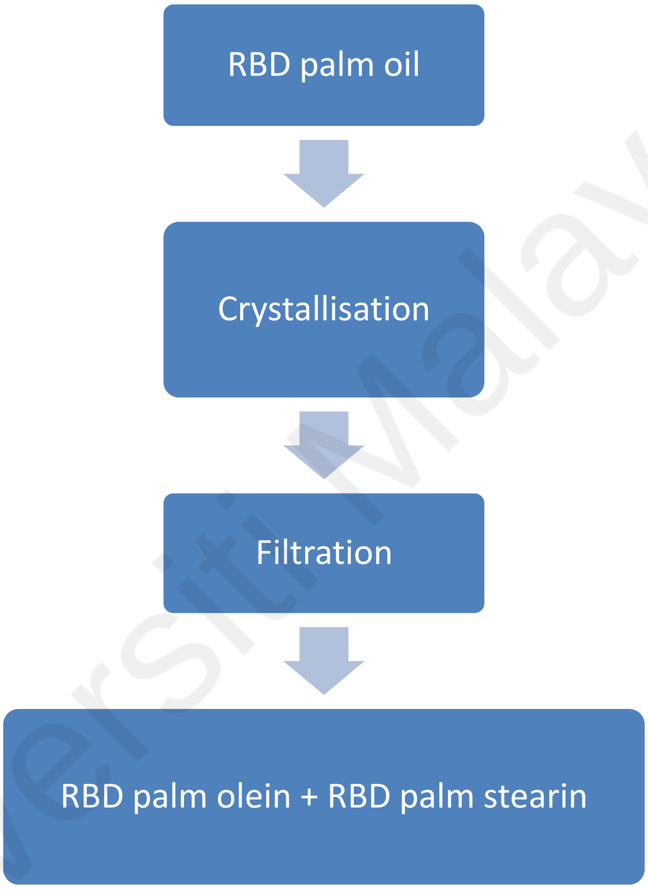


Figure 2.7: Process flow diagram of palm oil fractionation process

2.7 Palm Biodiesel in Malaysia

Increasing concern on the environment in particular carbon emissions, fluctuation in oil price and rapid technological advancement have catalysed the search for renewable fuels in particular biofuels to replace conventional fossil-based fuels. Today, biodiesel has emerged as an important alternative fuel. The total biodiesel production in the world was recorded at 33.34 million tonnes in 2018 (Bockey, 2019).

Biodiesel is defined as mono-alkyl esters of long-chain fatty acids derived from renewable lipid sources such as vegetable oils and animal fats (ASTM International, 2019). Biodiesel is a petroleum diesel substitute and it is used in compression ignition engines with little or no modification (Choo et al., 1997). It has physical properties similar to petroleum diesel (Knothe & Dunn, 2001). It is widely used as a blending stock for petroleum diesel.

MPOB has embarked on research and development of palm biodiesel or palm methyl esters (PME) way back in 1982 (Choo et al., 1997). The first pilot plant for the production of palm biodiesel was constructed in 1985. Subsequently, exhaustive field trials were carried out in collaboration with various parties, in particular, the Mercedes Benz-AG, Germany. The trials had concluded that PME is a suitable substitute for petroleum diesel with several benefits such as reduction of black smoke and improvement in cetane number (Choo et al., 1997). However, due to economic reasons, palm biodiesel was only commercially available in Malaysia in 2006. To date, there are a total of 33 commercial biodiesel plants in Malaysia with a total installed capacity of 3.686 million tonnes per annum (Lau et al., 2019). However, only 19 biodiesel plants were in commercial operation in 2019 (MPOB, 2020a).

B5 diesel, a blend of 5% palm biodiesel with 95% petroleum diesel based on volume percentage was introduced to the petrol stations to replace conventional petroleum diesel in June 2011 (Yung et al., 2016). The B5 programme was initiated in Putrajaya and gradually expanded to the whole of Peninsular Malaysia by the first quarter of 2014. In November 2014, the biodiesel blending ratio was increased from 5% to 7%. Subsequently, B7 diesel was introduced to petrol stations in East Malaysia i.e. Sabah, Sarawak and Labuan in the following months. In December 2018, the government has announced to raise the biodiesel content to 10% and B10 diesel was mandated in all petrol stations in Malaysia starting February 2019. Besides the transportation sector, B7 diesel was introduced to the industrial sector in July 2019. B20 diesel was mandated to replace the B10 diesel in the coming years. To date, B20 diesel has been made available in Langkawi, Labuan and Sarawak. The B20 diesel will be mandated in petrol stations throughout the country in stages according to the readiness of the blending facilities at oil depots.

The commercial production of palm biodiesel in Malaysia began in 2006 with the setting up of three commercial biodiesel plants. The total production of palm biodiesel in Malaysia was registered at 55 thousand tonnes then (Lau, 2018). With 15 plants in commercial production in 2018, the annual production volume of palm biodiesel had then exceeded one million tonnes. Out of the total biodiesel produced, 515 thousand tonnes were exported, generating export earnings of RM 1.43 billion (MPOB, 2019). 429 thousand tonnes of palm biodiesel were utilised for the biodiesel programme locally (Unnithan, 2019).

RBD palm oil is the typical feedstock for biodiesel production in Malaysia. During biodiesel manufacturing, RBD palm oil is reacted with methanol in the presence of an alkaline catalyst to produce palm biodiesel (Figure 2.8). The transesterification reaction is carried out at 60°C under atmospheric pressure (Van Gerpen & Knothe, 2010).

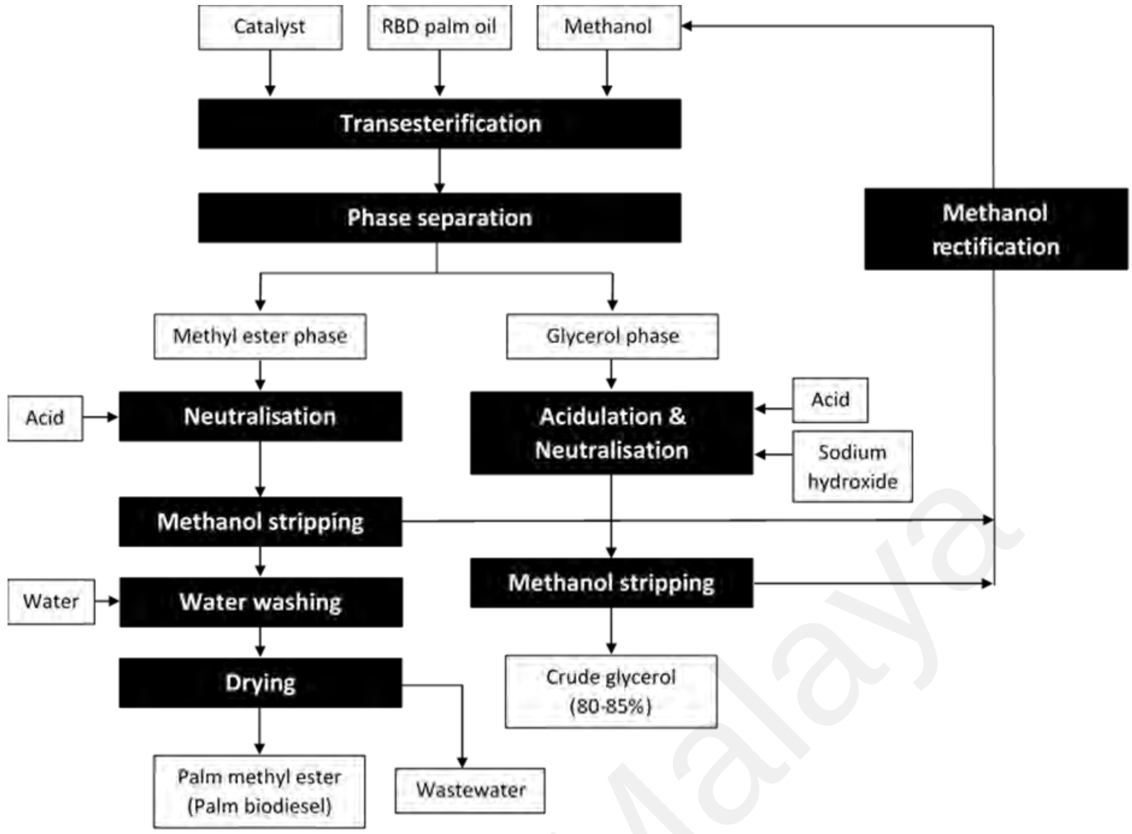


Figure 2.8: Process flow chart for the production of palm biodiesel

Commercially, the transesterification reaction is typically performed in stages with two or three reactors in a continuous flow system. Glycerol, the co-product of the transesterification reaction, is separated from the methyl ester phase in settling tanks by gravity. The phase separation can be expedited using a centrifuge system. Upon removal of the glycerol phase, acid is used to neutralise the residual catalyst in the methyl ester phase. At the same time, it also helps to split any soap that is formed between the alkaline catalyst and free fatty acids. Soap reacts with an acid to form water-soluble salts which will be removed by the water washing process. As a cost-saving measure, excess methanol removed from both methyl ester and glycerol phase is recovered, purified and reused in the transesterification reaction. Any remaining catalyst, soaps, salts, methanol and free glycerol are further removed from methyl ester during water washing. Lastly, water is removed from the methyl ester by a vacuum dryer to produce PME with water content below 500 mg/kg. Dried PME is stored at a bulk storage facility and ready to be used as biodiesel. The glycerol produced is also subjected to a series of purification, *i.e.* acidulation, neutralisation and methanol recovery to produce crude glycerol with a purity of 80% to 85%. Crude glycerol is typically sold to glycerol refiners for further purification before it is used for other downstream applications.

2.8 Hydroprocessed Renewable Diesel and Jet Fuel

Biodiesel is an oxygenated fuel and its usage in diesel vehicles is limited due to its unknown effects on vehicle exhaust treatment systems, combustion performance and material compatibility for high biodiesel blends. Hence, vehicle manufacturers e.g. Japanese Automobile Manufacturers Association (JAMA) has issued certain requirements for the use of palm biodiesel in Japanese diesel vehicles (JAMA, 2016).

Besides the commonly known palm biodiesel, palm oil and palm oil products can be converted into other types of biofuel through hydroprocessing technology. Biofuels produced from hydroprocessing technology do not face such limitations as biodiesel because they are mixtures of hydrocarbons having chemical structures that mimic fossil-based fuels e.g. gasoline, diesel or jet fuel. Hence, suitable cuts of the biofuel can be used for petrol, diesel or jet engines. Figure 2.9 showed a typical schematic process for hydroprocessing technology. Oils and fats are hydrogenated and deoxygenated in reaction zone R1. The deoxygenated oil is subjected to catalytic hydrocracking and isomerisation in the second reaction zone, R2. Upon separation and distillation, various biofuels are produced namely hydroprocessed renewable diesel (HRD), jet fuel (HRJ), naphtha (HRN) and propane mix gas. The parameter of the reaction can be adjusted for solely producing HRD with HRN and propane mix gas as co-products or HRJ as the main product with HRD, HRN and propane mix gas as co-products. Hydrogen gas is an important reactant for the reaction zones R1 and R2. Typically, hydrogen is produced through the steam methane reforming process using natural gas as feedstock.

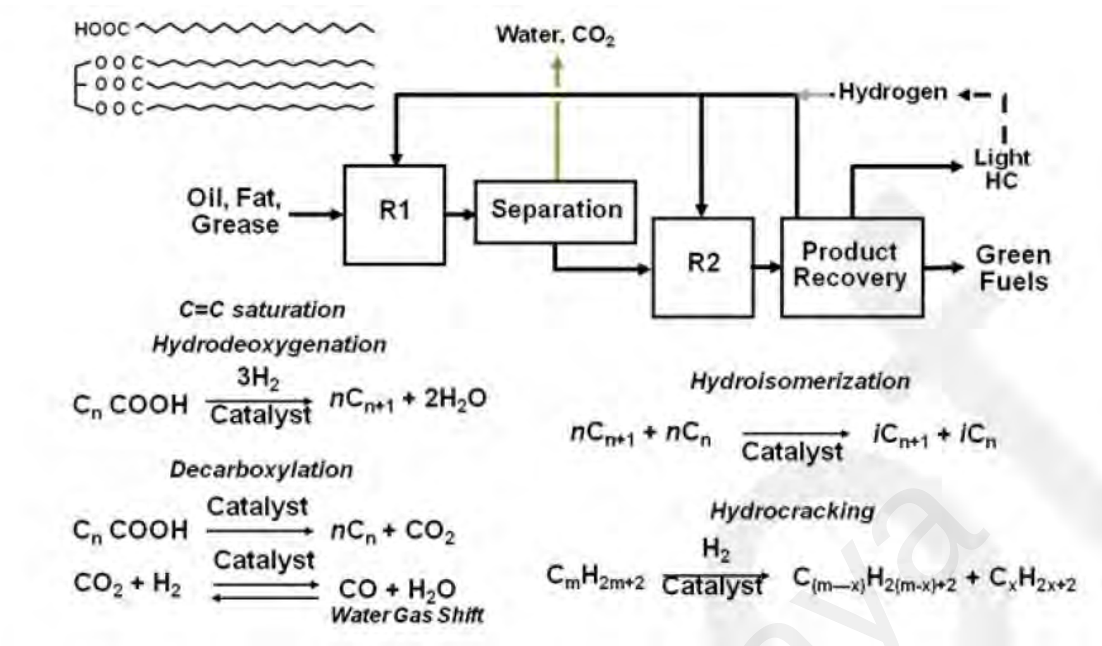


Figure 2.9: Overview of UOP renewable fuel process (Kalnes et al., 2009)

2.9 Previous Works on Life Cycle Assessment

2.9.1 Life Cycle Assessment of Palm Oil and Palm Biodiesel

A summary of the previous works on LCA of palm oil and palm biodiesel is listed in Table 2.2.

Sumiani and Hansen (2007) performed a screening LCA for CPO production in Malaysia. The system boundary of the study starts from oil palm cultivation in plantation, transportation of FFB from plantation to palm oil mill, and ends at CPO production in the palm oil mill. The functional unit of the LCA is the production of 1000 kg of CPO in Malaysia. The LCA is intended to serve as a guide for the LCA community in the country. The LCA was conducted based on inventory data collected mainly from secondary sources i.e. published literature and statistics. LCIA was performed according to the Eco-indicator 99 methodology. It was reported that the production of synthetic fertilisers, transportation of FFB and boiler emissions are the main contributors to the environmental impacts of fossil fuels depletion and respiratory inorganics. Due to lack of credible data, the study has omitted the treatment of palm oil mill effluent (POME) and biogas emissions from POME which is an important section in the palm oil milling stage. Also, no allocation of environmental burdens between the main product and co-product was conducted.

Schmidt (2008) conducted a cradle-to-gate LCA for the production of palm oil at United Plantations Berhad (UP). The functional unit of this LCA is one tonne of refined palm oil produced from a palm oil refinery in Malaysia. In this study, inventory data were collected from UP's operations in Malaysia which consist of nine oil palm estates, six palm oil mills and a palm oil refinery. Stepwise 2006 version 1.1 method was the chosen LCIA method in the study and a total of 14 midpoint impact categories were evaluated. It was reported that the environmental impacts are mostly contributed by oil palm plantation and palm oil mill subsystems. Hence, the proposed improvement options were focused on these two stages such as avoiding planting of oil palm on peat soil and biogas trapping for electricity generation in palm oil mills. Other LCIA methods such as EDIP97, Impact 2002+ and Eco-indicator 99 were evaluated as compared with the Stepwise method in the sensitivity analysis. Consistent results were reported for environmental impacts on global warming, acidification, eutrophication and photochemical smog. However, a significant difference is observed for the ecotoxicity impact category. Nevertheless, it must be noted that the results of this study only represent the chemical refining of palm oil based on UP's operation. Furthermore, the combination of refined palm oil and refined palm kernel oil were assumed in the context of one tonne of refined palm oil produced from the refinery, the functional unit of the LCA study.

Table 2.2: LCA studies on palm oil and palm biodiesel

Source	**Description of study**	**Method**	**Source of inventory data**
Sumiani and Hansen (2007)	LCA of CPO production in Malaysia	System boundary: Cradle-to-gate. Plantation and mill. Functional unit: 1000 kg of CPO produced Allocation procedure: No allocation Software: SimaPro 5 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use, Minerals and Fossil fuels.	Secondary data from published literature.
Schmidt (2008)	LCA of palm oil at United Plantations Berhad	System boundary: Cradle-to-gate. Plantation, mill and refinery. Consequential LCA Functional unit: 1 tonne of NBD palm oil (palm oil and palm kernel oil) produced. Allocation procedure: System expansion Software: SimaPro 7.1 LCIA: Stepwise 2006 Ver. 1.1 Impact categories: 14 midpoint impact categories. Global warming, Nature occupation, Acidification, Eutrophication (aquatic & terrestrial), Photochemical ozone, Respiratory inorganics, Respiratory organics, Human toxicity (carcinogens & non-carcinogens), Ecotoxicity (aquatic & terrestrial), Ozone layer depletion & Non-renewable energy.	Primary data collected from 9 oil palm estates, 6 palm oil mills and 1 palm oil refinery.
Yee et al. (2009)	LCA of palm biodiesel in Malaysia	System boundary: Cradle-to-gate. Plantation, mill and biodiesel plant. Functional unit: 1 tonne of palm biodiesel produced. Allocation procedure: No information. Software: No information. LCIA: No information.	Secondary data from published literature.

Source	Description of study	Method	Source of inventory data
		Impact categories: Greenhouse gas (GHG) emissions and energy balance.	
de Souza et al. (2010)	GHG emissions and energy balance of palm biodiesel in Brazil	System boundary: Cradle-to-gate. Nursery, plantation, mill and biodiesel plant. Functional unit: 1 hectare of palm tree. Allocation procedure: mass allocation. Software: No information. LCIA: No information. Impact categories: GHG emissions and energy balance.	Secondary data from published literature.
Halimah et al. (2010)	LCA of oil palm seedling production in Malaysia	System boundary: Cradle-to-gate. Nursery. Functional unit: 1 oil palm seedling produced. Allocation procedure: No allocation. Software: SimaPro 7.1 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use, Minerals and Fossil fuels.	Primary data collected from 21 oil palm nurseries.
Zulkifli et al. (2010)	LCA of FFB production in Malaysia	System boundary: Cradle-to-gate. Nursery and plantation. Functional unit: 1 tonne of FFB produced. Allocation procedure: No allocation. Software: SimaPro 7.1 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use, Minerals and Fossil fuels.	Primary data collected from 102 plantations.

Source	Description of study	Method	Source of inventory data
Vijaya et al. (2010)	LCA of CPO production in Malaysia	System boundary: Cradle-to-gate. Nursery, plantation and mill. Functional unit: 1 tonne of CPO produced. Allocation procedure: Mass allocation. Software: SimaPro 7.1 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use, Minerals and Fossil fuels.	Primary data collected from 12 palm oil mills.
Tan et al. (2010)	LCA of RBD palm oil production and fractionation in Malaysia	System boundary: Cradle-to-gate. Nursery, plantation, mill and refinery. Functional unit: 1 tonne of RBD palm oil produced, 1 tonne of RBD palm olein produced, 1 tonne of RBD palm stearin produced. Allocation procedure: Mass allocation. Software: SimaPro 7.1 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use, Minerals and Fossil fuels.	Primary data collected from 11 refineries.
Puah et al. (2010)	LCA for production and use of palm biodiesel in Malaysia	System boundary: Cradle-to-grave. Nursery, plantation, mill, refinery, biodiesel plant and combustion. Functional unit: 1 MJ of palm biodiesel produced and used in diesel engine vehicles. Allocation procedure: Mass allocation. Software: SimaPro 7.1 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change,	Primary data collected from 2 biodiesel plants.

Source	Description of study	Method	Source of inventory data
		Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use, Minerals and Fossil fuels.	
Choo et al. (2011)	GHG contributions in oil palm supply chain in Malaysia	System boundary: Cradle-to-grave. Nursery, plantation, mill, refinery, biodiesel plant and biodiesel combustion. Functional unit: 1 tonne of FFB produced, 1 tonne of CPO produced, 1 tonne of refined palm oil produced, 1 MJ of biodiesel produced and used in diesel engine vehicles. Allocation procedure: Mass allocation. Software: SimaPro 7.1 LCIA: Eco-indicator 99 Impact categories: GHG emissions.	Halimah et al. (2010), Zulkifli et al. (2010), Vijaya et al. (2010), Tan et al. (2010) and Puah et al. (2010).
Mohd Nor et al. (2011)	Life cycle GHG emissions of Malaysian palm biodiesel	System boundary: Cradle-to-grave. Plantation, mill, refinery, biodiesel plant and biodiesel combustion. Functional unit: 1 MJ of biodiesel domestic consumption. Allocation procedure: No allocation. Software: No information. LCIA: IPCC 4th report Impact categories: GHG emissions	Secondary data from published literature and public data.
Sampattagul et al. (2011)	LCA of palm biodiesel production in Thailand	System boundary: Cradle-to-grave. Plantation, mill, biodiesel plant and biodiesel combustion. Functional unit: 1 litre of biodiesel. Allocation procedure: No allocation. Software: SimaPro 7.1 LCIA: EDIP method. Impact categories: Global warming potential	Primary data obtained from oil palm agricultural area, palm oil mill and biodiesel production plant located in Krabi, Thailand. Secondary data on biodiesel utilisation

Source	Description of study	Method	Source of inventory data
			obtained from published literature.
Silalertruksa and Gheewala (2012)	Environmental sustainability of palm biodiesel production in Thailand	System boundary: Cradle-to-gate. Plantation, mill and biodiesel plant. Functional unit: 1000 litre of palm biodiesel produced. Allocation procedure: Economic allocation. Software: No information. LCIA: CML 2 method. Impact categories: 6 midpoint impact categories. Land use, Global warming, Photochemical oxidation, Acidification, Human toxicity, Eutrophication.	Secondary data from published literature.
Schneider and Finkbeiner (2013)	LCA of EU oilseed crushing and vegetable oil refining	System boundary: Gate-to-gate. Oilseed crushing plant and vegetable oil refinery. Functional unit: 1 tonne of refined vegetable oil produced. Allocation procedure: Energy allocation. Software: GaBi5. LCIA: CML Impact categories: 5 midpoint impact categories. Global warming potential, Eutrophication potential, Acidification potential, Photochemical ozone creation potential, Ozone depletion potential.	Primary data from FEDIOL member companies (more than 20 sites located in 6 different countries).
Soraya et al. (2014)	LCA of palm biodiesel production in Indonesia	System boundary: Cradle-to-gate. Plantation, mill and biodiesel pilot plant. Functional unit: 1 tonne of biodiesel produced. Allocation procedure: Mass allocation. Software: SimaPro 7.3 LCIA: CML 2 baseline 2000. Impact categories: 5 midpoint impact categories. Global warming, Photochemical oxidation, Eutrophication, Acidification and Abiotic resource depletion.	Primary data collected from an oil palm plantation and a palm oil mill located in Banyuasin, South Sumatra, and a biodiesel pilot plant located in South Jakarta.

Source	Description of study	Method	Source of inventory data
Kittithammavong et al. (2014)	Environmental LCA palm oil-based biofuel production in Thailand	System boundary: Cradle-to-gate. Plantation, mill and biodiesel plant. Functional unit: 1 litre of biodiesel produced. Allocation procedure: No allocation. Software: No information. LCIA: No information. Impact categories: GHG emissions, energy consumption and water consumption.	Primary data collected from a commercial biodiesel producer. Secondary data on oil palm cultivation and palm oil milling from published literature.
Norfaradila et al. (2014)	LCA for palm biodiesel production in Malaysia and Thailand	System boundary: Cradle-to-gate. Plantation, mill, refinery and biodiesel plant. Functional unit: 1 tonne of biodiesel produced. Allocation procedure: No allocation. Software: SimaPro 7.2 LCIA: Eco-indicator 99 Impact categories: 11 midpoint impact categories and 3 damage categories.	Primary data collected from a biodiesel producer in Malaysia and Thailand, respectively.
Siregar et al. (2015)	A comparison of LCA on oil palm and physic nut as feedstock for biodiesel production in Indonesia	System boundary: Cradle-to-gate. Plantation, mill and biodiesel plant. Functional unit: 1 tonne of biodiesel produced. Allocation procedure: No allocation. Software: MiLCA-JEMAI 1.1.2.5 LCIA: No information. Impact categories: 5 impact categories: Global warming potential, Acidification, Waste for landfill volume, Eutrophication and Energy consumption.	Primary data collected from plantations (oil palm and jatropha) in Java. Secondary data from published literature and reports.
Saswattecha et al. (2015)	Assessing the environmental impact of palm oil produced in Thailand	System boundary: Plantation and mill. Functional unit: 1 tonne of CPO produced. Allocation procedure: Mass allocation.	Primary data obtained from 21 plantations and 2

Source	Description of study	Method	Source of inventory data
Saswattecha et al. (2016)	Options to reduce environmental impacts of palm oil production in Thailand	Software: No information. LCIA: CML-IA. Impact categories: 6 midpoint impact categories. Global warming, Acidification, Eutrophication, Photochemical ozone formation, Human toxicity, Freshwater ecotoxicity.	mills. Secondary data from published literature Patthanaissaranukool et al. (2013) and Kaewmai et al. (2012).
Fauziah et al. (2017)	GHG emissions from transportation of palm oil, palm olein and palm stearin in Malaysia	System boundary: Cradle-to-gate. Nursery, plantation, mill and refinery. Functional unit: Transportation of a mass unit of products, based on the production of 1 t RBD palm oil. Allocation procedure: Mass allocation. Software: No information. LCIA: No LCIA Impact category: GHG emissions.	Primary data obtained from 8 nurseries, 113 plantations, 41 palm oil mills and 9 palm oil refineries.
Noorazah et al. (2017)	Environmental assessment on methyl ester production from RBD palm stearin in Malaysia	System boundary: Cradle-to-gate. Nursery, plantation, mill, refinery and methyl ester plant. Functional unit: 1 tonne of methyl ester produced. Allocation procedure: Mass allocation. Software: SimaPro 8.0.2 LCIA: Eco-indicator 99. 11 midpoint impact categories. Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer depletion, Ecotoxicity, Acidification/eutrophication, Land use, Minerals, Fossil fuels.	Primary data obtained from a commercial methyl ester plant. Secondary data from published literature Halimah et al. (2010), Zulkifli et al. (2010), Vijaya et al. (2010) and Tan et al. (2010).
Maharjan et al. (2017)	LCA of palm biodiesel in Taiwan	System boundary: Cradle-to-grave. Plantation, mill, refinery, biodiesel plant and biodiesel combustion. Functional unit: 1 kg of palm biodiesel produced and combusted.	Secondary data from published literature.

Source	**Description of study**	**Method**	**Source of inventory data**
		Allocation procedure: Economic allocation. Software: SimaPro 8.0 LCIA: LIME method. Impact categories: GHG emissions and Energy consumption.	
Permpool and Gheewala (2017)	Environmental and energy assessment of alternative fuels for diesel in Thailand	System boundary: Cradle-to-grave. Plantation, mill, biofuel plant and biofuel combustion. Functional unit: 1000 MJ of biodiesel produced and combusted. Allocation procedure: No information. Software: No information. LCIA: No information. Impact categories: Fossil resource depletion, Energy consumption, GHG emissions.	Secondary data from published literature.
Castanheira and Freire (2017)	Environmental LCA of biodiesel produced in Portugal with palm oil from Colombia	System boundary: Cradle-to-gate. Plantation, mill and biodiesel plant. Functional unit: 1 MJ of biodiesel Allocation procedure: Economic allocation. Software: SimaPro 7.1 LCIA: ReCiPe 1.10 and CML-IA 3.01. Impact categories: 4 midpoint impact categories: GHG intensity, Eutrophication, Photochemical oxidant formation, Terrestrial acidification.	Primary data from 5 Portuguese biodiesel plants and a Colombian palm plantation and extraction mill
Yoyon et al. (2020)	Environmental performance of palm biodiesel production in Indonesia	System boundary: Cradle-to-gate. Plantation, mill and biodiesel pilot plant. Functional unit: 1 tonne of biodiesel produced. Allocation procedure: No information Software: SimaPro 9.0.0.49 LCIA: GHG protocol and ReCiPe. Impact categories: Carbon footprint, 11 midpoint impact categories and 3 damages.	Secondary data from published literature Soraya et al. (2014).

Source	Description of study	Method	Source of inventory data
Siti et al. (2020)	Environmental sustainability assessment approach for palm oil production in Malaysia	System boundary: Cradle-to-gate. Nursery plantation, mill and refinery. Functional unit: 1 tonne of FFB, 1 tonne of CPO processed. Allocation procedure: Mass allocation. Software: SimaPro 8.4.0 LCIA: ReCiPe 2016. Impact categories: Global warming, freshwater eutrophication, fossil fuel depletion, 3 damages: damage to human health, ecosystem quality and resource availability.	Primary data from a palm oil mill and a palm oil refinery. Background data from Ecoinvent 3.0, Agri-footprint 3.0 and ELCD 3.2.

Yee et al. (2009) evaluated the energy balance and GHG emissions of palm biodiesel in Malaysia. The output energy of biodiesel was found higher than its input energy for biodiesel production resulted in the net positive energy of 3.53 reported for the utilisation of palm biodiesel. Also, it was concluded that the production of palm biodiesel does not result in a negative impact on the environment as the amount of CO_2 emitted to the atmosphere is lower than the amount absorbed by the oil palm trees. CO_2 emissions from the combustion of one litre of palm biodiesel were reported 38% lower than the same amount of petrol combusted.

de Souza et al. (2010) studied GHG emissions and energy balance for palm biodiesel production in Brazil. Allocation based on the mass of product and co-products was used. For GHG emissions, the agricultural stage and industrial stage were identified as main contributors, 64% and 21% respectively. Nitrogen fertiliser is responsible for the highest emissions in the agricultural stage while methanol is responsible for the highest emissions in the industrial stage. The industrial stage was found consuming most of the energy in the production of palm biodiesel, 54.88 GJ/ha or 81% of total input energy.

A comprehensive LCA for the Malaysian palm oil industry was conducted by MPOB using primary data obtained from relevant stakeholders in Malaysia. The activities of the palm oil industry are divided into five important subsystems namely nursery, plantation, palm oil mill, palm oil refinery and palm biodiesel plant. Inventory data of these five subsystems were gathered from industry stakeholders through survey questionnaires and interviews. The primary data collected were computed and analysed using SimaPro 7.1 software. LCIA was performed according to the Eco-indicator 99 methodology. Allocation of environmental impacts was conducted based on the mass of the products and co-products in the aforementioned subsystems. The LCA of these five subsystems were presented in five publications i.e. Halimah et al. (2010), Zulkifli et al. (2010), Vijaya et al. (2010), Tan et al. (2010) and Puah et al. (2010). As a summary, the greenhouse gas contributions in the oil palm industry were presented in Choo et al. (2011) by summing up the GHG emissions of the five important subsystems illustrated in Figure 2.10.

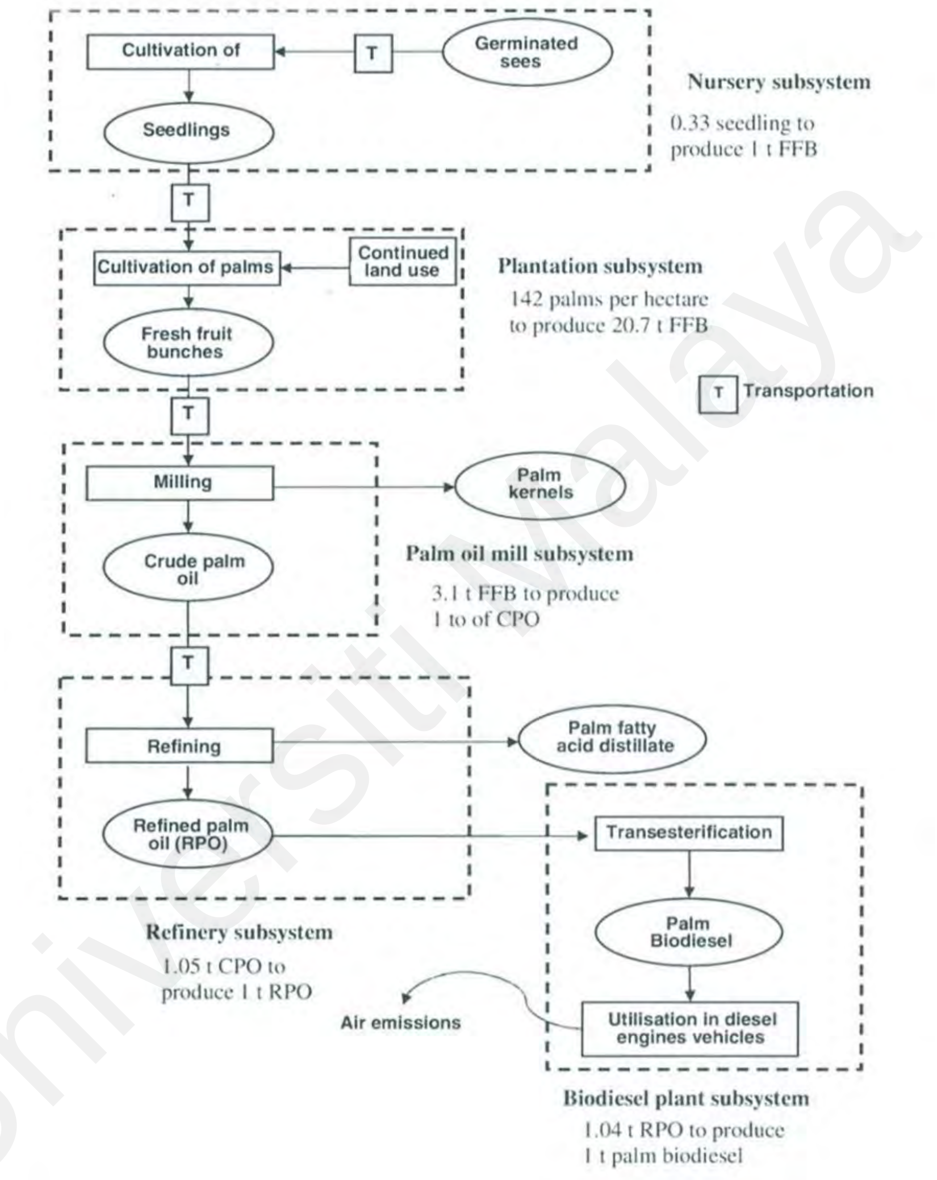


Figure 2.10: System boundary of LCA of the palm oil industry (Choo et al., 2011)

In the nursery stage, the functional unit of the LCA is the production of one oil palm seedling. Inventory data for a period of four years (2004 to 2007) were collected from 21 oil palm nurseries located in Peninsular Malaysia (Halimah et al., 2010). The system boundary of this subsystem starts from the transportation of germinated seeds to the oil palm nursery and ends at the production of oil palm seedlings. Oil palm seedling is the only product from the nursery hence allocation is not applicable at this stage. It was reported that the major impact category in this subsystem is ecotoxicity which is caused by pesticides used to control infection of fungi, insects and weeds. Choo et al. (2011) reported the GHG emissions of 0.05 kg CO_2 eq. per seedling produced and it has no significant contribution to the palm oil supply chain.

Oil palm seedlings are transported to the plantation for commercial planting when they reached 12-15 months old. The LCA for the plantation stage was reported by Zulkifli et al. (2010). Inventory data were collected from 102 plantation sites covering 1.1 million hectares of oil palm planted area, 25% of the total oil palm planted area then. The functional unit for the plantation stage is the production of 1 tonne of FFB. FFB is the only product from the plantation stage and again allocation is not applicable at this stage. LCIA indicated that fossil fuels, respiratory inorganics, climate change and acidification/eutrophication are the significant impact categories in the plantation subsystem. Choo et al. (2011) reported that the total GHG emitted for the production of one tonne of FFB is 119 kg CO_2 eq. Production of various fertilisers especially nitrogen fertiliser was reported as an energy-intensive process and it contributed significantly to the total GHG emissions, concurred the findings by Sumiani and Hansen (2007). It was reported that 80.7% of the total GHG emissions in the plantation stage are contributed by the production (32%) and the use (48.7%) of synthetic fertilisers. The use of transport vehicles for transportation of materials to the plantations and field tractors for plantation operations contributed the remaining 11.1% and 8.2% of GHG emissions, respectively.

LCA for palm oil mill operation was reported by Vijaya et al. (2010). Inventory data were collected from 12 palm oil mills in the country with various production capacities for a period of one year. FFBs harvested in the plantation are transported to the nearby palm oil mill for oil extraction. In the palm oil mill, the FFBs are subjected to various milling processes with the ultimate goal to produce a maximum yield of CPO. The functional unit of one tonne of CPO produced is set for this subsystem. Along with the milling processes, various by-products are also produced. These include the empty fruit bunch (EFB), mesocarp fibre, shell and palm kernel. EFB is usually sent back to the plantation for mulching, a process to reduce the consumption of inorganic fertilisers. Mesocarp fibre is used as solid biofuel in a boiler to produce steam for FFB sterilisation and electricity generation. In general, the palm oil mill is an energy self-sufficient entity in which the electricity used is mainly generated from the solid biofuel (biomass) available. Having higher energy content compared with mesocarp fibre, palm kernel shell is usually sold to a third party to create additional income for the palm oil mill. Palm kernel produced is supplied to kernel crushing plants for the production of palm kernel oil, which is not within the compound of the palm oil mill. Mass allocation of 61% to CPO, 25% to palm kernel and 14% to shell was used for this subsystem (Vijaya et al., 2010). Fossil fuels, respiratory inorganics and climate change were found as significant impact categories in this subsystem compared to other impact categories. Choo et al. (2011) reported that the production of one tonne of CPO in palm oil mill emits 971 kg CO_2 eq Significant reduction to 506 kg CO_2 eq was reported if the biogas was captured.

Before it can be used for food application, CPO is further processed into RBD palm oil. Palm oil refineries are typically located near to port to ease the export activity as most of the refined palm products are exported. As mentioned earlier, most of the palm oil refineries in Malaysia practices the physical refining process compared to the chemical refining process, as a cost-saving measure and to minimise the use of chemicals. The main product of refining is RBD palm oil and PFAD is the co-product. Tan et al. (2010) carried out the LCA of the palm oil refining based on the inventory data collected from 11 palm oil refineries in the country. The functional unit is the production of one tonne of refined palm oil. Mass allocation of 95.5% to RBD palm oil and 4.5% to PFAD was used in this subsystem. It was reported that the major environmental impact categories are fossil fuels, respiratory inorganics and climate change. Tan et al. (2010) explained that these impact categories are mainly caused by upstream processes i.e. FFB production in plantation and CPO production in palm oil mills. The production and use of synthetic fertilisers are the main contributors to the fossil fuels impact category while the application of nitrogen fertiliser and biogas emissions are the main contributors to climate change and respiratory inorganics. Activities in palm oil refineries were found insignificant to all environmental impacts evaluated. Similarly, fuel input for steam production and CPO transportation to the refinery has had a relatively small impact. Choo et al. (2010) reported carbon emissions of 1113 kg CO_2 eq per tonne of RBD palm oil produced. Significant reduction of GHG emissions to 626 kg CO2 eq was anticipated for CPO sourced from palm oil mills with biogas captured.

Puah et al. (2010) performed the LCA for palm biodiesel based on inventory data obtained from two local biodiesel plants. The functional unit of the LCA is one MJ of palm biodiesel produced and used in diesel vehicles. Mass allocation of 89.3% to palm biodiesel and 10.7% to glycerol was used in this subsystem. It was reported that the conversion of RBD palm oil to palm biodiesel contributed to two impact categories i.e. fossil fuels and respiratory inorganics while the use of palm biodiesel contributed to respiratory inorganics and acidification/eutrophication (Puah et al., 2010). The major contributors to environmental impacts are the use of fossil methanol for biodiesel production and the exhaust emissions of diesel engines. GHG emissions of 21.20 and 33.19 g CO_2 eq per MJ of biodiesel were reported for biodiesel produced from palm oil sourced from mills with and without biogas captured, respectively (Choo et al., 2011). Replacement of synthetic fertilisers with organic fertilisers, judicious fertiliser application and biogas capture were recommended as potential mitigation for the reduction of GHG emissions.

Mohd Nor et al. (2011) performed life cycle GHG emissions of palm biodiesel in Malaysia solely based on secondary data obtained from published literature and public data. The functional unit of the LCA is one MJ of land-to-wheel palm biodiesel for domestic consumption. No allocation was performed between product and co-products in various stages of palm oil and palm biodiesel production. It was reported that most of the GHG emissions are contributed by oil palm cultivation and CPO extraction, mainly due to the use of fertilisers and methane released from POME. Refining of CPO, production of biodiesel from refined palm oil and biodiesel combustion have relatively lower GHG emissions. Increased consumption of organic fertilisers, methane trapping for heat and electricity generation, and electricity generation from biomass and supply to the power grid were suggested as potential improvements to the life cycle GHG emissions.

Sampattagul et al. (2011) performed LCA for palm biodiesel production and utilisation in Thailand. The LCA was conducted based on primary data collected from an agricultural area, a palm oil mill and a biodiesel producer in Krabi, Thailand. The impact assessment was performed using the EDIP method. The functional unit of the study is one litre of palm biodiesel utilised. The authors discovered that the greatest environmental impact is contributed by the biodiesel utilization stage, 52.09% of total impact and followed by palm oil and biodiesel production stages, 41.21%. In terms of global warming potential, GHG emissions of 0.04 kg CO_2 eq per litre of palm biodiesel was reported. This figure was found much lower compared to petroleum diesel of 2.70 kg CO_2 eq per litre. For life cycle improvement, the following options were suggested. These include an increase of palm oil yield in the plantation stage through various research activities, replacement of fossil-based methanol with bioethanol, alcohol recovery using distillation equipment and energy recovery from biogas.

A similar study on biodiesel production and utilization in Thailand was reported by Silalertruksa and Gheewala (2012). The LCA was conducted based on inventory data obtained from a commercial biodiesel producer and secondary data obtained from published literature. The functional unit of the study is the production of 1000 litre palm biodiesel. Economic allocation was the allocation procedure selected to distribute the environmental burden among the product and co-products, both in palm oil milling and biodiesel production. LCIA was conducted according to the CML 2 method and five midpoint impact categories were evaluated. For global warming, 2 main contributors were identified. They are the production and application of N-fertilisers in the oil palm cultivation stage and methane emissions from POME at open effluent ponds in the palm oil milling stage. The methane emission was also found significant to the photochemical oxidation impact category. The production of synthetic fertilisers (N, P and K) was reported significant for acidification and human toxicity while eutrophication was found mainly contributed by the POME treatment. The impact of the land-use change was also evaluated in this LCA. It was reported that the conversion to oil palm plantation from an old paddy field, fruit orchards and other crop fields resulted in GHG benefits with an increase of soil organic carbon. However, the conversion of forest to oil palm plantation was found to cause the CO_2 emissions higher than petroleum diesel. Biogas capture for co-composting with EFB, good agricultural practices for oil palm cultivation and by-products management were proposed as strategies to mitigate the potential environmental impacts.

Schneider and Finkbeiner (2013) performed gate-to-gate LCA for the production of three refined vegetable oils i.e. rapeseed oil, soybean oil and palm oil in Europe. The scope of the study covered both oilseed crushing and crude oil refining for rapeseed and soybean while refining only for palm oil. Inventory data were obtained from six FEDIOL member companies comprise more than 20 sites and 6 different countries in Europe. The LCA was performed using GaBi 5 software in which secondary data from reliable databases were used for all auxiliary materials input including power generation. Allocation based on energy content was conducted in the study. The functional unit of the study is one tonne of refined vegetable oil produced. LCIA was performed according to the CML method with five midpoint impact categories evaluated i.e. global warming, eutrophication, acidification, photochemical ozone creation and ozone depletion. The study revealed that air emissions and energy consumption for steam and electricity are the main contributors to the environmental impacts at the oilseed crushing stage. The production of several auxiliary materials i.e. acids and bleaching earth were found to have significant impacts on the refining stage. Oilseed crushing was found to have relatively higher impacts compared to crude vegetable oil refining.

Soraya et al. (2014) performed LCA for the production of palm biodiesel in Indonesia. Inventory data were obtained from a plantation and a palm oil mill located in Banyuasin, South Sumatra province. For biodiesel production, inventory data were obtained from a biodiesel pilot plant located in South Jakarta. The functional unit of the study is one tonne of palm biodiesel produced. Mass allocation was used in both CPO production and biodiesel production. It was concluded that the use of fertilisers in the plantation stage and electricity from the power grid in both palm oil mill and biodiesel production are the major contributors to the environmental impacts evaluated. It was also demonstrated that methane capture and use as electricity can potentially reduce the environmental impacts in particular global warming, photochemical oxidation and acidification impacts.

Kittithammavong et al. (2014) compared the environmental performance of biodiesel (from palm stearin) purification through distillation versus the conventional water washing process using the LCA approach. The functional unit of the study is one litre of palm biodiesel produced. GHG emissions, energy and water consumption were evaluated. It was reported that palm oil mill is the major contributor to total GHG emissions, 59.56%, mainly due to methane gas released from the wastewater treatment process. In terms of energy consumption, oil palm cultivation was reported as the main contributor, 45.36%, mainly due to the acquisition of fertilisers and pesticides. For water consumption, most of the water consumed is from the oil palm cultivation stage. Water consumed in the palm oil milling, biodiesel production and purification stage were found negligible, less than 0.5%. This LCA also revealed that the alternative distillation process for biodiesel purification consumed more water compared to the conventional water washing method, mainly contributed by indirect water used for electricity generation as distillation is an energy-intensive process.

Norfaradila et al. (2014) conducted cradle-to-gate LCA for palm biodiesel production in Malaysia and Thailand. Inventory data were obtained from a biodiesel producer each in Malaysia and Thailand. The functional unit of the study is one tonne of palm biodiesel produced. The weighted results concluded that fossil fuels, respiratory inorganics and carcinogen are the important environmental impacts compared to the other 8 insignificant impact categories. The use of nitrogen fertiliser was identified as the main contributor to the environmental impacts evaluated. The use of organic fertilisers, improved oil palm planting materials, best management practices and biogas capture and use as renewable energy were suggested as possible mitigations for environmental impacts. In comparison, the production of biodiesel in Thailand was reported to have higher environmental impacts than Malaysia mainly due to higher material input at the Thai oil palm cultivation stage.

Siregar et al. (2015) compared the LCA for biodiesel produced from oil palm and jatropha in Indonesia. The LCA was conducted based on inventory data collected from plantations in Java, Indonesia. The functional unit of the study is one tonne of biodiesel produced. The environmental impacts of jatropha biodiesel were found lower than palm biodiesel. Oil palm planting and protection, CPO extraction and biodiesel production were found as the main contributors to the environmental impacts evaluated, in particular global warming potential and energy consumption. Throughout the 25 years economic life cycle, 37.83% and 63.61% reduction in global warming potential were registered for biodiesel produced from palm oil and jatropha compared to fossil diesel.

Saswattecha et al. (2015) assessed the environmental performance of palm oil production in Thailand. The study divided CPO producers into 3 categories i.e. RSPO certified, potential RSPO and non-RSPO. Inventory data for the operation of RSPO and potential RSPO producers were obtained from 21 plantations and 2 palm oil mills in the Tapi River basin, Thailand. Secondary data from published literature i.e. Patthanaissaranukool et al. (2013) and Kaewmai et al. (2012) were used to represent the non-RSPO producers. LCIA was conducted based on CML-IA methodology with six midpoint impact categories evaluated i.e. global warming, eutrophication, acidification, photochemical ozone formation, human toxicity and freshwater ecotoxicity. Five activities were identified as main contributors to environmental impacts of CPO production i.e. burning of fibres in boilers in palm oil mills, the use of synthetic fertilisers in plantations, wastewater treatment and empty fruit bunch disposal in palm oil mills, gasoline use by weed cutters and glyphosate use for weed control. CPO produced from RSPO producers was found to cause the lowest environmental impacts compared to potential RSPO producers and non-RSPO producers especially for global warming and photochemical ozone formation. CPO produced from non-RSPO producers was found to cause the highest environmental impacts due to poor practices in both plantations and palm oil mills. Evaluation on options to reduce the environmental impacts, from both plantations and mills, are presented in Saswattecha (2016). EFB combustion, wet scrubbers and pre-heating fibre were found to be effective in reducing multiple impact categories among the various options evaluated. EFB mulching was reported as the most cost-effective option.

Fauziah et al. (2017) studied the GHG emissions contributed by transportation in various stages of the palm oil industry based on inventory data obtained from 8 nurseries, 113 plantations, 41 palm oil mills and 9 palm oil refineries. It was reported that the transportation of FFB from plantation to palm oil mill and transportation of CPO from palm oil mill to palm oil refineries contributed the most GHG emissions to the production of RBD palm oil. It was suggested that transportation using rail transport may reduce the GHG emissions in the transportation sector with justifications that higher load and lower diesel consumption of rail transport compared to road transports.

Noorazah et al. (2017) presented LCA for the production of methyl ester of RBD palm stearin. The study was a cradle-to-gate LCA study in which the inventory data of methyl ester production was obtained from a commercial plant in Malaysia while the upstream processes i.e. nursery, plantation, palm oil mill and palm oil refining and fractionation, were referred to published literature i.e. Halimah et al. (2010), Zulkifli et al. (2010), Vijaya et al. (2010) and Tan, et al. (2010). The functional unit for the LCA study is the production of one tonne of methyl ester from RBD palm stearin. Eco-indicator 99 was chosen as the LCIA methodology and allocation based on mass was used. RBD palm stearin was identified as the main contributor to all environmental impacts evaluated. Similar to Tan et al. (2010), Vijaya et al. (2010) and Puah et al. (2010), the best-case scenario is palm oil sourced from palm oil mills with biogas capturing facilities. The authors also suggested the use of renewable energy generated from palm biomass to fulfil the energy requirement of the biodiesel plant and the replacement of fossil-based methanol with biomethanol as possible mitigation of the potential environmental impacts.

Maharjan et al. (2017) performed LCA for the production of palm biodiesel in Taiwan from palm oil imported from Malaysia. The study is a cradle-to-grave study that includes land-use change with oil palm plantation was assumed to be converted from tropical rainforest and peat forest. The functional unit for this study is one kg of palm biodiesel combusted. The study was performed based on secondary data from published literature and the Ecoinvent 3.0 database with an economic allocation procedure. Compared to all the stages involved, land-use change was found to be the main contributor to GHG emissions (80%) while the plantation phase was found as the main contributor to energy consumption (55%). The authors believed that the improvement of the fuel production process and the fuel quality can reduce the global warming impact.

Permpool and Gheewala (2017) compared the environment and energy assessment of three different types of biofuels i.e. palm biodiesel, bio-hydrogenated diesel and partially hydrogenated palm biodiesel using the LCA approach. The system boundary set is well-to-wheels and the functional unit of the study is 1000 MJ biofuels consumed. Three impact categories were evaluated i.e. fossil resource depletion, energy consumption and GHG emissions. No significant differences among the three biofuels were evaluated in terms of energy performances and GHG emissions. However, significant savings of fossil resources and substantial GHG reduction throughout 20 years were anticipated when fossil diesel was replaced by any of these three biofuels.

Castanheira and Freire (2017) performed LCA for palm biodiesel produced in Portugal with palm oil imported from Colombia. Inventory data were gathered from 5 biodiesel producers in Portugal, an oil palm plantation and a mill in Colombia. LCA was conducted by comparing the implications of land-use change, four different fertilizer schemes, two types of biogas management at palm oil mill using two LCIA methodologies on four environmental impacts i.e. GHG intensity, eutrophication, photochemical oxidant formation and acidification. GHG intensity was found to greatly depends on land-use change emissions and biogas management at palm oil mills. The increase of carbon stock is the result of the conversion of oil palm plantations from savanna grassland, shrubland and other croplands. The GHG intensity is significantly reduced from the land use change coupled with biogas capturing and flaring at the palm oil mill. It was suggested that the utilization of biogas for energy generation can contribute to a further reduction in GHG emissions. Sensitivity analysis on allocation procedures showed that both price and energy allocations resulted in slightly higher environmental impacts compared to mass allocation.

Yoyon et al. (2020) performed LCA for the production of palm oil biodiesel based on the Indonesia scenario. Inventory data were obtained from published literature i.e. Soraya et al., 2014. The functional unit of the study is one tonne of palm biodiesel produced. LCIA was performed on carbon footprint according to Greenhouse Gas Protocol while other environmental impacts were evaluated according to the ReCiPe method. A total of 17 midpoint impact categories and three damages were analysed. For carbon footprint, the GHG emissions are mainly contributed by the N_2O emission from drained peatlands for oil palm plantations. Upstream activities i.e. conversion of peatlands to oil palm plantation, cultivation of oil palm and CPO production are the main contributors to all the 17 midpoint impact categories except ozone depletion and fossil depletion, which methanol used for biodiesel conversion has a higher impact. In terms of endpoint damages, the upstream activities once again dominated the damages on human health and ecosystems while resources damage was found to be contributed by methanol, CPO production and electricity consumed.

Siti et al. (2020) evaluated the environmental performance of palm oil production and processing with special emphasis on activities in palm oil mill and palm oil refinery. It was reported that palm oil milling contributes to the most significant environmental impacts compared to insignificant contribution from the refinery, to both midpoint impacts and endpoint damages. Biogas capture was suggested as mitigation to potential environmental impacts, in particular a 40-50% reduction in the global warming impact category.

2.9.2 Life Cycle Assessment of Hydroprocessed Renewable Fuels

Kalnes et al. (2009) compared the GHG emissions of green diesel and syndiesel produced from soybean oil with petroleum diesel using the LCA approach. Three inventory data sources (US DOE, CONCAWE and PNAS) and two allocation methods (mass allocation and displacement) were used in the study. The whole life cycle i.e. oil extraction, transportation, Ecofining^{TM} process and combustion in an internal injection combustion engine were considered for one MJ of biofuel. Cumulative energy demand was used to evaluate the energy consumed while Eco-indicator 95 was used to quantify the GHG emissions. 66-84% savings on fossil fuels and 41-85% reduction in GHG emissions were reported for green diesel compared with fossil-based diesel.

Shonnard et al. (2010) demonstrated the environmental benefits of HRD and HRJ produced from camelina oil using the UOP Ecofining^{TM} process. Energy allocation was applied to distribute the environmental burden among products (HRD and HRJ) and co-products (fuel gas, LPG and naphtha). The contribution to GHG emissions was found according to the following descending order: production of camelina oil (cultivation of camelina and fertilisers application), biofuel production, chemicals and transportation (camelina seeds and oils). GHG emissions of 18.0 and 22.4 g CO_2 eq/MJ fuel was recorded respectively for HRD and HRJ. These represent savings of 80% and 75% relative to their petroleum counterparts.

Arvidsson et al. (2011) compared the environmental impact of hydrotreated vegetable oil (HVO) biofuel combusted in heavy-duty trucks in Germany. The HVO was assumed to be produced in Neste Oil's production plant in Porvoo, Finland. Three types of oils were evaluated as potential feedstocks for the HVO process, namely rapeseed oil from Germany, palm oil from Malaysia and Jatropha oil from India. The functional unit of the study is one kWh of energy produced from the engine of a heavy-duty truck. Results showed that HVO biofuel has a lower life cycle global warming potential than conventional fossil diesel for all feedstock investigated. HVO biofuel produced from palm oil with biogas captured for energy production has the lowest environmental impacts. Regardless of feedstock, the largest contribution to global warming potential is the emissions from soil.

Fan et al. (2013) evaluated the life cycle GHG emission and energy balance of HRD and HRJ produced from pennycress using SimaPro 7.2 software. Allocation (energy content and market value) and system expansion (displacement) approaches were used to distribute the environmental burdens to the products and co-products. The GHG impact assessment was calculated based on IPCC 2007 GWP 100a V1.01. The life cycle GHG for HRD and HRJ was found in the range of 13 to 41 g CO_2 eq/MJ and -18 to 45 g CO_2 eq/MJ, respectively. Pennycress cultivation was found as the leading contributor to GHG emissions. It is followed by fuel production and oil extraction. GHG emission of HRJ was reported higher than HRD due to higher oil and other materials used. Sensitivity analysis on replacing fossil-based hydrogen with integrated hydrogen production shown GHG reduction for HRD and HRJ for the allocation scenarios. An opposite trend was observed for the system displacement approach because co-products are utilised in the integrated hydrogen plant for hydrogen production. The cumulative energy demand (CED) and fossil energy demand were calculated according to Cumulative Energy Demand 1.07. The total energy demand calculated for energy allocation was found comparable to the petroleum counterparts. However, higher CED results were reported for the market value allocation and displacement approach. It was further explained that the energy demands are mainly contributed by renewable biomass.

Han et al. (2013) conducted a life cycle analysis of bio-based aviation fuels for various pathways including HRJ from various oilseeds, Fischer-Tropsch jet fuel and pyrolysis jet fuel. Greenhouse gases, Regulated Emissions, and Energy used in Transportation (GREET^{TM}) model was used in this study. Unlike other previous studies, variation in the fatty acid compositions of oils for various oil crops was considered in the study. The GHG emissions were found to be dominated by the fuel processing step as a large amount of hydrogen gas and natural gas are required. However, no significant difference among oil feedstocks was observed as compared to fertiliser production and N_2O emission from N fertiliser. 41-63% savings in GHG emissions were recorded for HRJ when compared with the petroleum jet fuel. The study has demonstrated that the LCA results are affected by co-product handling methods (allocation and displacement) and allocation boundary, as shown in the soybean HRJ case study.

Seber et al. (2014) quantified the viability of HRJ and HRD from tallow and used cooking oil from the environmental and economic perspectives. The life cycle GHG emissions of HRJ and HRD were calculated with the GREET framework and SimaPro 7.3.3 software using published literature data. Fuel production was found as the primary contributor to the total GHG emissions for the yellow grease derived fuels. 78% reduction in total GHG emissions was recorded for the yellow grease HRJ when compared to the conventional fossil-based jet fuel while 81-86% reduction in GHG emissions was reported for the yellow grease HRD compared with petroleum diesel. The allocation method was found to have very little influence on the total GHG emissions. Less than 5% differences were observed for market value allocation when compared with the energy allocation. 66% reduction in GHG emission was recorded for tallow-based HRJ when tallow was considered as a waste of the meat production industry. Significant higher GHG emissions for tallow-based HRJ when tallow was considered as a co-product. A similar trend was observed for the tallow-based HRD. It is also highlighted that price support is needed to make biofuels economically competitive since biofuels are more expensive than fossil-based fuels.

Li and Mupondwa (2014) conducted LCA of camelina oil biodiesel and HRJ. Allocation of co-products was carried out using a system expansion approach and the Impact 2002+ method was adopted for the environmental impact assessment in SimaPro 7.2 software using data from published literature. LCA results show that camelina biodiesel has relatively lower GHG emissions but higher non-renewable energy consumption than camelina HRJ. The top three contributors to camelina biodiesel are oil, sodium methoxide (catalyst) and methanol while the top three contributors to camelina HRJ are oil, natural gas and electricity. Camelina seed yield was found to have a significant influence on the LCA results. Lower environmental impacts were anticipated for higher seed yield.

Shonnard et al. (2015) conducted a review on environmental LCA studies of biofuels carried out in the Pan American Region and discovered a wide variety of the studies evaluated, for example, country-specific conditions, modelling assumptions, data quality, impact categories, system boundaries and co-product allocation methods. From a total of 74 articles evaluated, the majority of the studies were conducted in the US and Brazil. The preferred functional unit of the LCA studies is the energy content of the biofuel and followed by mass. In terms of co-product allocation, the largest number of studies (33%) however did not report the allocation method used. System expansion is the most common and it is followed by mass allocation, energy allocation and economic allocation. A very high percentage of the studies used inventory data from the literature (87%) and Ecoinvent is the most common inventory database used. Only 22 studies performed primary data collection from relevant parties. Eco-indicator 99 is the most common LCIA method used in these studies. Global warming potential and energy consumption are the common impact categories evaluated and discussed. In a case study on the LCA of jatropha HRJ, the effect of co-product allocation was analysed and results were presented as GHG emissions. HRJ production and jatropha cultivation are the major contributors to GHG emissions. GHG savings of 80% and 195% were reported for energy allocation and system expansion, respectively.

GHG emissions and energy demand of North Dakota canola-based HRJ was evaluated by Ukaew et al. (2016). In terms of allocation method, the displacement method shows the most favourable results for GHG emissions by GHG emissions credits contribution from canola meal and hydroprocessing co-products. GHG emissions for energy allocation are slightly higher than that from the market value allocation due to higher market prices for hyroprocessing co-products. In terms of cumulative energy demand, canola HRJ requires higher energy demand than fossil-based jet fuel, mainly from renewable biomass. Detailed analyses on the fossil energy demand show that canola HRJ requires lower fossil energy demand than fossil-based jet fuel. Canola cultivation is the most energy-intensive stage for the displacement method, mainly due to N fertilizer production. Energy consumption for the production of hydrogen from natural gas is the main contributor to fossil energy demand for both energy and market value allocation method. Hence, the hydrogen integration process was proposed to reduce GHG emissions.

The life cycle GHG emissions of renewable jet fuels produced from six different pathways were compared against the fossil jet fuel (de Jong et al., 2017). The study shows that fuel conversion technology, hydrogen consumption and conversion yield are the important contributors to GHG emissions. GHG emissions were found to be influenced by co-products allocation methods. The study recommends energy allocation as a base and compliment with economic allocation for systems involving non-energy co-products.

2.9.3 LCA Summary of Malaysian Palm Oil and Palm Biodiesel

In summary, the LCA of refined palm oil, palm products and palm biodiesel presented by MPOB is the most comprehensive study for Malaysia. The palm oil supply chain is divided into five subsystems and the environmental impacts of each subsystem are analysed accordingly with a summary of GHG emissions reported in Choo et al. (2011). Furthermore, the studies were conducted based on primary inventory data collected from relevant stakeholders from all five subsystems in the palm oil supply chain. In other words, the LCA results reflected the actual performance of the palm oil industry in Malaysia.

However, there are missing gaps in the palm oil refinery section. PFAD, an important co-product in the palm oil refining stage was not considered or clearly analysed and evaluated. Allocation of environmental burden was not performed or ignored in the refinery subsystem. Although PFAD represents just about 5% of the refining output, this value is significant as the production and the CPO refining have increased tremendously. Also, PFAD could be an important feedstock for biofuels production, in particular biodiesel and renewable jet fuel. Furthermore, PFAD is traded commercially in the commodity market, the environmental burden in the refining stage should also be shared between RBD palm oil (main product) and PFAD (co-product) in a justifiable percentage. This led to the evaluation of different allocation procedures, particularly at the refining subsystem. LCA studies by MPOB previously were solely conducted according to mass allocation which resulted in the same environmental impact per mass unit of RBD palm oil (main product) and PFAD (co-product) in the palm oil refinery subsystem, RBD palm olein and palm stearin in the fractionation plant, and palm biodiesel and crude glycerol in biodiesel subsystem.

There are also other missing gaps in the evaluation of palm oil as feedstocks for biofuel. The palm oil refining stage was not included in most of the LCA studies conducted (Table 2.2). In the real market scenario, most of the palm oil produced in Malaysia are refined to RBD palm oil. Also, most of the palm oil traded and exported from Malaysia are in the refined form (RBD palm oil), rather than CPO (MPOB, 2019). Comparison of biofuels produced from refined palm oil and PFAD should also be evaluated and included to further justify the use of non-edible PFAD as an important feedstock.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Method

The LCA study was performed in accordance with the principle and guidelines of two important ISO standards, namely ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework and ISO 14044:2006 Environmental Management – Life cycle assessment – Requirements and guidelines (ISO, 2006a; ISO, 2006b). A brief description of these two standards is presented in Chapter 2.

According to the ISO standards, the very first step of an LCA study is the setting up of the goal and scope of the study (ISO, 2006a; ISO, 2006b). A system boundary is then drawn based on the defined goal and scope. Activities to be included and excluded in data collection are also be determined based on the system boundary set. Other value choices such as allocation procedures, the methodology for impact assessment, type of impacts, assumptions, cut-off criteria etc are considered and described in this chapter.

3.2 Goal of Study

The goal of the current study is to gather and present the latest inventory data on gate-to-gate and cradle-to-gate LCA of palm oil refining and palm biofuels production representative of Malaysia situation. It is also aimed to evaluate the potential environmental impacts associated with the abovementioned activities in respective subsystems. Based on the latest inventory data and the LCIA results, this study also intended to identify the contributors to the potential environmental impacts of the subsystems evaluated and to propose recommendations for improvement, if any.

3.3 Scope of Study

The scope of the LCA study covers three subsystems i.e. palm oil refinery (refining and fractionation), palm biodiesel (transesterification) plant and hydroprocessing pilot plant. Both gate-to-gate and cradle-to-gate LCA were conducted based on respective system boundaries which will be explained in subsequent sections.

3.3.1 System Description

As shown in Table 3.1, previous LCA studies have segregated the palm oil industry into five subsystems namely nursery, plantation, palm oil mill, palm oil refinery and biodiesel plant (Halimah et al., 2010; Puah et al., 2010; Tan et al., 2010; Vijaya, et al., 2010; Zukifli et al., 2010,). The current study follows these subsystems as they are still valid and relevant to the palm oil industry in Malaysia. Table 3.1 also listed the activities of these subsystems, including the feedstocks and product output. One new subsystem on hydroprocessing is introduced in the present study as an alternative to the biodiesel subsystem identified in the previous studies.

3.3.2 Functional Unit

Palm oil and palm oil products including palm biodiesel are commonly traded based on mass at both local and international markets. Hence, the functional units of the LCA are defined as one tonne of RBD palm oil, one tonne of RBD palm olein and one tonne of RBD palm stearin produced at the palm oil refinery (including fractionation plant), one tonne of palm biodiesel at biodiesel plant, and one tonne of hydroprocessed biofuels (HRD or HRJ) produced at the hydroprocessing pilot plant (Table 3.2). Functional unit based on mass is also well justified as the production of palm oil and palm oil products including biodiesel and biofuels are recorded and traded in the commercial market based on mass value, in tonnage.

Table 3.1: Palm oil subsystems

Subsystem	Feedstock	Activity	Products
Nursery	Germinated seeds	Production of oil palm seedlings.	Oil palm seedling
Plantation	Oil palm seedlings	Planting of oil palm seedlings, fertilisation, harvesting of FFB.	FFB
Palm oil mill	FFB	Extraction of CPO.	CPO, palm kernel, empty fruit bunch, palm kernel shell, palm-pressed fibre.
Palm oil refinery	CPO	Refining and/or purification of CPO.	RBD palm oil and PFAD.
	RBD palm oil	Fractionation of RBD palm oil.	RBD palm olein and RBD palm stearin.
Biodiesel plant	RBD palm oil, RBD palm olein, RBD palm stearin and/or PFAD	Transesterification	Palm biodiesel, crude glycerol
Hydroprocessing plant	RBD palm oil, RBD palm olein, RBD palm stearin and/or PFAD	Hydroprocessing i.e. hydrocracking, isomerisation, distillation	HRD, HRJ, HRN, propane mix gas.

Table 3.2: Functional units of LCA of palm oil subsystems

Subsystem	Functional unit
Palm oil refinery	Refining: 1 tonne of RBD palm oil produced Fractionation: 1 tonne of RBD palm olein and 1 tonne of RBD palm stearin produced
Palm biodiesel plant	1 tonne of palm biodiesel produced
Hydroprocessing plant	1 tonne of hydroprocessed biofuels i.e. HRD and HRJ produced

3.3.3 System Boundary

Different system boundaries are set for the gate-to-gate LCA and the cradle-to-gate LCA. A gate-to-gate LCA is performed by omitting the upstream activities of the palm oil supply chain i.e. nursery, plantation and palm oil mill subsystems.

The system boundary of the gate-to-gate LCA for palm oil refining starts from the transportation of CPO from palm oil mills to palm oil refineries, physical refining of CPO to produce RBD palm oil and PFAD and ends at bulk storage of RBD palm oil and PFAD (Figure 3.1). Since the fractionation plants are located at the same premise as the physical refining plant, a gate-to-gate LCA for RBD palm oil fractionation to produce RBD palm olein and palm stearin includes the refining steps mentioned previously and ends at the bulk storage of RBD palm olein and RBD palm stearin (Figure 3.2).

The system boundary of the gate-to-gate LCA for palm biodiesel starts from transportation of RBD palm oil and/or other refined palm products (PFAD, olein or stearin) from palm oil refineries to biodiesel plants, transesterification of the RBD palm oil and/or refined palm products to produce biodiesel meeting standard specification and crude glycerol with 80-85% purity, and ends at the bulk storage of the palm biodiesel and crude glycerol (Figure 3.3).

For the production of hydroprocessed biofuels, the system boundary is similar to the production of palm biodiesel which starts from the transportation of RBD palm oil and/or PFAD from palm oil refineries to biofuel plant, hydroprocessing of RBD palm oil or PFAD to produce hydroprocessed renewable biofuels i.e. HRD or HRJ with propane mix gas and HRN as co-products, and ends at bulk storage of the biofuels produced (Figure 3.4).

For cradle-to-gate LCA, the system boundaries are extended to include the upstream activities i.e. production of palm seedlings at nursery, production of FFB at plantation and production of CPO at palm oil mills. The system boundaries for the respective cradle-to-gate LCA of RBD palm oil, RBD palm olein, RBD palm stearin, palm biodiesel and hydroprocessed palm biofuels are illustrated in Figures 3.5 to 3.8.

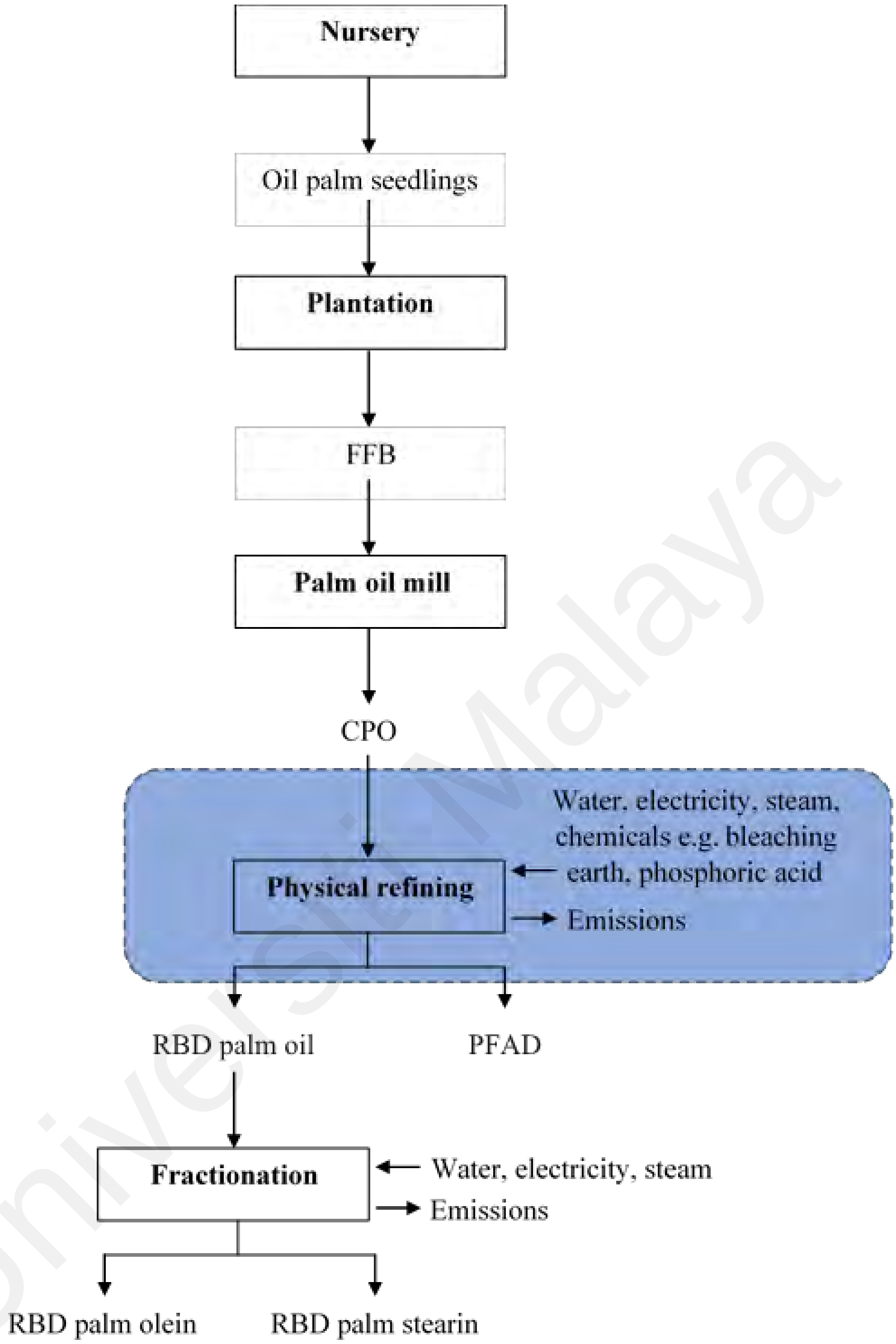


Figure 3.1: System boundary for gate-to-gate LCA of palm oil refining

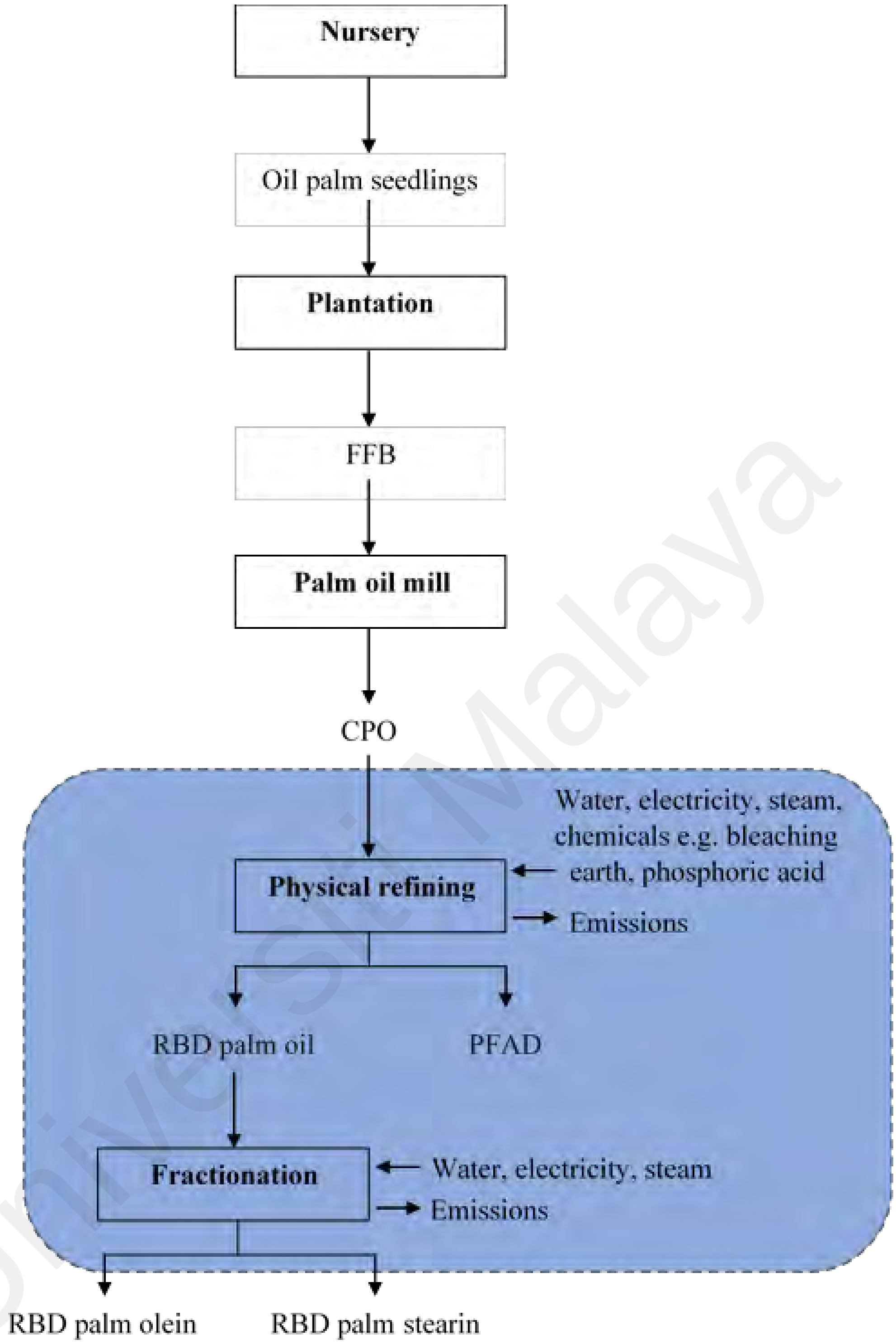


Figure 3.2: System boundary for gate-to-gate LCA of palm oil refining and fractionation

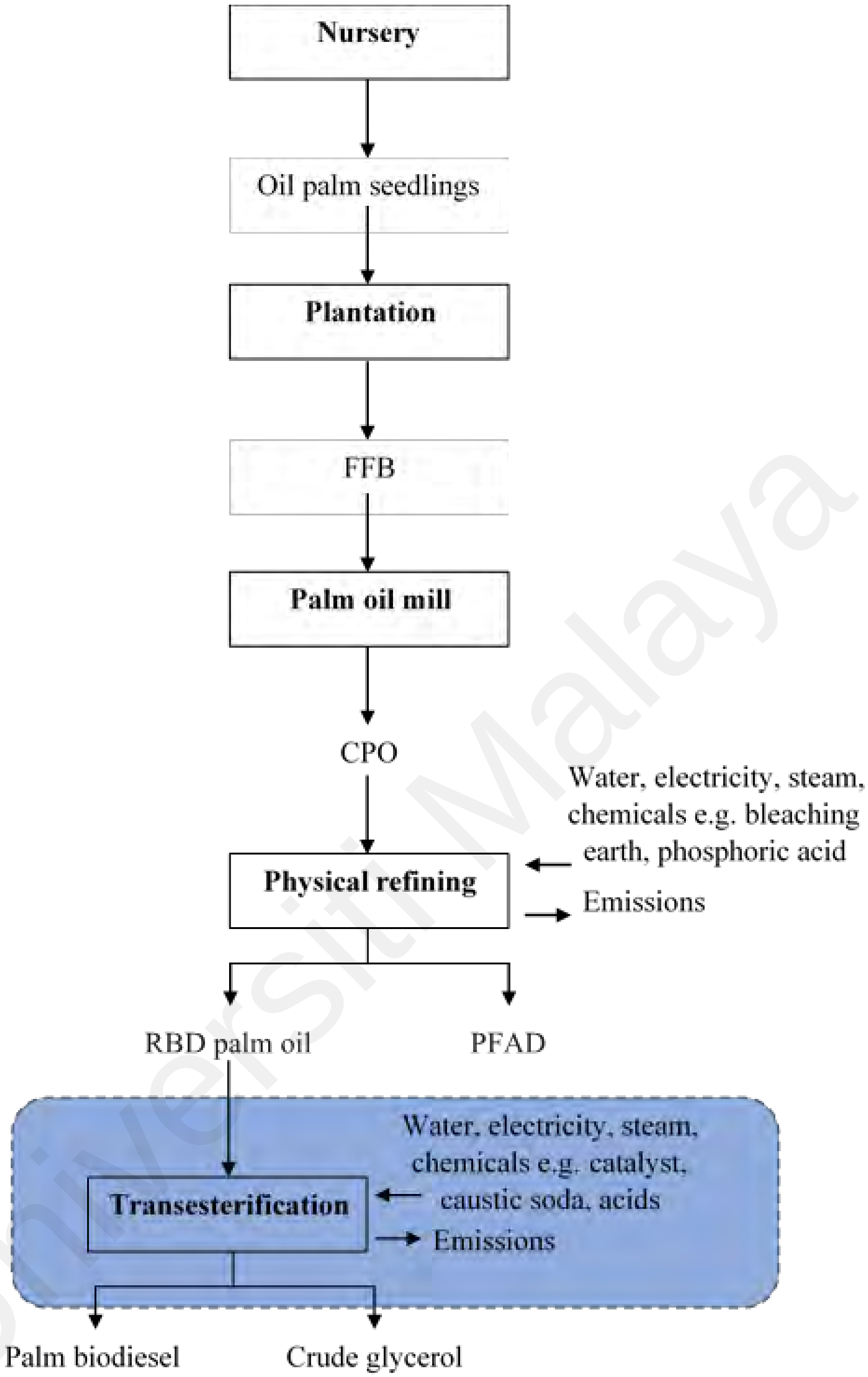


Figure 3.3: System boundary for gate-to-gate LCA of palm biodiesel production

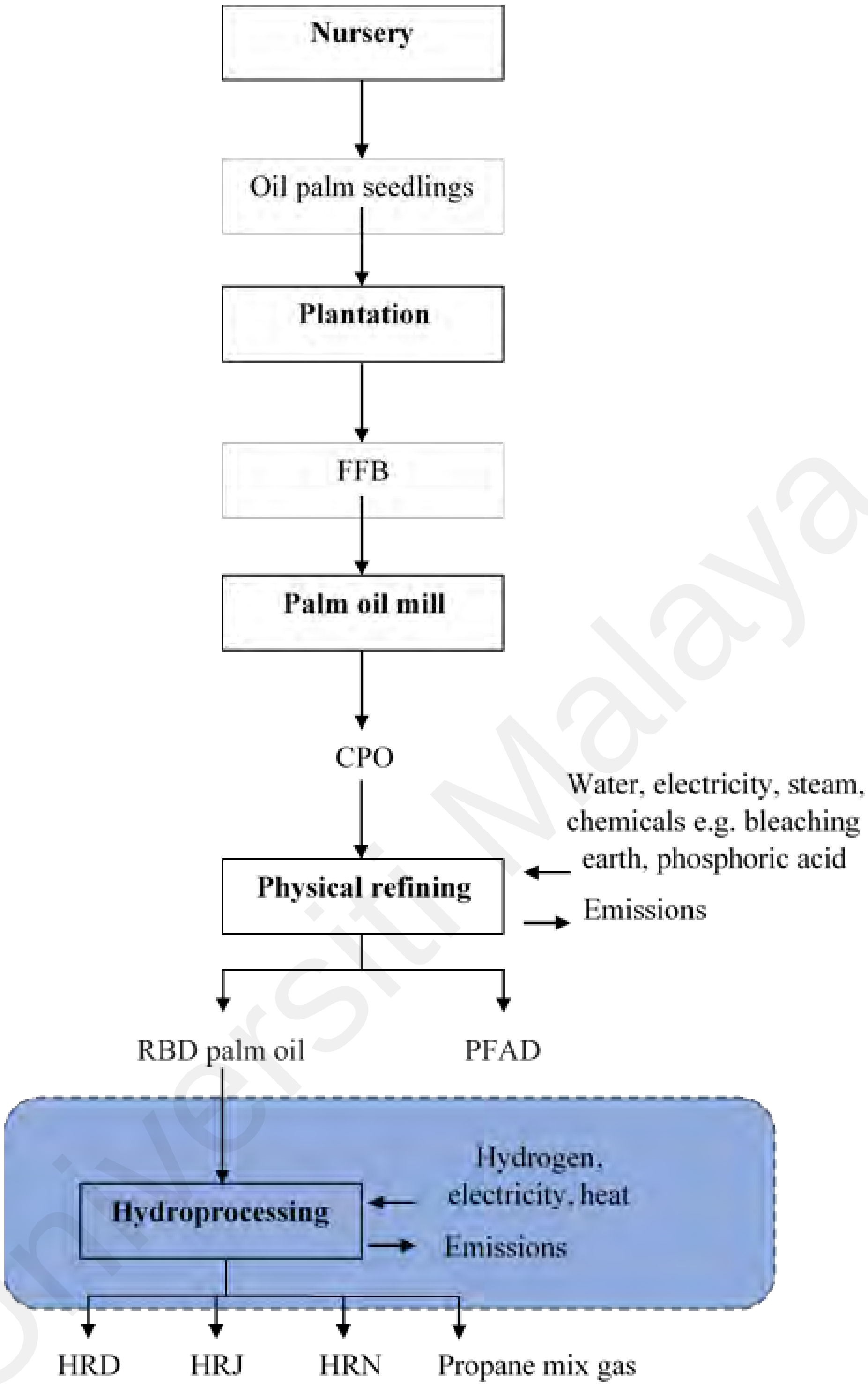


Figure 3.4: System boundary for gate-to-gate LCA of hydroprocessing

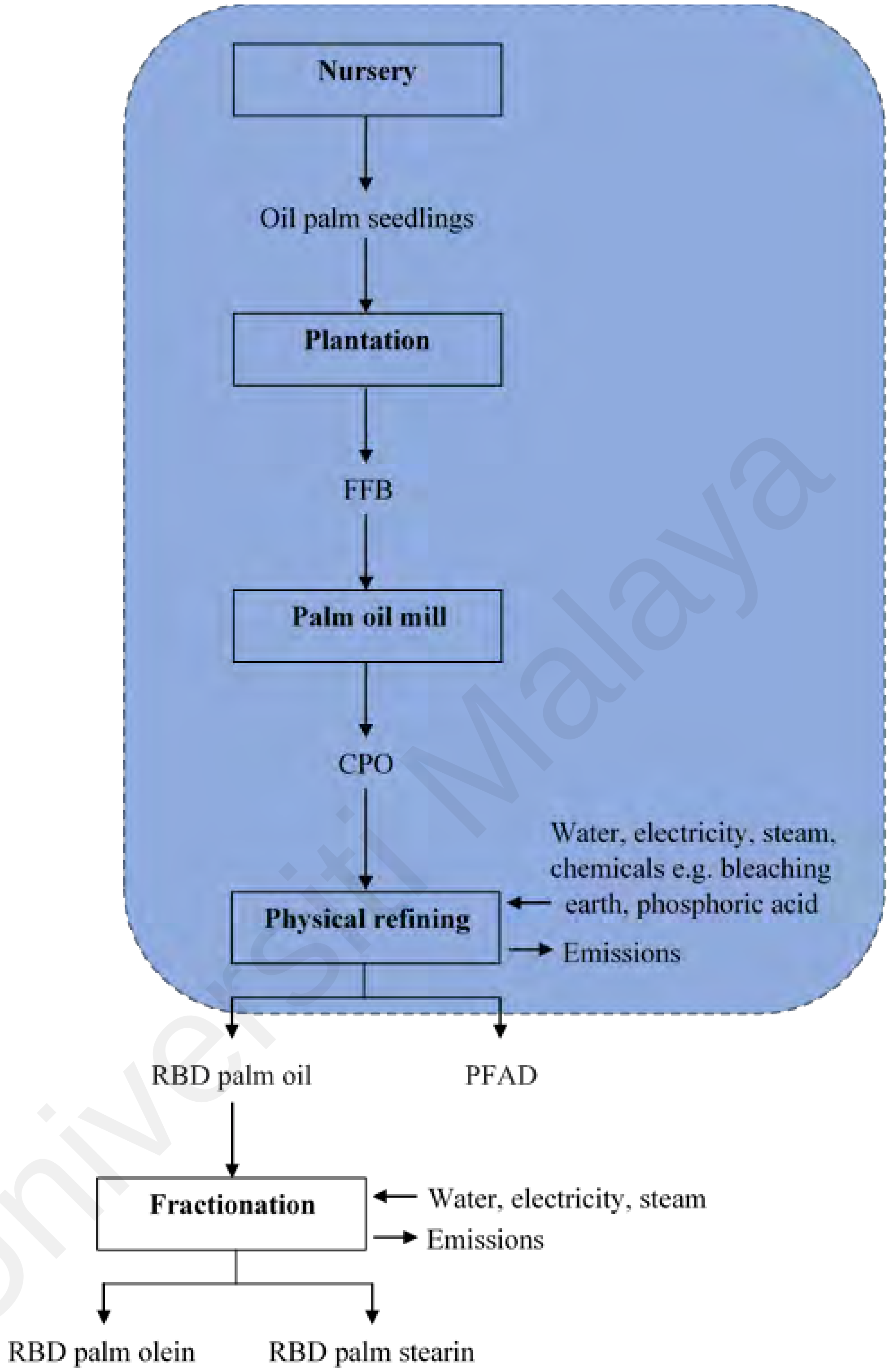


Figure 3.5: System boundary for cradle-to-gate LCA of palm oil refining

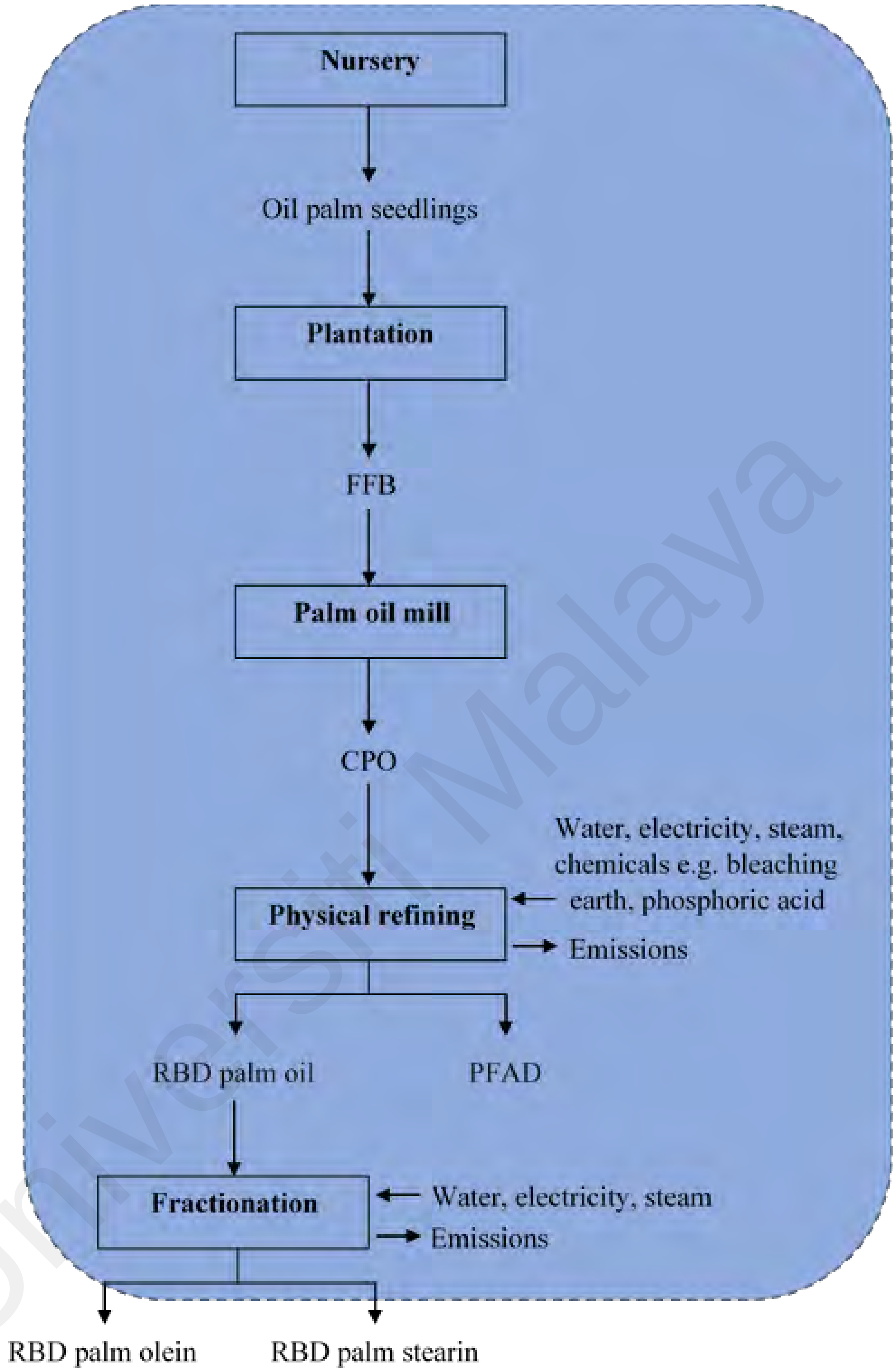


Figure 3.6: System boundary for cradle-to-gate LCA of palm oil refining and fractionation

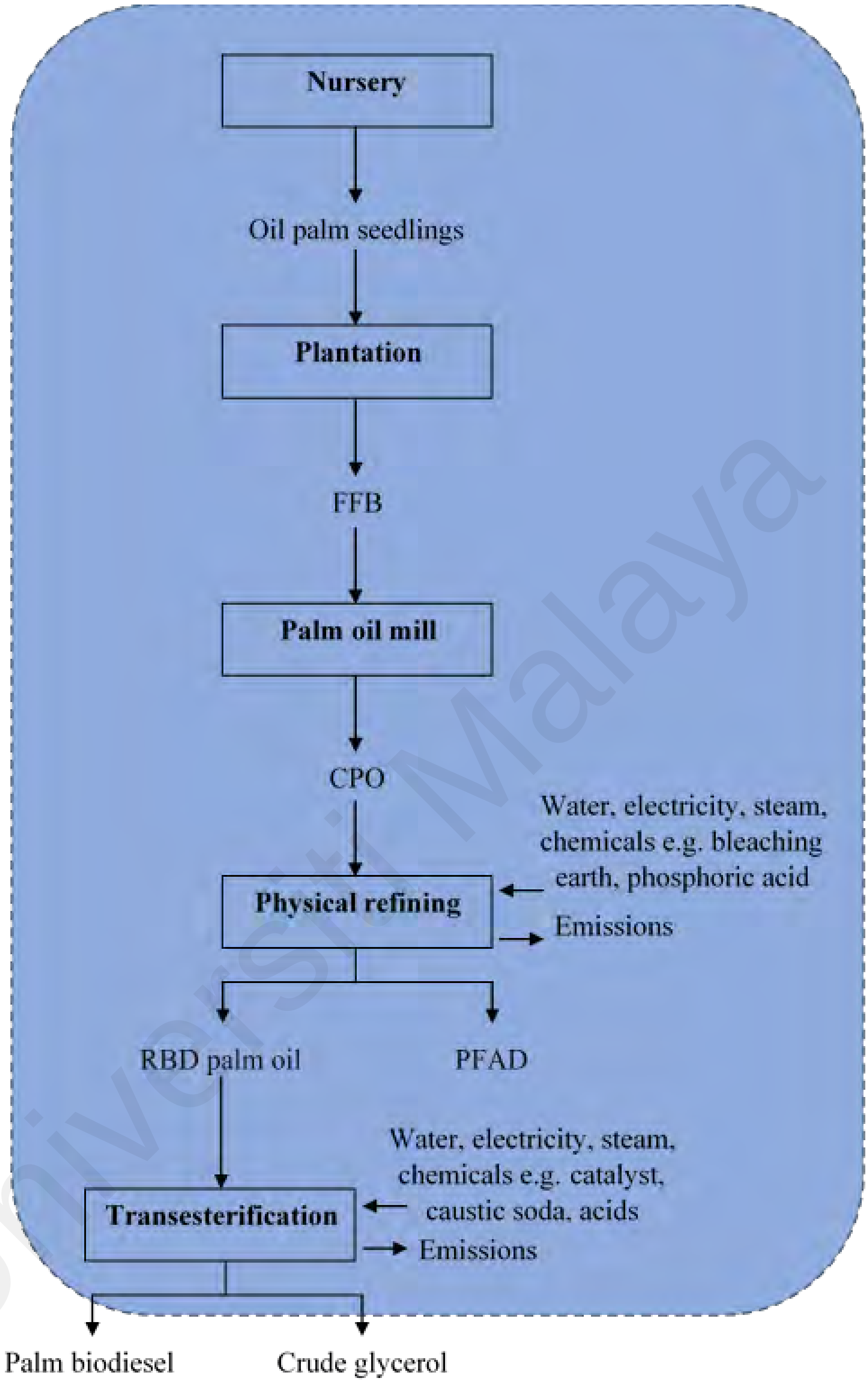


Figure 3.7: System boundary for cradle-to-gate LCA of palm biodiesel production

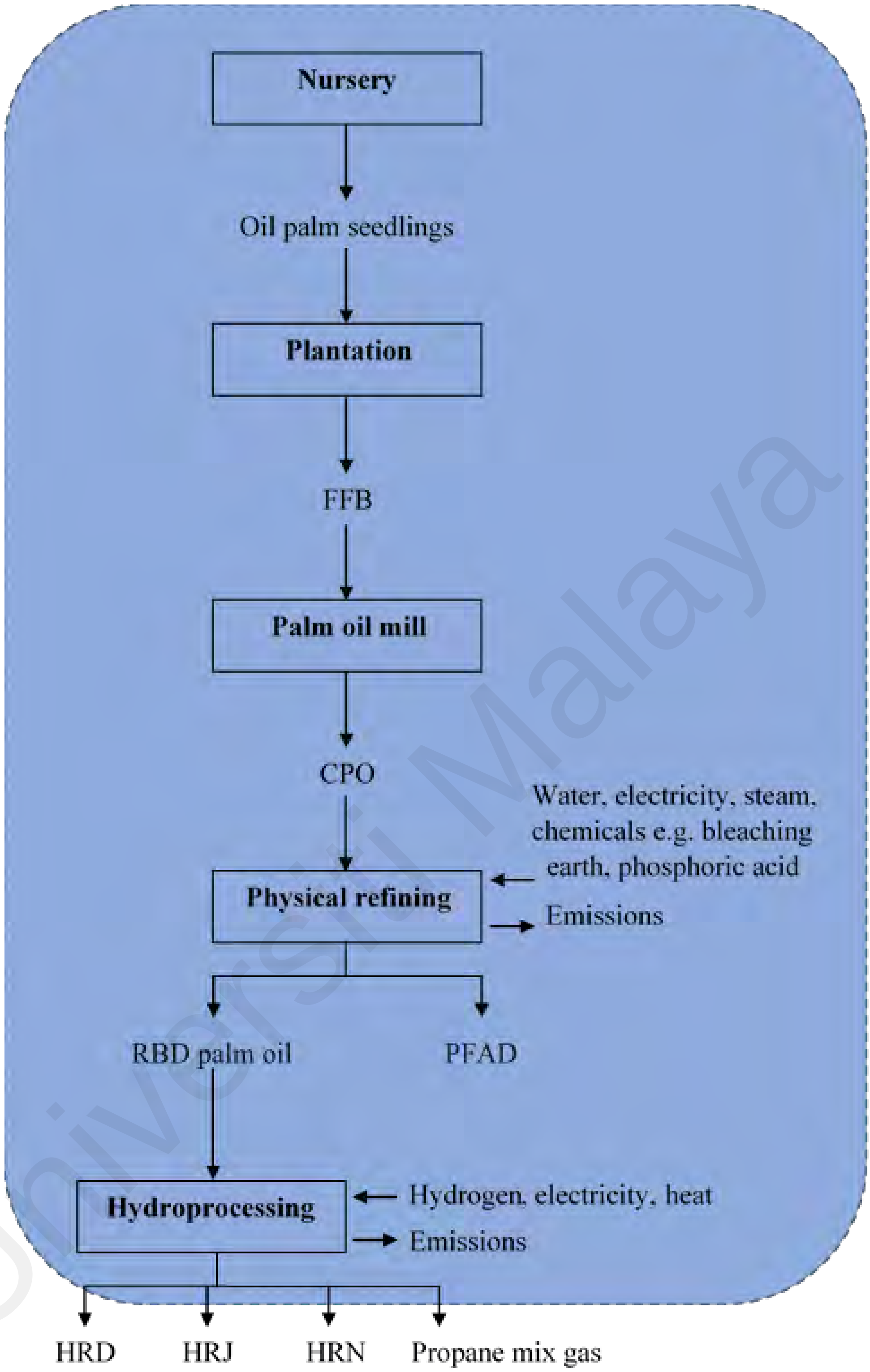


Figure 3.8: System boundary for cradle-to-gate LCA of RBD palm oil hydroprocessing

3.3.4 Data Collection and Data Sources

For this study, primary data were collected from relevant stakeholders i.e. palm oil refineries and palm biodiesel producers, in operation in Malaysia (Table 3.3). For hydroprocessing biofuels, data were obtained from pilot plant operation and data published in the literature (secondary data) since the hydroprocessing plant is not commercially available in Malaysia at the moment.

The collection of inventory data is one of the crucial and the most tedious activity in an LCA study, in particular for a study conducted in developing countries. This is because some of the factory operation data may not be properly, clearly or fully recorded. Furthermore, the operation data are commercially sensitive. These data are treated confidentially most of the time as it may review trade information and the performance of the particular factory. Hence, some of the industry players are reluctant to share and provide detailed operational data for any analyses.

In the present study, the collection of the inventory data was performed by circulating survey questionnaires prepared (Appendix A and B). Upon receiving the reply from the entities that were willing to share the operational information, the data received were analysed, evaluated and compared with literature and industry norms as well as data published in previous studies, if available. Clarification with respective entities was carried out when there are uncertainties or doubts. Clarification was conducted through email and telephone communications with the person in-charged in respective entities. Upon satisfactory clarification, usually after several rounds of communication, the data were accumulated to produce an industry weighted average data. These average data are used for inventory analysis and impact assessment study. The operational data collected from the entities that participated in the LCA study are known as foreground data or site-specific data. Besides this foreground data, background data that involve materials, chemicals, utilities are also needed for an LCA study. These data are obtained from reliable resources including databases available in the LCA software i.e. Ecoinvent 3.6 and USLCI.

Inventory data on the upstream activities are included when a cradle-to-gate LCA is performed. These upstream data are referring to activities before palm oil refining i.e. production of oil palm seedlings at nursery, production of FFB at plantations and production of CPO at palm oil mills. Inventory data from Halimah et al. (2010), Zulkifli et al. (2010) and Vijaya et al. (2010) were referred for the cradle-to-gate LCA. This is because these data are highly reliable national average data derived from primary data obtained directly from nurseries, plantations and palm oil mills in commercial operation in Malaysia. Differed from secondary data used by other studies which may not represent the actual scenario of the palm oil industry in the country.

Table 3.3: List of life cycle inventory tables and the data source

Process	**Source**
Production of palm seedling	Halimah et al. (2010)
Production of FFB	Zulkifli et al. (2010), MPOB (2020b)
Production of CPO	Vijaya Subramaniam et al. (2010), MPOB (2020b), Loh et al. (2019)
Refining of CPO to produce RBD palm oil	Primary data collected from commercial palm oil refineries through survey questionnaires
Fractionation of RBD palm oil	Primary data collected from commercial palm oil refineries through survey questionnaires
Transesterification of RBD palm oil and other refined palm products to produce palm biodiesel	Primary data collected from commercial palm biodiesel producers through survey questionnaires
Hydroprocessing of RBD palm oil and PFAD to produce hydroprocessed renewable biofuels	Pilot plant operation data
Transportation (a) CPO from palm oil mills to palm oil refineries (b) RBD palm oil and other refined palm products from refineries to biodiesel/biofuel plants	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.

Electricity supplied to refineries and biofuel plants	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of boiler fuels i.e. natural gas, diesel and fuel oil	Primary data collected from survey questionnaires, Ecoinvent 3.6 and USLCI database.
Production and supply of water	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Wastewater treatment in palm oil refineries and biodiesel plants	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of bleaching earth	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of phosphoric acid 85%	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of methanol	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of sodium methoxide	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of sodium hydroxide	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of acids used in the transesterification process	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.
Production and supply of hydrogen gas for hydroprocessing	Primary data collected from survey questionnaires and the Ecoinvent 3.6 database.

3.3.5 Data Quality and Representativeness

To safeguard the quality and to ensure the representativeness of the LCA, the primary data collected must meet the requirements stated in Table 3.4.

Table 3.4: Requirements of data quality

Parameter	**Requirement and implementation**
Temporal coverage	Data used shall be as latest as possible, preferably data from the past 5 years. The minimum length of time over the data collected should be at least 1-year operation data. Primary data: Palm oil refineries: 5-years operation data, from the year 2013 to 2017 Biodiesel plants: 3-years operation data, from the year 2015 to 2017. Secondary or background data: The latest databases that available in the LCA software e.g. Ecoinvent 3.6 and USLCI.
Geographical coverage	Data representing the average Malaysian situation.
Technological coverage	Average Malaysian situation. Refineries: Physical refining Biodiesel plants: Transesterification of RBD palm oil and other refined palm products
Precision	Variability of data values will be analysed and discussed in the sensitivity analysis.
Completeness	All relevant processes in refineries and biodiesel plants are included.
Representativeness	Inventory data complied with the temporal, geographic and technological frame, representing the average Malaysian situation.
Consistency	Primary data of the same level of detail shall be used. Data were checked through communication with the representatives of refineries and biodiesel plants.
Reproducibility	Data reported enabling reproducibility of the analyses.
Data sources	Data shall be obtained from reliable sources and databases. In the present study, primary data were obtained from refineries and biodiesel plants in operation in Malaysia while secondary data were referred to established databases e.g. Ecoinvent 3.6 and USLCI.

3.3.6 Allocation Procedures

As mentioned in the ISO standard, the inputs and outputs shall be allocated to the products if there is more than one product from the system evaluated (ISO, 2006b). According to ISO 14044, allocation should be avoided by either dividing the unit process into sub-processes or expanding the product system to include the additional functions of the co-products, wherever possible (ISO, 2006b). However, such procedure is not viable here since the focus of the current study is palm oil refining, fractionation and biodiesel or biofuel production which involve several co-products with different quality and usage. Allocation based on economic value was chosen for refinery and biodiesel production (Table 3.5). Yearly average prices of RBD palm oil, PFAD, RBD palm olein, RBD palm stearin, palm biodiesel and crude glycerol were obtained from market reports. Allocation based on mass and energy content is further evaluated and discussed in the sensitivity analysis in Section 4.5.1. Allocation based on energy content i.e. lower heating value (LHV) was applied for the production of hydroprocessed biofuels because all the products of hydroprocessing plant are energy products. At the moment, there is no commercial plant and commercial production of hydroprocessed biofuels in Malaysia. Hence, it is difficult to obtain reliable market information on the products. Nevertheless, allocation based on mass and economic value is further evaluated and discussed in the sensitivity analysis in Section 4.5.1.

Table 3.5: Allocation procedures of subsystems evaluated

Subsystem	Process	Allocation procedures
Palm oil refinery	Palm oil refining	Economic value
	Palm oil fractionation	Economic value
Biodiesel plant	Palm biodiesel production	Economic value
Hydroprocessing plant	Hydroprocessed palm biofuels production	Energy content: lower heating value

3.3.7 Cut-off Criteria

To the best knowledge, all relevant inputs and outputs of the foreground system (primary data) were gathered and presented in Section 4.1.

Wastewater treatment was not considered for refinery and biodiesel/biofuel subsystems in the present study. This is because the amount of wastewater is relatively small compared to the total output with regards to one tonne of products of the refinery. Also, the wastewater produced from refineries and biodiesel plants is much cleaner than the wastewater from palm oil mills. Previous studies by Puah et al. (2010), Tan et al. (2010) and Schneider and Finkbeiner (2013) have shown that wastewater treatment does not have any significant effect on the LCA. Nevertheless, wastewater treatment is analysed using generic data available in the Ecoinvent database and presented in the sensitivity analysis in Section 4.5.1.

Production of capital goods i.e. production equipment and building infrastructure were excluded from the assessment due to the reason that it has no significant impact on the LCA as shown by Puah et al. (2010) and Tan et al. (2010). Also, the inventory data for capital goods, in particular, the building infrastructure is difficult to obtain as the commercial palm oil refineries and biodiesel plants were established more than a decade ago.

Packaging of products was also not included in this LCA as the products are traded in bulk and transported in a reusable container through road tankers and/or ships.

3.4 Life Cycle Impact Assessment

After obtaining sufficient inventory data which satisfied the quality requirements, a life cycle impact assessment (LCIA) is carried out. According to the ISO standards, LCIA is a phase of LCA aimed to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO, 2006a, 2006b).

As stipulated in the ISO 14044, there are several mandatory elements in this LCIA phase which are:

(i) selection of impact categories, category indicators and characterisation models
(ii) classification - assignments of LCI results to the selected impact categories
(iii) characterisation – calculation of category indicator results

With the assistance of modern LCA software i.e. SimaPro used in the present study, these elements are satisfied by entering the inventory data into the software program and LCIA is performed by selecting relevant LCIA methodologies. ReCiPe 2016 is the methodology chosen for LCIA in the present study. The midpoint impact categories listed in the ReCiPe 2016 methodology are evaluated (Figure 2.3).

Besides the mandatory elements, there are a few optional elements in the LCIA phase e.g. normalisation, grouping and weighting. Normalisation is a calculation of the characterised results relative to some reference information. Grouping is an assignment of impact categories into one or more sets with an aim to sort the impact categories on a nominal basis or to rank the impact categories in a given hierarchy. Weighting is a process of converting the characterised results with selected weighing factors and aggregating them across impact categories. Both grouping and weighting are based on value choices.

Only the mandatory elements of LCIA are considered and evaluated in the present LCA study. This is also in line with the LCIA methodology chosen.

3.5 Life Cycle Interpretation

Life cycle interpretation is performed according to ISO 14044, which comprises the following elements:

(i) Identification of significant issues based on the results of LCI and LCIA.

(ii) Evaluation on the completeness, sensitivity and consistency checks.

(iii) Conclusions, limitations and recommendations of the present study.

3.6 Assumptions and Limitations

3.6.1 Assumptions and Potential Limitations Related to Subsystems

The results of the present study are valid based on the subsystems presented in Table 3.1. Physical refining of CPO in refining plant of the palm oil refineries, fractionation of RBD palm oil in the fractionation plant of the palm oil refineries, transesterification of RBD palm oil and other refined palm products in palm biodiesel plants and hydroprocessing of RBD palm oil and PFAD, are the processes identified for the subsystems.

3.6.2 Potential Limitations Related to System Boundary

The results of the present study are valid for the system boundaries set in section 3.3.3. Activities outside the system boundaries are excluded from the assessment. No data collection and no evaluation of these activities are conducted.

3.6.3 Potential Limitations Related to Allocation

Different allocation procedures are evaluated in the sensitivity analysis, as mentioned in section 3.3.6. The environmental burden allocated to product and co-products may be different, depends on the allocation procedures.

3.6.4 Assumptions Related to Biogas Capturing Facilities

It has been reported in the literature that biogas capturing facilities play a significant role in determining the environmental impacts, in particular, the global warming impact, on the production of CPO, refined palm oil and palm biodiesel (Choo et al., 2011). However, none of the literature presents the actual GHG emissions of Malaysia scenario possibly due to the lack of reliable data on biogas facilities available then. Loh et al. (2019) reported 28% of nationwide biogas implementation or 125 biogas plants are in operation as of December 2019. Hence, it is assumed that 28% of the total CPO produced in Malaysia are produced from palm oil mills with biogas trapping facilities.

3.7 LCA Software

In modern days, the LCA exercise is usually carried with the assistance of LCA software. There are a few LCA software available in the market. SimaPro and GaBi are the common ones. SimaPro 9.1.1.1 is used in the current study because of the following reasons:

(i) the up-to-date version of SimaPro software,

(ii) availability and accessibility of the software,

(iii) to synchronise with other LCA studies carried out previously using the same software,

(iv) availability of robust LCIA methodologies i.e. ReCiPe 2016, CML, etc. and

(v) resourceful background databases available in the SimaPro software i.e. the Ecoinvent 3.6, Agri-footprint, USLCI databases (PRé Consultants, 2018). These databases are very useful in providing the environmental loads of the materials and chemicals that are used in industrial processes.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Inventory Analyses

4.1.1 Palm Oil Refining

Collection of inventory data from palm oil refineries was performed in two phases. In phase one, inventory data were obtained from a total of 14 palm oil refineries in operation in Malaysia for a period of two years, from 2013 to 2014. Of these 14 refineries, seven are located in Peninsular Malaysia, five in Sabah and two in Sarawak. As shown in Figure 4.1, the installed capacities of CPO refining in these refineries vary from around 100 thousand tonnes per annum to 1.3 million tonnes per annum.

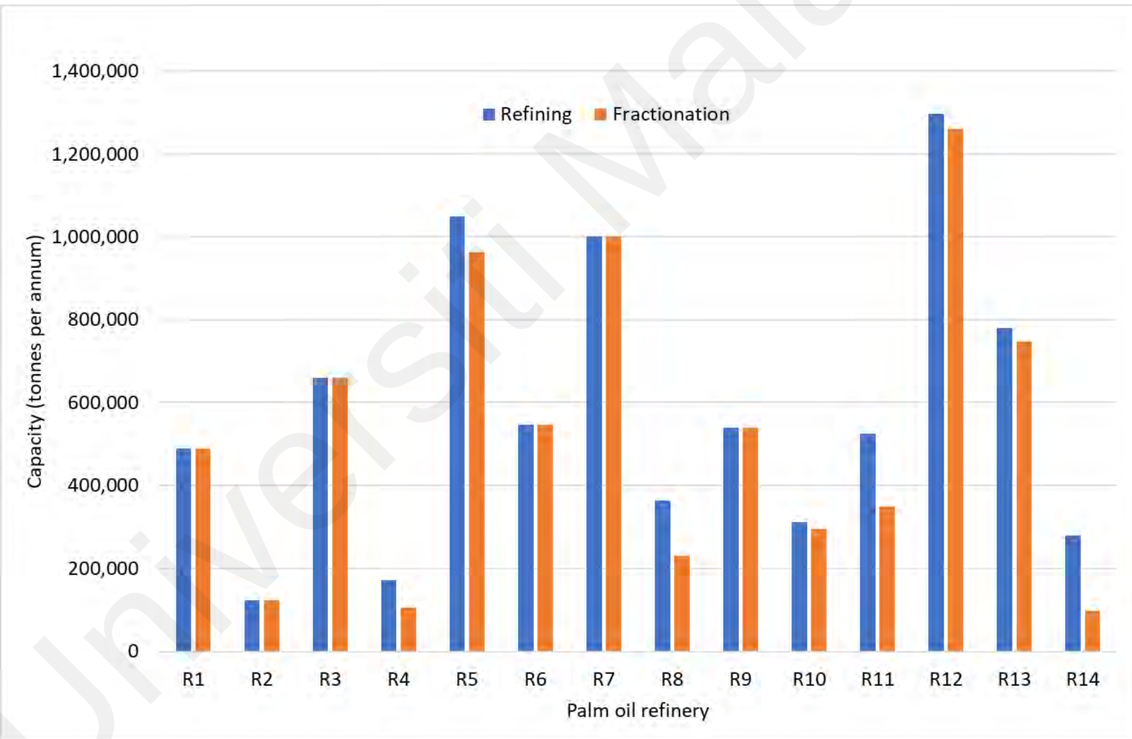


Figure 4.1: Refining and fractionation installed capacities of 14 palm oil refineries

Due to data confidentiality, the inventory data for palm oil refining are presented as a total of 14 refineries in Table 4.1, instead of by individual refinery. A total of 12.117 million tonnes of CPO were refined in these 14 palm oil refineries to produce 11.482 million tonnes of RBD palm oil in 2013 and 2014. This amount represents 39.57% of the total RBD palm oil produced in Malaysia for these two years. Besides RBD palm oil, 562.904 thousand tonnes of PFAD were also produced as a co-product from the refineries.

Table 4.1: 2-years inventory data of palm oil refining obtained from 14 palm oil refineries (2013 to 2014)

Item	**Unit**	**Total**	**Per tonne of RBD palm oil produced**
Input:			
Crude palm oil (CPO)	t	12,117,355	1.0553
Phosphoric acid	kg	6,615,897	0.5762
Bleaching earth	kg	123,875,736	10.7884
Electricity	kWh	123,050,390	10.7165
Boiler fuels:			
(i) Natural gas	m^3	23,472,564	2.0442
(ii) Diesel	kg	5,686,848	0.4953
(iii) Fuel oil	kg	8,836,650	0.7696
Water	L	2,266,294,679	197.3726
Weighted average distance from palm oil mills to refineries	km	-	159.0052
Transport of CPO to refineries	tkm	1,926,721,985	167.7991
Output:			
Refined, bleached and deodorised (RBD) palm oil	t	11,482,314	1.0000
Palm fatty acid distillate (PFAD)	kg	562,904,115	49.0236
Wastewater	L	323,264,644	28.1533
Wastewater BOD	g	3,877,655	0.3377
Wastewater COD	g	24,412,880	2.1261

Collection of the subsequent three years (2015 to 2017) inventory data was carried out in the second phase of the project. However, only six palm oil refineries participated in the survey by providing their operation data. The other eight refineries were reluctant to provide further operation data. This shows the difficulty to obtain primary operation data from relevant stakeholders in the country. Nevertheless, the operation data collected were combined with the data from phase one to produce 5-years (2013 to 2017) operation data for these six palm oil refineries and they are presented in Table 4.2. The locations of these six palm oil refineries are as follow, three located in Peninsular Malaysia, two in Sabah and one in Sarawak. The total RBD palm oil produced from these six palm oil refineries for the period of five years was recorded at 17.415 million tonnes, 24.60% of total RBD palm oil produced in Malaysia from 2013 to 2017.

Table 4.2: 5-years inventory data of palm oil refining obtained from 6 palm oil refineries (2013 to 2017)

Item	**Unit**	**Total**	**Per tonne of RBD palm oil produced**
Input:			
Crude palm oil (CPO)	t	18,377,131	1.0552
Phosphoric acid	kg	9,641,813	0.5536
Bleaching earth	kg	192,411,442	11.0483
Electricity	kWh	177,183,441	10.1739
Boiler fuels:			
(i) Natural gas	m^3	36,256,427	2.0818
(ii) Diesel	kg	4,135,389	0.2375
(iii) Fuel oil	kg	8,739,400	0.5018
Water	L	3,228,050,109	185.3547
Weighted average distance from palm oil mills to refineries	km	-	172.0651
Transport of CPO to refineries	tkm	3,162,062,668	181.5657
Output:			
Refined, bleached and deodorised (RBD) palm oil	t	17,415,533	1.0000
Palm fatty acid distillate (PFAD)	kg	853,825,325	49.0267
Wastewater	L	462,852,423	26.5770
Wastewater BOD	g	7,000,754	0.4020
Wastewater COD	g	40,785,385	2.3419

The inventory data per tonne of RBD palm oil produced, the functional unit of palm oil refining, are also presented in Table 4.1 and Table 4.2. No significant difference between the 2-years and 5-years inventory data were observed. The data were found to fall in the same order for both 2-years and 5-years duration. Hence, the 5-years inventory data are used for further inventory analysis and impact assessment in section 4.3.

The inventory data in Table 4.2 are similar to those reported a decade ago by Tan et al. (2010). On average, 1.06 tonnes of CPO are required to produce 1 tonne of RBD palm oil and 49 kg of PFAD. The use of chemicals in the refining process is in accordance with the typical practice of a physical palm oil refining plant, i.e. 0.05-0.2% phosphoric acid for degumming and 0.8-2.0% bleaching earth for the absorption of undesired contaminants (Yusof, 1996). Similar to Tan et al. (2010), energy for CPO refining is met by electricity supplied from the national power grid and steam/heat from boilers in the refineries. However, the type of boiler fuels used for steam production in boilers in the current study differed from those reported by Tan et al. (2010). Previously, it was reported that the fuel used for steam production was solely medium fuel oil. However, it has shifted to natural gas for refineries in Peninsular Malaysia. This is mainly due to price changes of fossil fuels and their availability in the country. Nevertheless, refineries in Sabah and Sarawak are still using liquid fossil fuels e.g. fuel oil and petroleum diesel as boiler fuels due to the absence of gas piping facilities in these two states. 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 compared to Tan et al. (2010). 0.40 g BOD and 2.34 g COD per tonne of RBD palm oil produced which translate to 15.13 mg/L for BOD and 88.12 mg/L for COD. These values are below the limits enforced by the Department of Environment Malaysia (DOE, 2009). Besides, Tan et al. (2010) also reported that spent bleaching earth was a waste from palm oil refineries. Appropriate treatment and disposal were needed to comply with the requirements of local authorities. However, it was discovered in the current survey that the spent bleaching earth is no longer treated as waste. They are sold to a third party for oil recovery at present days. Hence, the transportation, treatment and disposal of spent bleaching earth are not considered in the present study. Furthermore, the insignificant environmental impact of the treatment of spent bleaching earth was reported previously by Tan et al. (2010).

4.1.2 Palm Oil Fractionation

Collection of operation data for fractionation plants was conducted concurrently with the refining plants since they are located at the same premise and all palm oil refineries in Malaysia are equipped with both refining and fractionation plants. Similar to the refining, fractionation data from 14 and 6 refineries were obtained respectively in phase 1 and phase 2 of the data collection. As shown in Figure 4.1, the size of the fractionation plants was found similar or slightly lower than its refining capacity. This is because the feed material for palm oil fractionation is the RBD palm oil produced from the refining plants. Hence, it is economically and technologically justifiable for such installed capacities.

The inventory data for fractionation are presented in Table 4.3 and Table 4.4 for 2-years and 5-years operations, respectively. As mentioned earlier, most of the RBD palm oil produced in the country are subjected to the fractionation process in the fractionation plants. From the inventory data obtained, 83.71% and 84.90% of the total RBD palm oil produced were fractionated for the 2-years (14 refineries) and 5-years (6 refineries) operations. Similar to palm oil refining, the inventory data per tonne of RBD palm oil fractionated in Table 4.3 and Table 4.4 were also found to be in a similar range. Again, the 5-years inventory data are used for further analysis and impact assessment in section 4.3.

In the fractionation process, 0.80 tonnes of RBD palm olein and 0.20 tonnes of RBD palm stearin are produced from the fractionation of one tonne of RBD palm oil. Fractionation is just a physical separation process that does not require the use of any chemicals. Similar to refining, energy inputs required are electricity supplied from the national power grid and steam/heat from boilers. Besides, water supply and fossil fuels are needed to generate steam for heating the RBD palm oil prior to crystallisation and separation. The amount of wastewater produced per tonne of RBD palm oil fractionated and its quality are also reported in Table 4.3 and Table 4.4. No transportation is needed as the fractionation plants are just located adjacent to the refining plants in the same premises, within the battery limit of the refinery.

Table 4.3: 2-years inventory data of palm oil fractionation obtained from 14 palm oil refineries (2013 to 2014)

Item	**Unit**	**Total**	**Per tonne of RBD palm oil processed**
Input:			
Refined, bleached and deodorised (RBD) palm oil	t	9,612,260	1.0000
Electricity	kWh	126,832,685	13.1949
Boiler fuels:			
(i) Natural gas	m^3	10,770,729	1.1205
(ii) Diesel	kg	2,434,454	0.2533
(iii) Fuel oil	kg	3,942,739	0.4102
Water	L	1,429,533,010	148.7218
Output:			
Refined, bleached and deodorised (RBD) palm olein	t	7,664,073	0.7973
Refined, bleached and deodorised (RBD) palm stearin	t	1,948,182	0.2027
Wastewater	L	146,252,034	15.2152
Wastewater BOD	g	1,528,586	0.1590
Wastewater COD	g	10,434,111	1.0855

Table 4.4: 5-years inventory data of palm oil fractionation obtained from 6 palm oil refineries (2013 to 2017)

Item	**Unit**	**Total**	**Per tonne of RBD palm oil processed**
Input:			
Refined, bleached and deodorised (RBD) palm oil	t	14,786,596	1.0000
Electricity	kWh	194,069,424	13.1247
Boiler fuels:			
(i) Natural gas	m^3	21,854,169	1.4780
(ii) Diesel	kg	1,295,183	0.0876
(iii) Fuel oil	kg	3,569,900	0.2414
Water	L	2,426,331,022	164.0899
Output:			
Refined, bleached and deodorised (RBD) palm olein	t	11,856,580	0.8018
Refined, bleached and deodorised (RBD) palm stearin	t	2,930,036	0.1982
Wastewater	L	198,258,511	13.4080
Wastewater BOD	g	2,354,686	0.1592
Wastewater COD	g	19,471,838	1.3169

4.1.3 Palm Biodiesel Production

Three-years operation data (2015-2017) for palm biodiesel production were obtained from six biodiesel plants operated by five commercial producers in the country. The installed capacities of these plants range from 100 to 150 thousand tonnes per annum (Figure 4.2). In terms of location, four plants are located in Peninsular Malaysia and one each in Sabah and Sarawak.

The aggregated data of six biodiesel plants are presented in Table 4.5. The total volume of palm biodiesel produced by these five producers for a period of three years was recorded at 802 thousand tonnes or 42.33% of the total biodiesel production in Malaysia from 2015 to 2017. The inventory data are also presented as per tonne of palm biodiesel produced, the functional unit of palm biodiesel production. The inventory data differed from the data reported by Puah et al. (2010) which focussed on the production and use of one megajoule (MJ) of palm biodiesel in diesel vehicles. The units of other material inputs were also converted and presented in energy form, as MJ, based on inventory data collected from two biodiesel producers then.

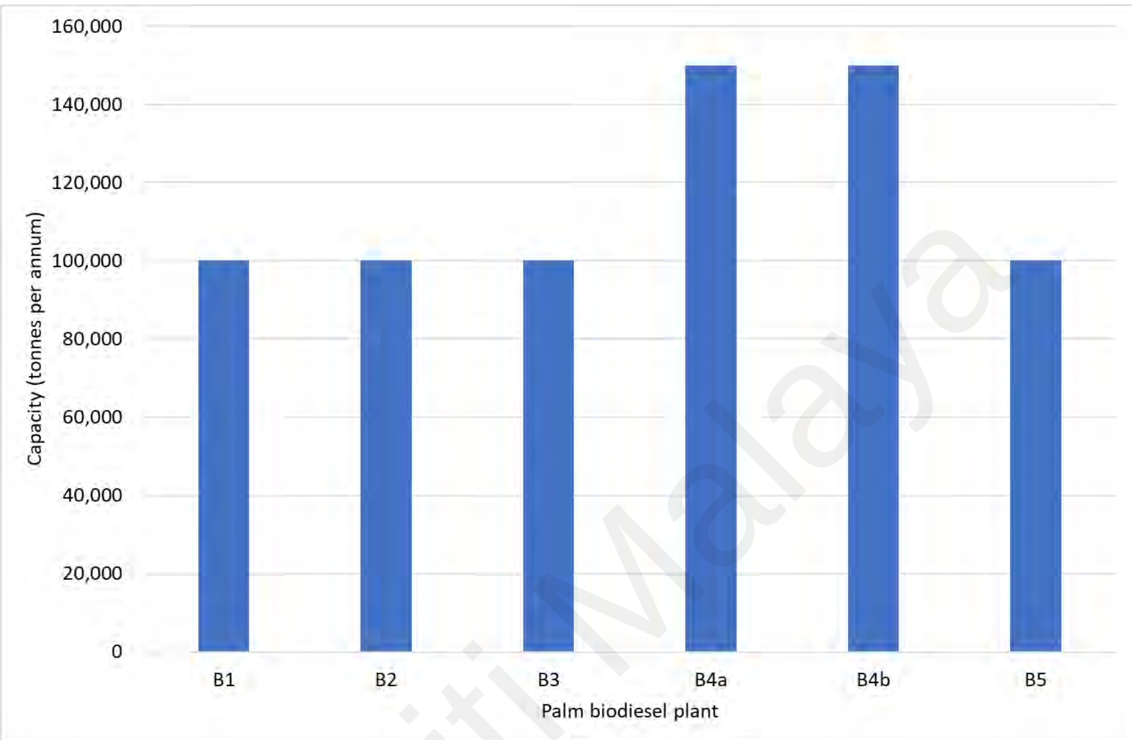


Figure 4.2: Installed capacities of 6 palm biodiesel plants

Based on the inventory data collected, the major feed materials for biodiesel production in Malaysia are similar to those reported by Puah et al. (2010), i.e. RBD palm oil and methanol. In general, the predominant feedstock for biodiesel production in Malaysia is still RBD palm oil after more than a decade of commercial operation. This is mainly due to the availability of RBD palm oil, as most of the CPO produced in the country are refined into RBD palm oil before being used for downstream edible and non-edible applications. Furthermore, RBD palm oil is easier to handle in biodiesel plants compared to CPO. No pre-treatment or additional acid esterification is required due to its low acidity and low contamination e.g. water and dirt. Besides RBD palm oil, other feedstocks in use are RBD palm stearin (3.82%) and PFAD (1.67%), producing a small volume of biodiesel which catered for the export market. Methanol is commonly used simply because it is the least expensive alcohol available.

Table 4.5: 3-years inventory data of palm biodiesel production obtained from 6 biodiesel plants (2015 to 2017)

Item	**Unit**	**Total**	**Per tonne of palm biodiesel produced**
Input:			
RBD palm oil	t	754,432	0.9406
RBD palm stearin	t	30,489	0.0380
PFAD	t	13,325	0.0166
Total feed material	t	798,246	0.9952
Methanol	kg	87,344,545	108.8932
Sodium methoxide 30% (catalyst)	kg	7,569,648	9.4371
Hydrochloric acid	kg	7,683,241	9.5788
Citric acid	kg	699,845	0.8725
Acetic acid	kg	112,000	0.1396
Sodium hydroxide (neutralising agent)	kg	629,922	0.7853
Electricity	kWh	29,791,153	37.1409
Boiler fuels*:			
(i) Natural gas	m^3	4,269,326	6.0749
(ii) Diesel	kg	5,701	0.0081
(iii) Fuel oil	kg	94,769	0.1348
Water	L	483,778,390	603.1306
Average distance from palm oil refineries to biodiesel plant	km	9.29	
Transport of feed oil to biodiesel plants	tkm	7,412,938	9.2418
Output:			
Palm biodiesel	t	802,112.14	1.0000
Crude glycerol	t	102,215.34	0.1274
Wastewater	L	186,068,576	231.9733

Note: *Data from five biodiesel plants, based on total 702,780.72 t palm biodiesel produced

On average, approximately one tonne of palm feedstocks (mainly RBD palm oil) is consumed to react with 109 kg of methanol to produce one tonne of palm biodiesel and 127 kg of crude glycerol. The catalyst used by all five producers for the transesterification process for the past three years is sodium methoxide with 30% concentration, which differed from the sodium hydroxide as reported previously by Puah et al. (2010). Sodium methoxide is widely available in the commercial market in the present day. Its global market value was estimated at around US$ 0.3 billion (MarketWatch, 2019). It is more convenient for biodiesel producers in handling and storing sodium methoxide compared to sodium hydroxide. Furthermore, the on-site preparation of sodium hydroxide in a liquid solution will potentially produce water. The presence of water might adversely affect the transesterification reaction if it is not removed thoroughly from the solution (Van Gerpen & Knothe, 2010). Nevertheless, sodium hydroxide solution is used instead as a neutralising agent at the glycerol polishing stage. Acids in the form of hydrochloric acid, citric acid and acetic acid are commonly used by the producers to facilitate the separation of crude glycerol from the methyl ester phase. Similar to palm oil refineries, fossil fuels are used for steam production in the boiler house. Natural gas is used by producers in Peninsular Malaysia and Sarawak while petroleum diesel is the only option for the producer in Sabah. The average water consumption reported in this study is 603 L per tonne of palm biodiesel produced, 66% higher than the value reported by Puah et al. (2010). In general, biodiesel plants are located in industrial areas near palm oil refineries. Some of the biodiesel plants are in fact part of the downstream activities situated next to the refinery complexes. Hence, the distance between the supply of RBD palm oil to biodiesel plants is very minimal. From the inventory data collected, less than 10 tkm was reported for transportation of feed oil (feedstock) to biodiesel plants.

4.1.4 Hydroprocessed Palm Biofuels

No commercial hydroprocessing plant is available in Malaysia at the moment. Hence, the inventory data for the production of hydroprocessed biofuels i.e. HRD and HRJ are referred to confidential pilot plant data with some assumptions. Transportation of feed materials i.e. RBD palm oil and PFAD was omitted due to the same reason. The inventory data used for the gate-to-gate and cradle-to-gate LCA are not presented and discussed in this section due to data confidentiality.

Similar to Fan et al. (2013), two biofuels production modes i.e. diesel mode and jet fuel mode, are proposed and evaluated. Maximum HRD production with no HRJ is assumed in the diesel mode while maximum HRJ production with some HRD as a co-product is assumed in the jet fuel mode. Propane mix gas and HRN are produced in both diesel and jet fuel modes as co-products. Propane mix gas is derived from hydrogenation of glycerol molecule of triglyceride backbone after fatty acids are stripped off during hydrocracking process. HRN is a mixture of C5 and C6 hydrocarbons produced from hydrocracking and isomerisation of HRD to produce HRJ. Both propane mix gas and HRN are potential energy sources. HRN can be used as a blendstock for gasoline (petrol).

Two types of palm feedstocks were evaluated in the pilot plant studies i.e. RBD palm oil and PFAD. It has been tested and verified in the pilot plant studies that both RBD palm oil and PFAD are suitable feedstocks for the production of hydroprocessed biofuels without pretreatment process since both RBD palm oil and PFAD are purified in the typical palm oil refining process described in section 2.6. However, RBD palm oil and PFAD are different in terms of their chemical composition. RBD palm oil mainly consists of triglycerides with very low acidity (<0.1% free fatty acids) while PFAD contains more than 70% free fatty acids (Tang, 2009). Hence, less hydrogen is needed for hydrocracking and hydroprocessing of PFAD compared with RBD palm oil. Also, less propane mix gas is produced from PFAD due to a much lower concentration of glycerides. Comparing the diesel mode and jet fuel mode, the hydrogen gas consumption for the production of HRJ was found higher than the production of HRD. This is because more hydrogen is needed to crack and to isomerise the HRD to produce HRJ. Also, a slightly higher biofuels yield was found for the PFAD.

In summary, four scenarios are evaluated in the current study for the production of hydroprocessed biofuels based on two hydroprocessing modes i.e. diesel mode and jet fuel mode, and two potential feedstocks i.e. RBD palm oil and PFAD. These four scenarios are:

1) Production of HRD from RBD palm oil,
2) Production of HRD from PFAD,
3) Production of HRJ from RBD palm oil, and
4) Production of HRJ from PFAD.

4.2 Allocation Procedures

4.2.1 Palm Oil Refining

4.2.1.1 Allocation based on Mass

Allocation based on mass is the most straightforward procedure. The allocation percentages are calculated based on the mass percentages of the products and co-products of the refining plants. From Table 4.1 and 4.2, it is noted that RBD palm oil is the main product and PFAD is the co-product of the refining plants. The total production of RBD palm oil and PFAD from 6 palm oil refineries for 5-years operation are 17,415,533 tonnes and 853,825 tonnes, respectively. Hence, the calculated mass percentages of RBD palm oil and PFAD are 95.33% and 4.67%, respectively (Table 4.6).

Table 4.6: Mass percentages of RBD palm oil and PFAD

Product/co-product	**Production volume**	
	tonne	**Mass %**
RBD palm oil	17,415,533	95.33
PFAD	853,825	4.67
Total	18,269,358	100.00

4.2.1.2 Allocation based on Economic Value

Allocation based on economic value is performed according to the commercial values of the products i.e. RBD palm oil and PFAD. Hence, a list of commercial values of the products is needed. Palm oil and palm oil products are typically traded according to mass in the commercial market and the prices are presented per tonne of products. In the current study, the annual prices of RBD palm oil and PFAD for a period of 10 years are obtained from MPOB statistics and presented in Table 4.7. The 10-years average prices of RBD palm oil and PFAD are calculated and are used to derive the allocation percentages presented in Table 4.8.

Table 4.7: Annual prices of RBD palm oil and PFAD (MPOB, 2020a)

Year	Annual prices (RM/t)	
	RBD palm oil	PFAD
2010	2,801.50	2,310.00
2011	3,426.00	2,495.00
2012	2,970.50	2,522.50
2013	2,478.50	1,883.50
2014	2,502.00	2,269.50
2015	2,279.50	1,902.50
2016	2,710.50	2,462.50
2017	2,880.00	2,733.00
2018	2,297.50	1,922.00
2019	2,245.50	1,807.50
Average	2,659.15	2,230.80

Table 4.8: Allocation percentages of RBD palm oil and PFAD according to economic value

	Unit	RBD palm oil	PFAD
Production volume	t	17,415,533	853,825
Average prices	RM/t	2,659.15	2,230.80
Value	RM	46,310,514,576.95	1,904,712,810.00
Allocation percentage	%	96.05	3.95

4.2.1.3 Allocation based on Energy Content

Allocation based on energy content is performed according to the gross heat of combustion of RBD palm oil and PFAD, which were recorded at 39.305 MJ/kg and 38.780 MJ/kg. Hence, the allocation percentages of RBD palm oil and PFAD are 95.39% and 4.61%, respectively (Table 4.9).

Table 4.9: Allocation percentages of RBD palm oil and PFAD according to energy content

	Unit	RBD palm oil	PFAD
Production volume	t	17,415,533	853,825
Gross heat of combustion (ASTM D240)	MJ/kg	39.305	38.780
Energy value	MJ	6.845×10^{11}	3.311×10^{10}
Allocation percentage	%	95.39	4.61

4.2.2 Palm Oil Fractionation

4.2.2.1 Allocation based on Mass

The allocation percentages are calculated based on the mass percentages of RBD palm olein and RBD palm stearin produced from the palm fractionation plants. The total production of RBD palm olein and RBD palm stearin from 6 palm oil refineries for 5-years operation are 11,856,580 tonnes and 2,930,036 tonnes, respectively (Table 4.4). Hence, the calculated mass percentages of RBD palm olein and RBD palm stearin are 80.18% and 19.82%, respectively (Table 4.10).

Table 4.10: Mass percentages of RBD palm olein and RBD palm stearin

Product/co-product	Production volume	
	tonne	Mass %
RBD palm olein	11,856,580	80.18
RBD palm stearin	2,930,036	19.82
Total	14,786,616	100.00

4.2.2.2 Allocation based on Economic Value

Allocation based on economic value is performed according to the commercial values of RBD palm olein and RBD palm stearin. In the current study, the 10-years annual prices of the two palm products are obtained from MPOB statistics (Table 4.11). The 10-years average prices of RBD palm olein and RBD palm stearin are calculated and used to derive the allocation percentages in Table 4.12.

Table 4.11: Annual prices of RBD palm olein and RBD palm stearin (MPOB, 2020a)

Year	Annual prices (RM)	
	RBD palm olein	RBD palm stearin
2010	2,852.50	2,701.00
2011	3,507.50	3,103.00
2012	2,963.00	2,786.00
2013	2,525.50	2,257.00
2014	2,494.50	2,446.00
2015	2,289.00	2,058.00
2016	2,769.50	2,650.50
2017	2,953.50	2,799.50
2018	2,328.50	2,232.00
2019	2,236.50	2,169.00
Average	2,692.00	2,520.20

Table 4.12: Allocation percentages of RBD palm olein and RBD palm stearin according to economic value

	Unit	RBD palm olein	RBD palm stearin
Production volume	t	11,856,580	2,930,036
Average prices	RM/t	2,692.00	2,520.20
Value	RM	31,917,913,360.00	7,384,276,727.20
Allocation percentage	%	81.21	18.79

4.2.2.3 Allocation based on Energy Content

Allocation based on energy content is performed according to the gross heat of combustion of RBD palm olein and RBD palm stearin, which were recorded at 39.340 MJ/kg and 39.435 MJ/kg. Hence, the allocation percentages of RBD palm olein and RBD palm stearin are 80.15% and 19.85%, respectively (Table 4.13).

Table 4.13: Allocation percentages of RBD palm olein and RBD palm stearin according to energy content

	Unit	RBD palm olein	RBD palm stearin
Production volume	t	11,856,580	2,930,036
Gross heat of combustion (ASTM D240)	MJ/kg	39.340	39.435
Energy value	MJ	4.664×10^{11}	1.155×10^{11}
Allocation percentage	%	80.15	19.85

4.2.3 Palm Biodiesel Production

4.2.3.1 Allocation based on Mass

The allocation percentages are calculated based on the mass percentages of palm biodiesel and crude glycerol produced from palm biodiesel plants. From Table 4.5, the total production of palm biodiesel and crude glycerol from six biodiesel plants for three years operation are 802,112.14 tonnes and 102,215.34 tonnes, respectively. Hence, the calculated mass percentages of palm biodiesel and crude glycerol are 88.70% and 11.30%, as shown in Table 4.14.

Table 4.14: Mass percentages of palm biodiesel and crude glycerol

Product/co-product	Production volume	
	tonne	Mass %
Palm biodiesel	802,112.14	88.70
Crude glycerol	102,215.34	11.30
Total	904,327.48	100.00

4.2.3.2 Allocation based on Economic Value

Allocation based on economic value is performed according to the commercial values of palm biodiesel and crude glycerol. In the current study, the 10-years annual prices of the two products are obtained from Thomson Reuters (2019) and presented in Table 4.15. The 10-years average prices of palm biodiesel and crude glycerol are calculated to derive the allocation percentages presented in Table 4.16, 96.82% for palm biodiesel and 3.18% for crude glycerol.

Table 4.15: Annual prices of palm biodiesel and crude glycerol (Thomson Reuters, 2019)

Year	Annual prices (US$/t)	
	Palm biodiesel	**Crude glycerol**
2009	647.53	113.80
2010	783.08	190.10
2011	1,309.00	250.90
2012	1,122.10	299.20
2013	868.20	243.10
2014	906.10	183.90
2015	886.80	218.20
2016	616.10	187.00
2017	819.50	268.00
2018	664.90	264.90
Average	862.33	221.91

Table 4.16: Allocation percentages of palm biodiesel and crude glycerol according to economic value

	Unit	Palm biodiesel	Crude glycerol
Production volume	t	802,112.14	102,215.34
Average prices	US$/t	862.33	221.91
Value	US$	691,685,361.69	22,682,606.10
Allocation percentage	%	96.82	3.18

4.2.3.3 Allocation based on Energy Content

Allocation based on energy content is performed according to the gross heat of combustion of palm biodiesel and crude glycerol, which were recorded at 39.940 MJ/kg and 18.500 MJ/kg. Hence, the allocation percentages of palm biodiesel and crude glycerol are 94.43% and 5.57% (Table 4.17).

Table 4.17: Allocation percentages of palm biodiesel and crude glycerol according to energy content

	Unit	**Palm biodiesel**	**Crude glycerol**
Production volume	t	802,112.14	102,215.34
Gross heat of combustion (ASTM D240)	MJ/kg	39.940	18.500
Energy value	MJ	3.204×10^{10}	1.891×10^{10}
Allocation percentage	%	94.43	5.57

4.2.4 Hydroprocessed Palm Biofuels Production

Similar methods are used to derive the allocation percentages for the palm-based hydroprocessed biofuels i.e. HRD and HRJ. However, the allocation percentages are not disclosed here due to data confidentiality.

4.3 Life Cycle Impact Assessment

4.3.1 Gate-to-Gate LCA of Palm Oil Refining

4.3.1.1 Contribution Analysis of Palm Oil Refining

The gate-to-gate characterised LCIA of palm oil refining at midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is shown in Figure 4.3. For all impact categories, significant contributors are the transportation of CPO, bleaching earth, electricity, phosphoric acid, boiler fuels and its combustion for steam production.

Transportation of CPO from palm oil mills to palm oil refineries is the highest contributor to 10 impact categories i.e. global warming, stratospheric ozone depletion, ozone formation for both effects on human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, terrestrial ecotoxicity, human non-carcinogenic toxicity, land use and fossil resource scarcity. Besides, it also contributes significantly to the other seven impact categories i.e. ionising radiation, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and mineral resource scarcity.

Bleaching earth is the highest contributor to ionising radiation, freshwater ecotoxicity, marine ecotoxicity and mineral resource scarcity. It is also important in the other 14 impact categories in particular the freshwater eutrophication and marine eutrophication with more than one-third of the contribution.

Electricity consumption from the national power grid is the highest contributor to both freshwater eutrophication and marine eutrophication. More than 70% of the impact on eutrophication are due to electricity and bleaching earth.

Phosphoric acid 85% concentration used for degumming has the highest contribution to human carcinogenic toxicity. Boiler fuels are significant in fossil resource scarcity while their combustion in boilers for steam generation is significant in global warming, fine particulate matter formation, terrestrial acidification and fossil resource scarcity. Water required for steam generation and process cooling is obvious in the water consumption impact category.

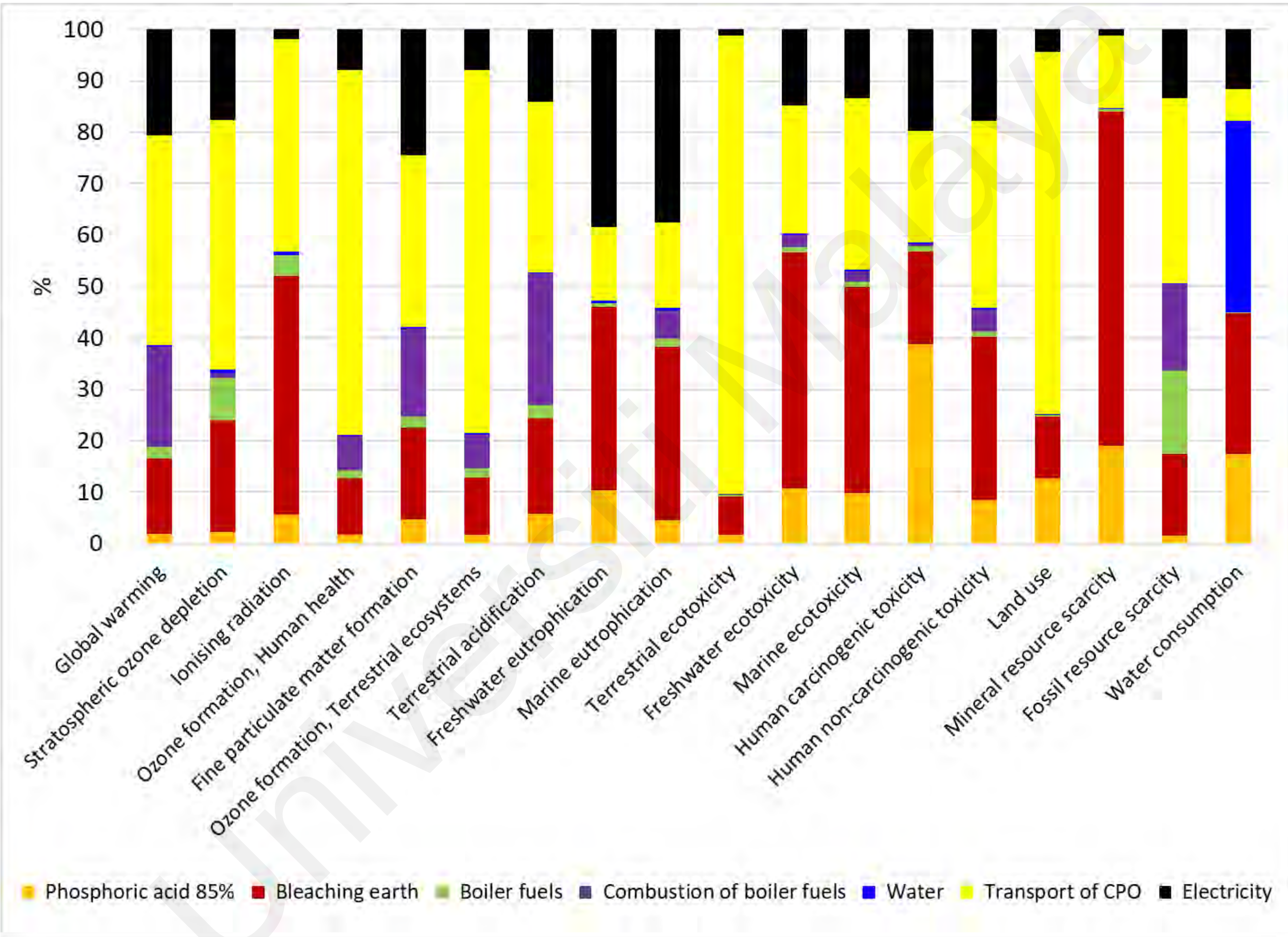


Figure 4.3: Characterised gate-to-gate LCIA of palm oil refining

4.3.1.2 Global Warming

The global warming potential is presented as kg CO_2 eq per tonne of refined palm products produced i.e. RBD palm oil and PFAD. The main sources of global warming potential are the transportation of CPO from palm oil mills to palm oil refineries, electricity from the national power grid and combustion of fossil fuels for steam generation in boiler house (Figure 4.4). These top three contributors directly relate to gas carbon dioxide released from the combustion of fossil fuels in vehicles, power plants and industrial boilers which account for 80.80% of the total global warming potential recorded. Besides, the production of bleaching earth used in the refinery also contributes significantly to the global warming impact category, 14.63% of the total GHG emitted. According to allocation based on economic value, gate-to-gate GHG emissions of 40.24 kg CO_2 eq is recorded for the production of one tonne of RBD palm oil while 33.75 kg CO_2 eq is recorded for the same amount of PFAD produced.

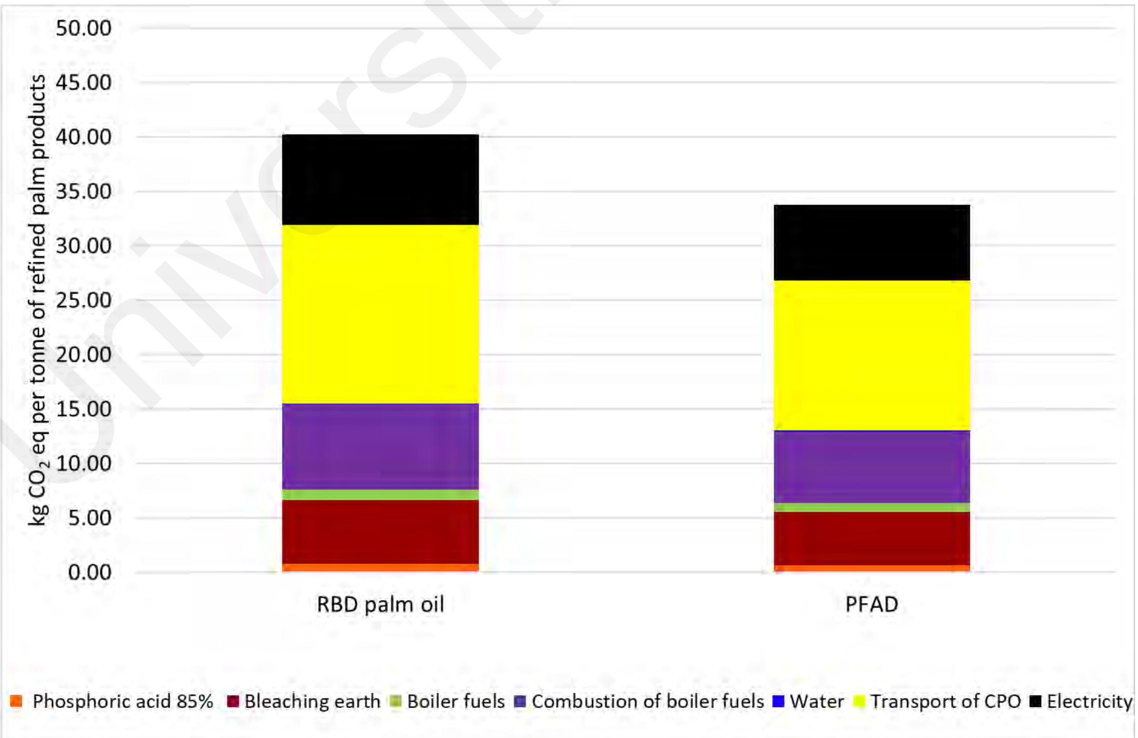


Figure 4.4: Global warming potential of palm oil refining

4.3.1.3 Stratospheric Ozone Depletion

The stratospheric ozone depletion potential is measured as kg CFC11 eq per tonne of refined palm products produced. Three main contributors to ozone depletion are the transportation of CPO from palm oil mills to palm oil refineries, bleaching earth and electricity from the national power grid (Figure 4.5). 87.93% of the total impact are attributed to these three contributors. Fossil fuels used for steam generation play a marginal contribution, 8.25%. Stratospheric ozone depletion potential of 13.07×10^{-6} kg CFC11 eq and 10.96×10^{-6} kg CFC11 eq are recorded per tonne of RBD palm oil and PFAD produced, respectively.

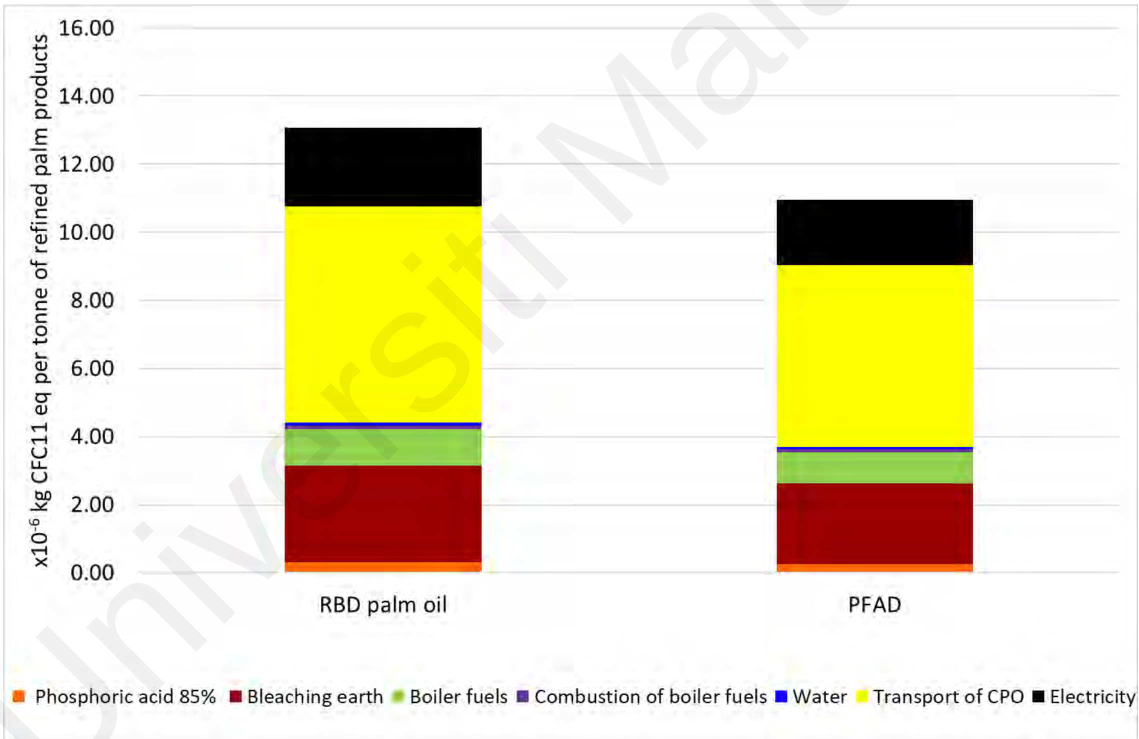


Figure 4.5: Stratospheric ozone depletion potential of palm oil refining

4.3.1.4 Ionising Radiation

The ionising radiation potential is measured as kBq Co-60 per tonne of refined palm products produced. Figure 4.6 clearly shows that the main contributors to ionising radiation are the bleaching earth used in the refining process and the transportation of CPO from palm oil mills to palm oil refineries. 87.87% of the ionising radiation potential are due to these two contributors. The production of phosphoric acid contributes marginally, 5.56%. Ionising radiation potential for the production per tonne of RBD palm oil and per tonne of PFAD are respectively recorded at 0.72 kBq Co-60 eq and 0.61 kBq Co-60 eq.

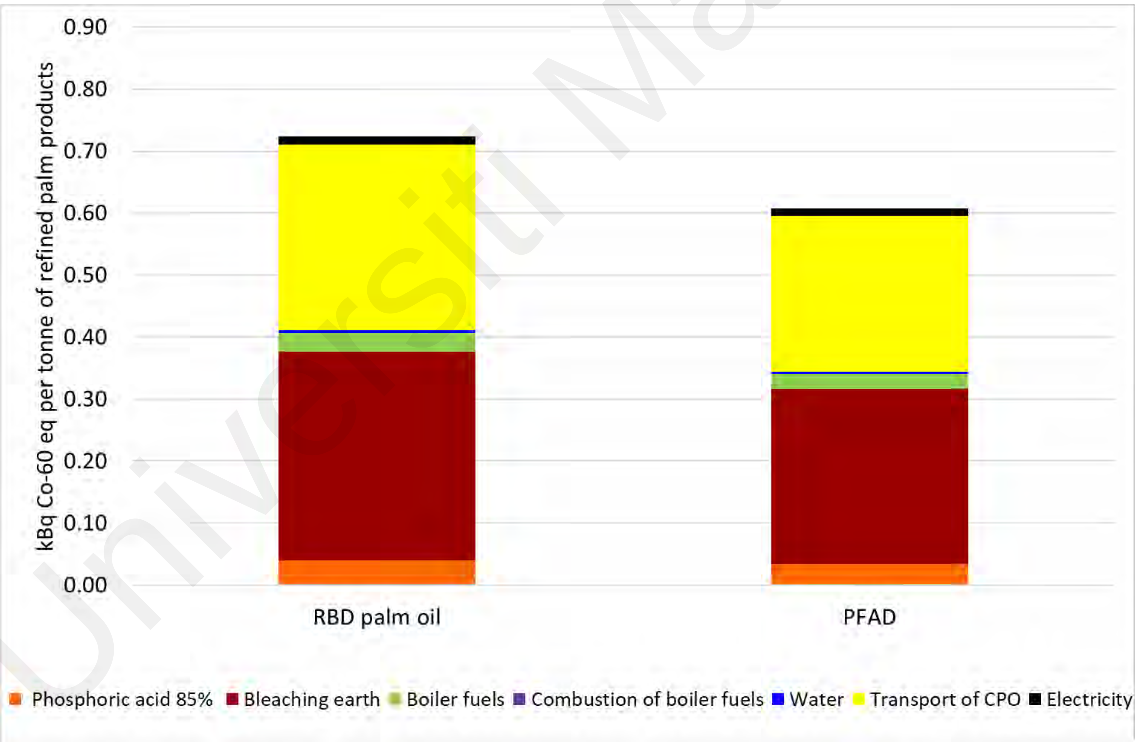


Figure 4.6: Ionising radiation potential of palm oil refining

4.3.1.5 Ozone Formation

The impact of ozone formation on both human health and terrestrial ecosystems are measured as kg NO_x eq per tonne of refined palm products produced. Transportation of CPO is the principal contributor to ozone formation potential for both impacts on human health and terrestrial ecosystems, 70.99% and 70.77%, respectively (Figure 4.7). Bleaching earth, electricity and combustion of boiler fuels for steam contribute marginally to the ozone formation impact category. Ozone formation potential of 0.17 kg NO_x eq and 0.14 kg NO_x eq are recorded respectively for the production of one tonne of RBD palm oil and one tonne of PFAD.

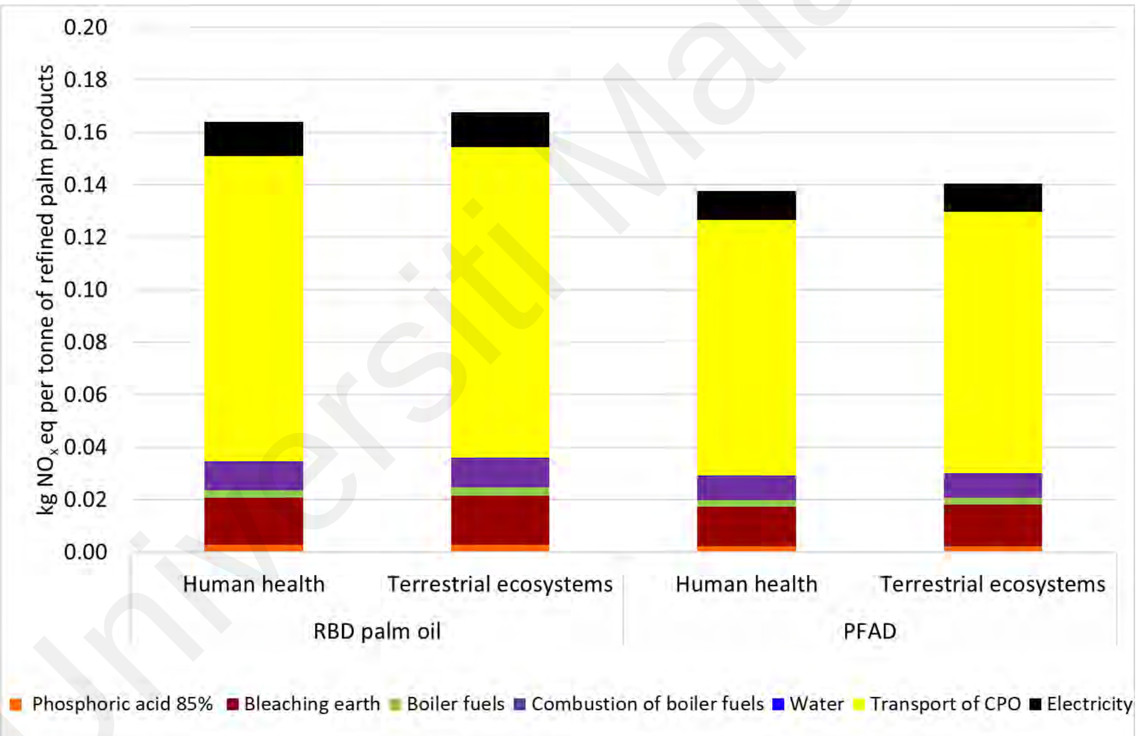


Figure 4.7: Ozone formation potential of palm oil refining

4.3.1.6 Fine Particulate Matter Formation

The fine particulate matter formation impact category is assessed according to kg PM2.5 eq per tonne of refined palm products produced. Four main contributors to this impact category are the transportation of CPO, electricity from the national power grid, bleaching earth and combustion of boiler fuels for steam generation (Figure 4.8). 93.00% of the fine particulate matter formation potential are due to these four contributors. The contribution of these four contributors to fine particulate matter formation is similar to their contribution to the global warming impact category (Figure 4.3). 0.085 kg PM2.5 eq and 0.071 kg PM2.5 eq are recorded respectively for every tonne of RBD palm oil and PFAD produced.

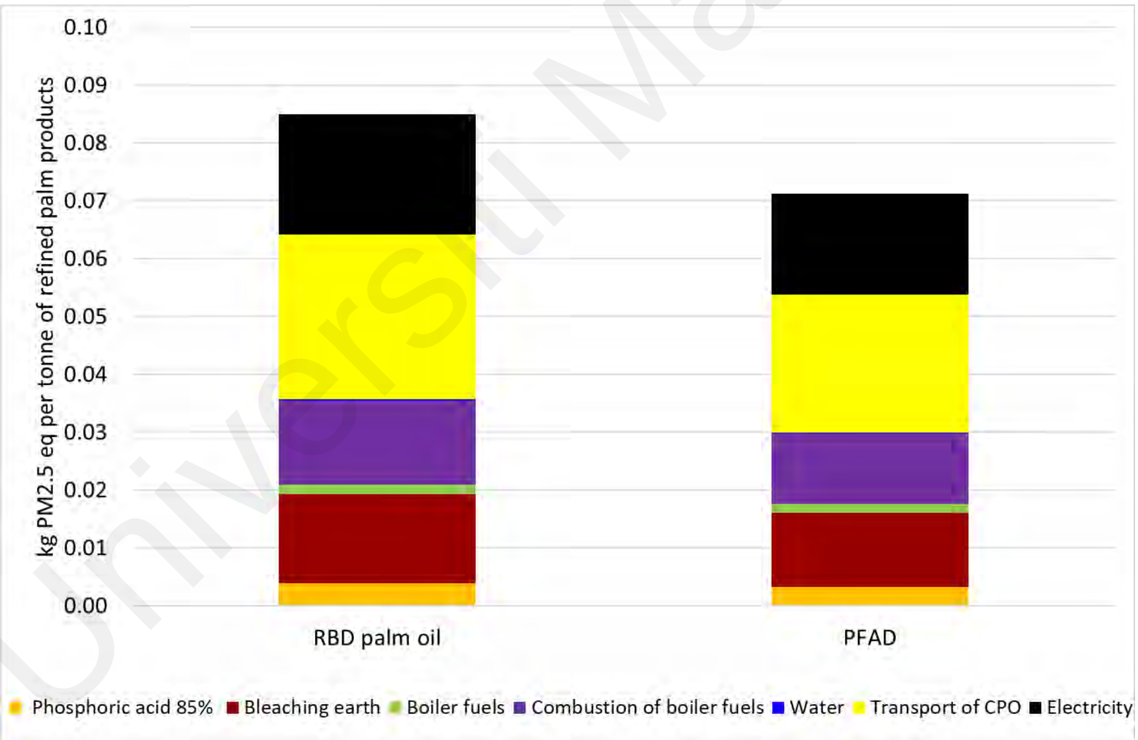


Figure 4.8: Fine particulate matter formation potential of palm oil refining

4.3.1.7 Terrestrial Acidification

The terrestrial acidification potential is measured as kg SO_2 eq per tonne of refined palm products produced. Transportation of CPO, combustion of boiler fuels for steam generation and bleaching earth are the three main contributors to terrestrial acidification potential with a total contribution of 77.16% (Figure 4.9). Electricity from the national power grid contributes 14.08% to this impact category. Terrestrial acidification potential of 0.19 kg SO_2 eq and 0.16 kg SO_2 eq are recorded for every tonne of RBD palm oil and PFAD produced for allocation based on economic value.

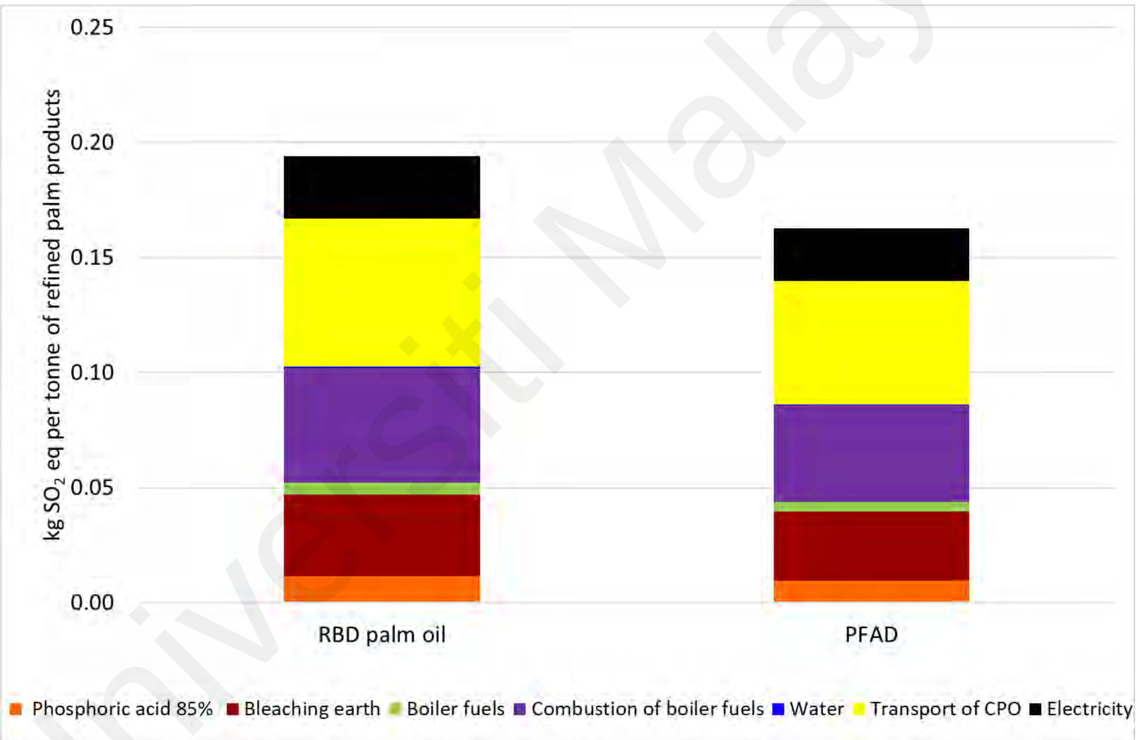


Figure 4.9: Terrestrial acidification potential of palm oil refining

4.3.1.8 Freshwater Eutrophication

The freshwater eutrophication potential is measured as kg P eq per tonne of refined palm products produced. As shown in Figure 4.10, electricity from the national power grid and bleaching earth are the two main contributors to this impact category, 38.41% and 35.71%, respectively. Transportation of CPO and phosphoric acid 85% concentration are the third and fourth highest contributors, 14.43% and 10.33%. Freshwater eutrophication potential of 0.0092 kg P eq and 0.0077 kg P eq are recorded respectively for every tonne of RBD palm oil and PFAD produced based on economic allocation.

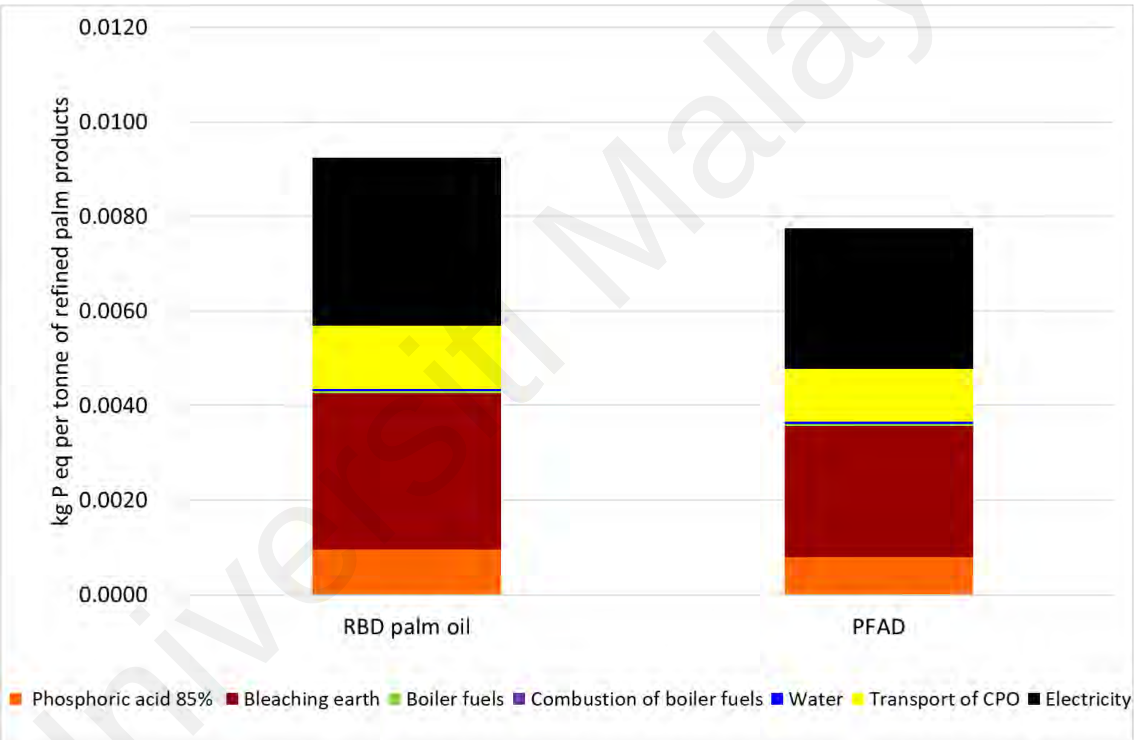


Figure 4.10: Freshwater eutrophication potential of palm oil refining

4.3.1.9 Marine Eutrophication

The marine eutrophication potential is measured as kg N eq per tonne of refined palm products produced. Similar to freshwater eutrophication, the two major contributors to the marine eutrophication impact category are electricity from the national power grid and bleaching earth (Figure 4.11), 37.55% and 33.67%, respectively. Transportation of CPO is the third-highest contributor, 16.57%. Both phosphoric acid and combustion of boiler fuels for steam generation contributes marginally, 4.57% and 5.43%, respectively. Marine eutrophication potential of 6.27×10^{-4} kg N eq and 5.26×10^{-4} kg N eq are recorded respectively for RBD palm oil and PFAD.

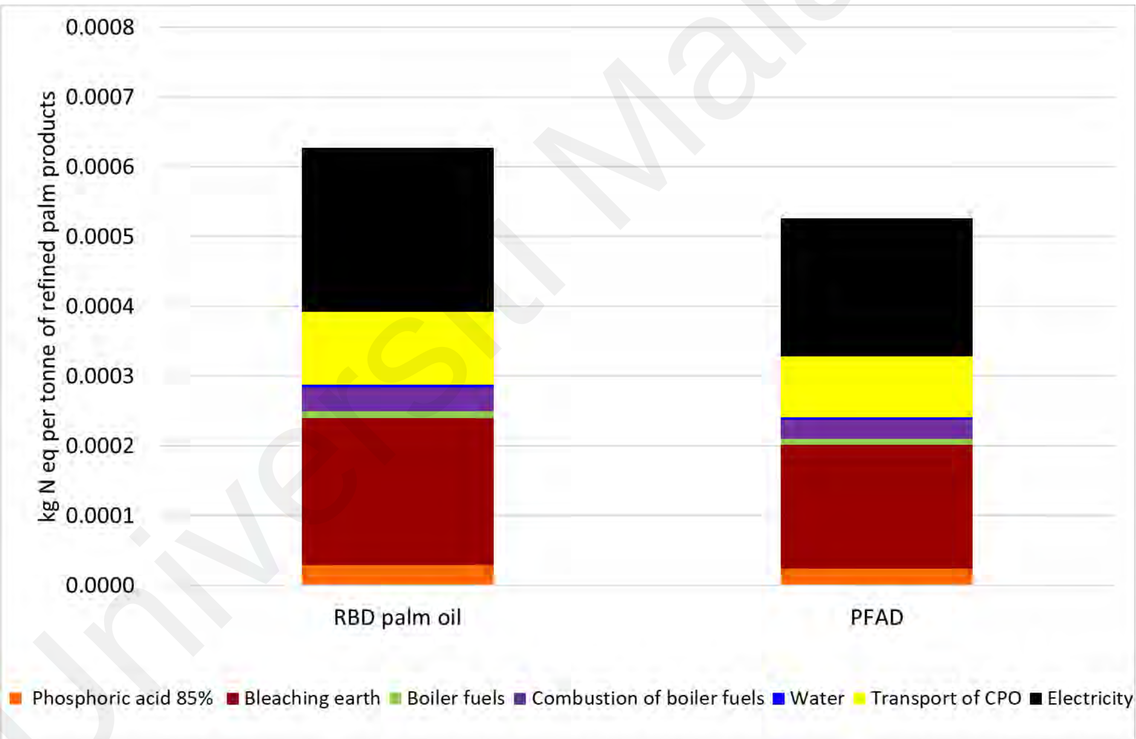


Figure 4.11: Marine eutrophication potential of palm oil refining

4.3.1.10 Mineral Resource Scarcity

The mineral resource scarcity potential is measured as kg Cu eq per tonne of refined palm products produced. As shown in Figure 4.12, the impact on mineral scarcity is mainly related to chemicals used i.e. bleaching earth and phosphoric acid 85% concentration. The bleaching earth is the highest contributor, 65.03% while phosphoric acid is the second-highest contributor, 19.01%. Mineral resource scarcity of 0.32 kg Cu eq and 0.27 kg Cu eq are recorded respectively for every tonne of RBD palm oil and PFAD produced.

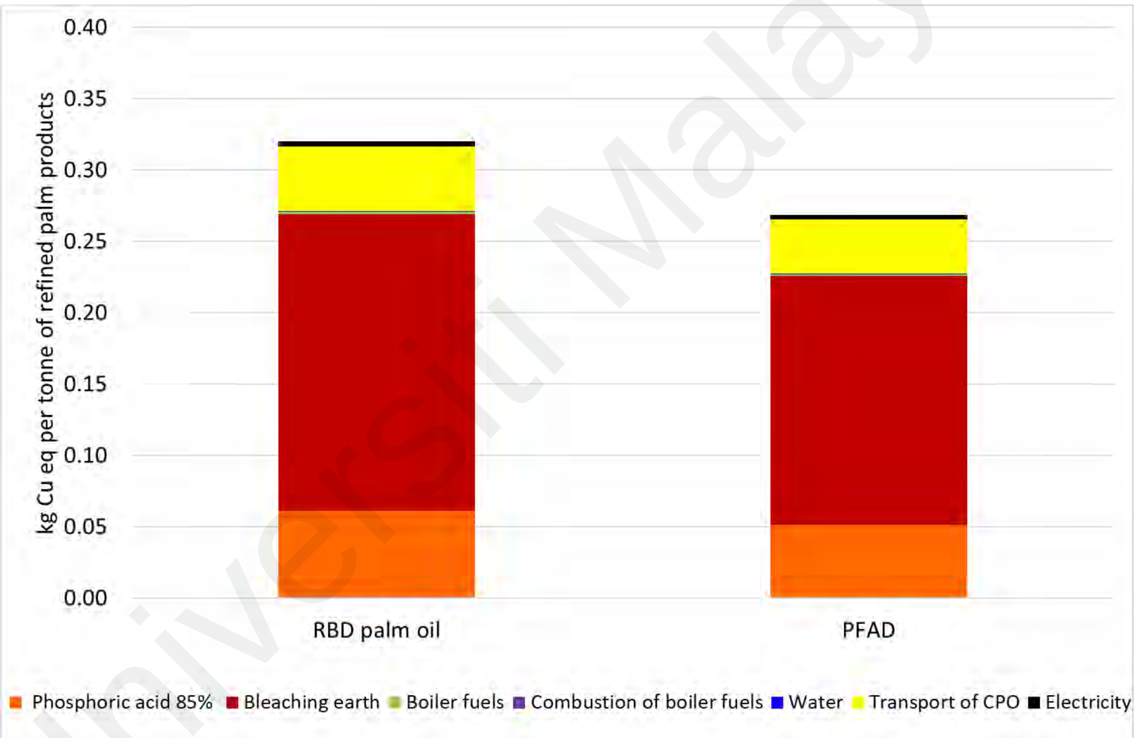


Figure 4.12: Mineral resource scarcity potential of palm oil refining

4.3.1.11 Fossil Resource Scarcity

The fossil resource scarcity potential is expressed in kg oil eq per tonne of refined palm products produced. Fossil resource scarcity is related to the amount of fossil fuels used directly in the refining process and indirectly for the production of materials input. From Figure 4.13, the transportation of CPO from palm oil mills to palm oil refineries is the main contributor, 36.01%. This is followed by boiler fuels and its combustion for steam generation, bleaching earth and electricity from the national power grid. In total, 16.14 kg oil eq and 13.54 kg oil eq are recorded for the production of one tonne of RBD palm oil and PFAD, respectively.

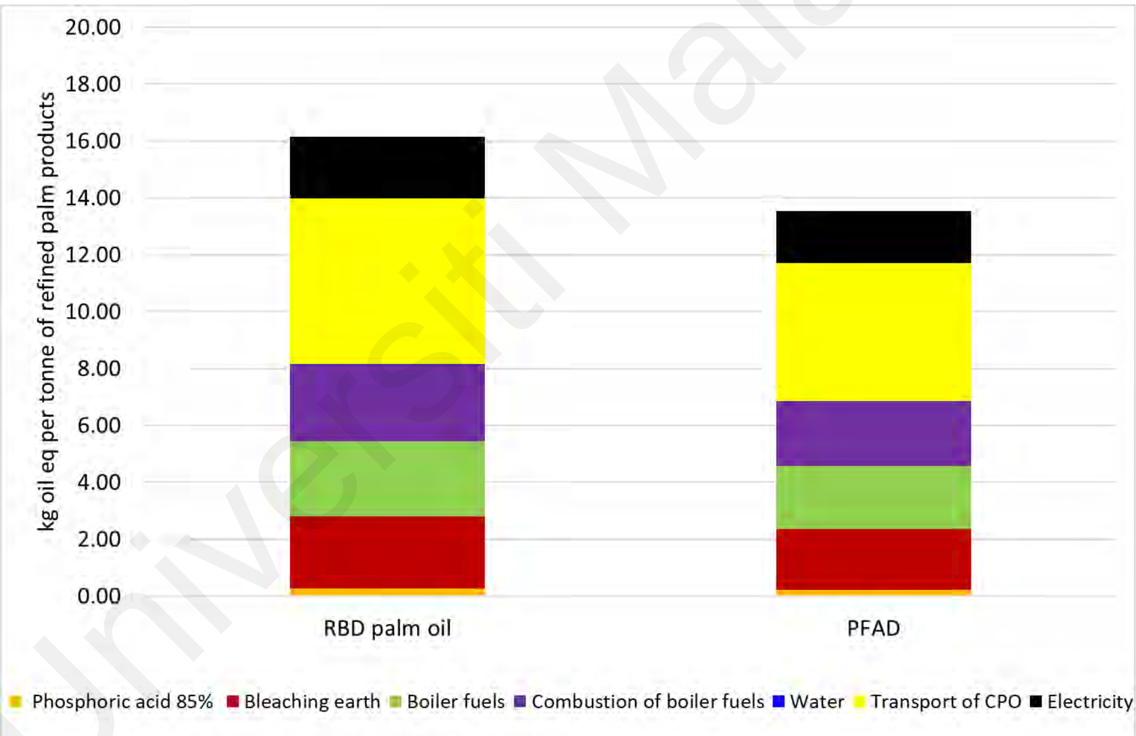


Figure 4.13: Fossil resource scarcity potential of palm oil refining

4.3.1.12 Water Consumption

The water consumption impact category is measured as the volume of water consumed (m^3) per tonne of refined palm products produced. Water consumed for heating (as steam) and cooling in the refining plant is the main contributor, 37.24% (Figure 4.14). Indirect water consumption for the production of bleaching earth and phosphoric acid are also significant, 27.47% and 17.35%. Water used during electricity generation contributes 11.54% to the total water consumption. In total, 0.49 m^3 and 0.41 m^3 of water are respectively required per tonne of RBD palm oil and PFAD produced, according to economic allocation.

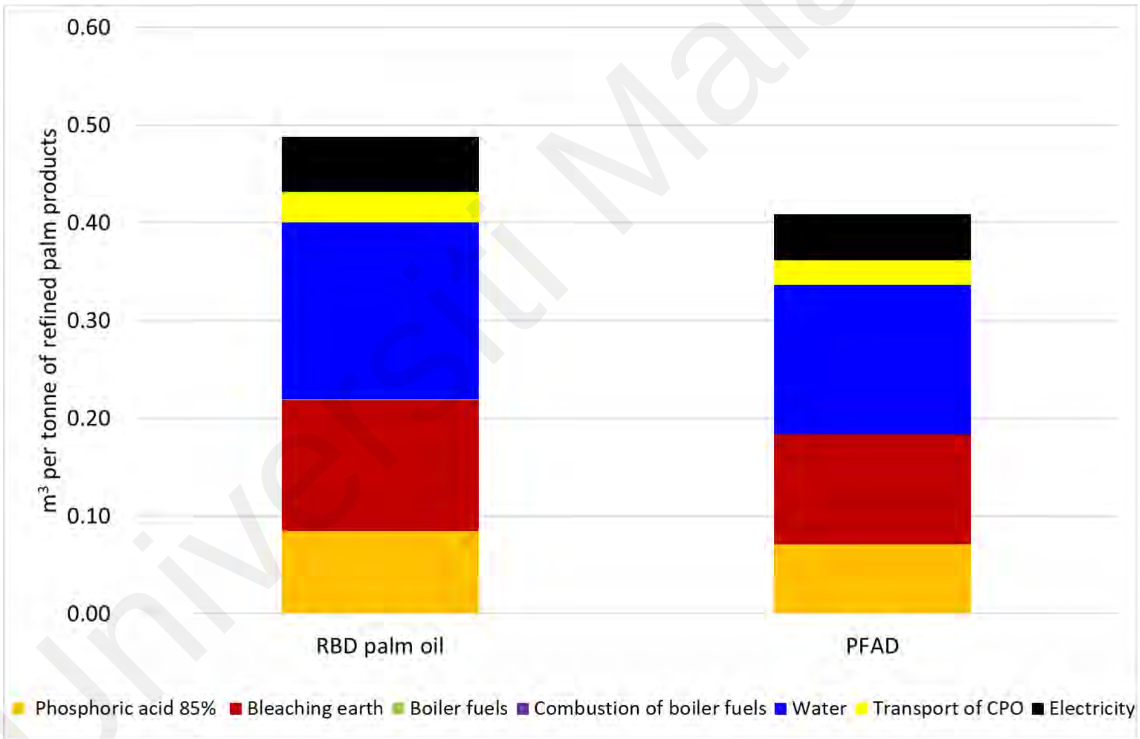


Figure 4.14: Water consumption potential of palm oil refining

4.3.2 Gate-to-Gate LCA of Palm Oil Fractionation

4.3.2.1 Contribution Analysis of Palm Oil Fractionation

The gate-to-gate characterised LCIA of the fractionation of RBD palm oil at the midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is shown in Figure 4.15. RBD palm oil is the single major contributor to all impact categories evaluated, 64% to 98% contributions to the impact categories evaluated according to the ReCiPe 2016 methodology. This is because fractionation is just a physical separation process without any chemical input. The main material input for the fractionation process is RBD palm oil produced in the refining stage while the energy input to satisfy the fractionation process is the electricity from the national power grid and steam from the boiler house. Electricity consumption from the national power grid is an important contributor, which has an important impact on freshwater eutrophication, marine eutrophication, fine particulate matter formation, global warming, stratospheric ozone depletion, human carcinogenic toxicity, human non-carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity, fossil resource scarcity and water consumption. Fossil fuels used for steam generation in boiler house is obvious in fossil resource scarcity and stratospheric ozone depletion. Combustion of the fossil fuels in the boiler has minimal contributions to terrestrial acidification, fossil resource scarcity, global warming and fine particulate matter formation. Similar to refining, water use in the fractionation process in the forms of steam and cooling water is only significant in the water consumption impact category.

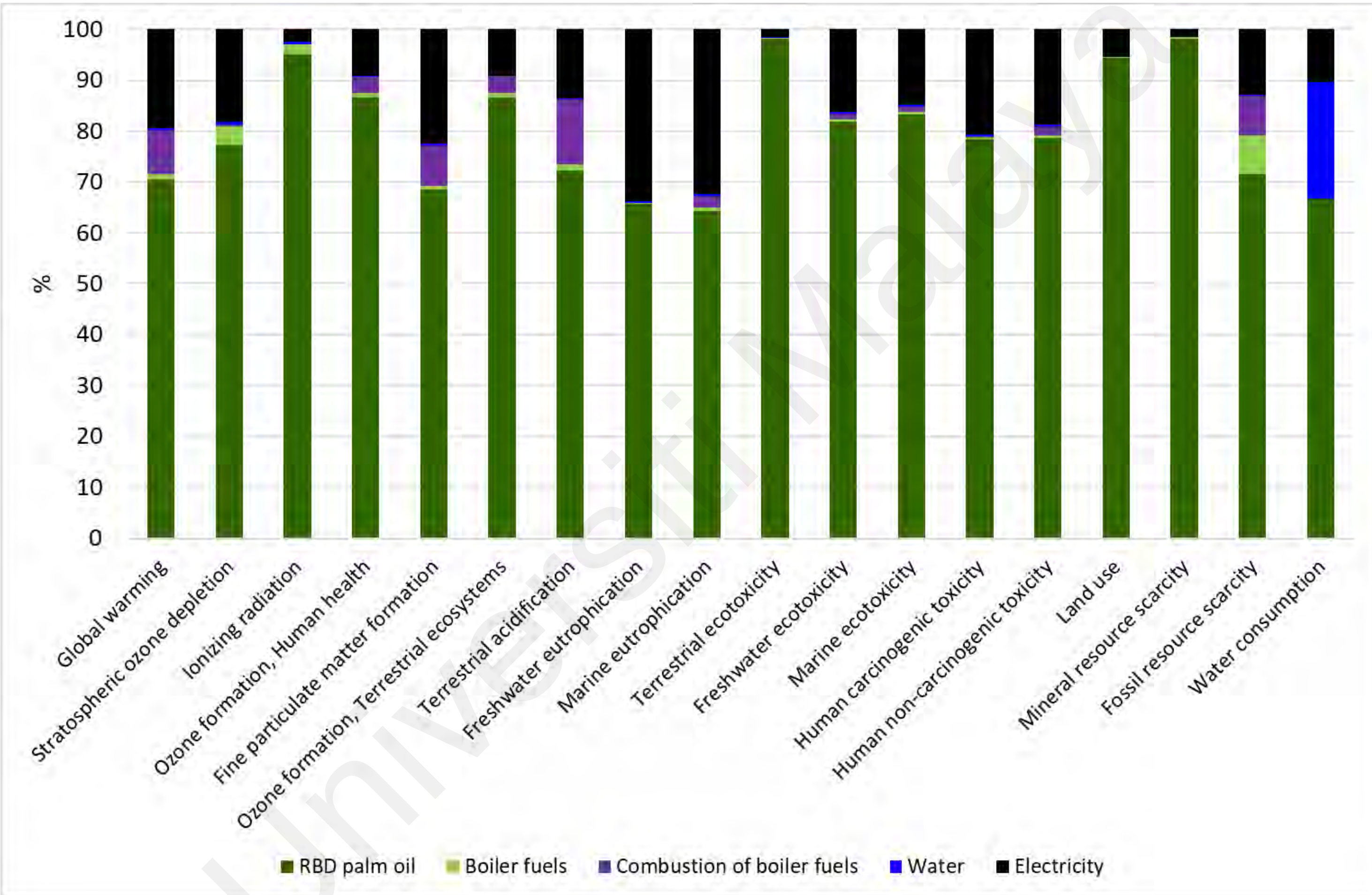


Figure 4.15: Gate-to-gate characterised LCIA of palm oil fractionation

4.3.2.2 Global Warming

The global warming potential for the production of one tonne of fractionated palm products i.e. RBD palm olein and RBD palm stearin is presented in Figure 4.16. 70.45% of the total contribution are due to RBD palm oil, the feed material for palm oil fractionation. Consumption of electricity to power the equipment in the fractionation plants has a significant role, 19.52%. The remaining 1.08% and 8.75% are due to boiler fuels and their combustion in the boiler for steam generation. Global warming potential of 57.84 kg CO_2 eq and 54.14 kg CO_2 eq are recorded for every tonne of RBD palm olein and RBD palm stearin produced, based on economic allocation.

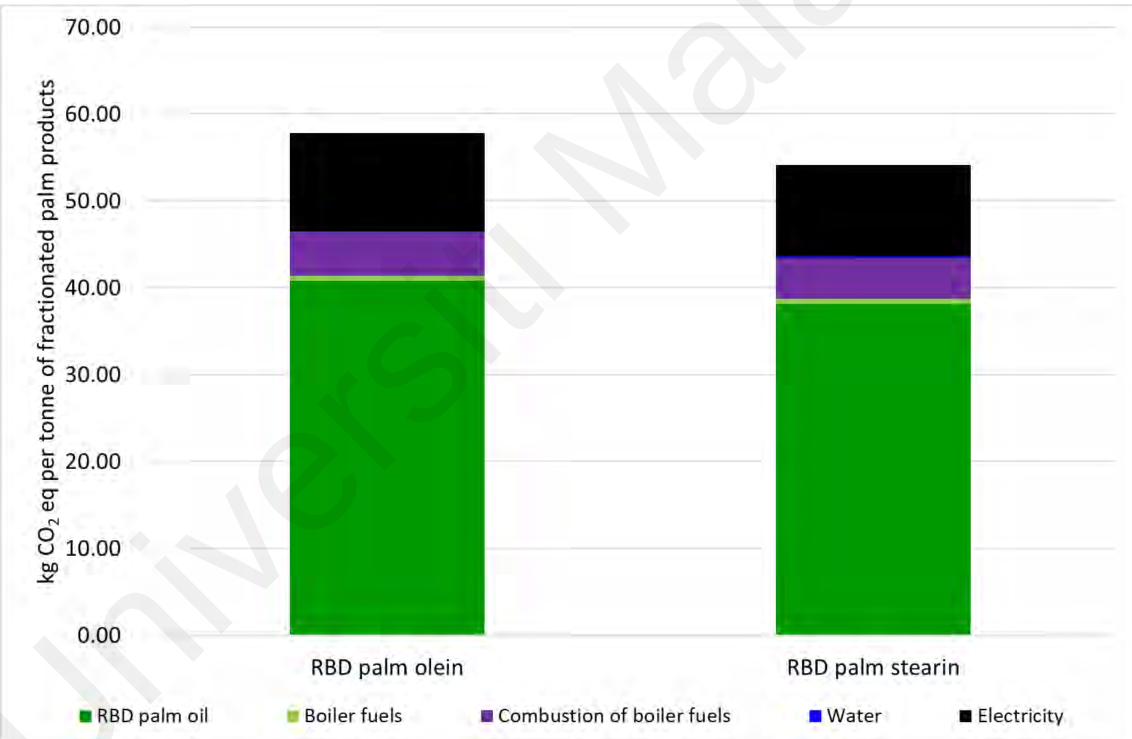


Figure 4.16: Global warming potential of palm oil fractionation

4.3.2.3 Stratospheric Ozone Depletion

The stratospheric ozone depletion is mainly due to RBD palm oil, 77.25% (Figure 4.17). Electricity from the national power grid contributes 18.29% while boiler fuels used for steam generation contributes marginally, 3.65%. Stratospheric ozone depletion potential of 17.13×10^{-6} kg CFC11 eq and 16.04×10^{-6} kg CFC11 eq are reported respectively for one tonne of RBD palm olein and one tonne of RBD palm stearin produced.

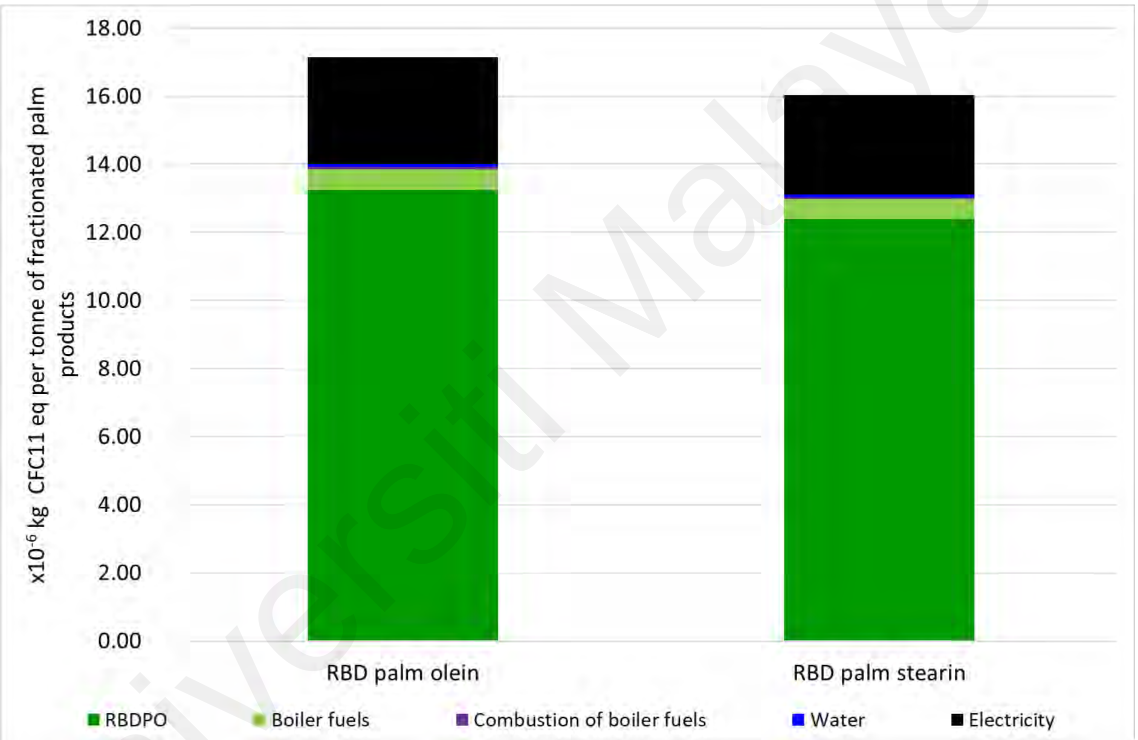


Figure 4.17: Stratospheric ozone depletion potential of palm oil fractionation

4.3.2.4 Ionising Radiation

Activities in the fractionation plants are insignificant to the ionising radiation impact category, less than 5% contribution (Figure 4.18). 95.03% of the impact are contributed by the material input i.e. RBD palm oil, which the environmental burden inherited mainly from the bleaching earth used in the refining step and the transportation of CPO from palm oil mills to palm oil refineries (Figure 4.6). No contribution from the transportation of RBD palm oil in the fractionation stage as the fractionation plants are located adjacent to the refining plants. Ionising radiation potential of 0.77 kBq Co-60 eq and 0.72 kBq Co-60 eq are recorded respectively per tonne of RBD palm olein and RBD palm stearin produced.

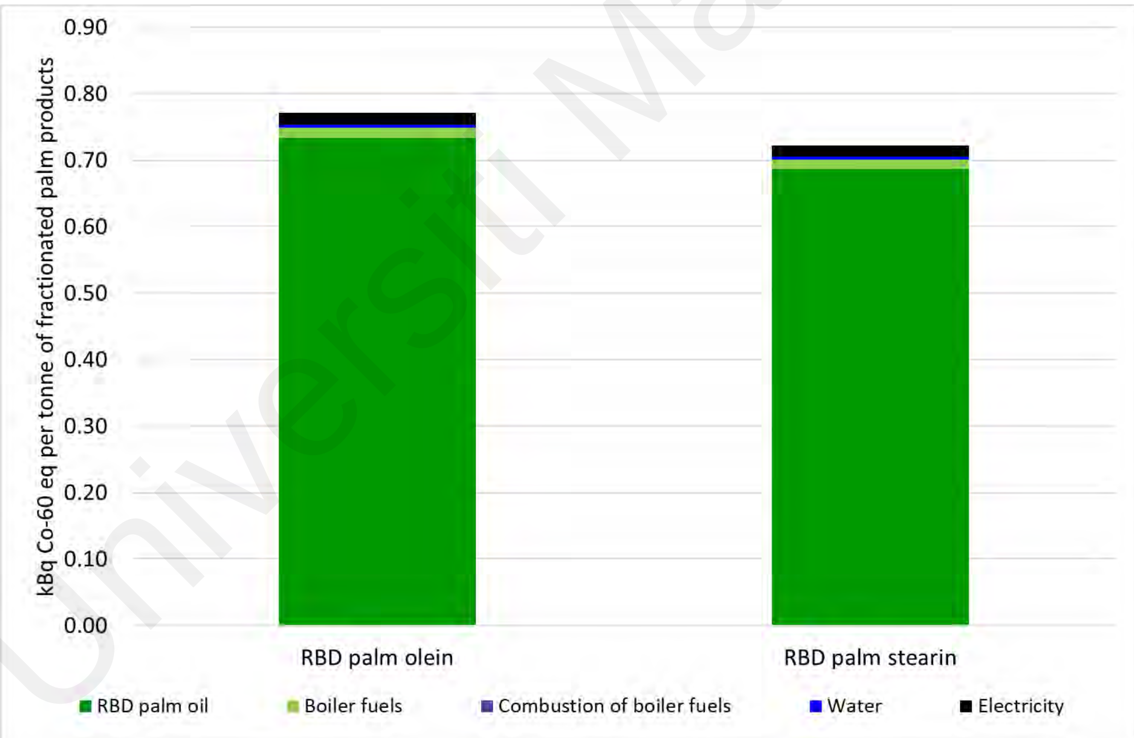


Figure 4.18: Ionising radiation potential of palm oil fractionation

4.3.2.5 Ozone Formation

The fractionation process has a relatively less significant impact on ozone formation impact category on both human health and terrestrial ecosystems (Figure 4.19). 86.51% of the impact on human health and 86.54% of the impact on terrestrial ecosystems are contributed by RBD palm oil, the feed material for the fractionation process. Figure 4.7 clearly shows that the impact in palm oil refining is mainly contributed by CPO transportation. However, no transportation of RBD palm oil is needed in the fractionation stage as mentioned earlier. Hence, no contribution from the transportation to this impact category is observed. Ozone formation potential of 0.19 kg NO_x eq and 0.18 kg NO_x eq are recorded respectively for the production of one tonne of RBD palm olein and RBD palm stearin.

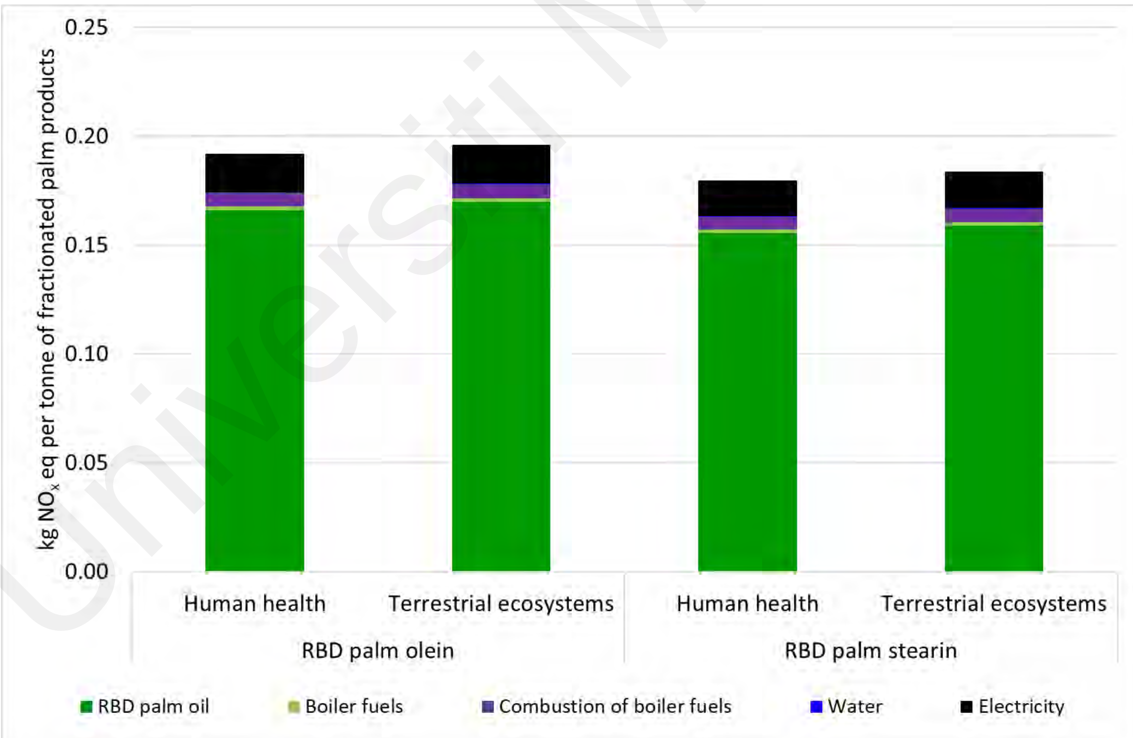


Figure 4.19: Ozone formation potential of palm oil fractionation

4.3.2.6 Fine Particulate Matter Formation

Fine particulate matter formation is related to the combustion of fossil fuels for electricity generation, steam production and transportation. In this impact category, 68.42% of the contribution are due to RBD palm oil (Figure 4.20). 22.55% and 8.90% are contributed by electricity supply from the national power grid and combustion of fossil fuels for steam generation in the boiler house. Again, the impact on fine particulate matter formation is quite similar to the impact on global warming impact category (Figure 4.15). 0.126 kg PM2.5 eq and 0.118 kg PM2.5 eq are recorded respectively for one tonne of RBD palm oil and one tonne of PFAD produced.

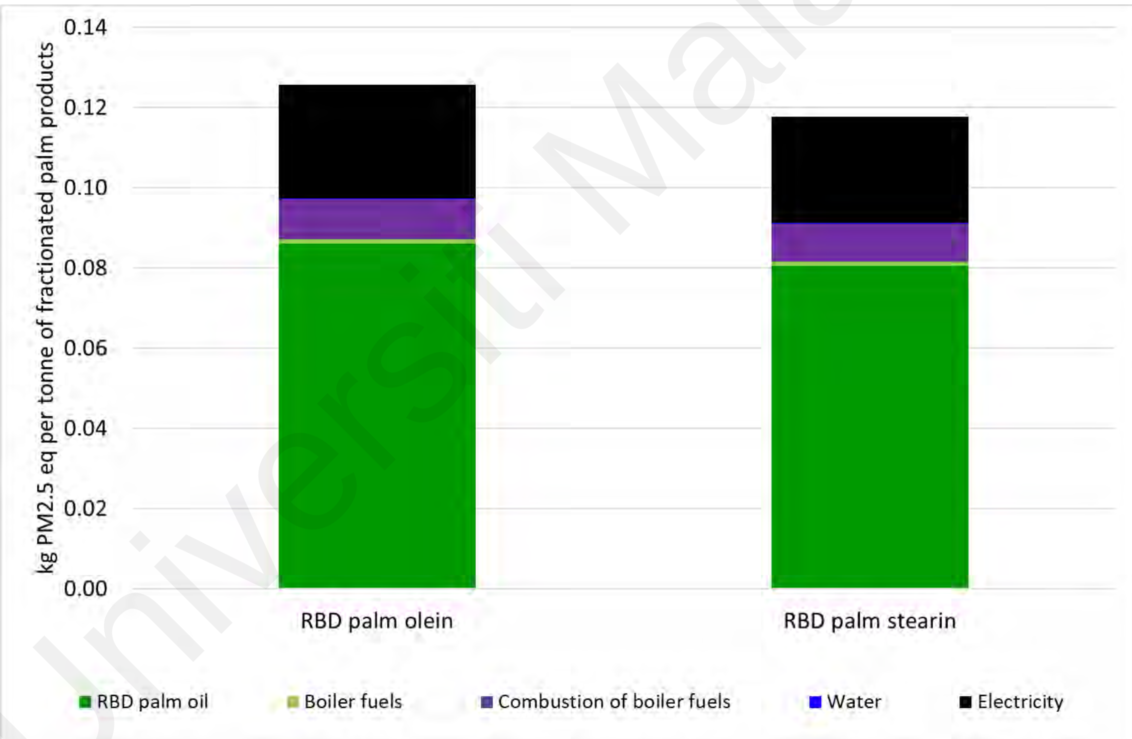


Figure 4.20: Fine particulate matter formation potential of palm oil fractionation

4.3.2.7 Terrestrial Acidification

72.30% of the contribution to terrestrial acidification for palm oil fractionation are due to RBD palm oil (Figure 4.21). Electricity from the national power grid and combustion of boiler fuels for steam generation compliment the remaining 13.67% and 12.74%, respectively. For every tonne of RBD palm olein and RBD palm stearin produced, terrestrial acidification potential of 0.27 kg SO_2 eq and 0.25 kg SO_2 eq are recorded, respectively.

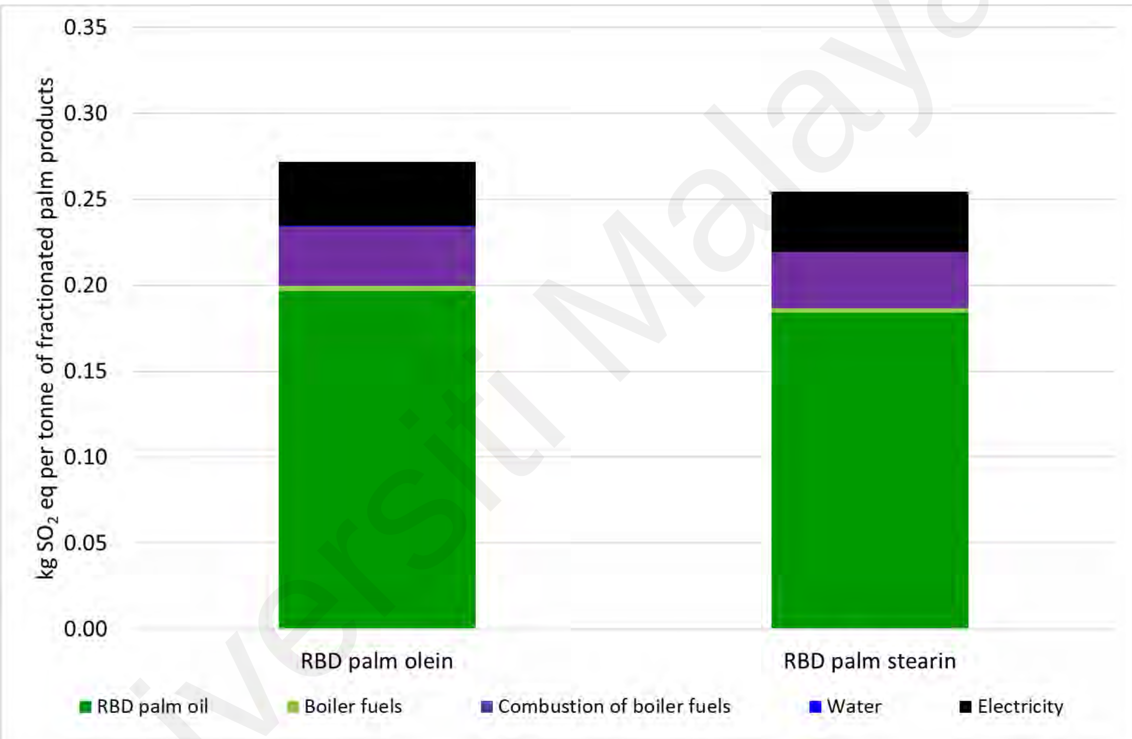


Figure 4.21: Terrestrial acidification potential of palm oil fractionation

4.3.2.8 Freshwater Eutrophication

For the freshwater eutrophication impact category, there are only two significant contributors in the fractionation process namely RBD palm oil and electricity (Figure 4.22). RBD palm oil contributes 65.61% of the burden while 33.84% are due to the electricity supply from the national power grid. Contributions from others are negligible. Freshwater eutrophication potential of 0.0143 kg P eq and 0.0133 kg P eq are recorded for every tonne of RBD palm olein and palm stearin produced, according to the economic allocation procedure.

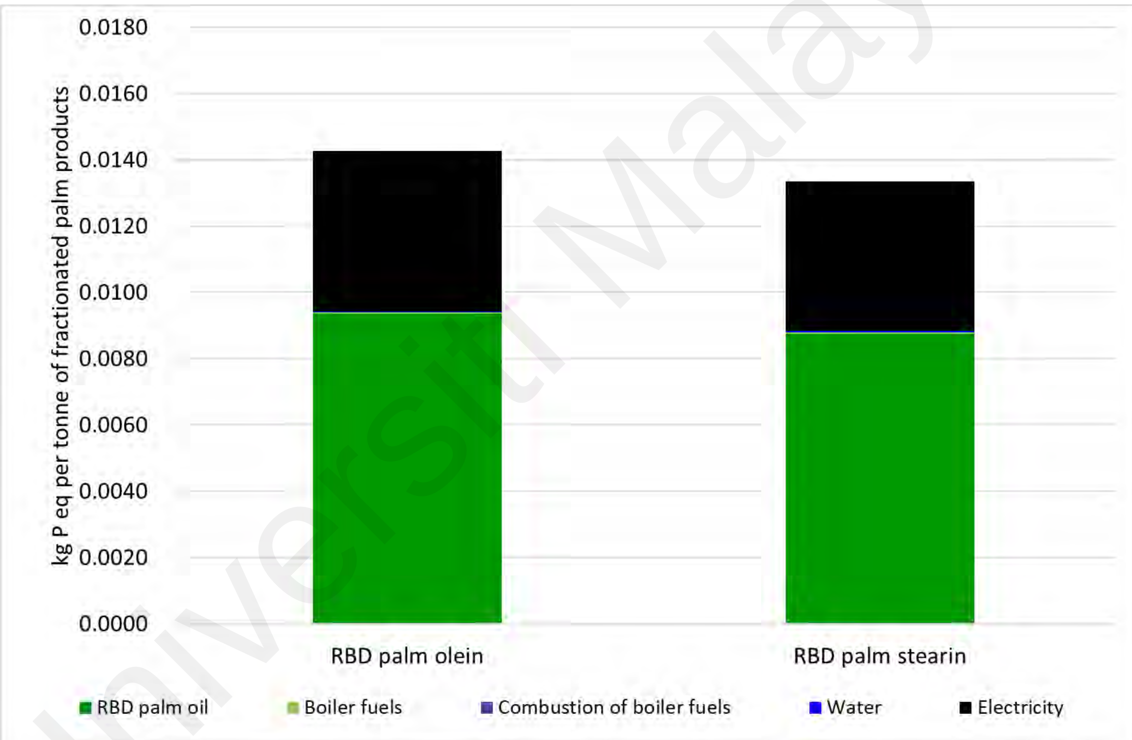


Figure 4.22: Freshwater eutrophication potential of palm oil fractionation

4.3.2.9 Marine Eutrophication

Similar to the freshwater eutrophication impact category, RBD palm oil and electricity are the two major contributors to marine eutrophication although both impacts are measured in different units (Figure 4.23). RBD palm oil and electricity supply from the national power grid contribute 64.30% and 32.43%, respectively. Marine eutrophication potential of 9.88×10^{-4} kg N eq and 9.24×10^{-4} kg N eq are recorded respectively for RBD palm olein and RBD palm stearin.

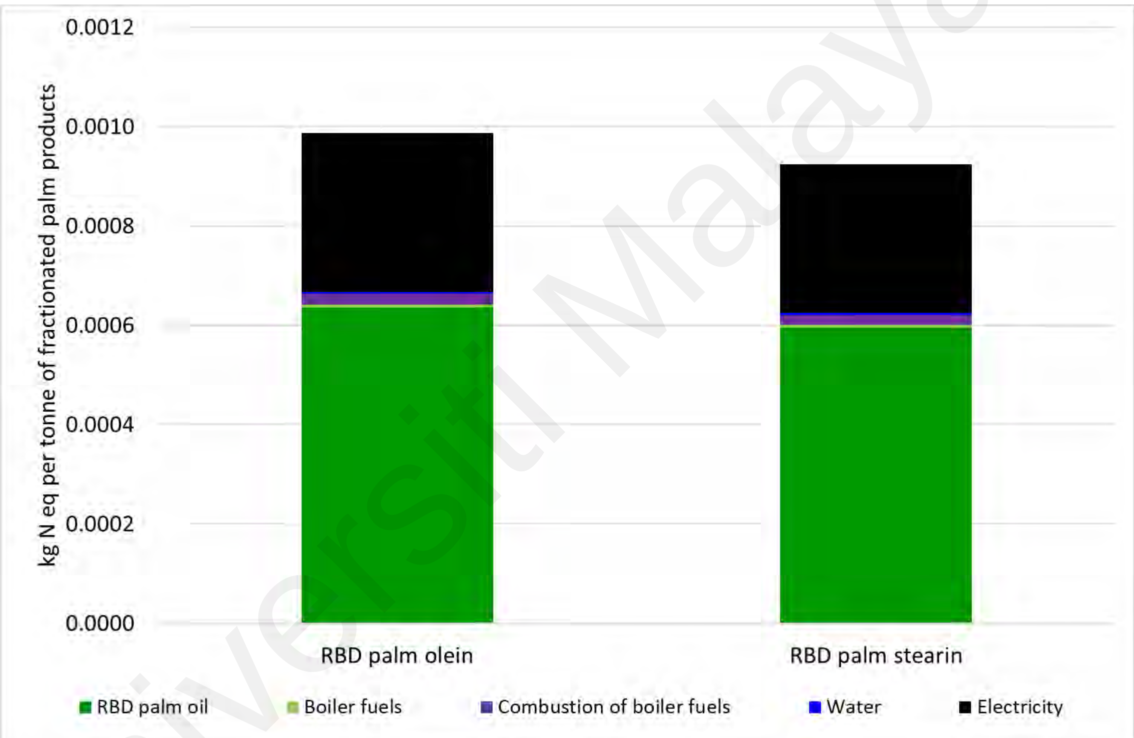


Figure 4.23: Marine eutrophication potential of palm oil fractionation

4.3.2.10 Mineral Resource Scarcity

As shown in Figure 4.24, the mineral resource scarcity is solely contributed by RBD palm oil since no chemical is used in the palm oil fractionation process. 98.11% are recorded for RBD palm oil, which is mainly attributed to the use of bleaching earth and phosphoric acid 85% concentration in the refining process (Figure 4.12). Mineral resource scarcity potential of 0.324 kg Cu eq and 0.303 kg Cu eq are respectively recorded for the production of one tonne of RBD palm olein and one tonne of palm stearin, based on economic allocation.

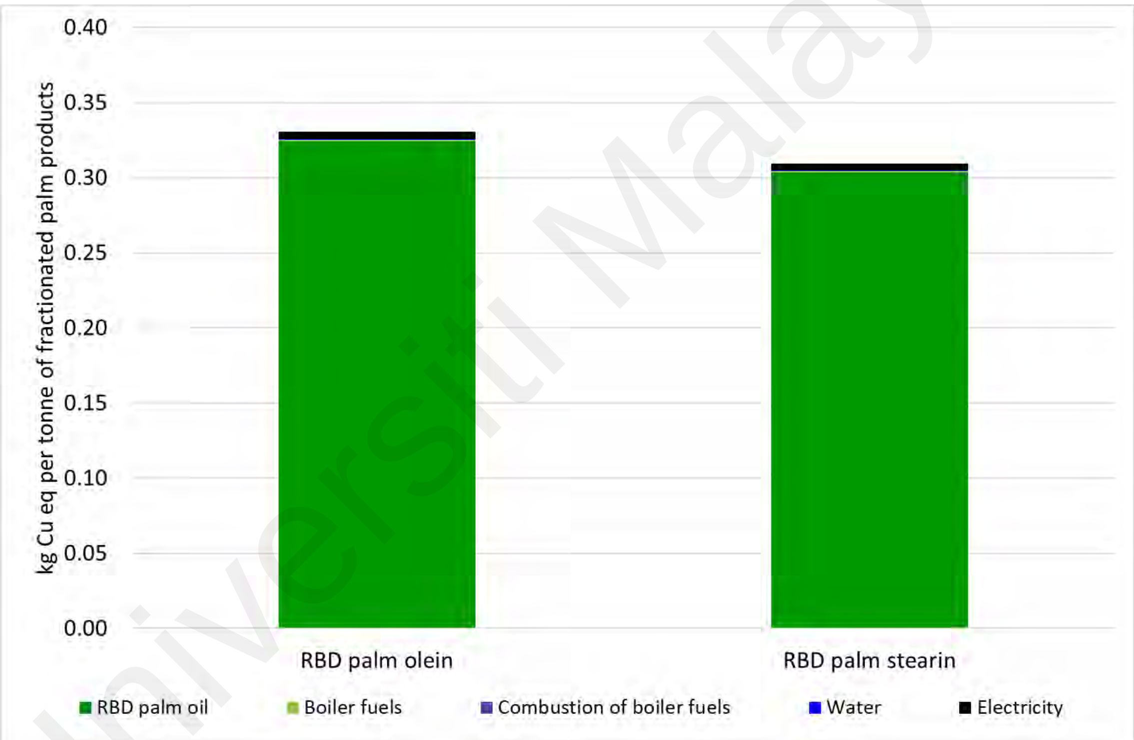


Figure 4.24: Mineral resource scarcity potential of palm oil fractionation

4.3.2.11 Fossil Resource Scarcity

Fossil resource scarcity is mainly attributed to the use of fossil fuels as energy in the form of electricity and heat/steam. For this impact category, 71.56% are contributed by RBD palm oil, 12.93% by electricity, 7.61% by fossil fuels and 7.79% by the combustion of fossil fuels in the boiler for steam generation (Figure 4.25). For the production of one tonne of RBD palm olein and one tonne of palm stearin, fossil resource scarcity potential of 22.85 kg oil eq and 21.39 kg oil eq are recorded, respectively.

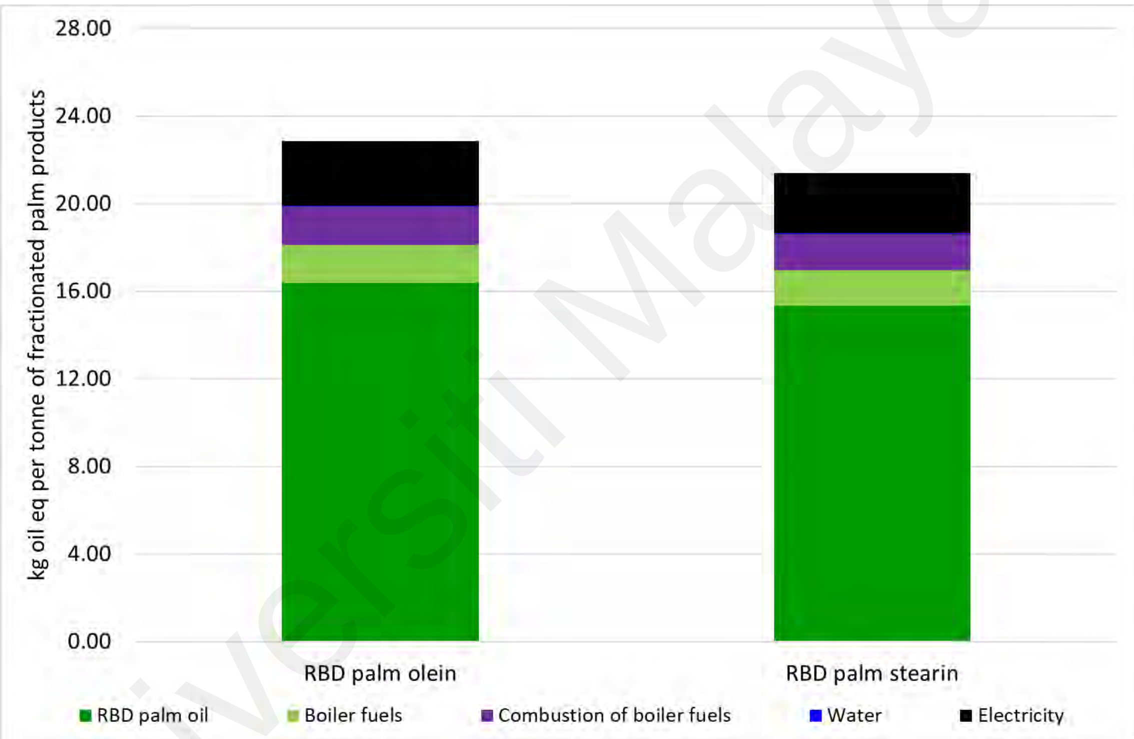


Figure 4.25: Fossil resource scarcity potential of palm oil fractionation

4.3.2.12 Water consumption

As shown in Figure 4.26, 66.71% of the water consumption are inherited from RBD palm oil. 22.90% of the water consumption are contributed by the water use in the fractionation process for heating and cooling purposes. The remaining 10.34% are due to water used for electricity generation at the national power grid. 0.74 m^3 and 0.69 m^3 of water consumption are anticipated per tonne of RBD palm olein and RBD palm stearin produced.

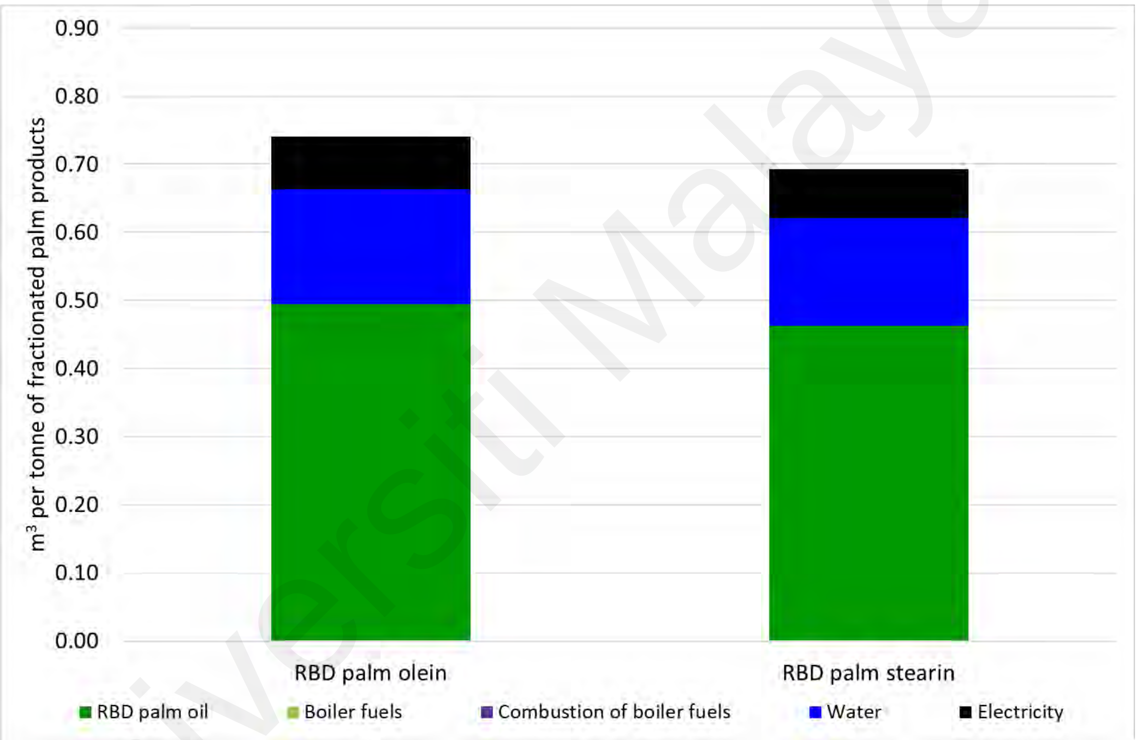


Figure 4.26: Water consumption potential of palm oil fractionation

4.3.3 Gate-to-Gate LCA of Palm Biodiesel Production

4.3.3.1 Contribution Analysis of Palm Biodiesel Production

The gate-to-gate characterised LCIA of the palm biodiesel production at the midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is presented in Figure 4.27. Methanol is the top contributor to 12 impact categories i.e. global warming, stratospheric ozone depletion, ozone formation on human health, ozone formation on terrestrial ecosystems, terrestrial acidification, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, mineral resource scarcity and fossil resource scarcity. It is important to note that more than 70% of the fossil resource scarcity impact are due to methanol which is produced mainly from fossil-based natural gas. Methanol also contributes significantly to ionising radiation, more than one-third of the contribution. Acids used to facilitate phase separation and electricity consumed to power the equipment plays a substantial contribution in respective impact categories. Acids used in the form of hydrochloric acid, citric acid and acetic acid is the highest contributor to marine eutrophication and land use. Electricity is the top contributor to fine particulate matter formation and freshwater eutrophication. Sodium methoxide used as the transesterification catalyst is the highest contributor to ionising radiation. Combustion of fossil fuels in boiler for steam production is an important contributor to terrestrial acidification, fine particulate matter formation and global warming. The use of sodium hydroxide as a neutralising agent, boiler fuels, water and transportation barely play any significant role in all the impact categories except for water consumption. Approximately 30% of the impact on water consumption are caused by the amount of water consumed directly in the biodiesel plant mainly for biodiesel cleansing.

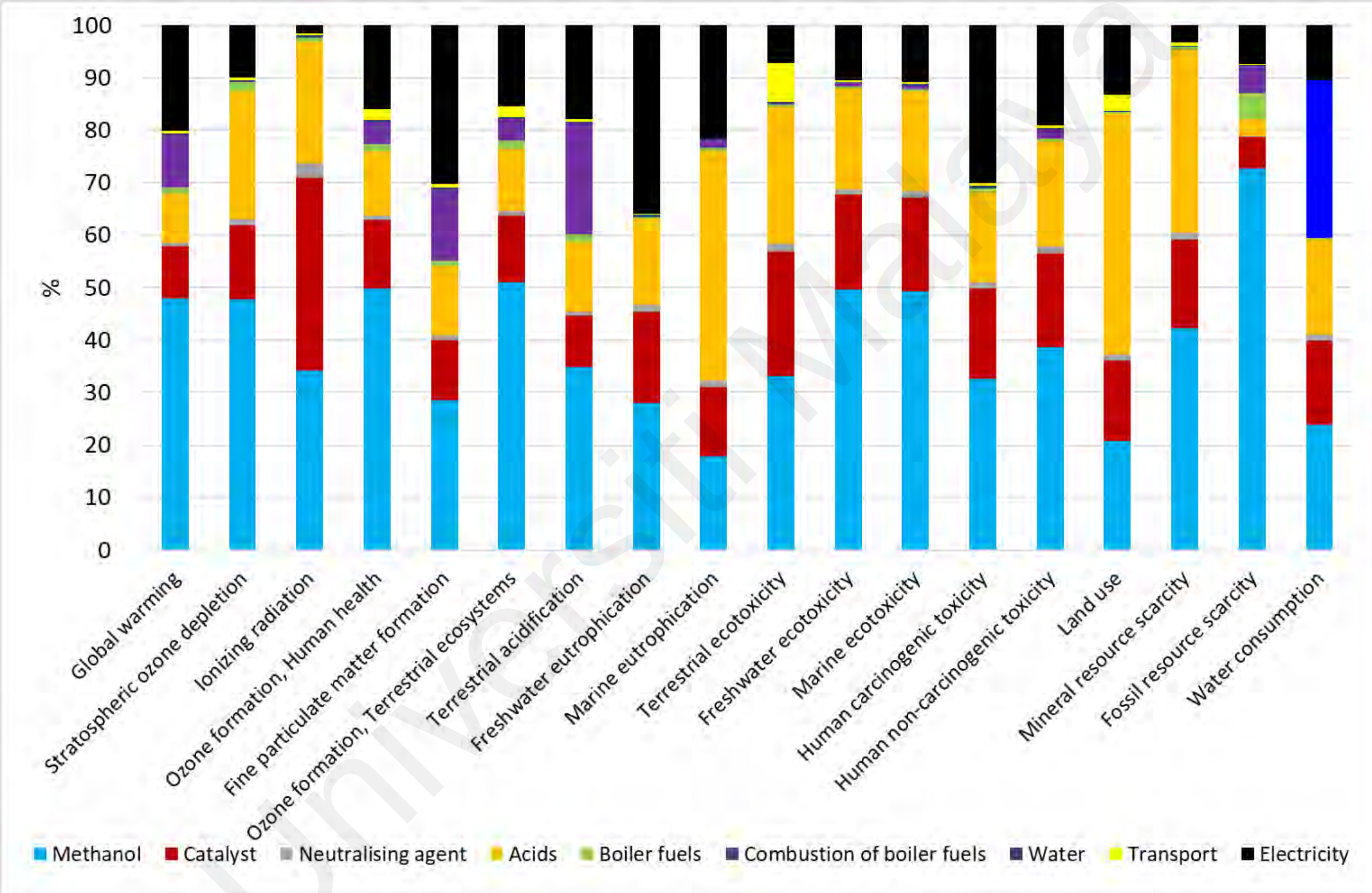


Figure 4.27: Gate-to-gate characterised LCIA of palm biodiesel production

4.3.3.2 Global Warming

In the gate-to-gate LCIA for palm biodiesel production, methanol is the major contributor to the global warming impact category (Figure 4.28). 47.88% of the global warming impact are due to the background process for the production of methanol, mainly from fossil-based natural gas. Electricity from the national power grid is the second-highest contributor, 20.06% of the total impact. Background processes for the production of sodium methoxide used as the catalyst in the transesterification process and the acids used for phase separation respectively contribute 10.07% and 9.27%. 10.05% of the global warming potential are due to the emissions of greenhouse gases during the combustion of fossil fuels to generate steam for heating purpose in the biodiesel plants. Using the allocation procedure based on economic value, the greenhouse gas emissions for the production of one tonne of palm biodiesel and one tonne of crude glycerol are recorded respectively at 152.27 kg CO_2 eq and 39.25 kg CO_2 eq.

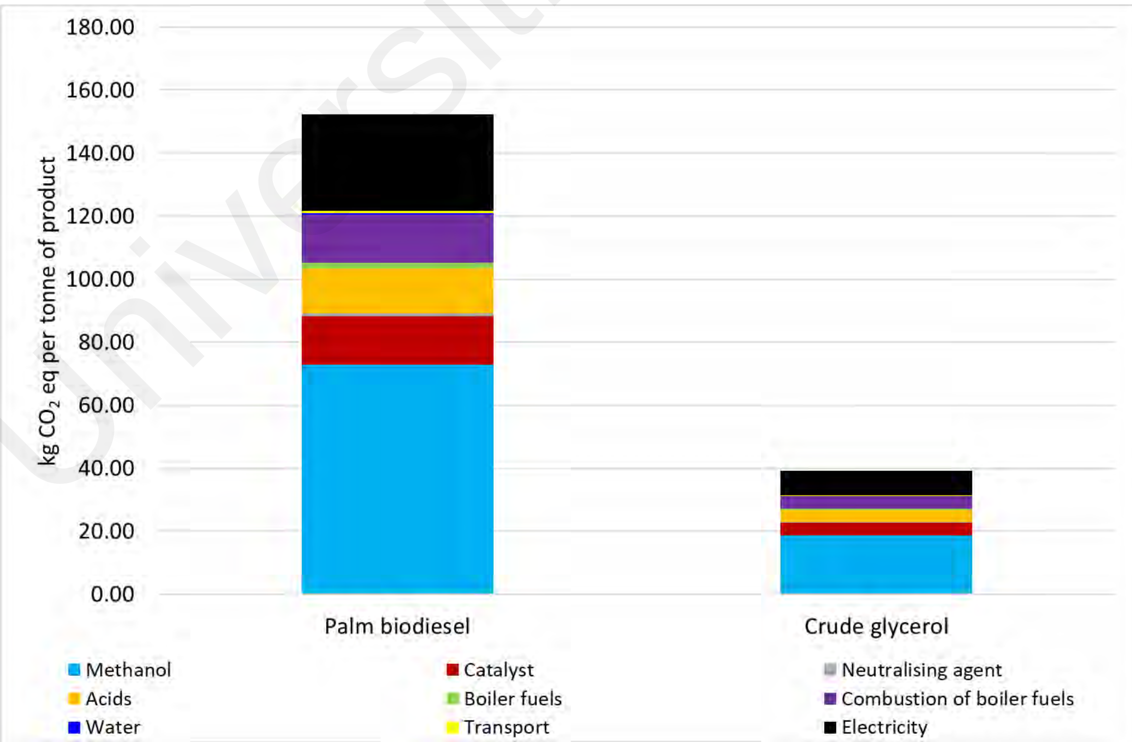


Figure 4.28: Global warming potential of palm biodiesel production

4.3.3.3 Stratospheric Ozone Depletion

As shown in Figure 4.29, the main contributor to stratospheric ozone depletion is methanol. About half of the contribution to this impact category is due to methanol, 47.75%. It is followed by acids used for neutralisation and phase separation, 24.49% of the total impact. 14.16% of the ozone depletion potential are due to transesterification catalyst as the third contributor. Electricity from the national power grid contributes 10.04%. The remaining are insignificant, less than 5% contributions. 84.47×10^{-6} kg CFC11 eq and 21.77×10^{-6} kg CFC11 eq are recorded as the stratospheric ozone depletion potential per tonne of palm biodiesel and crude glycerol produced, respectively.

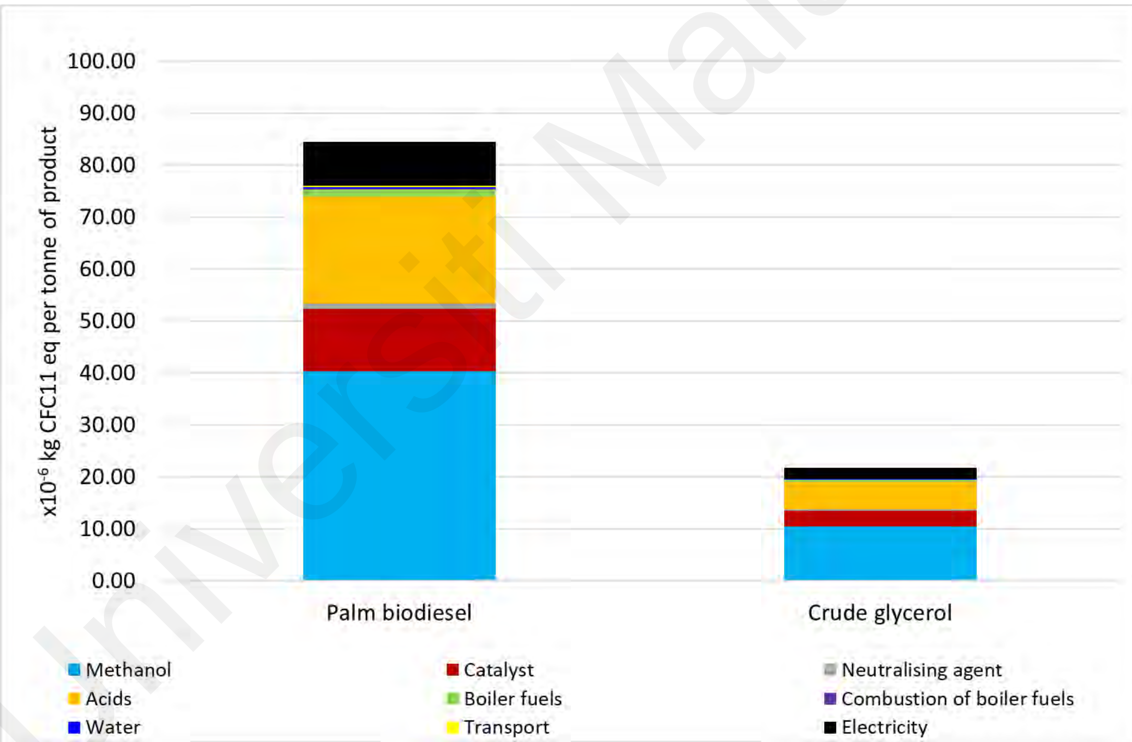


Figure 4.29: Stratospheric ozone depletion potential of palm biodiesel production

4.3.3.4 Ionising Radiation

The major contributors to the ionising radiation impact category are the transesterification catalyst and methanol (Figure 4.30). Catalyst contributes 36.75% while 34.18% are due to methanol. Acids used is the third contributor, 23.18% of the impact. Ionising radiation potential of 3.42 kBq Co-60 eq and 0.88 kBq Co-60 eq are recorded respectively for the production of one tonne of palm biodiesel and one tonne of crude glycerol, based on economic allocation procedure.

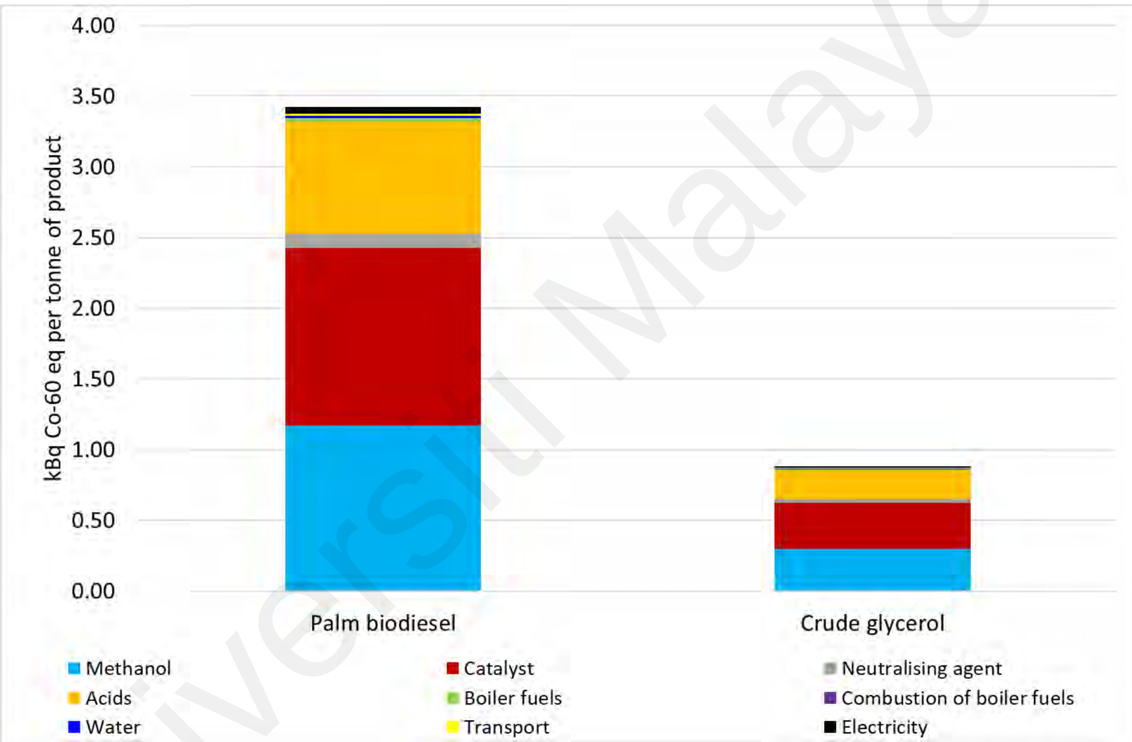


Figure 4.30: Ionising radiation potential of palm biodiesel production

4.3.3.5 Ozone Formation

Methanol is the primary contributor to the ozone formation impact category, both impacts on human health and terrestrial ecosystems (Figure 4.31). 49.89% and 51.01% of the impact on human health and terrestrial ecosystems are anticipated. It is followed by the electricity consumption from the national power grid, 15.97% on human health and 15.50% on terrestrial ecosystems. A similar magnitude of impact from the transesterification catalyst and acids is observed. Ozone formation potential of 0.30 kg NO_x eq and 0.31 kg NOx eq are recorded per tonne of palm biodiesel for impact on human health and terrestrial ecosystems while 0.08 kg NO_x eq are recorded per tonne of crude glycerol produced.

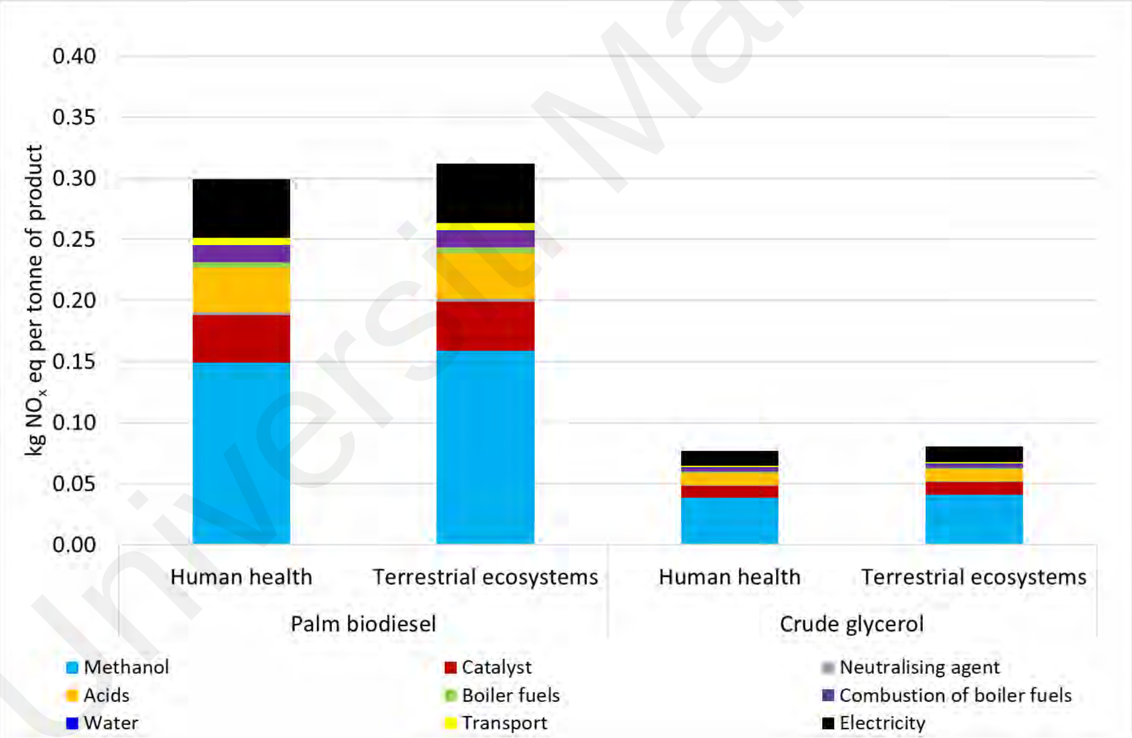


Figure 4.31: Ozone formation potential of palm biodiesel production

4.3.3.6 Fine Particulate Matter Formation

Electricity from the national power grid and methanol are the two main contributors to fine particulate matter formation, 30.30% and 28.59%, respectively (Figure 4.32). It is followed by the combustion of boiler fuels for steam generation, acids and transesterification catalyst. Contributions of 13.70%, 13.23% and 11.48% are recorded respectively for these three contributors. For every tonne of palm biodiesel and crude glycerol produced, 0.25 kg PM2.5 eq and 0.07 kg PM2.5 eq are anticipated according to economic allocation.

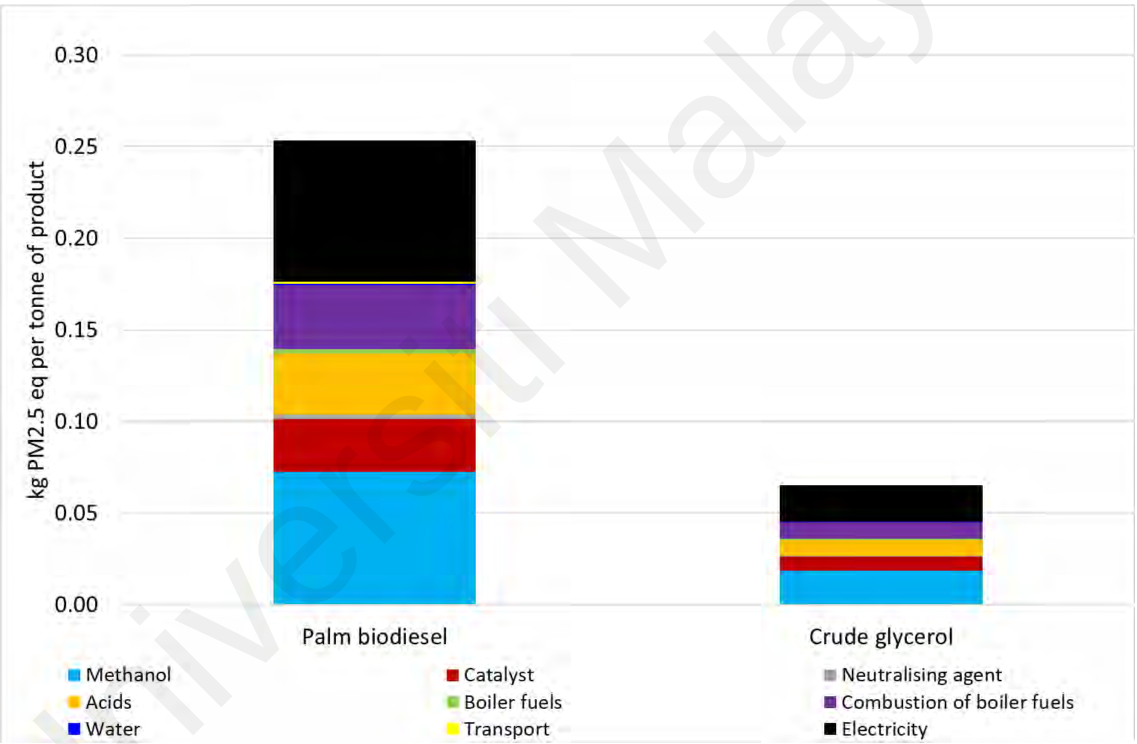


Figure 4.32: Fine particulate matter formation potential of palm biodiesel production

4.3.3.7 Terrestrial Acidification

Methanol is the main contributor to the terrestrial acidification impact category (Figure 4.33). It is followed by the combustion of boiler fuels, electricity from the national power grid, acids and transesterification catalyst. According to allocation based on economic value, terrestrial acidification potential of 0.56 kg SO_2 eq and 0.15 kg SO_2 eq are recorded respectively for the production of one tonne of palm biodiesel and one tonne of crude glycerol.

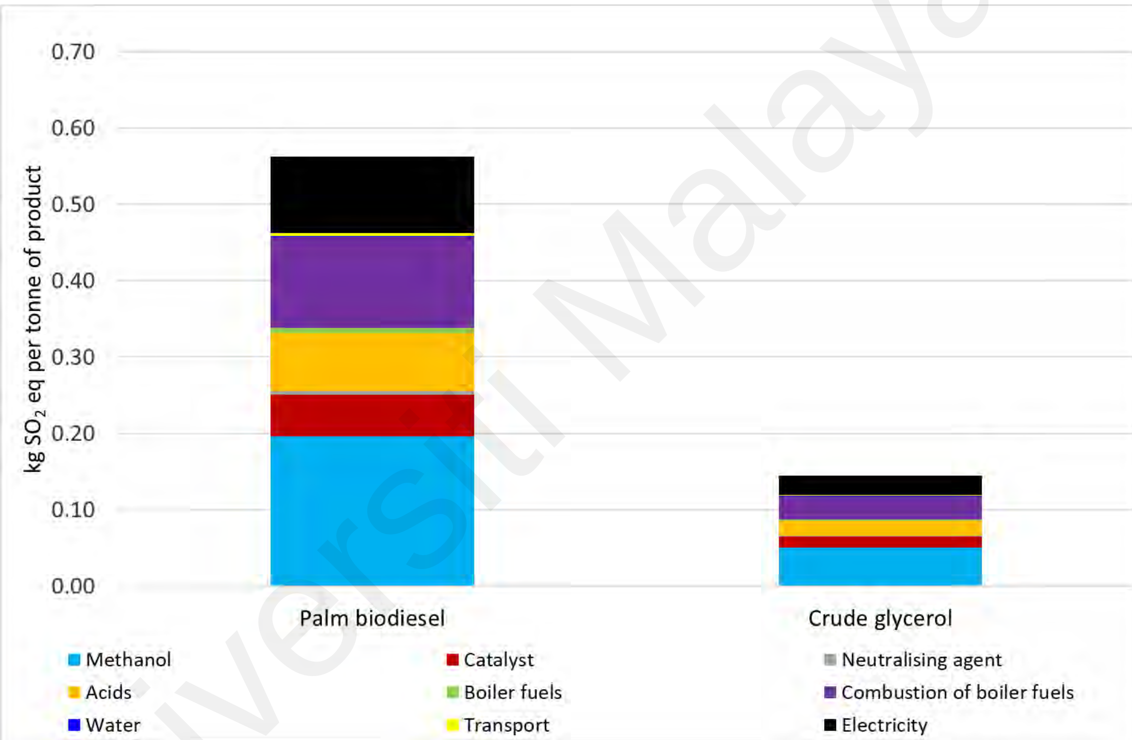


Figure 4.33: Terrestrial acidification potential of palm biodiesel production

4.3.3.8 Freshwater Eutrophication

The main contributor to the freshwater eutrophication impact category is the electricity from the national power grid, 35.94% (Figure 4.34). Methanol is the second contributor, 27.98%. Transesterification catalyst and acids stand at third and fourth place, 17.42% and 16.48%. These four contributors dominate the total contribution of 97.82%. Freshwater eutrophication potential of 36.32×10^{-3} kg P eq and 9.36×10^{-3} kg P eq are recorded for the production of one tonne of palm biodiesel and one tonne of crude glycerol, respectively.

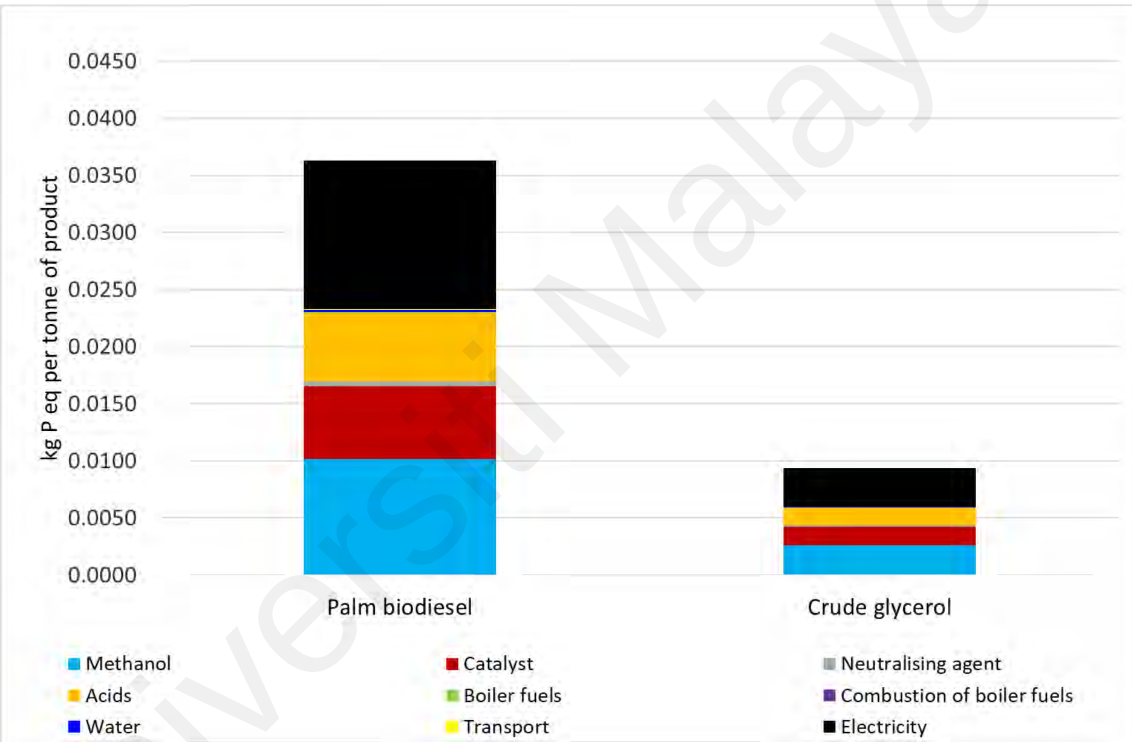


Figure 4.34: Freshwater eutrophication potential of palm biodiesel production

4.3.3.9 Marine Eutrophication

Unlike other impact categories, methanol is not the highest contributor to the marine eutrophication impact category (Figure 4.35). Marine eutrophication is dominated by the acids used, 43.77% of the total impact. Detailed analysis shows that 77.82% of the acids contribution are due to the citric acid used. Electricity, methanol and transesterification catalyst are the second, third and fourth contributors. Marine eutrophication potential of 4.05×10^{-3} kg N eq and 1.04×10^{-3} kg N eq are recorded for every tonne of palm biodiesel and crude glycerol produced.

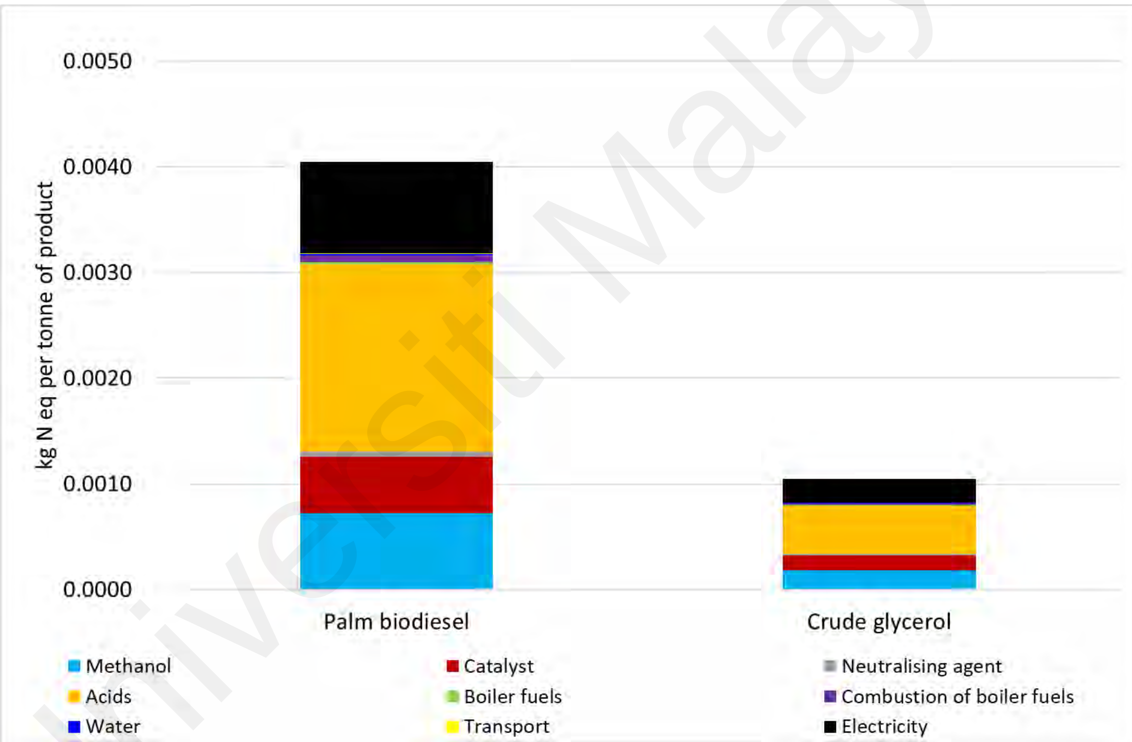


Figure 4.35: Marine eutrophication potential of palm biodiesel production

4.3.3.10 Mineral Resource Scarcity

Methanol and acids are the main contributors to mineral resource scarcity, 42.32% and 34.80% (Figure 4.36). Detailed analysis shows that hydrochloric acid is the main contributor among the acids used, 71.97% of the acids contribution. Transesterification catalyst is the third contributor to mineral resource scarcity, 16.87%. Mineral resources scarcity is dominated by these three chemicals, 93.99%. Mineral resource scarcity of 0.41 kg Cu eq and 0.11 kg Cu eq are respectively anticipated for every tonne of palm biodiesel and crude glycerol produced.

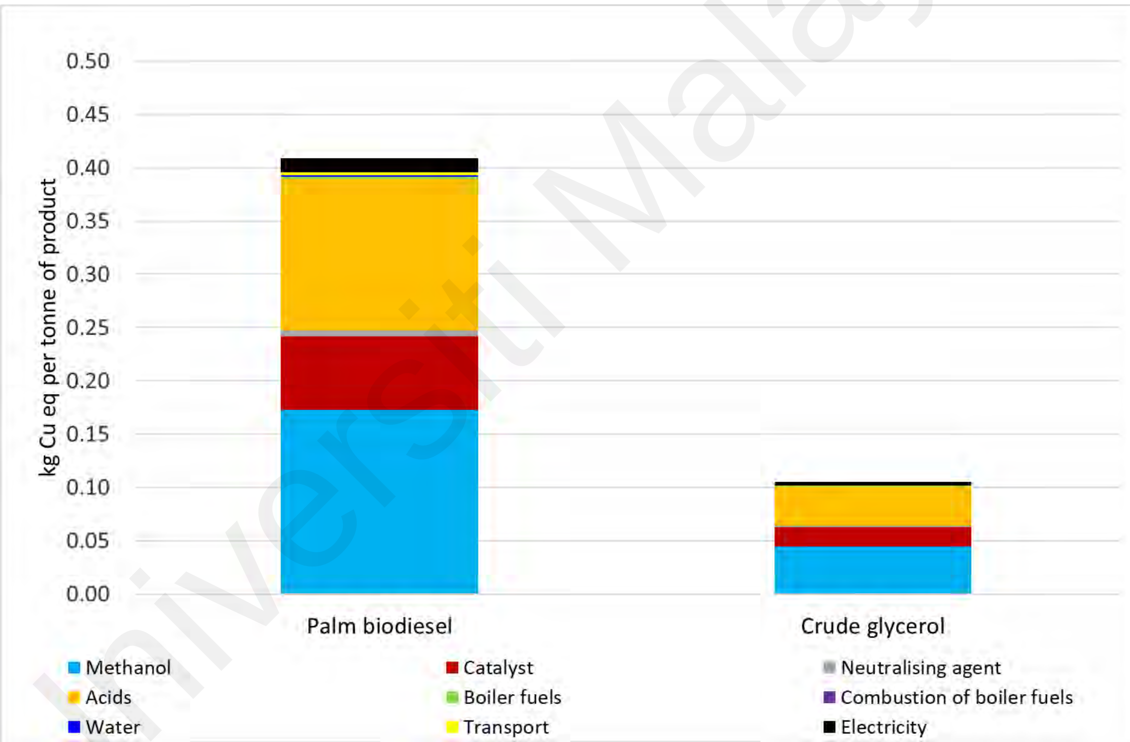


Figure 4.36: Mineral resource scarcity potential of palm biodiesel production

4.3.3.11 Fossil Resource Scarcity

Figure 4.37 shows that methanol is the primary contributor to fossil resource scarcity. 72.69% of the fossil resource impact are due to methanol which is produced mainly from steam methane reforming of fossil-based natural gas. Other less significant contributors are electricity, transesterification catalyst, boiler fuels and their combustion for steam generation. For every tonne of palm biodiesel and crude glycerol produced, 109.39 kg oil eq and 28.19 kg oil eq are anticipated.

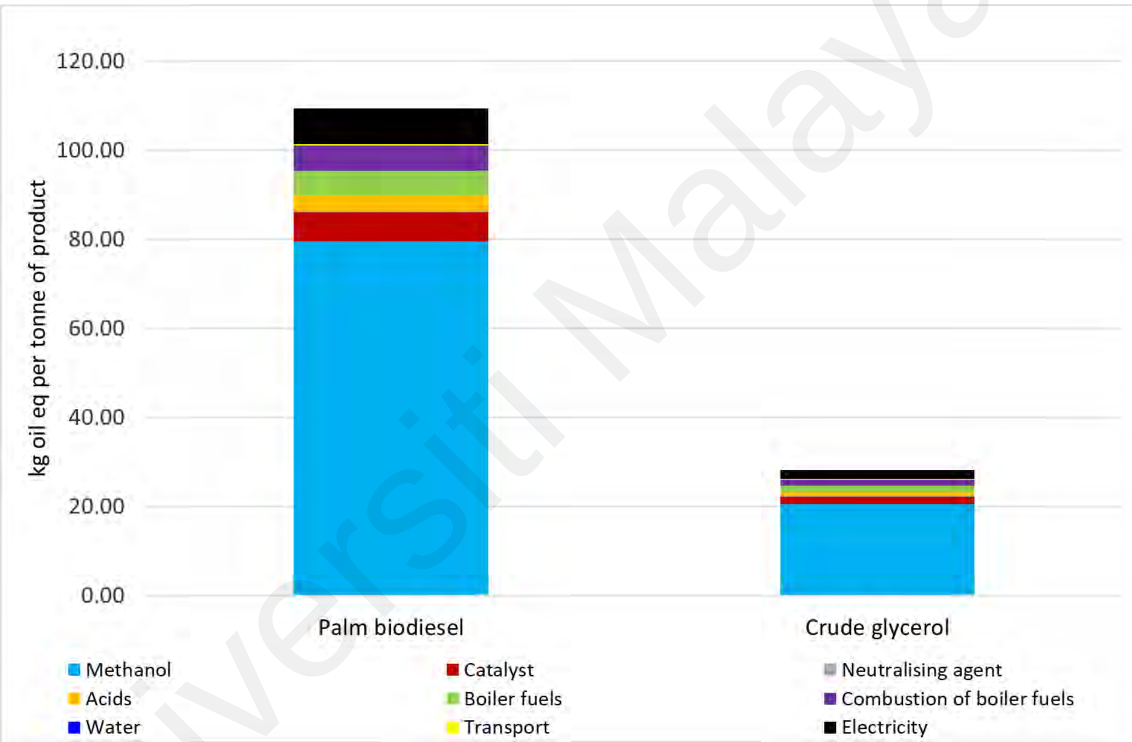


Figure 4.37: Fossil resource scarcity potential of palm biodiesel production

4.3.3.12 Water Consumption

The allocated water consumption for the production of one tonne of palm biodiesel and crude glycerol are 1.98 m^3 and 0.51 m^3. As shown in Figure 4.38, 30.09% of the total water consumption are due to the direct water consumed in the biodiesel plants for steam generation, cooling, biodiesel washing and purification. 68.51% of the water consumption are due to the background processes for the production of methanol, acids, transesterification catalyst and electricity generation.

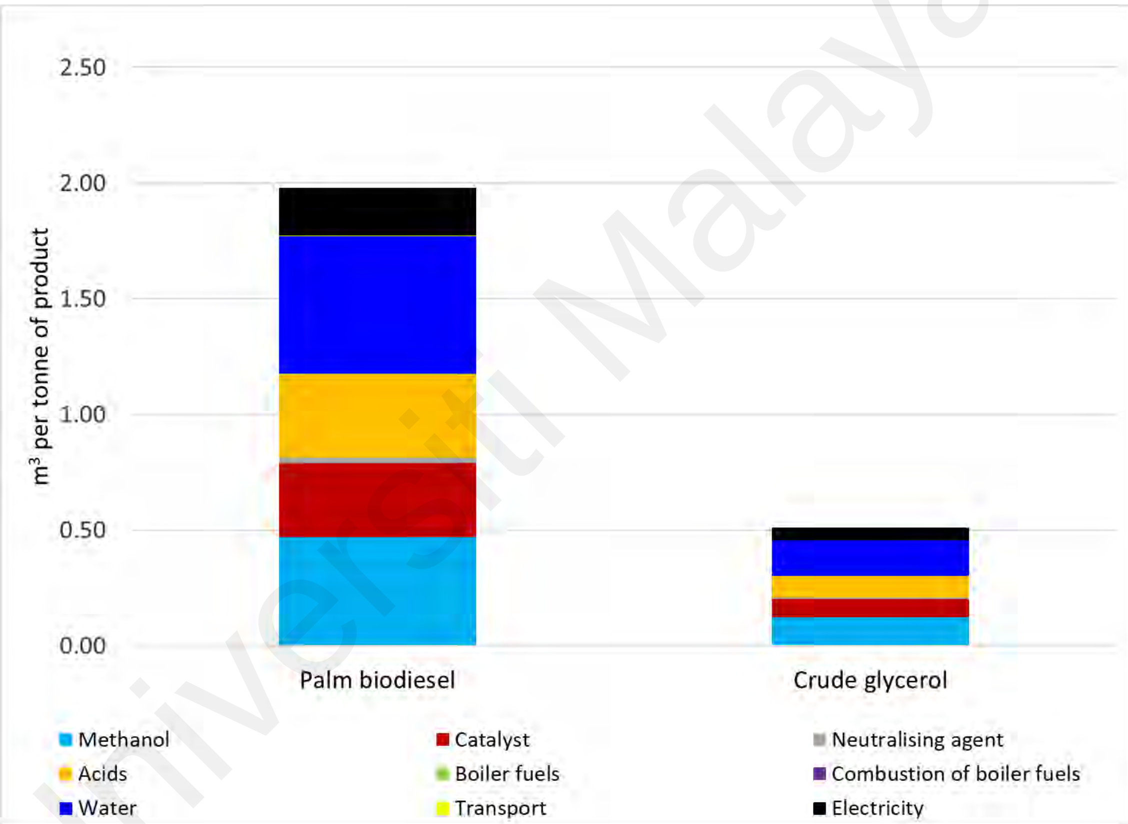


Figure 4.38: Water consumption potential of palm biodiesel production

4.3.4 Gate-to-gate LCA of Hydroprocessed Palm Biofuels Production

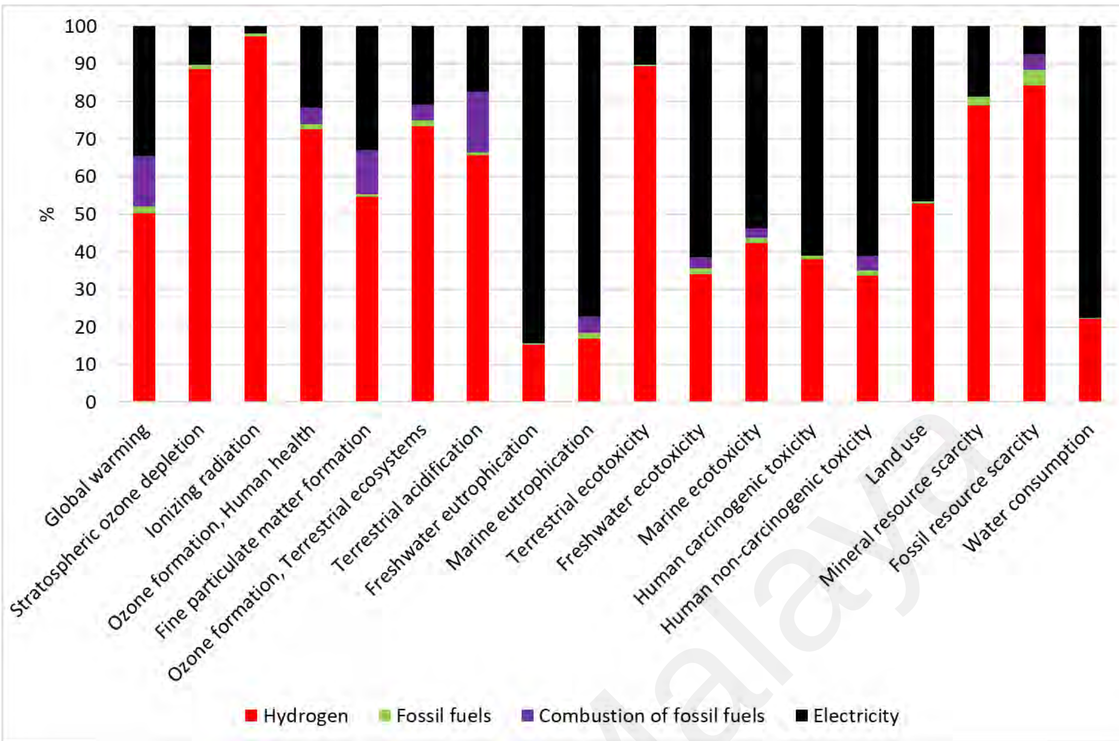
4.3.4.1 Contribution Analysis of Hydroprocessed Palm Biofuels Production

The gate-to-gate characterised LCIA of the production of hydroprocessed palm biofuels i.e. HRD and HRJ at the midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) are presented in Figure 4.39 and Figure 4.40. Within the hydroprocessing system boundary, hydrogen and electricity are the main contributors to all impact categories. A similar contribution is observed for all four scenarios evaluated i.e. production of HRD from RBD palm oil, production of HRD from PFAD, production of HRJ from RBD palm oil and production of HRJ from PFAD.

Hydrogen is the principal contributor to 11 midpoint impact categories, namely global warming, stratospheric ozone depletion, ionising radiation, ozone formation on human health, ozone formation on terrestrial ecosystems, fine particle matter formation, terrestrial acidification, terrestrial ecotoxicity, land use, mineral resource scarcity and fossil resource scarcity. Electricity from the national power grid has a major contribution to freshwater and marine eutrophication, freshwater and marine ecotoxicity, human carcinogen toxicity, human non-carcinogen toxicity and water consumption. Combustion of fossil fuels i.e. natural gas for heat production has minimal impact on global warming, fine particulate matter formation and terrestrial acidification.

Since no commercial production of the hydroprocessing biofuels is available in the country, data on feedstock (RBD palm oil or PFAD) transportation, catalyst and its treatment and/or disposal, direct water consumption and wastewater treatment are not available for a detailed analysis.

(a)



(b)

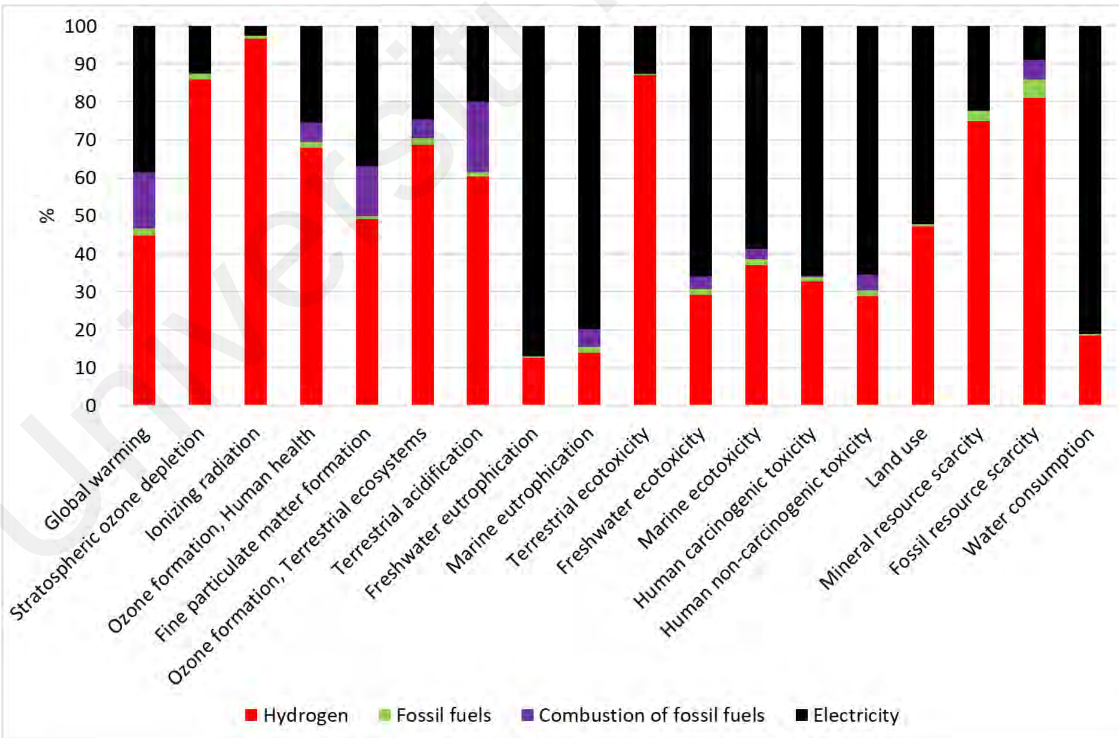
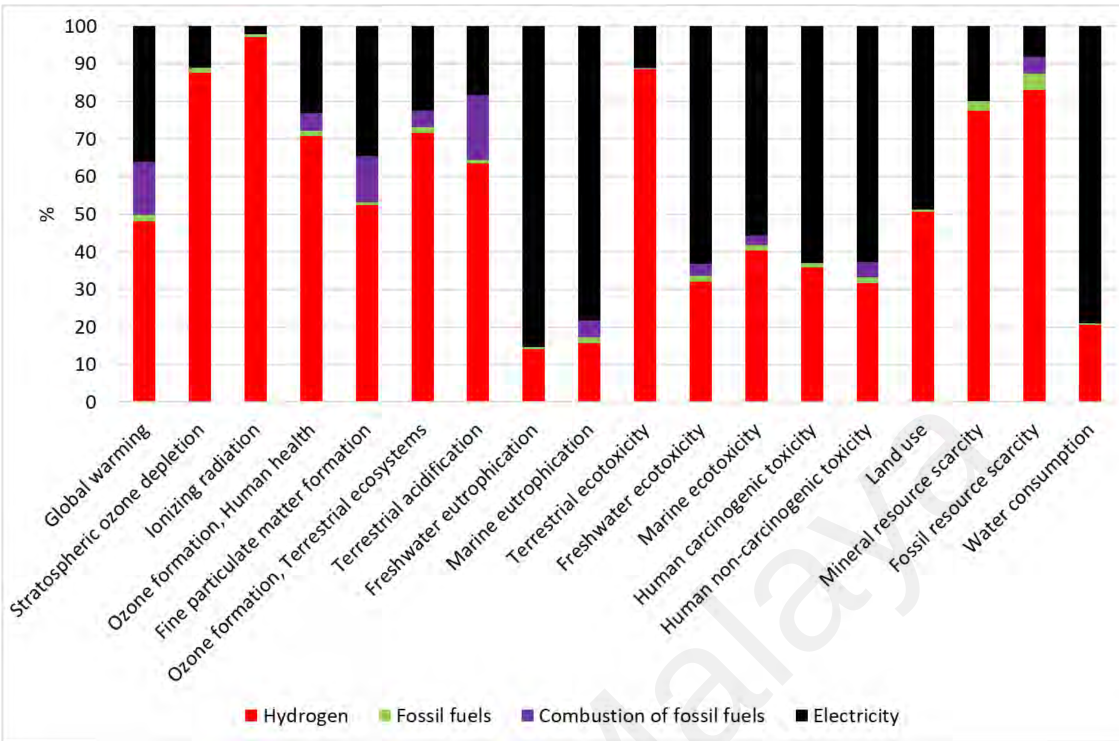


Figure 4.39: Gate-to-gate characterised LCIA of HRD production from (a) RBD palm oil and (b) PFAD

(a)



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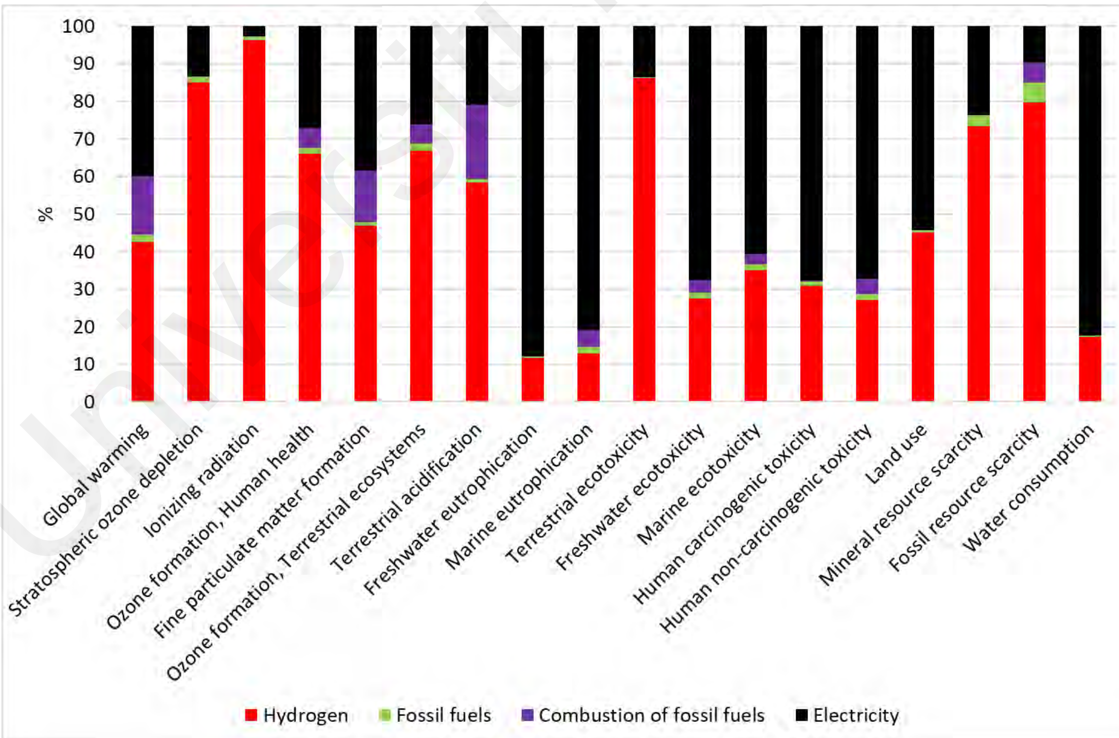


Figure 4.40: Gate-to-gate characterised LCIA of HRJ production from (a) RBD palm oil and (b) PFAD

4.3.4.2 Global Warming

In the gate-to-gate LCIA for the production of HRD and HRJ, hydrogen and electricity from the national power grid are the two main contributors to the global warming impact category, 82% to 85% in total (Figure 4.41). The global warming impact of HRJ production is higher than the HRD production. This is because more hydrogen and energy are needed for isomerisation of HRD to produce HRJ with properties mimic to fossil-based jet fuel, in particular low freezing point characteristic. Comparing the feedstocks, both HRD and HRJ produced from PFAD possesses a lower global warming impact compared to RBD palm oil. This is also due to the lower hydrogen requirement for the biofuels (HRD and HRJ) production from PFAD, as observed in the pilot plant study. Global warming potential of 112 to 123 kg CO_2 eq and 134 to 141 CO_2 eq are anticipated respectively per tonne of HRD and HRJ produced.

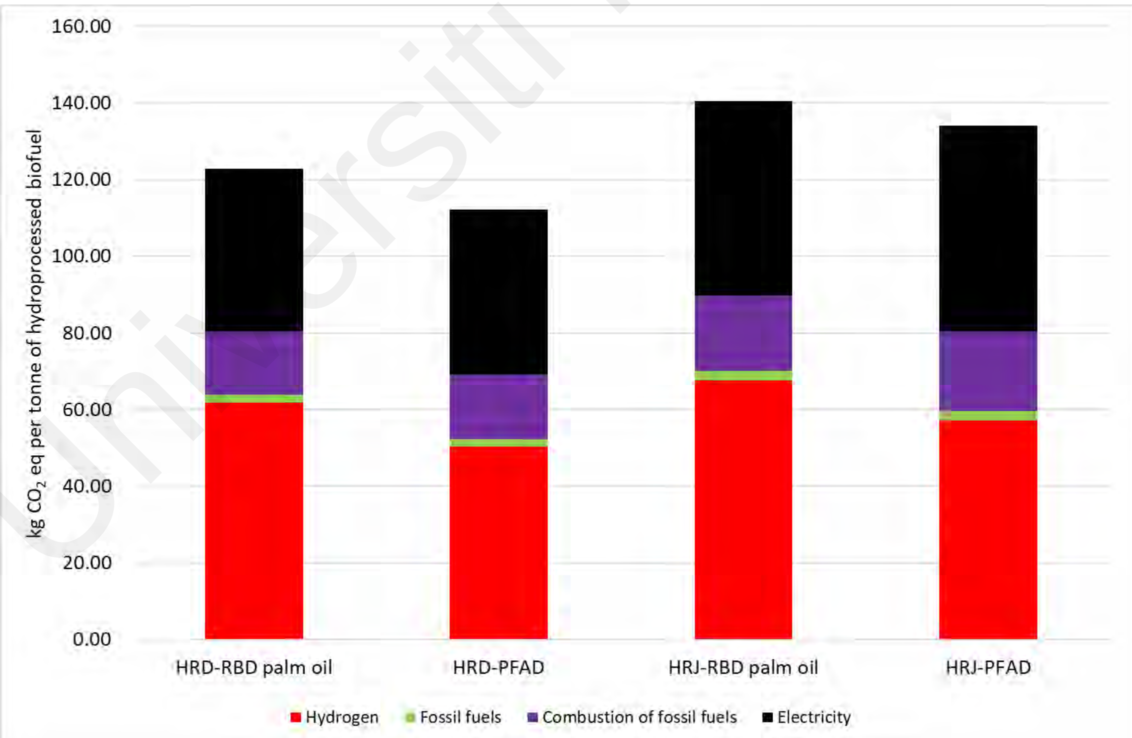


Figure 4.41: Global warming potential of palm-based HRD and HRJ production

4.3.4.3 Stratospheric Ozone Depletion

Hydrogen dominates the impact on stratospheric ozone depletion, 85% to 89% (Figure 4.42). Electricity consumption from the national power grid contributes 10% to 13% to the total impact. The contributions of fossil fuels and their combustion for heat generation are insignificant, <2%. 96×10^{-6} to 115×10^{-6} kg CFC11 eq and 110×10^{-6} to 128×10^{-6} kg CFC11 eq are recorded as the stratospheric ozone depletion potential per tonne of HRD and HRJ produced.

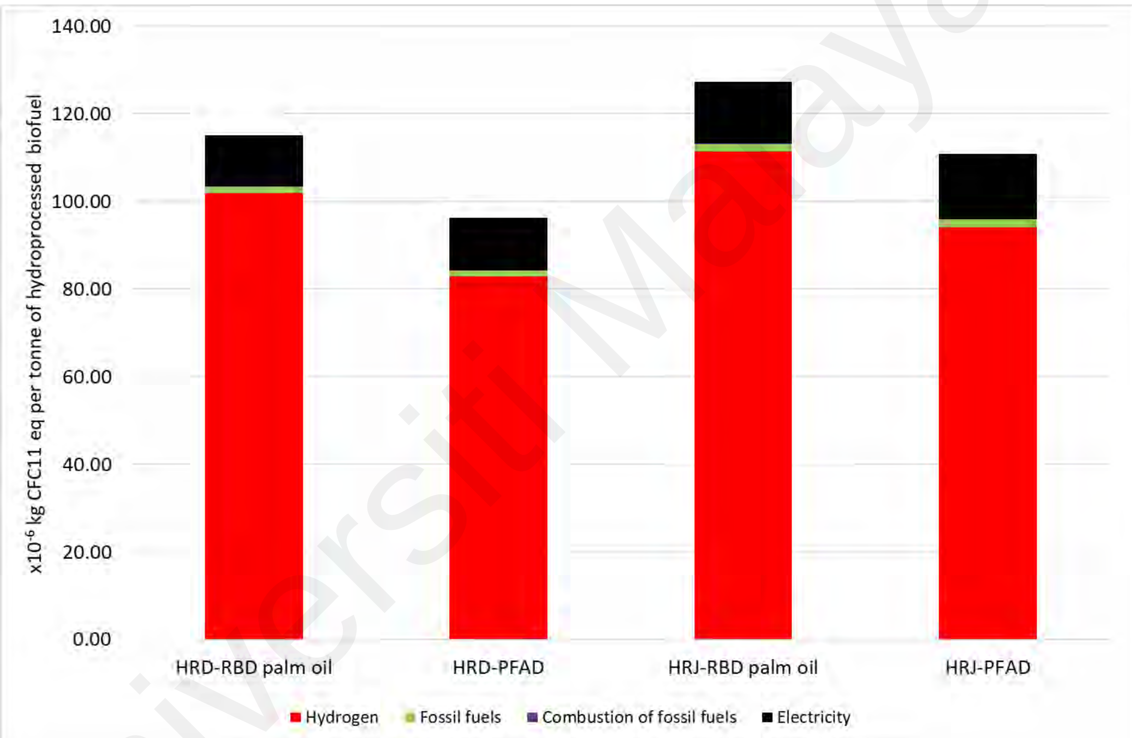


Figure 4.42: Stratospheric ozone depletion potential of palm-based HRD and HRJ production

4.3.4.4 Ionising Radiation

As shown in Figure 4.43, hydrogen is the sole contributor to ionising radiation impact with more than 96% recorded for all four scenarios. Contributions from the others are negligible. Ionising radiation potential of 3.40 kBq Co-60 eq and 3.73 kBq Co-60 eq are recorded respectively for the production of one tonne of HRD and one tonne of HRJ from RBD palm oil. 18% and 15% lower impact are observed for the same amount of HRD and HRJ produced from PFAD.

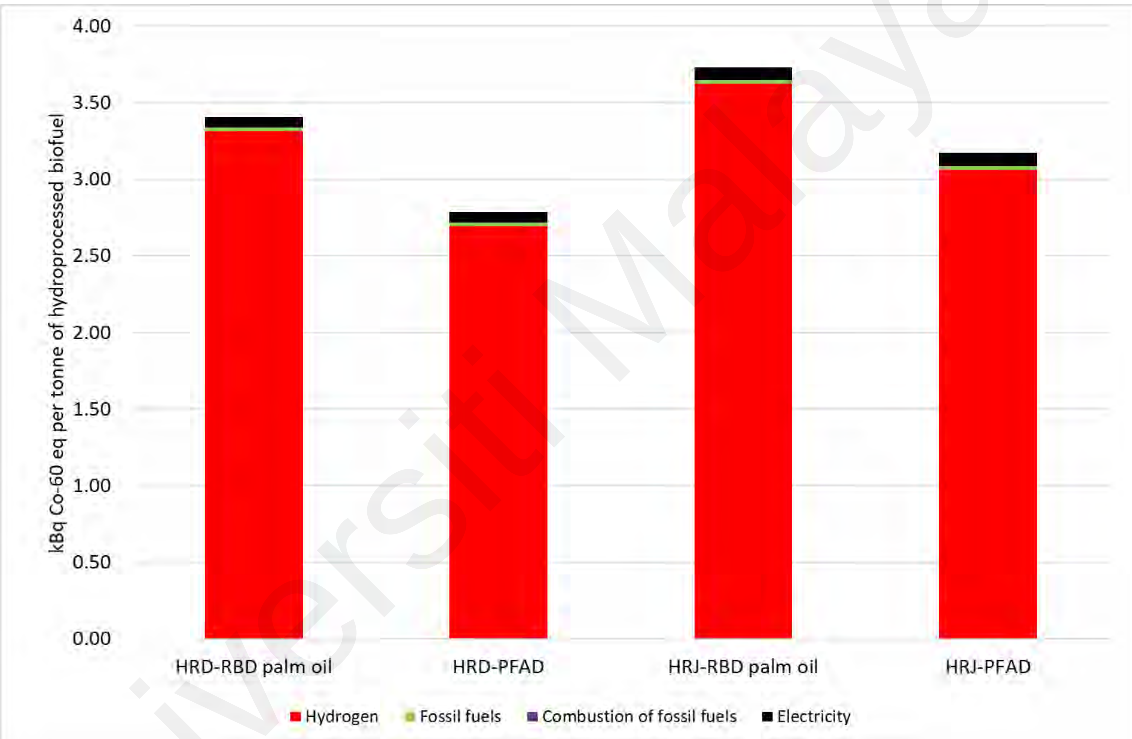


Figure 4.43: Ionising radiation potential of palm-based HRD and HRJ production

4.3.4.5 Ozone Formation

The impact of ozone formation on human health and terrestrial ecosystems for the production of HRD and HRJ is shown in Figure 4.44. Hydrogen is the main contributor and it is followed by electricity consumption from the national power grid. The contribution of fossil fuels combustion is minimal, around 5%. Ozone formation potential of 0.26 to 0.36 kg NOx eq are anticipated per tonne of the hydroprocessed biofuels produced.

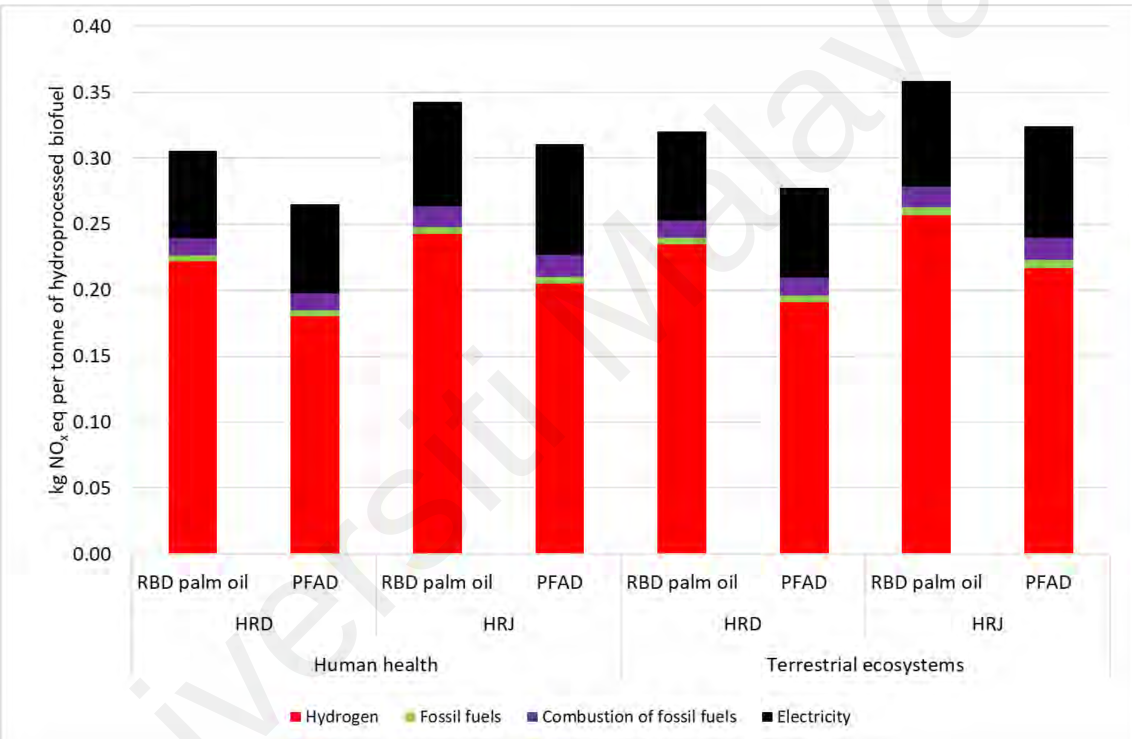


Figure 4.44: Ozone formation potential of palm-based HRD and HRJ production

4.3.4.6 Fine Particulate Matter Formation

For the production of HRD from the RBD palm oil scenario, 54.69% of the fine particulate formation potential are contributed by the background process for the production of hydrogen (Figure 4.45). As mentioned previously, fine particulate matter formation is mainly related to the combustion of fossil fuels. 32.85% and 11.71% are respectively due to electricity from the national power grid and the combustion of fossil fuels to generate heat, to fulfil the energy and heat demand of the hydroprocessing process. For every tonne of HRD and HRJ produced, fine particulate matter formation potential of 0.29 to 0.32 kg PM2.5 eq and 0.35 to 0.37 kg PM2.5 eq are anticipated.

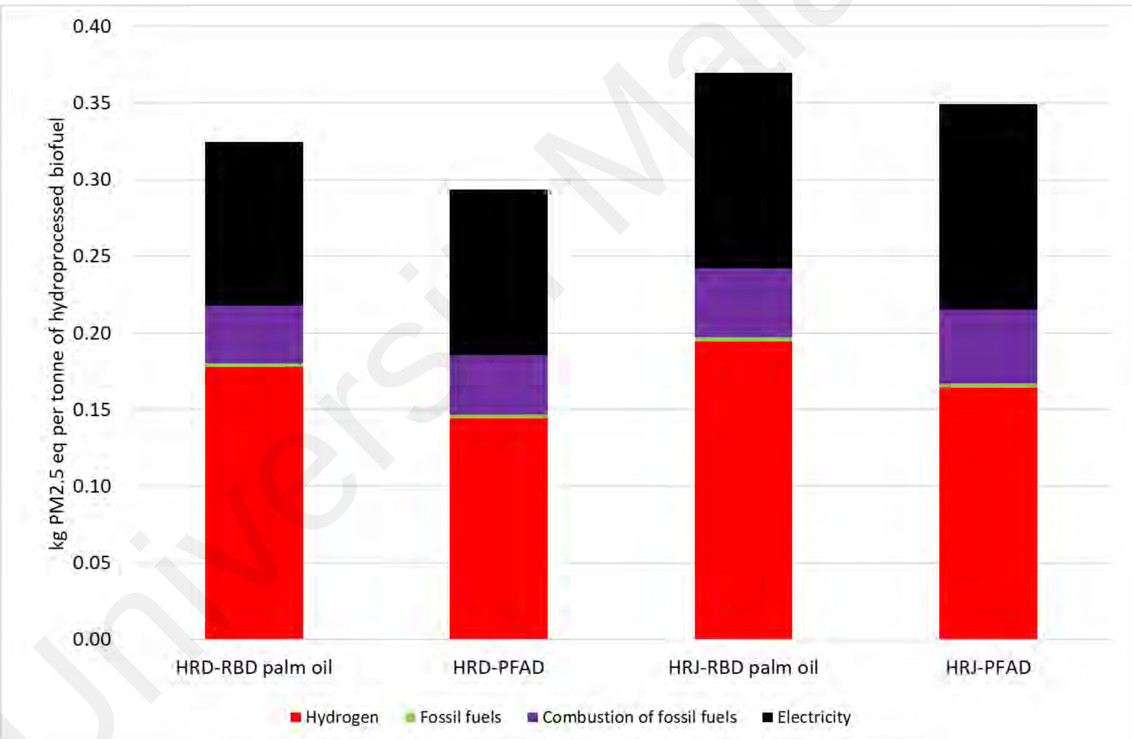


Figure 4.45: Fine particulate matter formation potential of palm-based HRD and HRJ production

4.3.4.7 Terrestrial Acidification

From Figure 4.46, it can be observed that approximately two-thirds of the terrestrial acidification impact are due to hydrogen. The remaining one-third of the impact are almost equally contributed by the electricity and the combustion of fossil fuels for heat generation. Terrestrial acidification potential of 0.81 kg SO_2 eq and 0.91 kg SO_2 eq are recorded for the production of one tonne of HRD and one tonne of HRJ, from RBD palm oil. 12% and 8% lower impact are anticipated respectively for HRD and HRJ produced from PFAD.

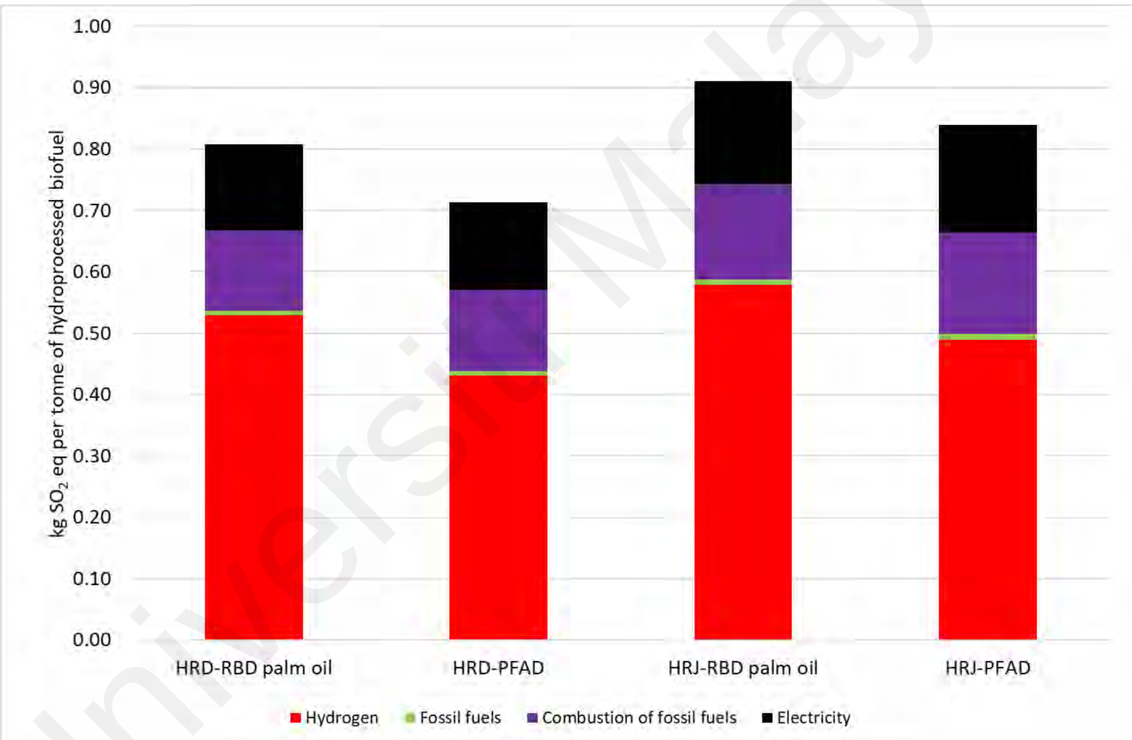


Figure 4.46: Terrestrial acidification potential of palm-based HRD and HRJ production

4.3.4.8 Freshwater Eutrophication

Freshwater eutrophication is dominated by electricity from the national power grid, 84% to 88%, as shown in Figure 4.47. The remaining 11% to 16% are contributed by hydrogen used in the hydroprocessing processes. Freshwater eutrophication potential of 21×10^{-3} kg P eq and 26×10^{-3} kg P eq are recorded for the production of one tonne of HRD and one tonne of HRJ, irrespective of feedstock difference.

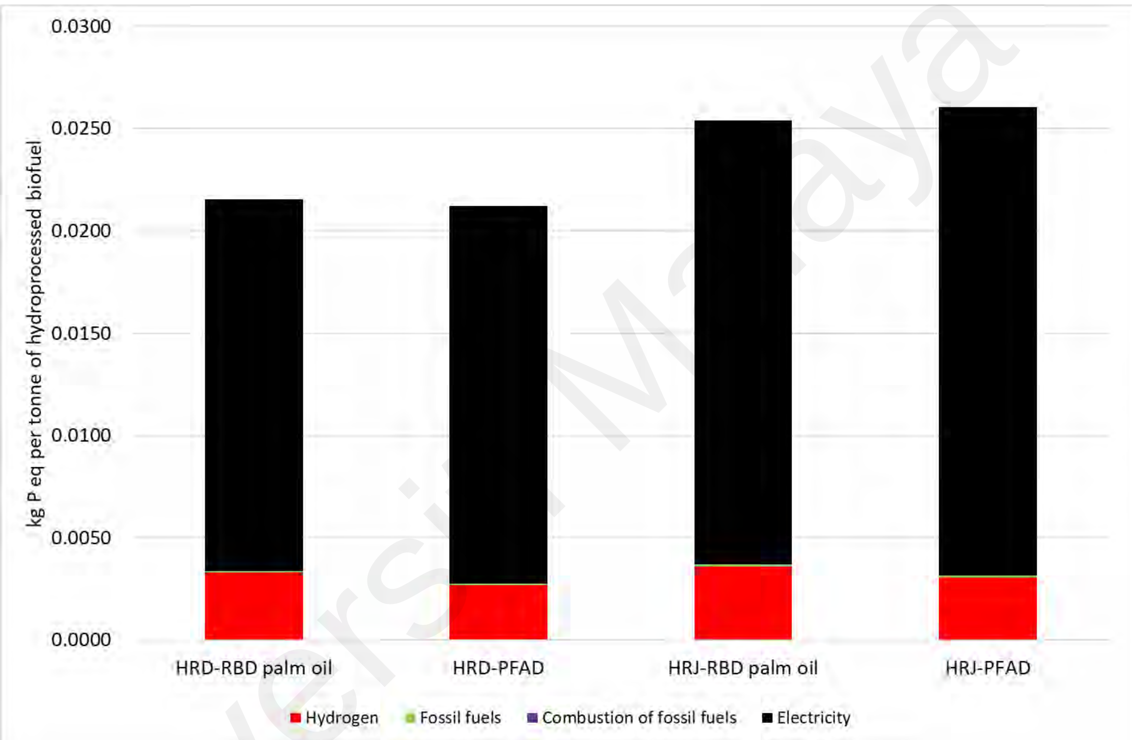


Figure 4.47: Freshwater eutrophication potential of palm-based HRD and HRJ production

4.3.4.9 Marine Eutrophication

Similar to freshwater eutrophication, the main contributors to marine eutrophication are electricity consumption from the national power grid and hydrogen used (Figure 4.48). The contributions of fossil fuels and their combustion for heat generation are minimal, around 6%. Marine eutrophication potential of 1.5×10^{-3} kg N eq and 1.8×10^{-3} kg N eq are recorded for every tonne of HRD and HRJ produced, irrespective of feedstock.

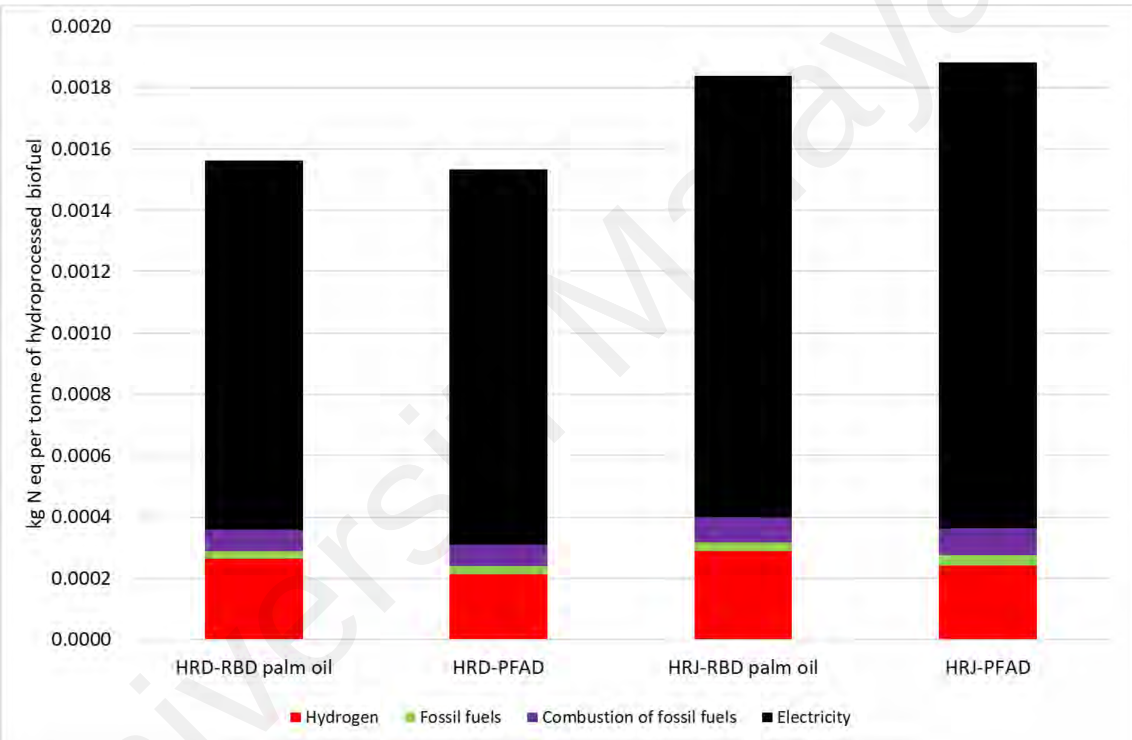


Figure 4.48: Marine eutrophication potential of palm-based HRD and HRJ production

4.3.4.10 Mineral Resource Scarcity

As shown in Figure 4.49, hydrogen is the main contributor to mineral resource scarcity since it is the only chemical evaluated in the gate-to-gate LCA, 73% to 79%. The electricity from the national power grid contributes 18% to 24%. Contribution from fossil fuels is minimal, 2% to 3%. Mineral resource scarcity of around 0.1 kg Cu eq is anticipated per tonne of the hydroprocessed biofuels produced. This figure is anticipated to be higher if the catalyst used for hydroprocessing is taken into consideration. However, such data is not available for evaluation at this point.

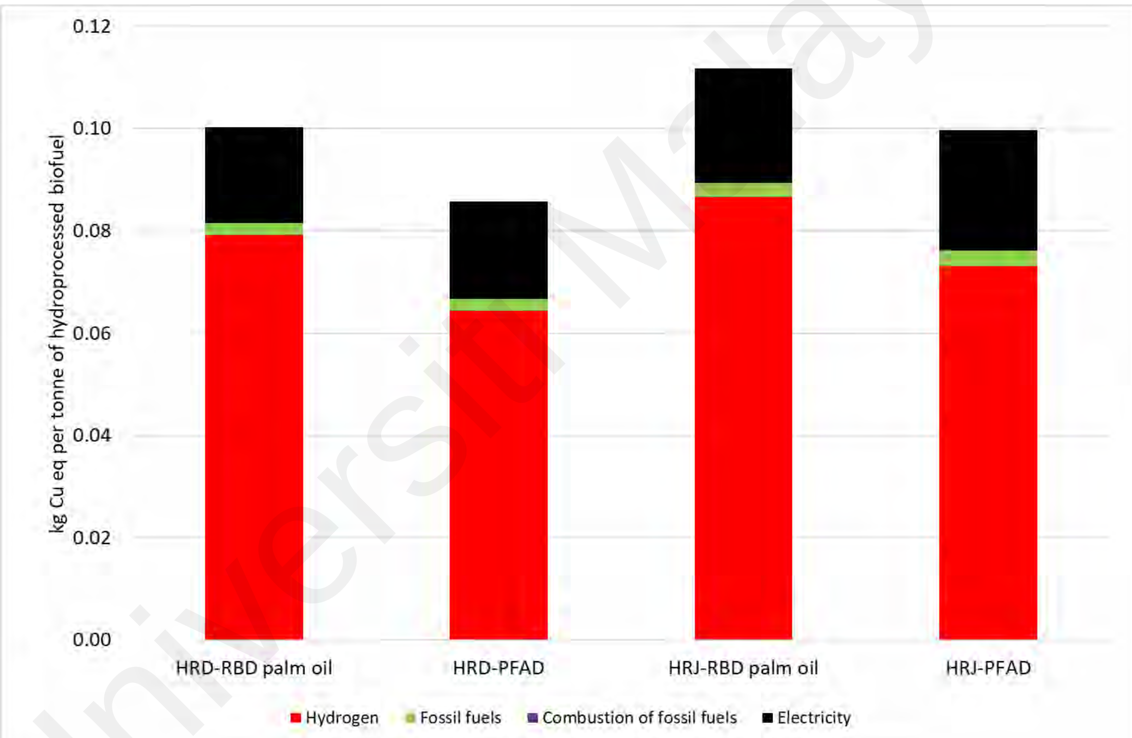


Figure 4.49: Mineral scarcity potential of palm-based HRD and HRJ production

4.3.4.11 Fossil Resource Scarcity

Again, hydrogen is the main contributor to fossil fuel scarcity, 79% to 85% (Figure 4.50) since it is the main ingredient for the hydroprocessing processes besides the feed oil. The high contribution is because the hydrogen is mainly produced from the steam methane reforming of fossil-based natural gas. A similar contribution is observed for methanol in the fossil resource scarcity as shown in Figure 4.37. Fossil resource scarcity of 147.65 kg oil eq and 163.77 kg oil eq are recorded respectively for the production of one tonne of HRD and one tonne of HRJ from RBD palm oil. 16% and 12% lower are anticipated for the HRD and HRJ produced from PFAD.

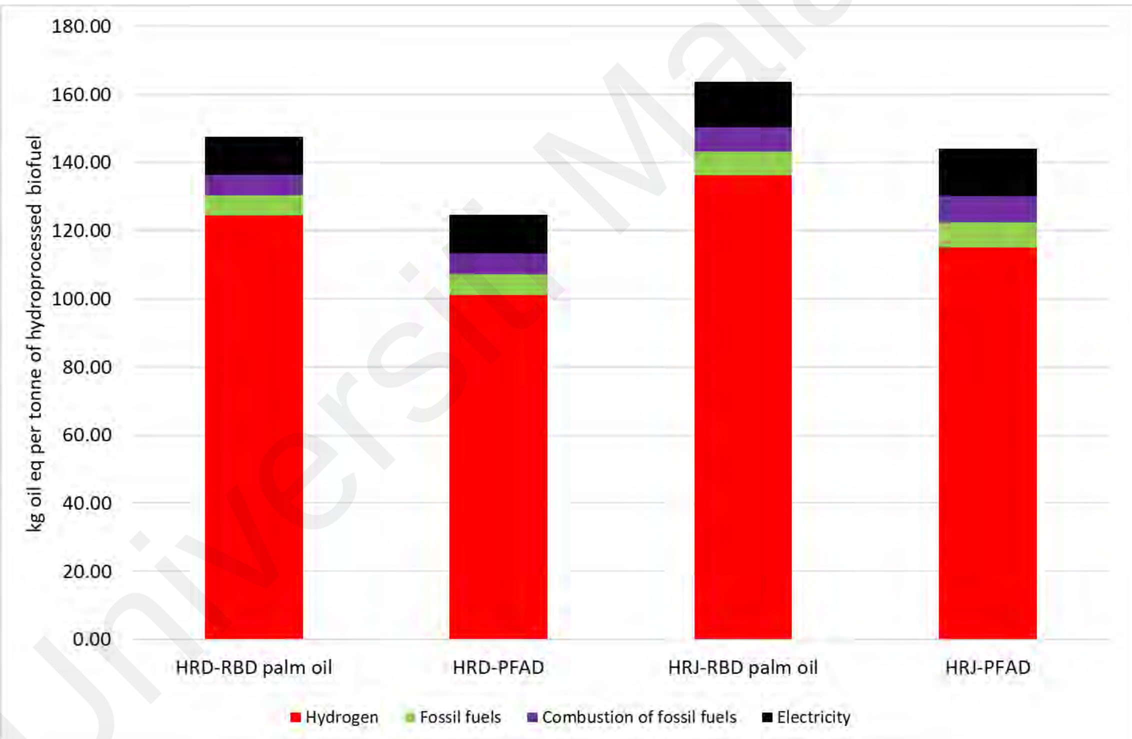


Figure 4.50: Fossil resource scarcity potential of palm-based HRD and HRJ production

4.3.4.12 Water Consumption

The total water consumption for the production of HRD and HRJ are much lower compared to biodiesel (Figure 4.38 and Figure 4.51). This is mainly due to insufficient inventory data on the direct water used in the commercial hydroprocessing plant. Another possible reason is no water washing is required for HRD and HRJ compared to biodiesel. Evaluation of the available inventory data shows that the water consumption mainly contributed by electricity (77% to 83%) and hydrogen (17% to 23%). The allocated water consumption for the production of one tonne of HRD and one tonne of HRJ are around 0.37 m^3 and 0.44 m^3, respectively.

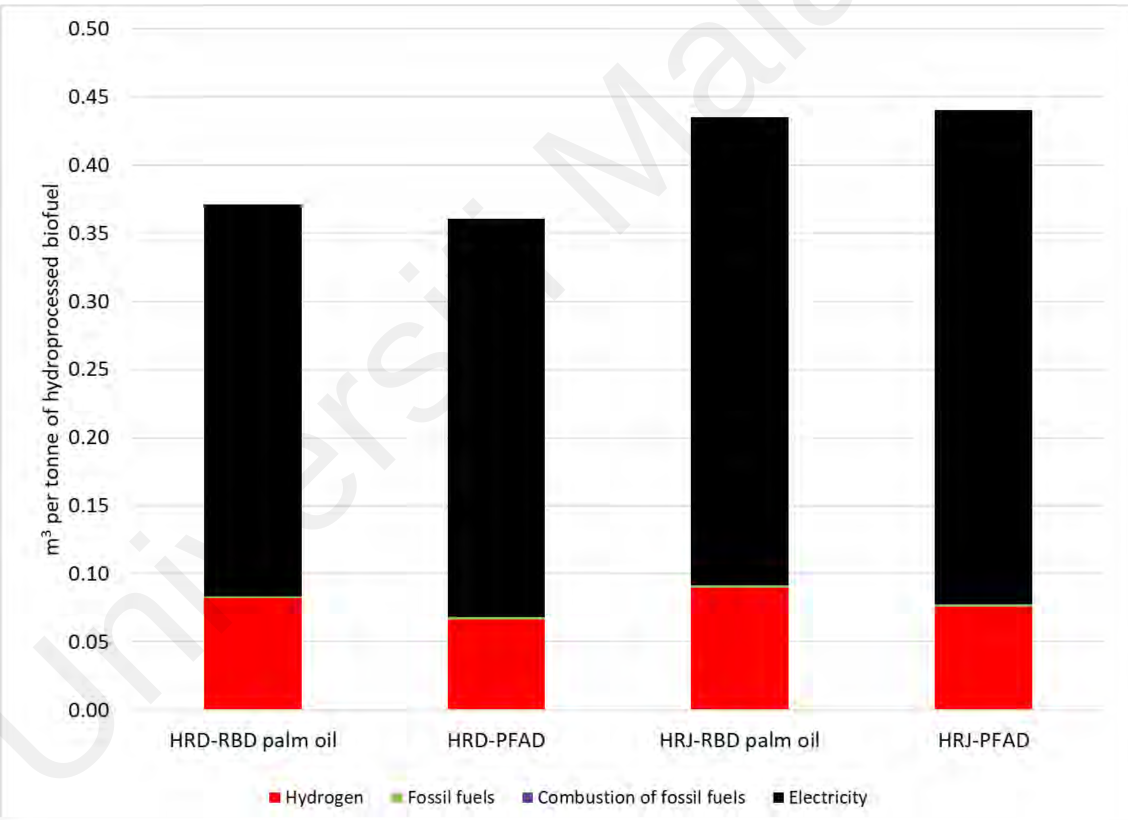


Figure 4.51: Water consumption potential of palm-based HRD and HRJ production

4.3.5 Cradle-to-Gate LCA of Palm Oil Refining

The cradle-to-gate characterised LCIA of palm oil refining at midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is shown in Figure 4.52. Environmental burden inherited from the upstream processes which is labelled as CPO is the main contributor to all impact categories evaluated. The activities in the refining plant play an insignificant contribution in this cradle-to-gate LCA, similar to results displayed in the previous study (Tan et al., 2010). However, activities in the refining plant have minimal impact on six impact categories i.e. ozone formation on human health, ozone formation on terrestrial ecosystems, fine particulate matter formation, human carcinogenic toxicity, land use and fossil resource scarcity. The contributions of refining activities range from 8% to 12 % to the overall impact. CPO transportation is the main contributor, in particular, to the ozone formation on human health and terrestrial ecosystems impact categories.

Detail investigation of the environmental impacts based on subsystems is presented in Figure 4.53. It can be observed that most of the impact categories are due to the plantation subsystem. The palm oil mill subsystem is significant to global warming, ozone formation (human health and terrestrial ecosystems) and water consumption impact categories. Global warming impact from palm oil mills is mainly due to biogas emissions from the palm oil mill effluent as reported by Vijaya et al. (2010). Water consumption is mainly due to the high water used in the typical palm oil milling activities.

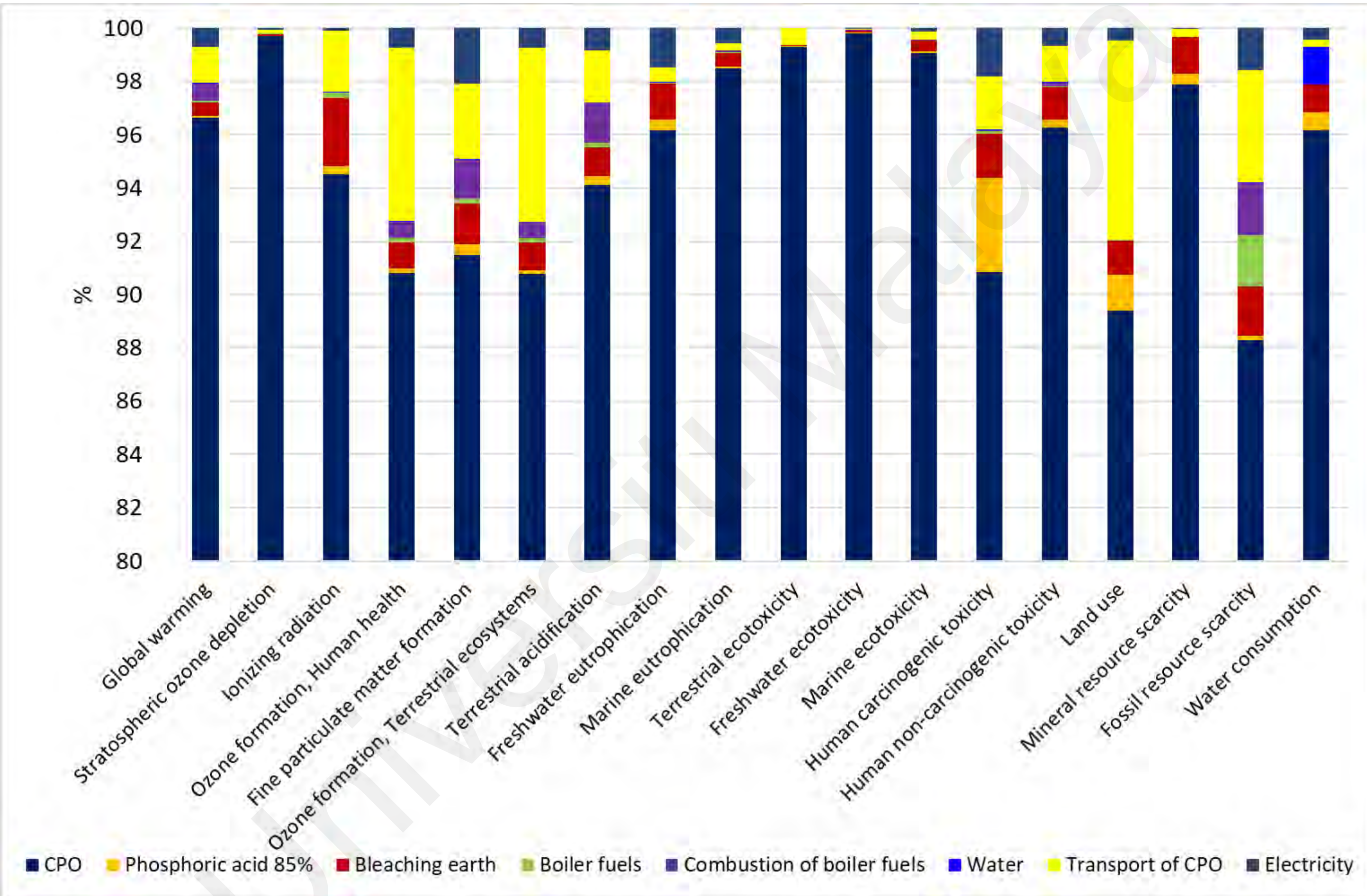


Figure 4.52: Cradle-to-gate characterised LCIA of palm oil refining

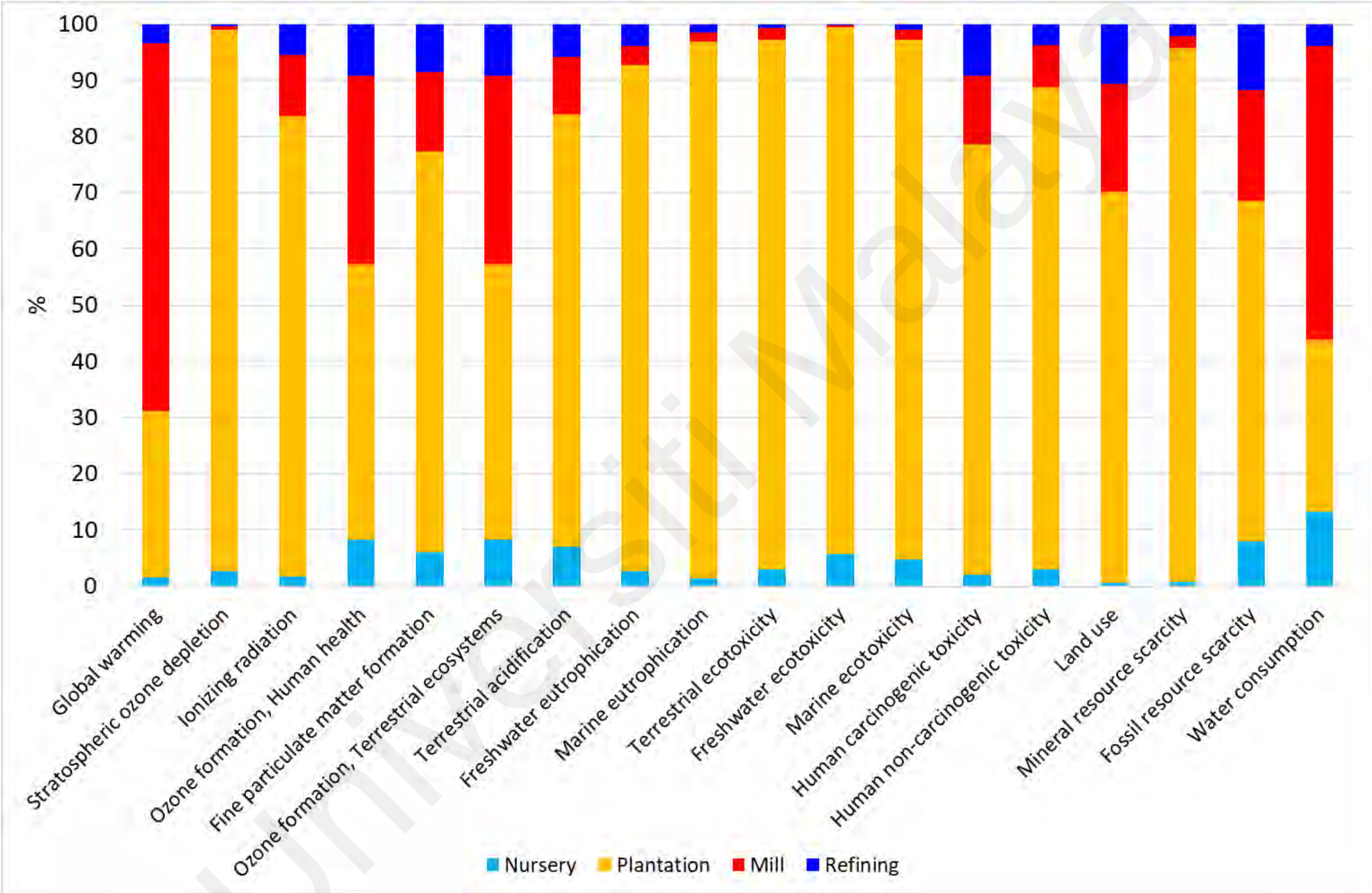


Figure 4.53: Cradle-to-gate characterised LCIA of palm oil refining according to subsystems

4.3.6 Cradle-to-Gate LCA of Palm Oil Fractionation

The cradle-to-gate characterised LCIA of palm oil fractionation at midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is shown in Figure 4.54. Environmental burden inherited from the upstream processes which is labelled as RBD palm oil is the dominant contributor to all impact categories evaluated. The activities in the fractionation plant are insignificant in this cradle-to-gate LCA with less than 5% contribution is observed for all 18 impact categories.

Further investigation on the environmental impacts based on subsystems is presented in Figure 4.55. Similar to the cradle-to-gate LCA for palm oil refining, the plantation subsystem is the most prominent subsystem to all impact categories evaluated except global warming and water consumption which are dominated by the palm oil mill subsystem. Besides, the palm oil mill subsystem is also important to the two impact categories on ozone formation (human health and terrestrial ecosystems).

The palm oil refineries subsystem has a marginal contribution to ozone formation (human health and terrestrial ecosystems), fine particulate matter formation and fossil resource scarcity impact categories. The consumption of petroleum diesel by the vehicles is in particular significant for the transportation of CPO from palm oil mills to refineries which contribute towards ozone formation impacts on both human health and terrestrial ecosystems.

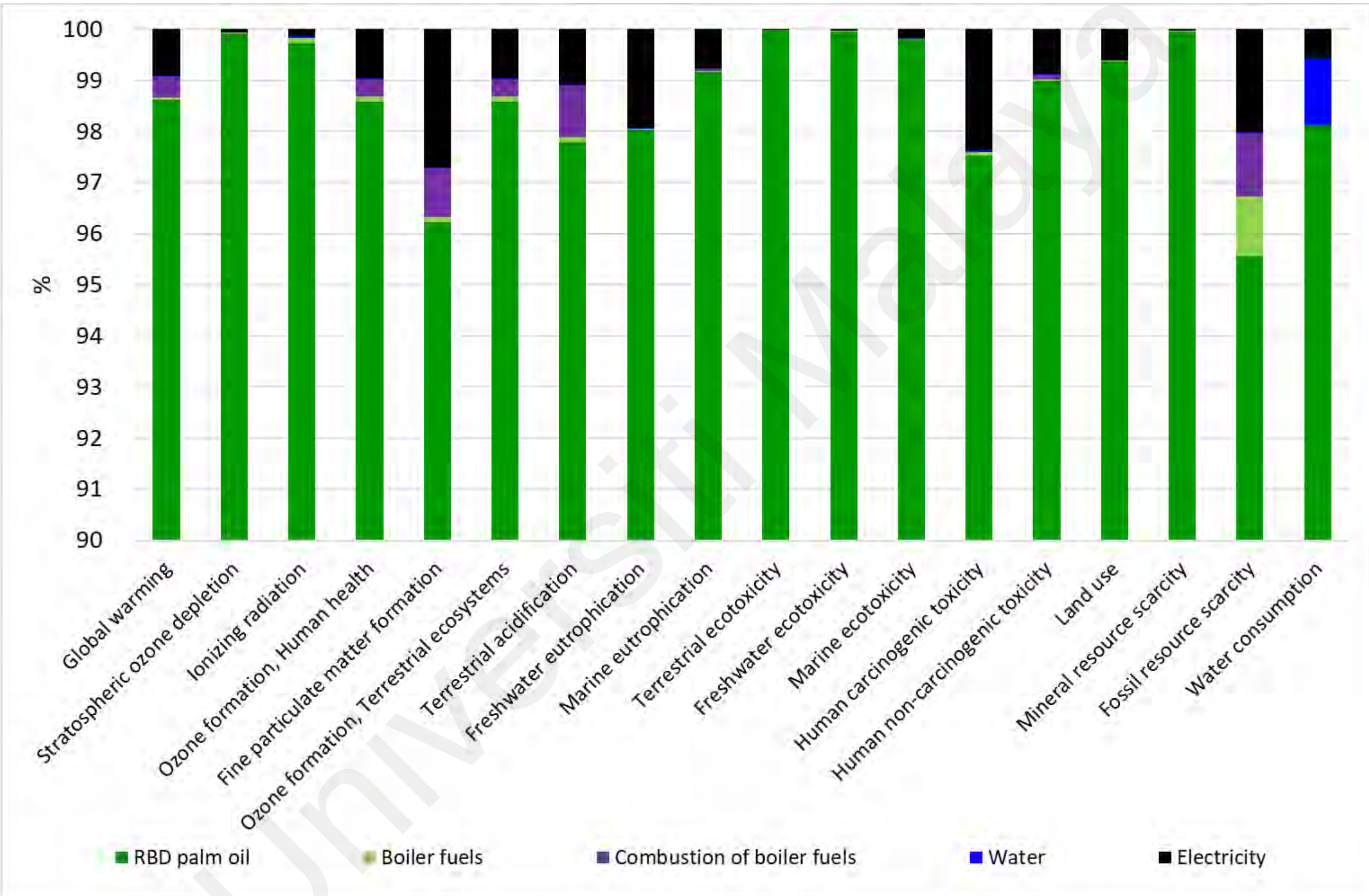


Figure 4.54: Cradle-to-gate characterised LCIA of palm oil fractionation

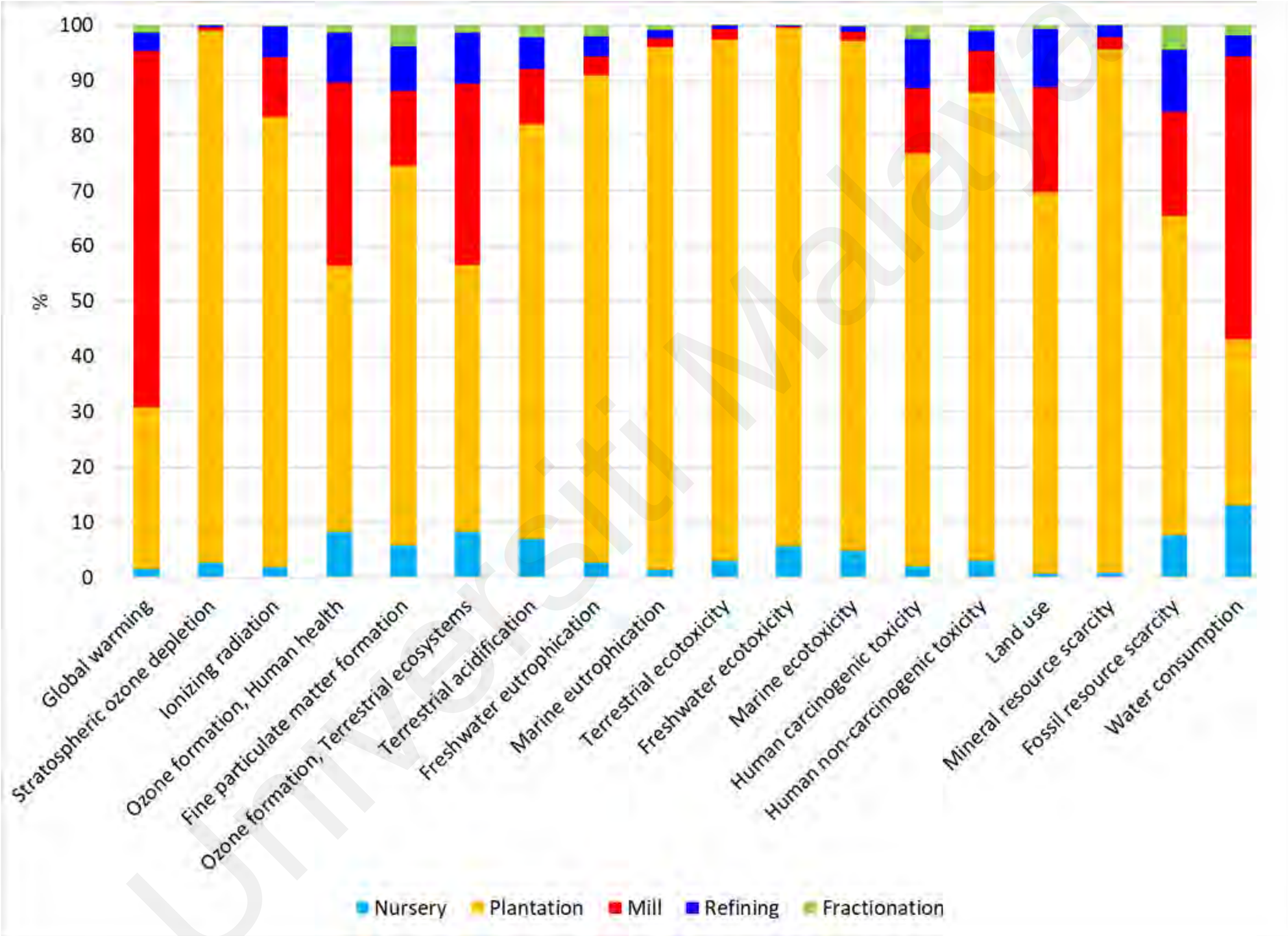


Figure 4.55: Cradle-to-gate characterised LCIA of palm oil fractionation according to subsystems

4.3.7 Cradle-to-Gate LCA of Palm Biodiesel Production

The cradle-to-gate characterised LCIA of palm biodiesel production at midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is shown in Figure 4.56. Feed oil used for biodiesel production in particular RBD palm oil is the main contributor to all impact categories evaluated. The environmental burdens are mostly carried over from the upstream subsystems. However, the activities in the biodiesel plant play a substantial contribution, in particular to the fossil resource scarcity impact category which is mainly due to the fossil methanol used for the transesterification process.

Further investigation on the environmental impacts based on subsystems is presented in Figure 4.57. Similar to palm oil refining and fractionation, the plantation subsystem is the most prominent subsystem to most of the impact categories evaluated. Global warming and water consumption are mainly due to the palm oil mill subsystem. The palm oil mill subsystem is also important to the ozone formation for both impacts on human health and terrestrial ecosystems. Palm oil refining and fractionation subsystems play an insignificant impact with a total contribution of less than 10% in all the impact categories evaluated. Biodiesel subsystem is important in fossil resource scarcity, ionising radiation and fine particulate matter formation. More than 20% of the contribution in these three impact categories are due to activities in the biodiesel subsystem.

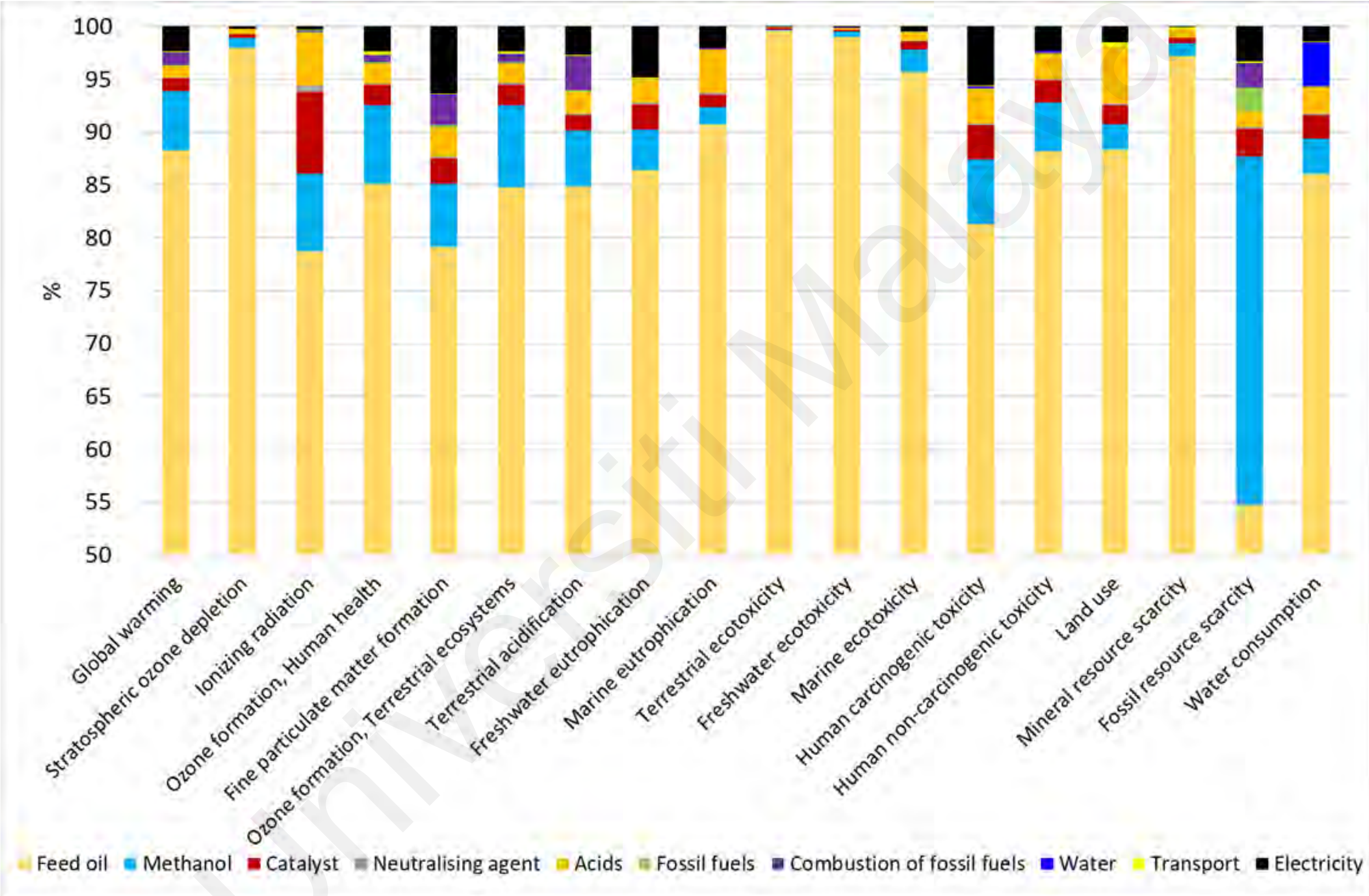


Figure 4.56: Cradle-to-gate characterised LCIA of palm biodiesel production

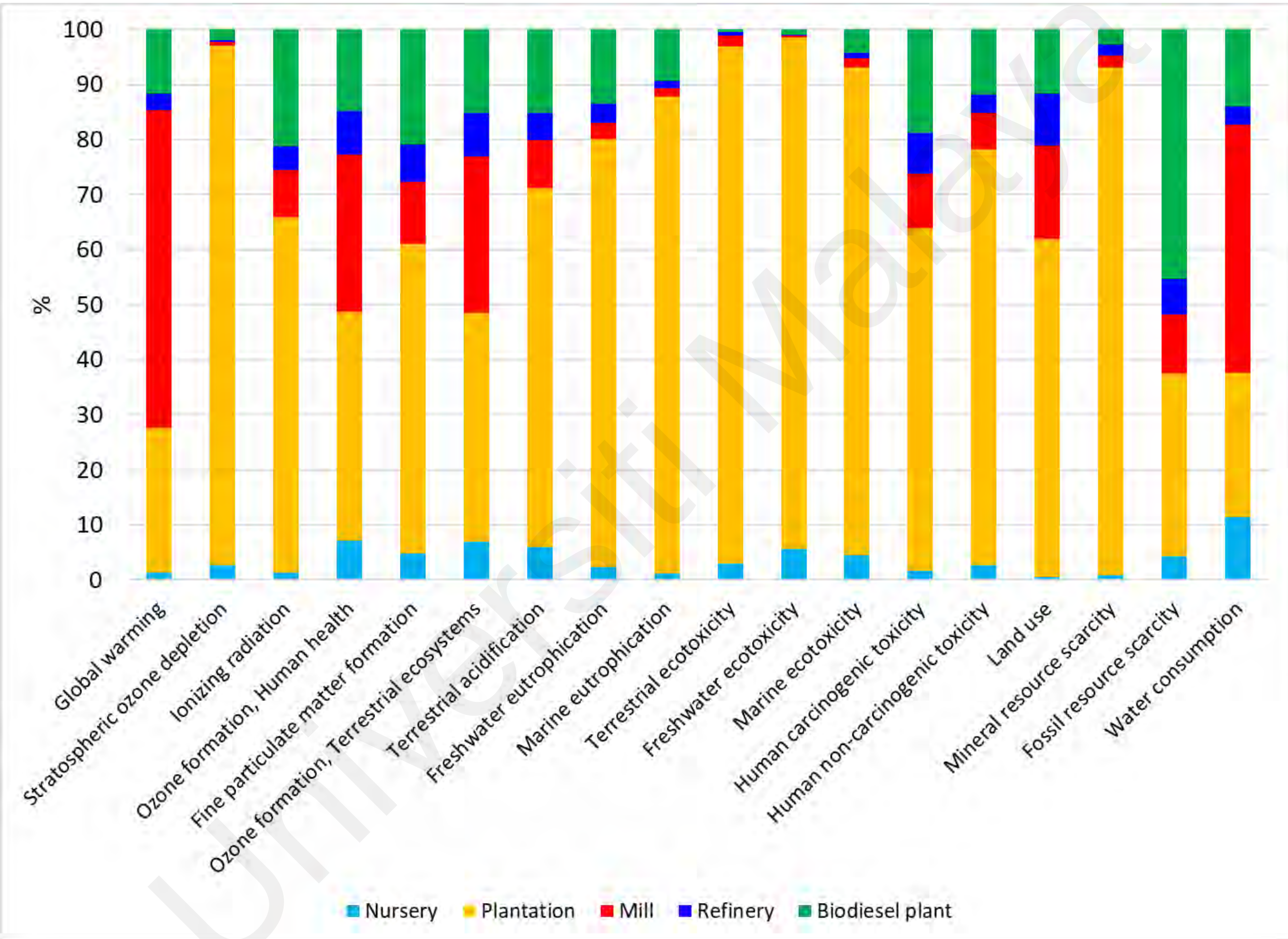


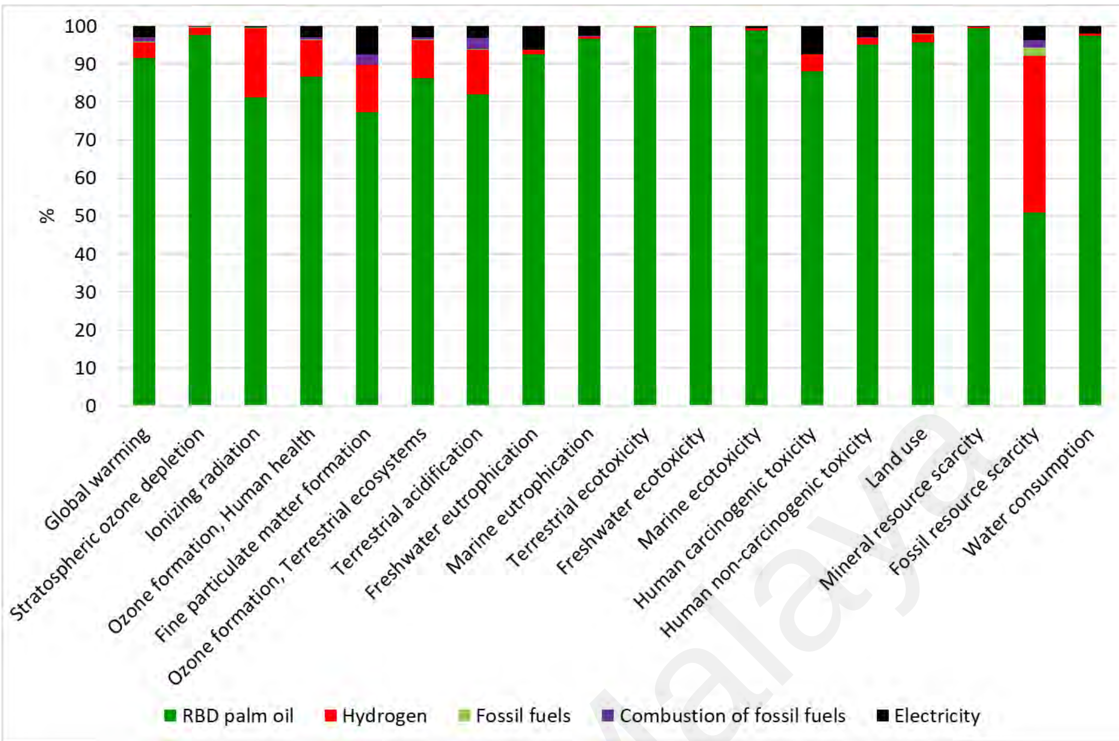
Figure 4.57: Cradle-to-gate characterised LCIA of palm biodiesel production according to subsystems

4.3.8 Cradle-to-Gate LCA of Hydroprocessed Palm Biofuels Production

The cradle-to-gate characterised LCIA of the palm-based HRD and HRJ production at midpoint level according to ReCiPe 2016 methodology (Hierarchist perspective) is shown in Figure 4.58 and Figure 4.59. Feed oil used for the hydroprocessed palm biofuels production i.e. RBD palm oil in Figure 4.58(a) and Figure 4.59(a) and PFAD in Figure 4.58(b) and Figure 4.59(b), is the main contributor to all impact categories evaluated. Similar to biodiesel production, the environmental burdens are mostly inherited from the upstream subsystems. Nevertheless, the activities in the hydroprocessing plant also play a substantial contribution, in particular to the fossil resource scarcity impact category which is mainly due to the hydrogen used.

Further investigation on the environmental impacts based on subsystems are presented in Figure 4.60 and Figure 4.61. Again, similar to the results reported for the production of palm biodiesel in Figure 4.57, the plantation subsystem is the most prominent subsystem to most of the impact categories evaluated. Global warming and water consumption are mainly due to the palm oil mill subsystem. The palm oil mill subsystem is also important to the ozone formation for both impacts on human health and terrestrial ecosystems. Again, the contribution from palm oil refining is not significant. The Hydroprocessing subsystem is important in impact categories of fossil resource scarcity, ionising radiation, fine particulate matter formation and terrestrial acidification.

(a)



(b)

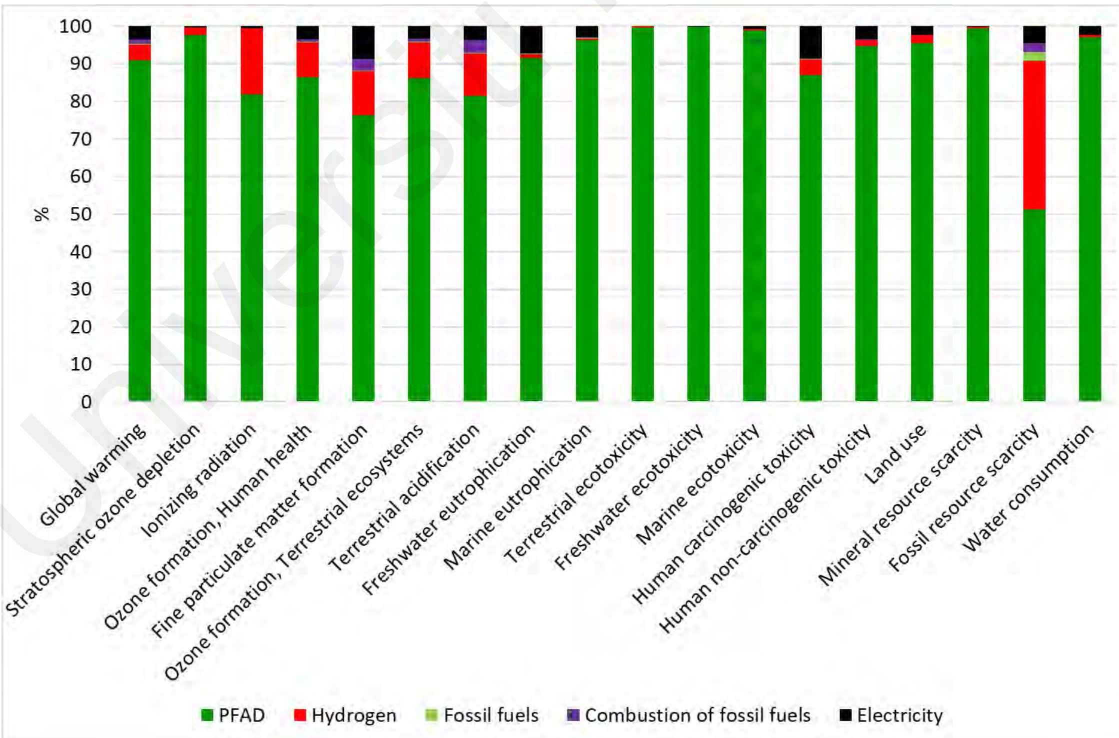
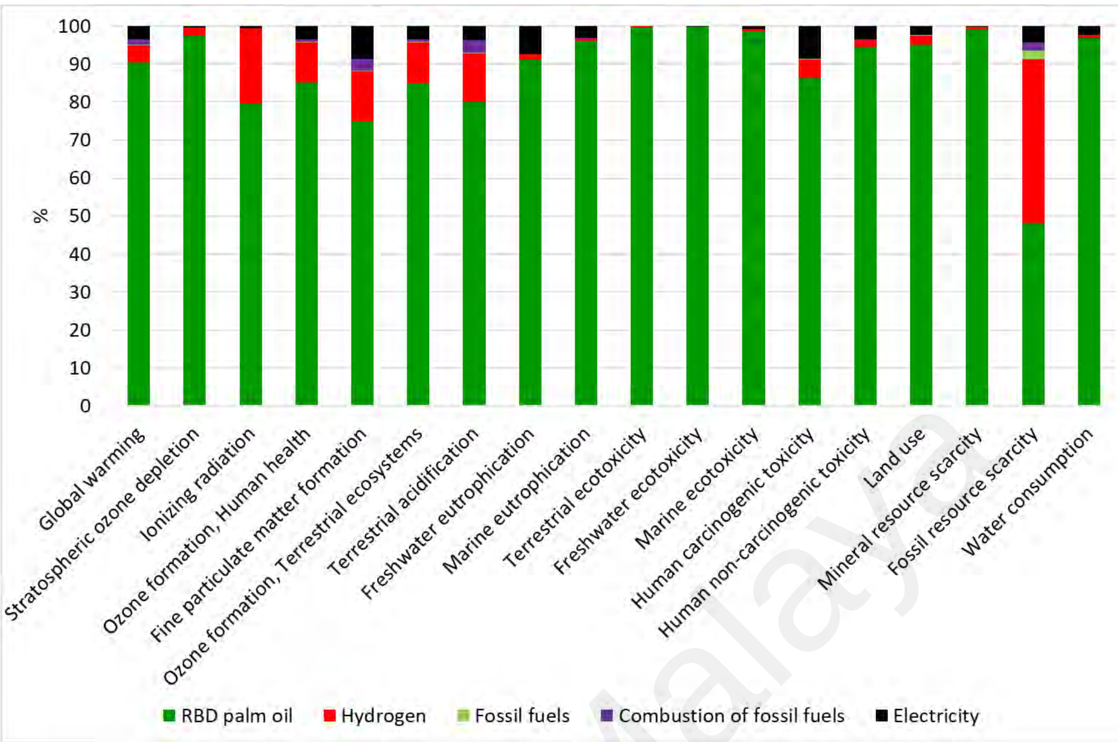


Figure 4.58: Cradle-to-gate characterised LCIA of HRD production from (a) RBD palm oil and (b) PFAD

(a)



(b)

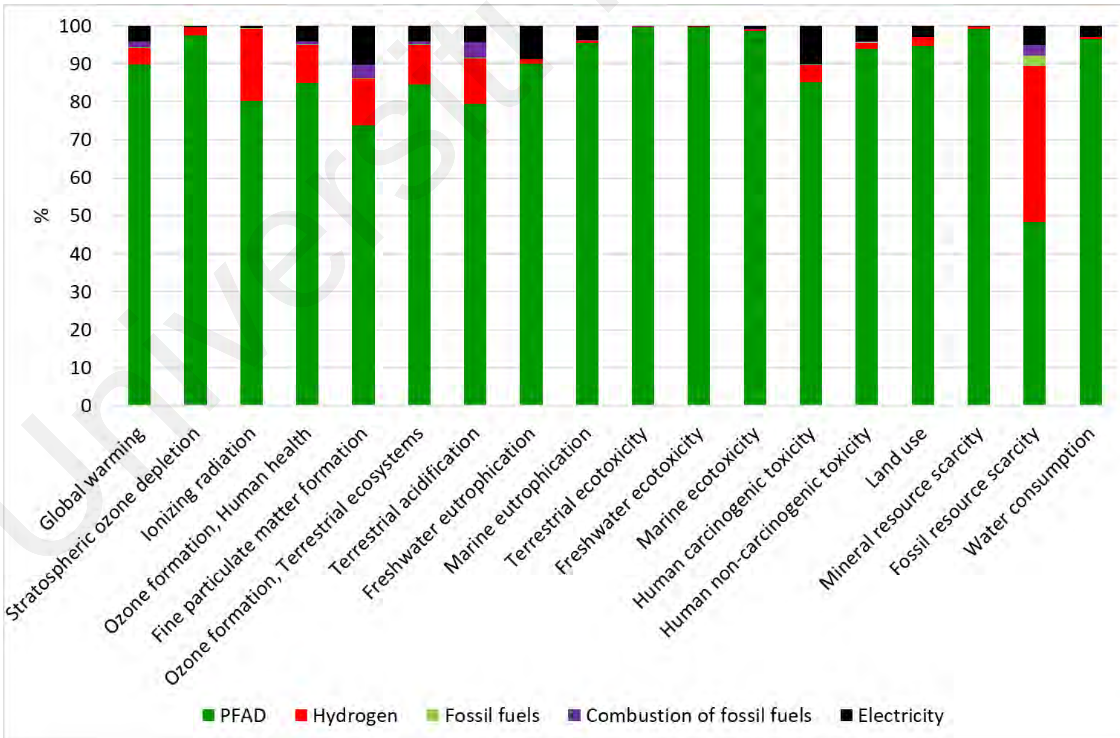
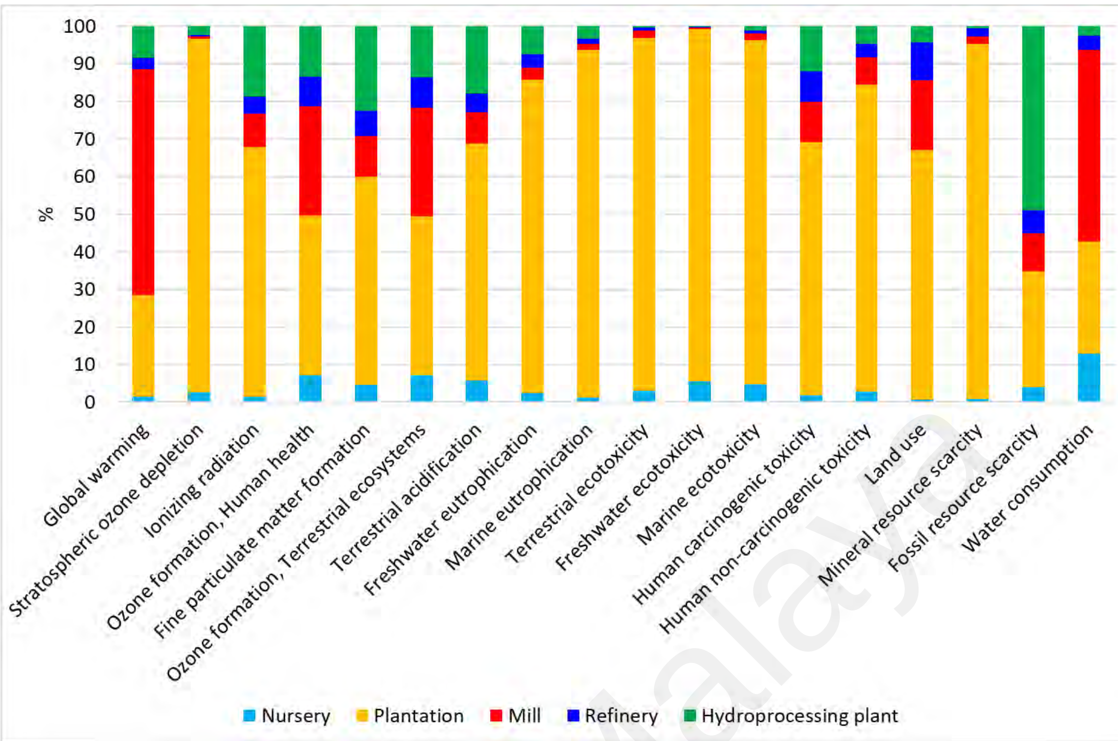


Figure 4.59: Cradle-to-gate characterised LCIA of HRJ production from (a) RBD palm oil and (b) PFAD

(a)



(b)

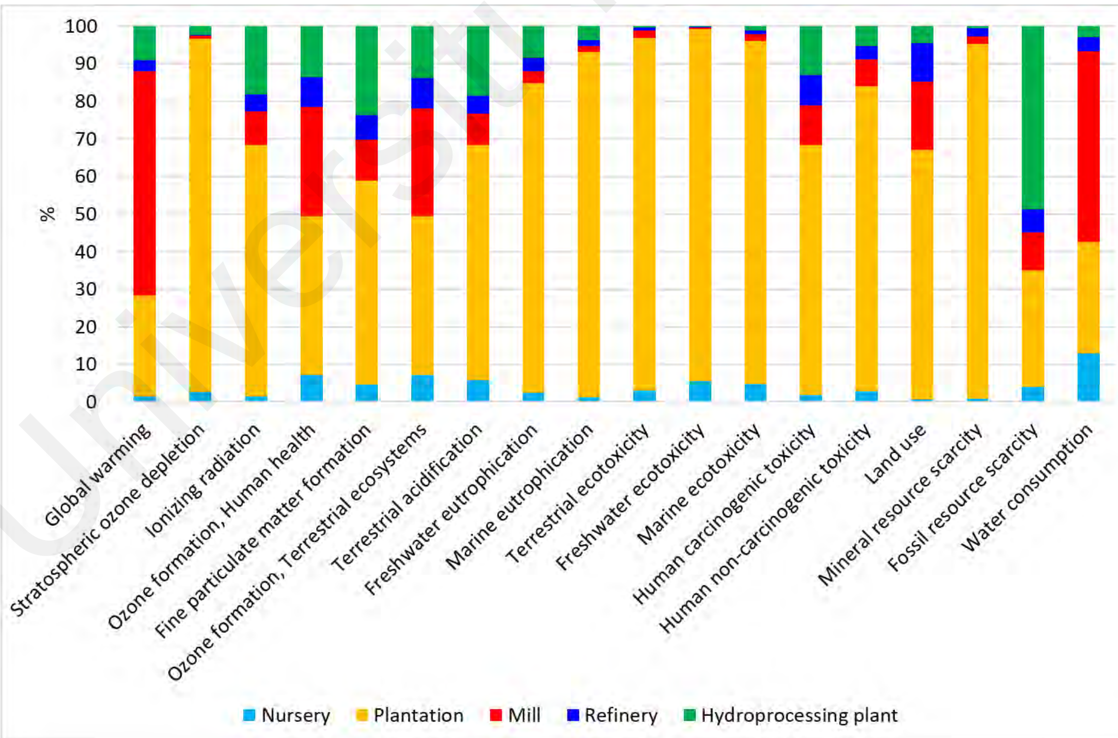
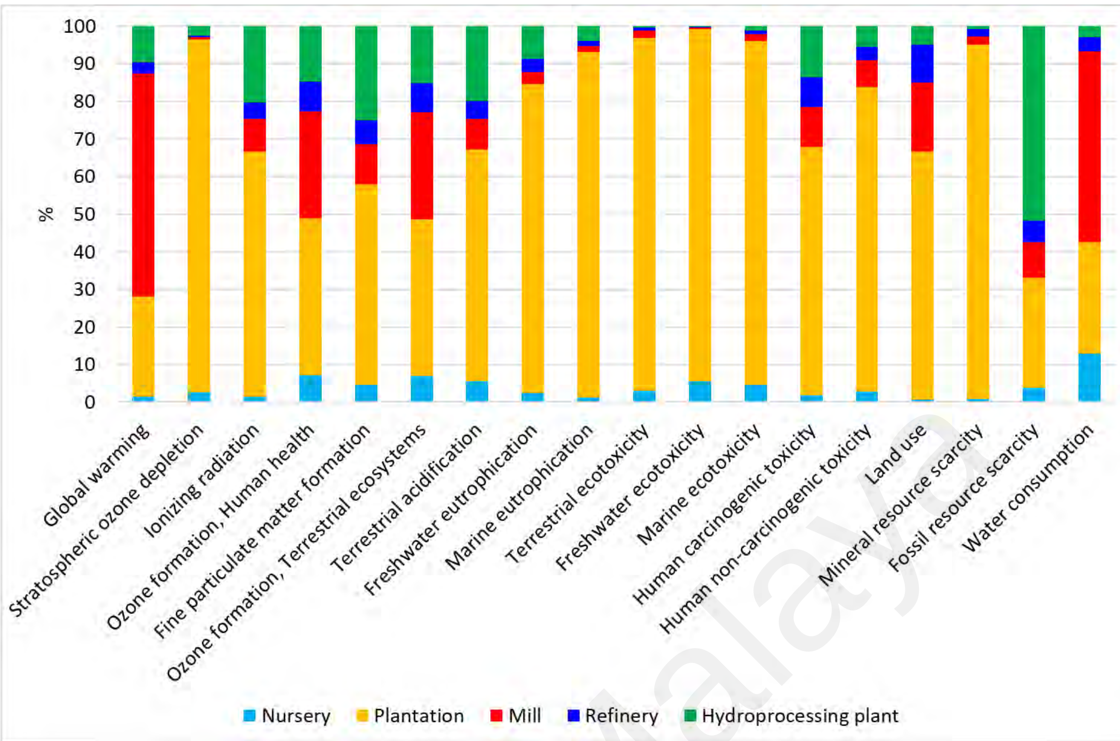


Figure 4.60: Cradle-to-gate characterised LCIA of HRD production from (a) RBD palm oil and (b) PFAD, according to subsystems

(a)



(b)

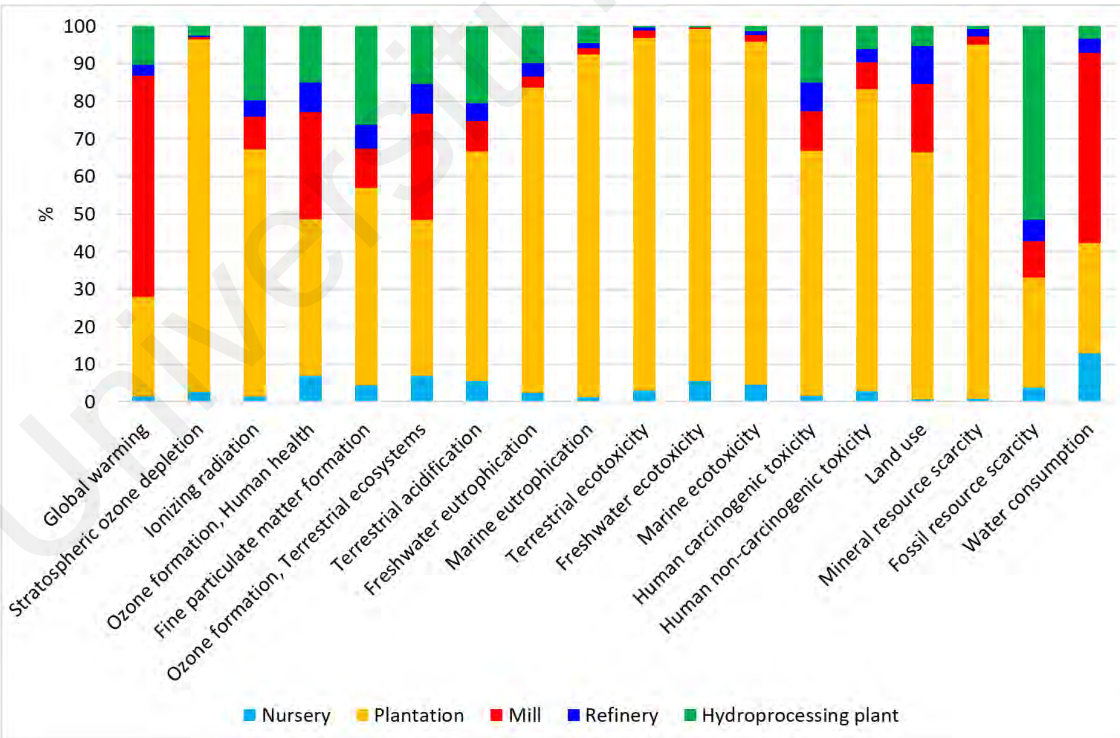


Figure 4.61: Cradle-to-gate characterised LCIA of HRJ production from (a) RBD palm oil and (b) PFAD, according to subsystems

4.3.9 Comparison of Cradle-to-Gate LCA

In this section, the cradle-to-gate LCA for the production of refined and fractionated palm products, palm biodiesel and hydroprocessed palm biofuels i.e. HRD and HRJ are compared. The comparison is carried out based on the absolute value of the global warming impact category which is expressed in kg CO_2 eq per tonne of products produced, the functional unit of refining, fractionation, biodiesel and hydroprocessed biofuels production.

As shown in Figure 4.62, the global warming potential for the production of one tonne of RBD palm oil in Malaysia is 1199.02 kg CO_2 eq while 1005.76 kg CO_2 eq is reported for the same amount of PFAD produced as a co-product, based on economic allocation in the refining stage. For the fractionated products, 1231.51 kg CO_2 eq and 1152.71 kg CO_2 eq are recorded respectively for the production of one tonne of RBD palm olein and one tonne of RBD palm stearin, based on economic allocation in the fractionation stage.

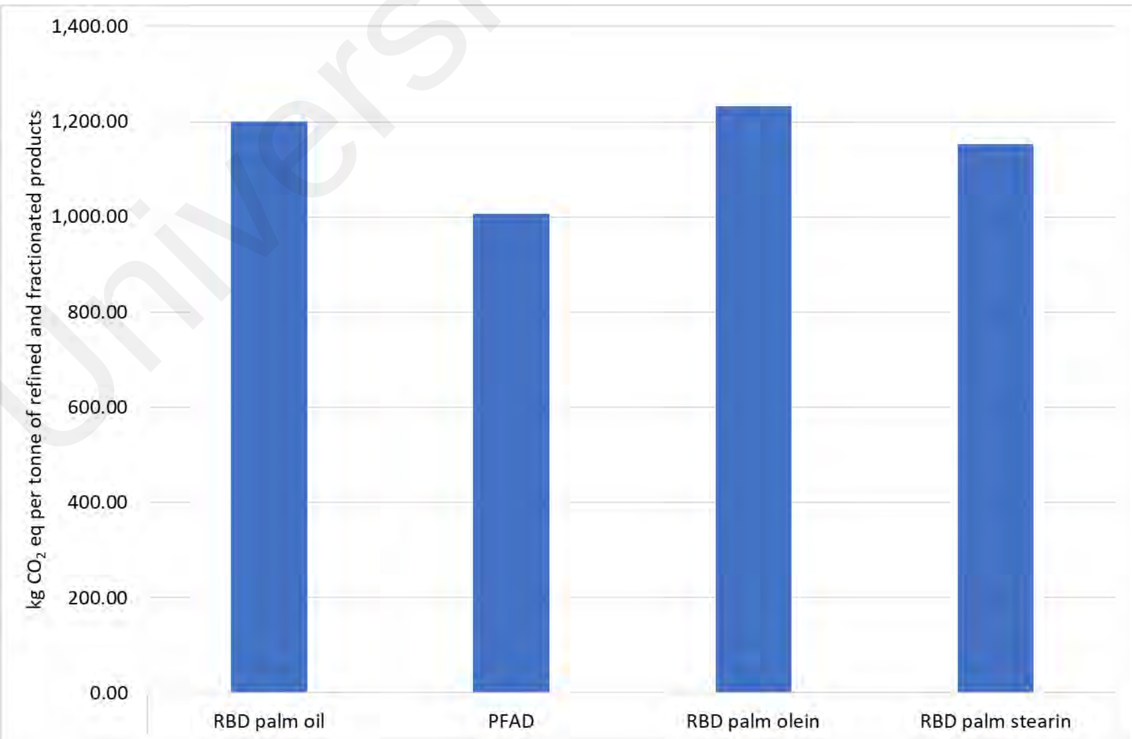


Figure 4.62: Global warming potential for the production of 1 tonne refined and fractionated palm products (cradle-to-gate)

For the production of palm biofuels i.e. palm biodiesel, HRD and HRJ, the global warming impact are shown in Figure 4.63. For the production of one tonne of palm biodiesel in Malaysia which is mostly derived from RBD palm oil (Table 4.5), the global warming potential anticipated is 1302.78 kg CO_2 eq.

Similar to the gate-to-gate LCA, higher environmental impacts are observed for the production of HRJ when compared with HRD simply due to higher hydrogen and energy requirements for the isomerisation process mentioned earlier. However, the difference is not significant in the cradle-to-gate LCA, <5%. This is because most of the environmental impacts of the cradle-to-gate LCA are contributed by the upstream processes as shown previously in Figures 4.60 dan 4.61.

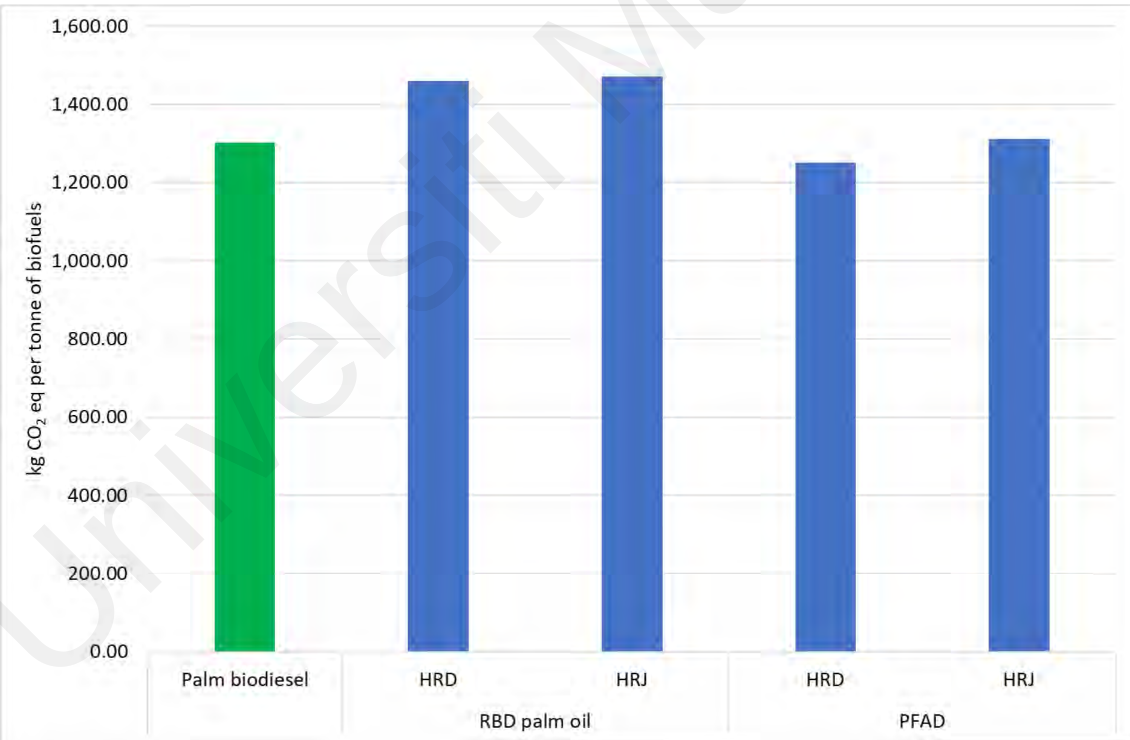


Figure 4.63: Global warming potential for the production of 1 tonne of palm biofuels (cradle-to-gate)

Compared to palm biodiesel, hydroprocessed biofuels (HRD and HRJ) produced from RBD palm oil possess a higher global warming impact per mass unit (tonne) of biofuels produced. While comparable global warming impact per tonne of palm biodiesel and HRD or HRJ from PFAD is observed. This is mainly due to the lower global warming potential of PFAD compared to RBD palm oil (Figure 4.62) based on the economic allocation procedure in the refining subsystem.

Comparison of biofuels (biodiesel, HRD and HRJ) in terms of energy content based on the LHV is also carried out since palm biodiesel, HRD and HRJ are energy products. Different ranking of global warming potential is observed. Results presented in Figure 4.64 show that the global warming potential of palm biodiesel is the highest due to the reason that palm biodiesel possesses lower LHV compared to HRD or HRJ (Table 4.18).

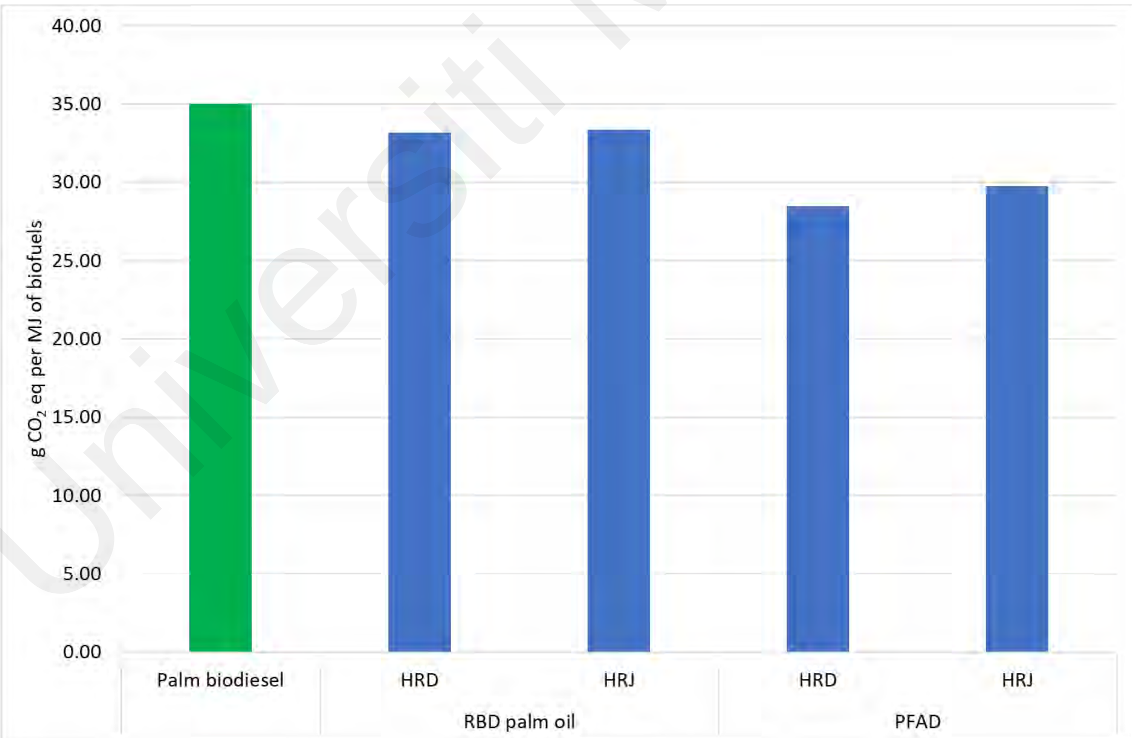


Figure 4.64: Global warming potential for the production of 1 MJ of palm biofuels (cradle-to-gate)

Table 4.18: Lower heating values of palm biodiesel, HRD and HRJ

	Unit	Palm biodiesel	HRD	HRJ
Lower heating value	MJ/kg	37.21	43.98	44.08

4.3.10 Cradle-to-Grave LCA for Palm-based Biofuels

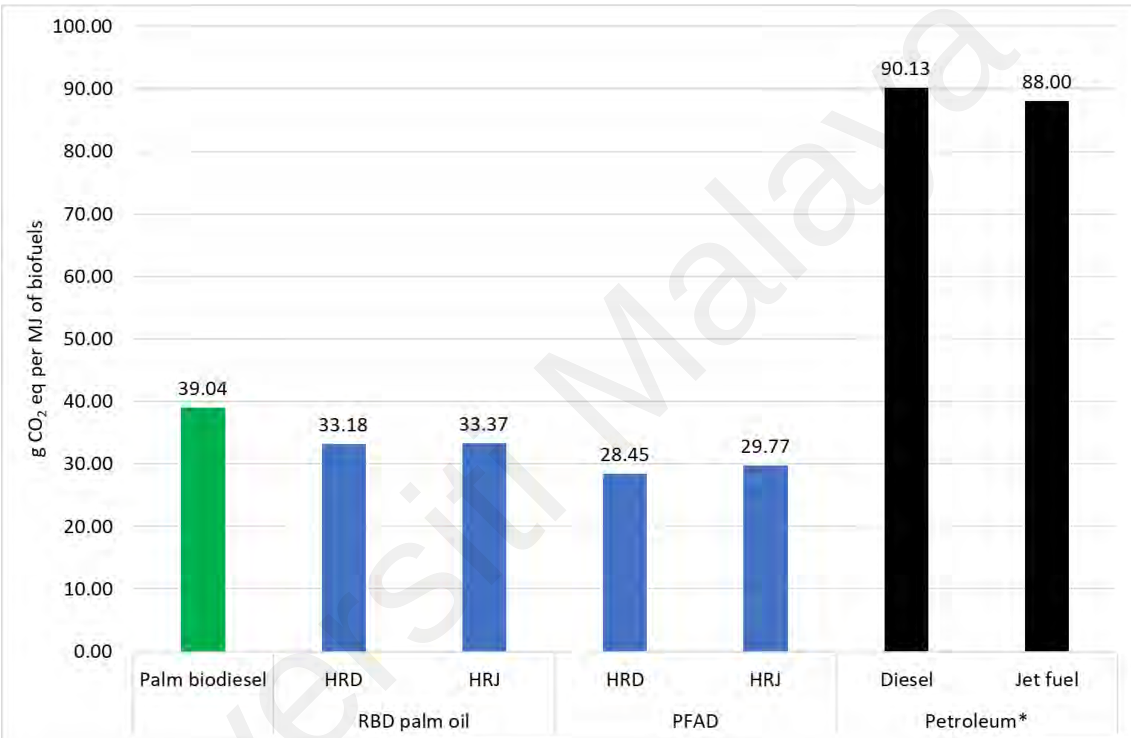
In this section, the cradle-to-grave LCA for the production of palm biodiesel and hydroprocessed palm biofuels i.e. HRD and HRJ are compared against petroleum-based diesel and jet fuel. Again, the comparison is carried out for the global warming impact category which is expressed in g CO_2 eq per MJ of the fuels.

Combustion of fuels releases carbon dioxides into the atmosphere. However, there is a distinct difference between fossil fuels and biofuels. Combustion of fossil fuels emits carbon which has been stored underground for millions of years but combustion of biofuels merely emits carbon which is part of the existing biogenic carbon cycle. In other words, the combustion of biofuels simply returns the carbon that was absorbed during plant growth and it does not increase the total amount of carbon in the atmosphere.

However, because the methanol used for the production of biodiesel is derived from fossil-based natural gas, hence the combustion of biodiesel is not carbon neutral. 4.02 g fossil CO_2 is emitted for the combustion of one MJ of palm biodiesel. This value is calculated from the volume of methanol consumed for the palm biodiesel production in Table 4.5 based on the formula shown in Fan et al. (2013).

In total, GHG emissions of 39.04 g CO_2 eq/MJ is recorded for the cradle-to-grave global warming impact and this value represent 57% GHG savings from petroleum diesel (Figure 4.65). This value is slightly higher than the value reported by Choo et al. (2011) which neglected the fossil CO_2 emissions contributed by the fossil-based methanol.

In general, the savings on GHG emissions for the hydroprocessed palm biofuels are greater than palm biodiesel mainly due to the higher LHV of the hydroprocessed biofuels compared with biodiesel shown in Table 4.18. HRD produced from PFAD has the lowest GHG emissions because less environmental burden is assigned to PFAD in the refining subsystem due to its lower commercial value coupled with less energy and hydrogen requirement in the hydroprocessing subsystem mentioned earlier.



Note: *Skone and Gerdes, 2008

Figure 4.65: Global warming potential for 1 MJ of palm biofuels (cradle-to-grave)

4.4 Completeness Check

As elaborated in the ISO 14044, the objective of a completeness check is to ensure that all the relevant information and data needed for the interpretation of the LCA are available and complete (ISO, 2006b).

In the present study, the system boundaries and data needed for gate-to-gate and cradle-to-gate LCA of various palm subsystems have been comprehensively described in Chapter 3. Data collection, the source of the inventory data and its quality are also presented in detail in sections 3.3.4 and 3.3.5. In summary, all relevant data and information used are sufficient for the current LCA to derive credible and reliable results and conclusions, satisfied the goal and the scope of the present study.

4.5 Sensitivity Check

A sensitivity check is performed with the objective to assess the reliability of the LCA results by uncertainties in inventory data, allocation methods or calculation of category indicator results (ISO, 2006b). The following analyses have been conducted to address the issue of data uncertainty and also at the same time to evaluate the LCA results of scenarios proposed for possible environmental improvement.

4.5.1 Sensitivity Analysis on Allocation Procedures

4.5.1.1 Palm Oil Refining and Fractionation

Evaluation on the impacts of different allocation procedures, i.e. allocation based on economic value, energy content and mass value, is conducted and compared with no allocation. For the no allocation scenario, all the environmental burden (100%) in the refining process is attributed to RBD palm oil and no burden is assigned to the co-product PFAD. Hence, the total impact per tonne of RBD palm oil produced is the highest compared to the other allocation procedures (Figure 4.66).

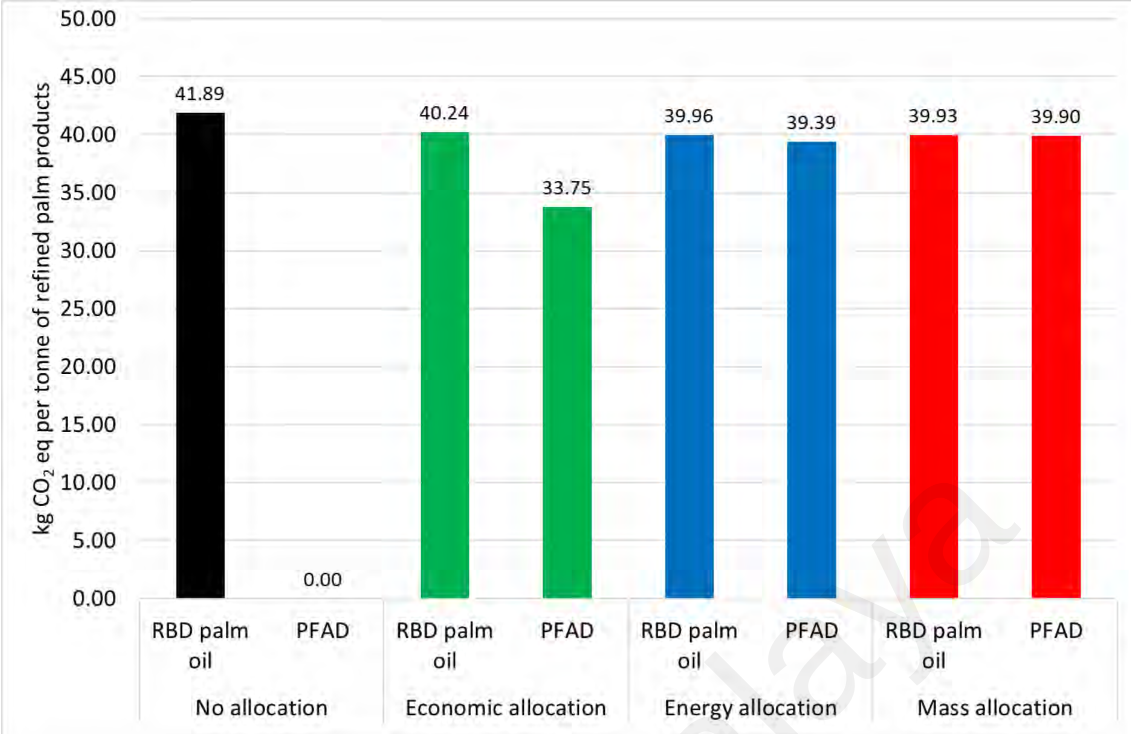


Figure 4.66: Global warming impact per tonne of RBD palm oil and PFAD produced, comparison of different allocation procedures for gate-to-gate LCA

Consideration should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems (ISO, 2006a). RBD palm oil is the main product of the refining process. It comprised 95.33% of total product output measured in mass (Table 4.6). PFAD is the co-product that comprised 4.67% of the total output volume. When allocation based on mass is chosen as the allocation procedure, the environmental burden is distributed evenly between RBD palm oil and PFAD according to their mass percentages. This resulted in the same environmental burden per mass unit of RBD palm oil and PFAD, as shown by the red bars in Figure 4.66. This allocation procedure is the most straightforward and the easiest since all the refined palm products are recorded based on mass value as the industry practice. However, the appropriateness of such a procedure can be challenged when there is a significant difference between the main product and co-products. For the current case, RBD palm oil and PFAD differ in terms of quality, applications and commercial values. Hence, allocation based on mass may not be a suitable procedure taken into consideration of the aforementioned differences and the fairness of allocation.

Being the main product of the refining process, RBD palm oil is always traded at a higher price compared to PFAD in the commercial market. PFAD was traded at a 16% discount to RBD palm oil based on the 10-years average prices (Table 4.7). Allocation percentages of 96.05% to RBD palm oil and 3.95% to PFAD are derived (Table 4.8). Although a higher environmental load is attributed to RBD palm oil due to its higher commercial value, an insignificant increase in the environmental burden per mass unit of RBD palm oil is observed. This is because of the high product output volume (measured in mass) of the RBD palm oil. However, this is not the case for the production of PFAD. Significant lower environmental impacts (15%) is observed for PFAD with allocation based on economic value compared to that based on mass because of its lower commercial value coupled with the relatively smaller production volume.

Allocation based on energy content resulted in an insignificant difference between the allocation based on energy content and mass value for both RBD palm oil and PFAD. This is mainly because of the similar calorific values for both products (Table 4.9).

Unlike the refining stage, different allocation procedures in the fractionation stage show a less significant variation (Figure 4.67). Less than 5% difference is observed among the allocation procedures. Similar to palm oil refining, allocation based on mass resulted in the same environmental burden per mass unit of the products i.e. RBD palm olein and RBD palm stearin. Allocation based on energy content resulted in a similar environmental burden with allocation based on mass due to the similar energy content of both products (Table 4.13). Again, allocation based on economic values assigns a higher environmental burden to the higher value RBD palm olein. The environmental burden per unit mass of RBD palm olein produced is approximately 6% higher than that of RBD palm stearin, in line with the minor difference between the commercial values of both RBD palm olein and RBD palm stearin shown in Table 4.11.

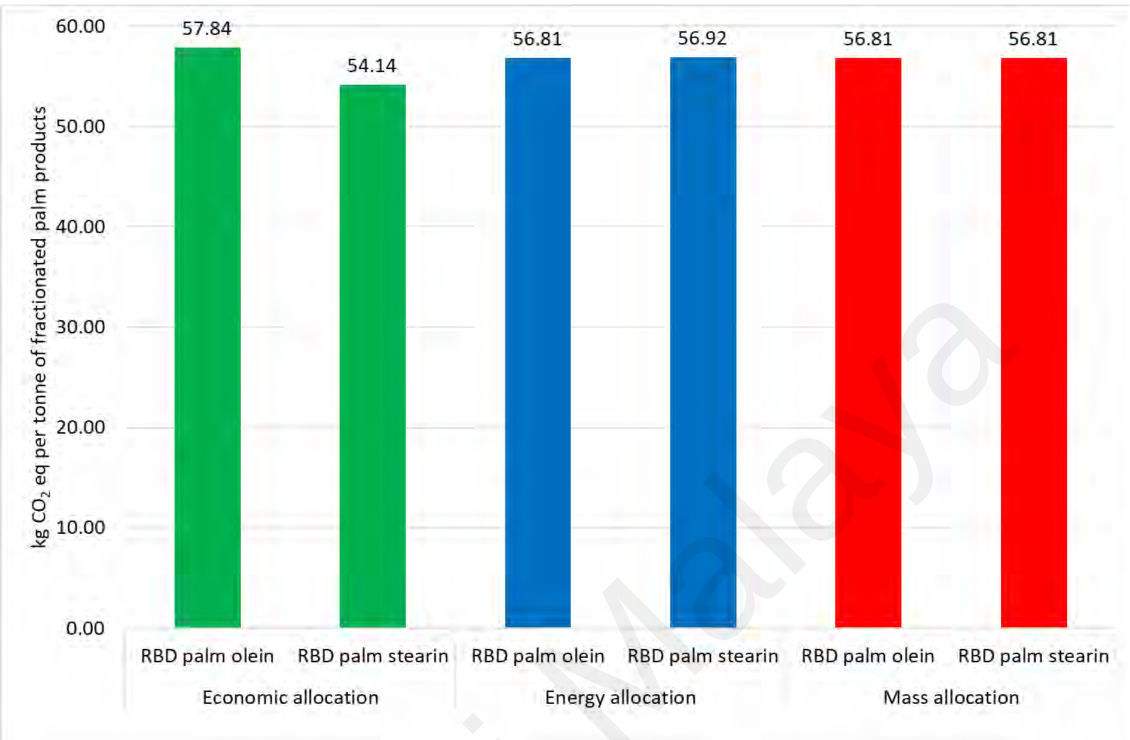


Figure 4.67: Global warming impact per tonne of RBD palm olein and RBD palm stearin produced, comparison of different allocation procedures for gate-to-gate LCA

4.5.1.2 Palm Biodiesel Production

Palm biodiesel and crude glycerol are the main product and co-product of biodiesel plants. Based on the inventory data collected for the 3-years operation of six commercial biodiesel plants, 88.70% of the total products measured by mass is palm biodiesel and the remaining 11.30% is crude glycerol. As presented in section 4.2, the economic allocation ratio of 96.82:3.18 is derived from the average 10-year prices, while the energy allocation ratio of 94.43:5.57 is deduced from the energy contents of palm biodiesel and crude glycerol.

Evaluation on different allocation methods, *i.e.* allocation based on economic value, energy content and mass value to that of no allocation is conducted. All the environmental burden is assigned to palm biodiesel only for the no allocation approach, represented by the black bar (Figure 4.68). This allocation procedure is viable and justifiable if the crude glycerol produced is treated as waste with no commercial value. The environmental impacts attributed to palm biodiesel is reduced by 11% for mass allocation compared to no allocation. As mentioned previously, allocation based on mass value is straightforward and can be easily performed based on the systematic record of the biodiesel plants. Again, such an allocation approach may not be appropriate. The same environmental burden per mass unit of both palm biodiesel and crude glycerol are derived, as shown by the red bars (Figure 4.68).

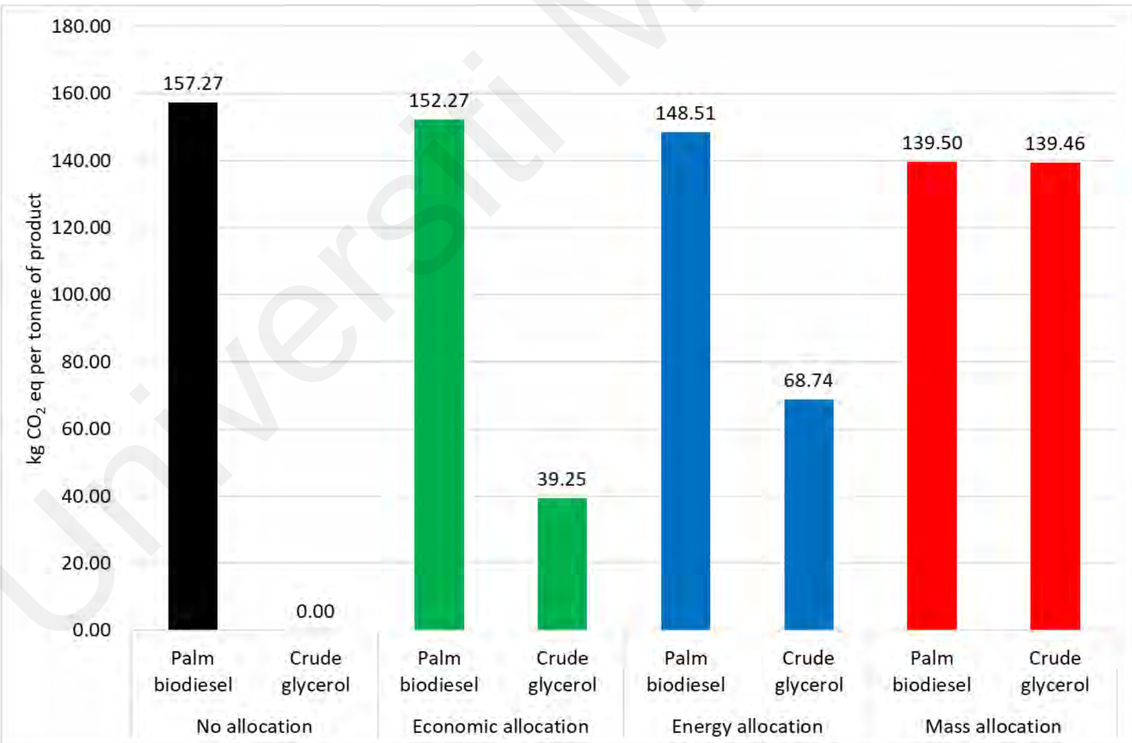


Figure 4.68: Global warming impact per tonne of palm biodiesel and crude glycerol produced, comparison of different allocation procedures for gate-to-gate LCA

It is known in the industry that these two products are different in terms of their economic (commercial) values and energy contents. It might be more appropriate to assign the environmental burden based on other allocation procedures i.e. economic allocation and energy allocation. As such, 3.18% and 5.57% of the overall environmental burden are allocated to the 127 kg of crude glycerol produced according to economic allocation and energy allocation procedures (Table 4.16 & 4.17). Based on the economic value, the environmental burden for the production of one tonne of palm biodiesel is about four times higher than that for one tonne of crude glycerol. If crude glycerol was assumed to be used as an energy source *e.g.* as a fuel for boiler or industrial burner, its environmental burden will be slightly less than half that of one tonne of palm biodiesel when allocation based on energy content is used.

4.5.1.3 Hydroprocessed Palm Biofuels Production

There is no obvious difference between the mass allocation and the energy allocation for the production of hydroprocessed biofuels i.e. HRD and HRJ. The products and co-product of the hydroprocessing are hydrocarbon products typically use as energy sources. The products and co-products are having similar energy content measured in LHV. However, there is a significant difference in the economic values of the products and co-products. HRJ or also known as sustainable aviation fuel (SAF) is traded at 1.6 times higher than HRD in the commercial market at present days. While HRD is about 3-4 times higher than other co-products e.g. propane and naphtha. Hence, a much higher environmental burden is assigned to HRJ and HRD when the economic allocation procedure is practised.

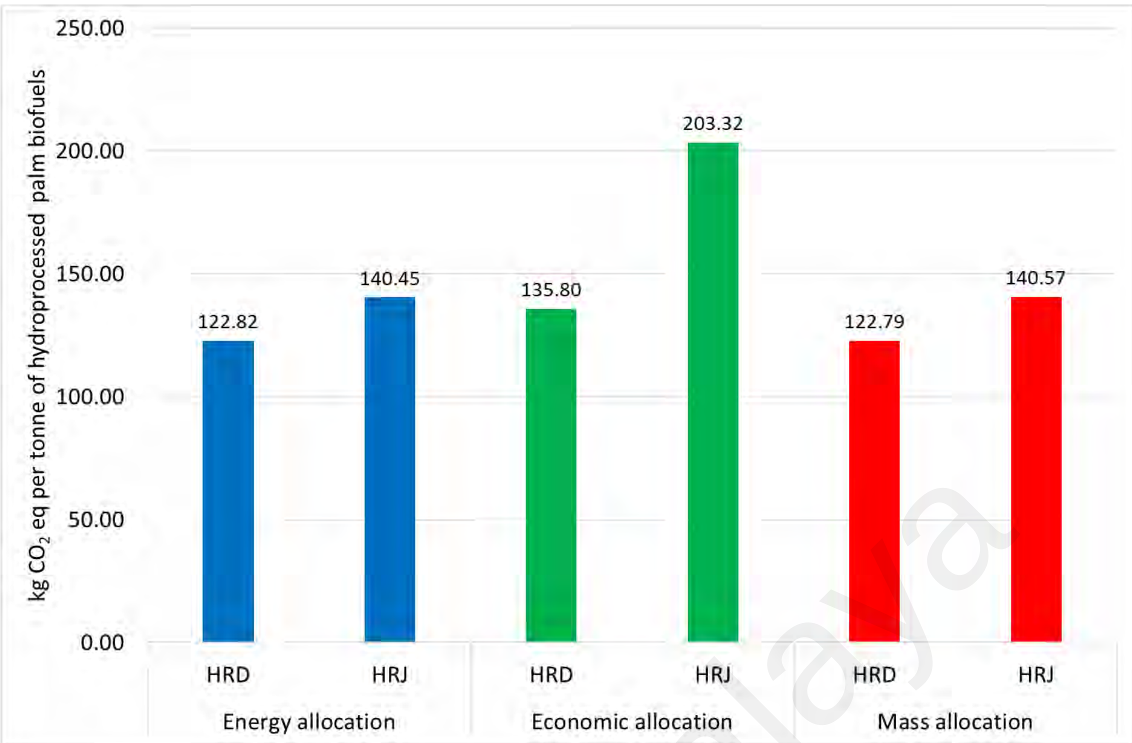


Figure 4.69: Global warming impact per tonne of HRD and HRJ produced, comparison of different allocation procedures for gate-to-gate LCA

4.5.2 Sensitivity Analysis on Prices Movement

The variation of environmental impacts by different allocation procedures has been presented in the previous section. Allocation based on economic value has been identified to be a suitable choice for refined and fractionated palm products and palm biodiesel. However, there are concerns on the limitation of the economic allocation procedure i.e. the instability or volatility of market prices and non-disclosure contracts and prices of the products. Hence, it is critical to conduct a sensitivity analysis on the effect of prices movement to the allocated environmental impacts.

Regarding the confidentiality of contracts and prices, the average prices of all types of Malaysian refined palm oil, palm olein and palm stearin are consistently gathered from the commercial market and published by MPOB in the public domain. Hence, there is no issue with the availability of the prices to perform the economic allocation procedure.

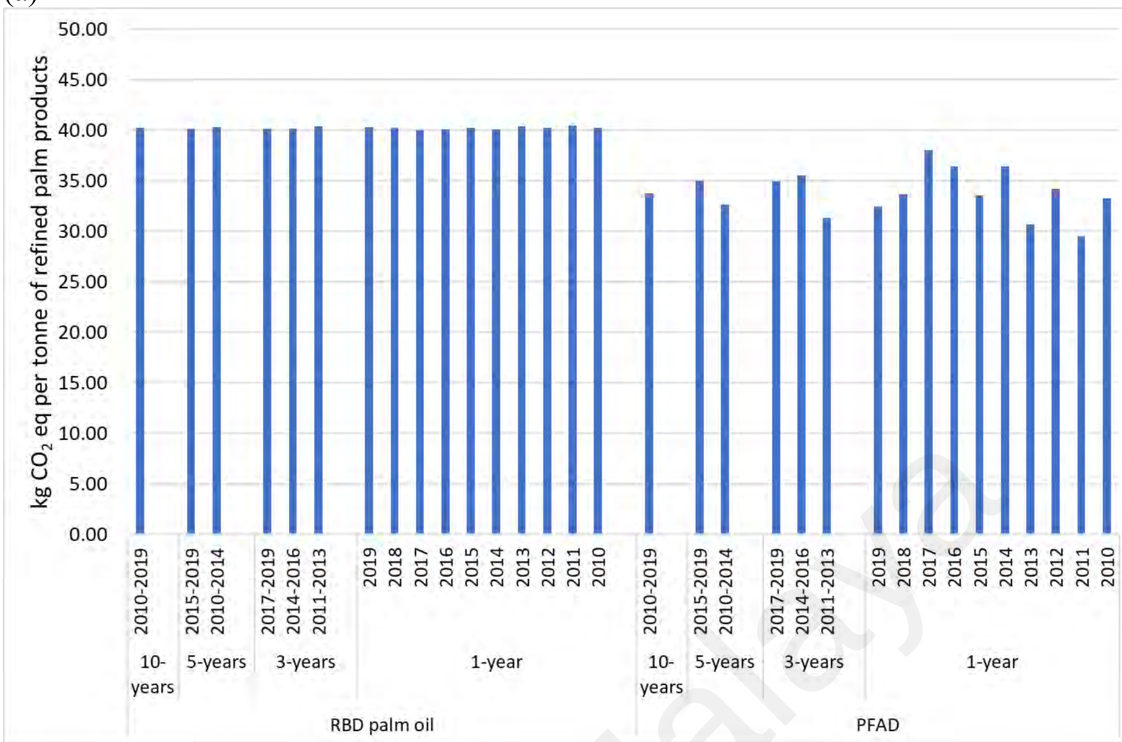
However, prices for palm biodiesel and crude glycerol are thus far not available in the public domain for free. Subscription fees are needed to track the prices in commercial web domains e.g. Thomson Reuters, Argus Media, ICIS etc.

Concerning prices volatility, the average prices for 1-year, 3-year and 5-years are used to generate the allocation ratios between RBD palm oil and PFAD. The results of the environmental impact based on these allocation ratios are compared with the results obtained from the average 10-years prices shown earlier. Results presented in Figure 4.70 show insignificant variation in the environmental impacts i.e. global warming potential per tonne of RBD palm oil produced. Minor variations of 5% to 8% are observed for PFAD, as shown in Figure 4.70(b).

Similar analyses are performed for the palm fractionated products i.e. RBD palm olein and RBD palm stearin. Results in Figure 4.71 show a minimal variation (<3%) in the environmental impacts i.e. global warming potential per tonne of RBD palm olein and RBD palm stearin produced, respectively.

For palm biodiesel production, results in Figure 4.72 show a very minimal variation in the environmental impacts per tonne of palm biodiesel produced, less than 1%. Similar to the refining stage, obvious variations are observed for the co-products, the crude glycerol in the biodiesel subsystem. The variations are greater when 1-year and 3-years prices were used to derive the allocation percentages. This is mainly due to the high volatility of the prices of both palm biodiesel and crude glycerol and also their price difference as shown in Table 4.15.

(a)



(b)

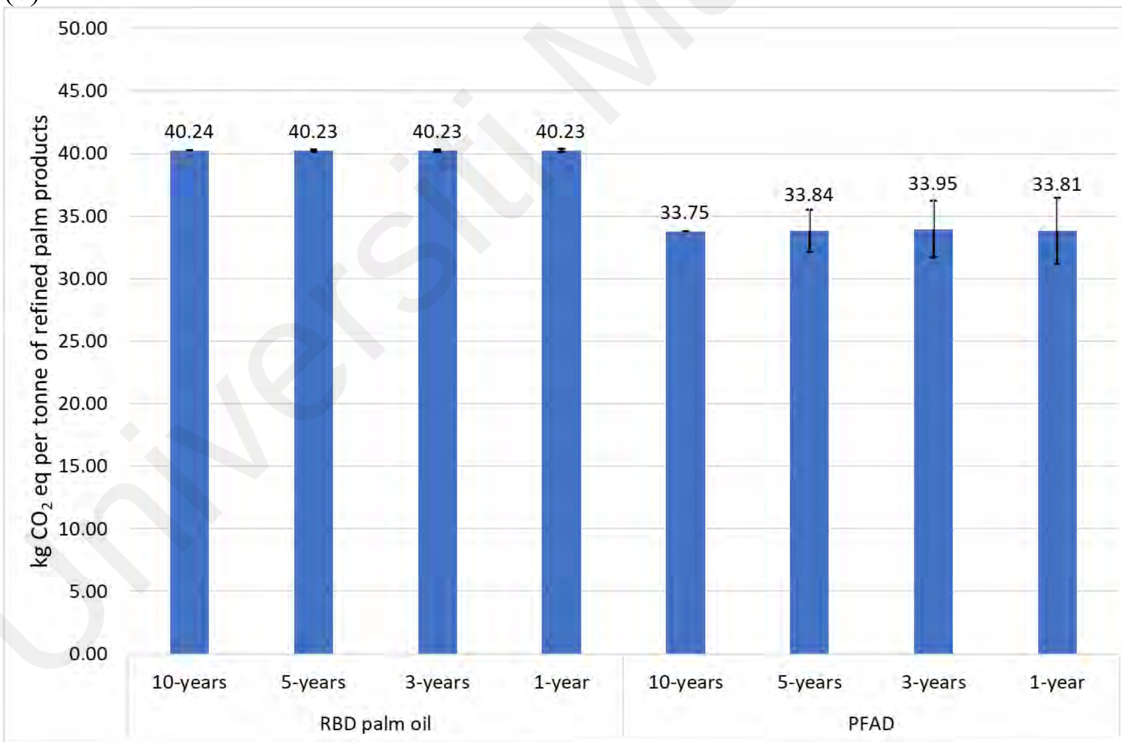
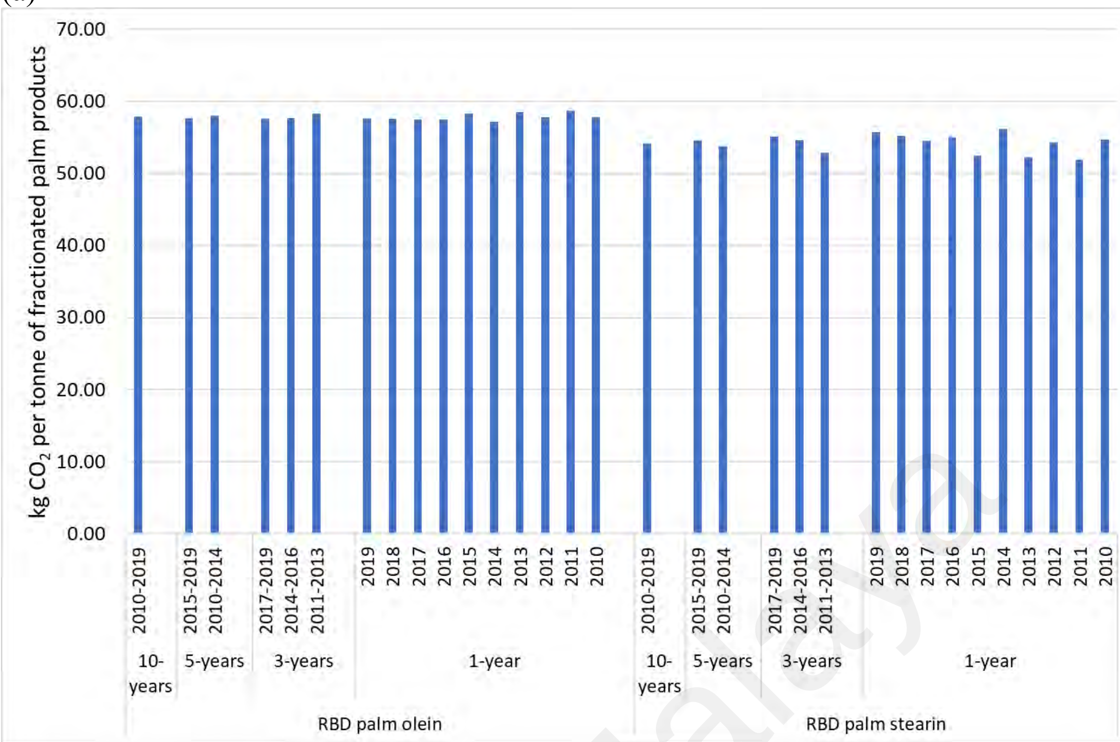


Figure 4.70: The effects of prices movement on the allocated global warming impact per tonne of RBD palm oil and PFAD produced for gate-to-gate LCA

(a)



(b)

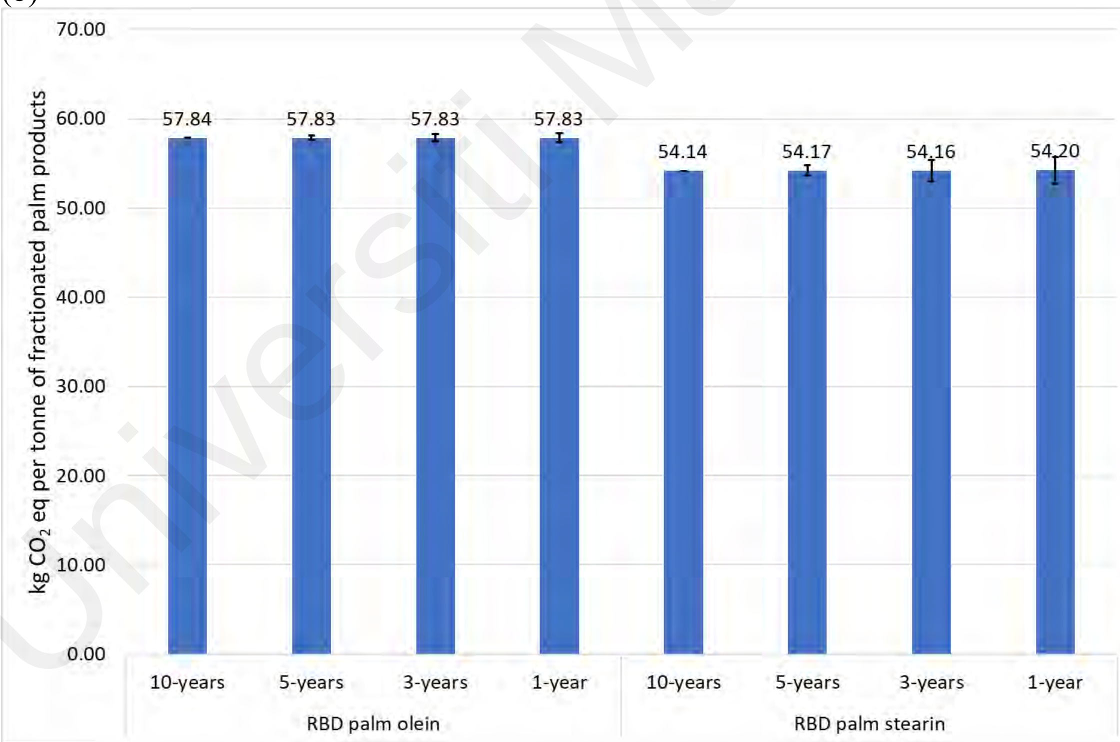


Figure 4.71: The effects of prices movement on the allocated global warming impact per tonne of RBD palm olein and RBD palm stearin produced for gate-to-gate LCA

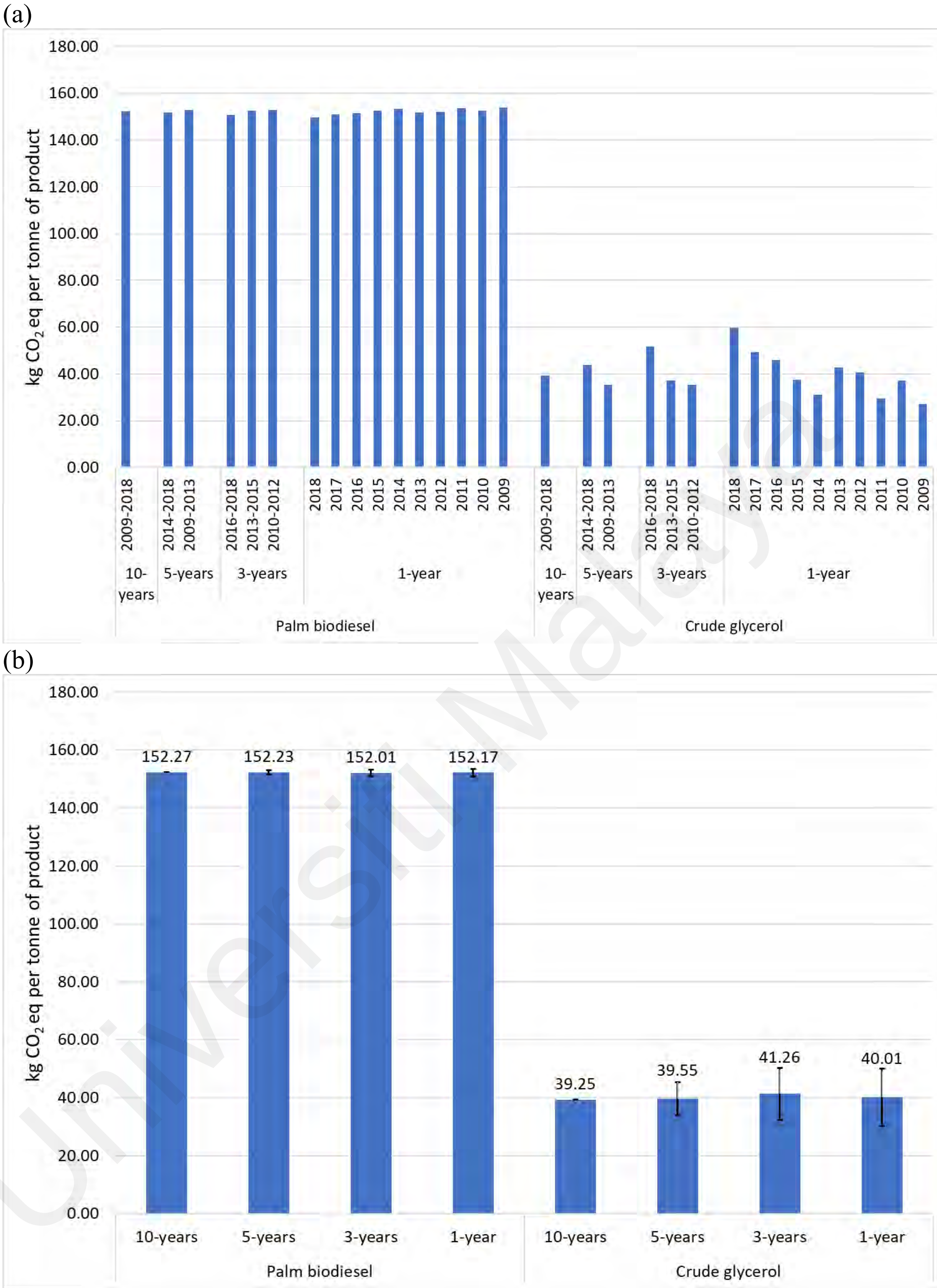


Figure 4.72: The effects of prices movement on the allocated global warming impact per tonne of palm biodiesel and crude glycerol produced for gate-to-gate LCA

4.5.3 Sensitivity Analysis on Wastewater Treatment

4.5.3.1 Palm Oil Refining

Choo et al. (2011) reported that wastewater played a substantial role in 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 is evaluated based on the 5-years wastewater data supplied by the refineries that participated in the current study and background data on wastewater treatment available in the Ecoinvent 3.6 database. The impact of wastewater treatment was found to be insignificant to most of the midpoint impact categories evaluated using the ReCiPe 2016 methodology except the eutrophication impact categories (Figure 4.73). Higher impacts on both freshwater eutrophication and marine eutrophication are observed. This may be due to the chemicals used in the wastewater treatment process. The result concurred with the findings reported by Schneider and Finkbeiner (2013).

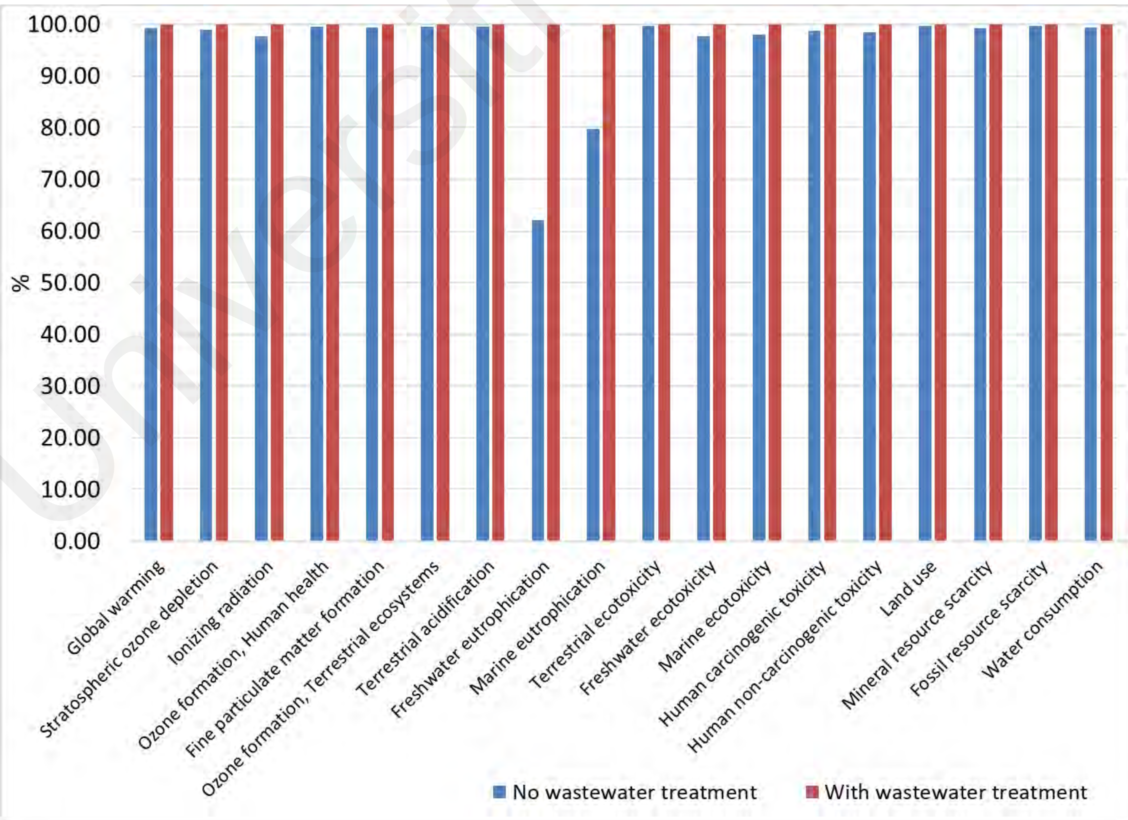


Figure 4.73: The effects of wastewater treatment on the impact assessment of gate-to-gate LCA of palm oil refining

4.5.3.2 Palm Biodiesel Production

The effect of wastewater treatment is evaluated based on the 3-years of wastewater data supplied by the biodiesel producers who participated in the current study and background data on wastewater treatment available in the Ecoinvent 3.6 database. The impact of wastewater treatment was found to be insignificant to most of the midpoint impact categories evaluated using the ReCiPe 2016 methodology (Figure 4.74). However, a higher impact on marine eutrophication is observed when wastewater treatment is considered. This may be attributed to the chemicals used in the wastewater treatment process. A 10% saving of water consumption is anticipated for the scenario with wastewater treatment, possibly due to the credits of the treated water.

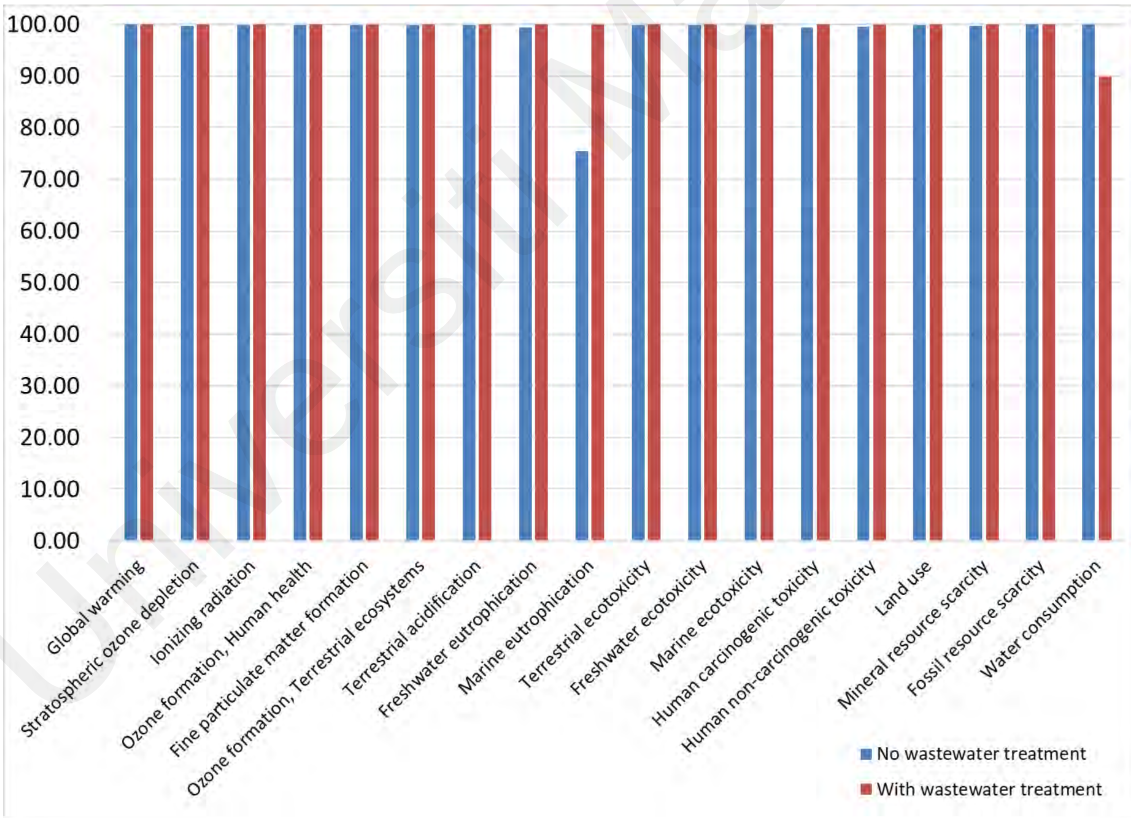


Figure 4.74: The effects of wastewater treatment on the impact assessment of gate-to-gate LCA of palm biodiesel production

4.5.4 Sensitivity Analysis on CPO Transportation

In the refinery stage, the transportation of CPO from palm oil mills to refineries is identified as one of the major hotspots to the potential environmental impacts evaluated. For example, 40% of the total GHG emissions are contributed by transportation (Figure 4.4). To reduce the impact of transportation, two areas of improvement are proposed and evaluated.

The first approach is the sourcing of CPO from nearby palm oil mills. Based on the inventory data obtained, the average distance between palm oil mills and refineries is 172 km, 43% higher than the 120 km reported previously by Tan et al. (2010). The shorter the distance, the lower the fuel consumption by the transportation trucks and ultimately contributed to lower environmental impacts. Based on the simulated scenarios, significant reductions of 9% and 30% on ozone formation potential are recorded for both impacts on human health and terrestrial ecosystems, when the transportation distance is reduced to 150 km and 100 km (Figure 4.75). For the same distances of 150 km, mild reduction of 4% to 6% are observed for six impact categories namely global warming, stratospheric ozone depletion, ionising radiation, fine particulate matter formation, terrestrial acidification and fossil resource scarcity (Figures 4.76-4.81). Reduction of the environmental impacts for these six impact categories is in the range of 14% to 20% if the distance is shortened to 100 km.

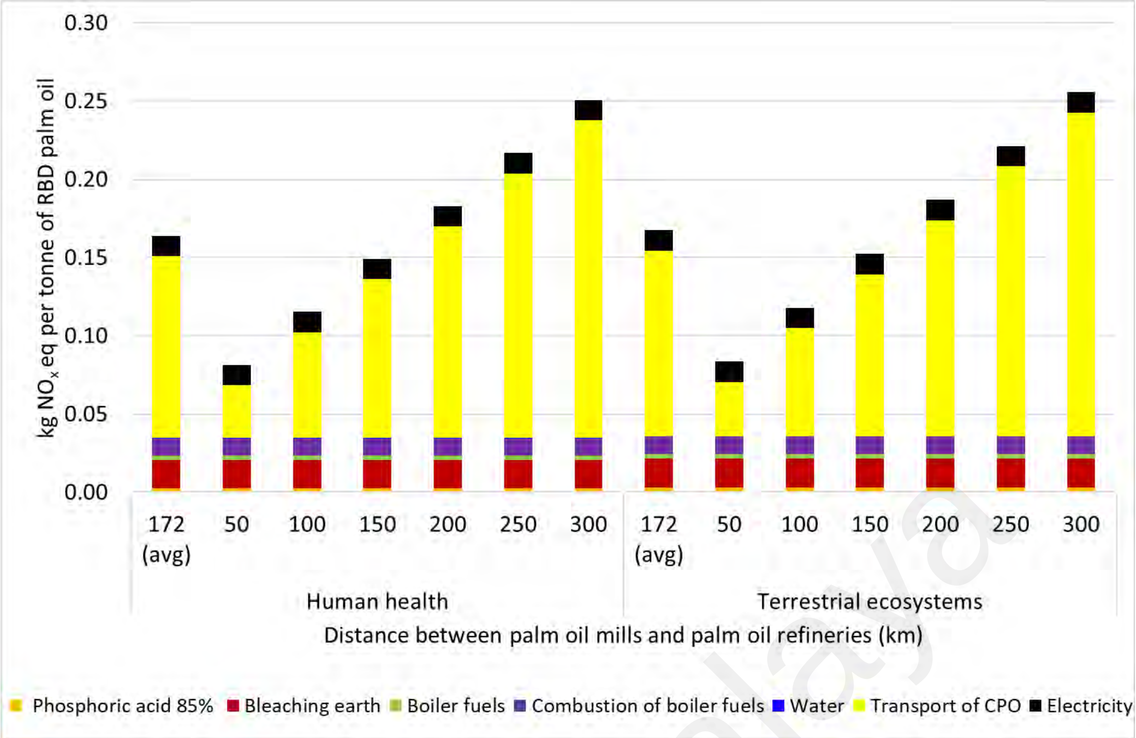


Figure 4.75: The effects of CPO transportation distance on ozone formation potential for gate-to-gate LCA of palm oil refining

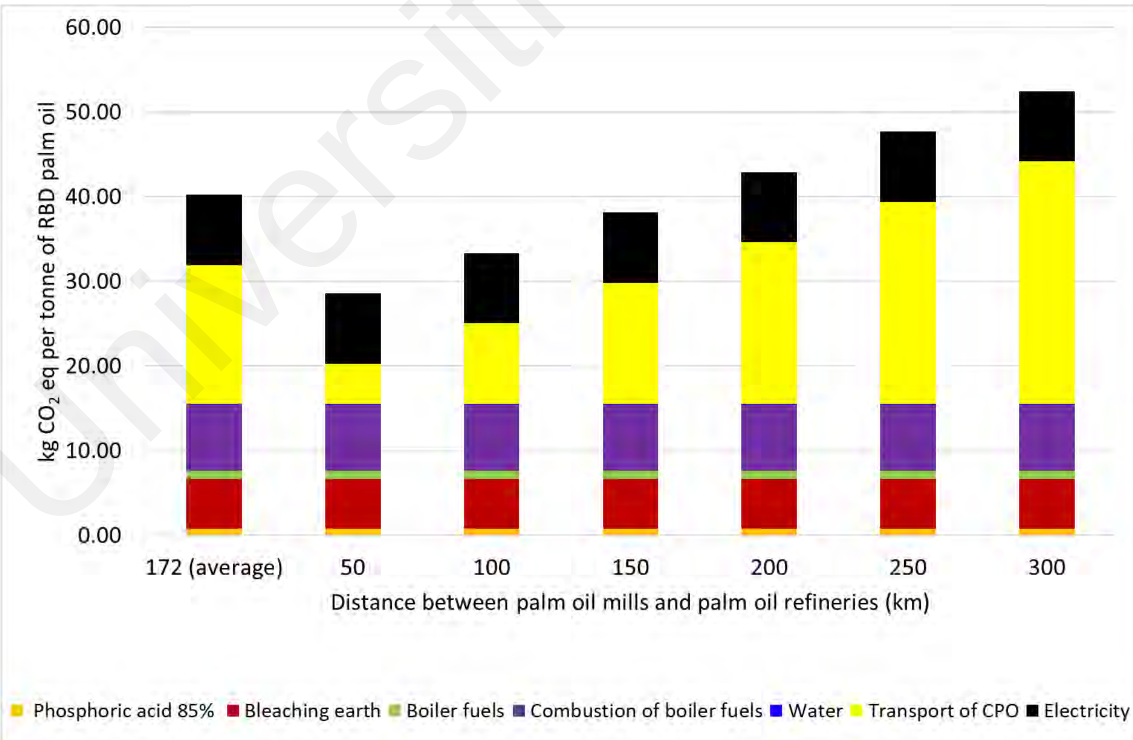


Figure 4.76: The effects of CPO transportation distance on global warming potential for gate-to-gate LCA for palm oil refining

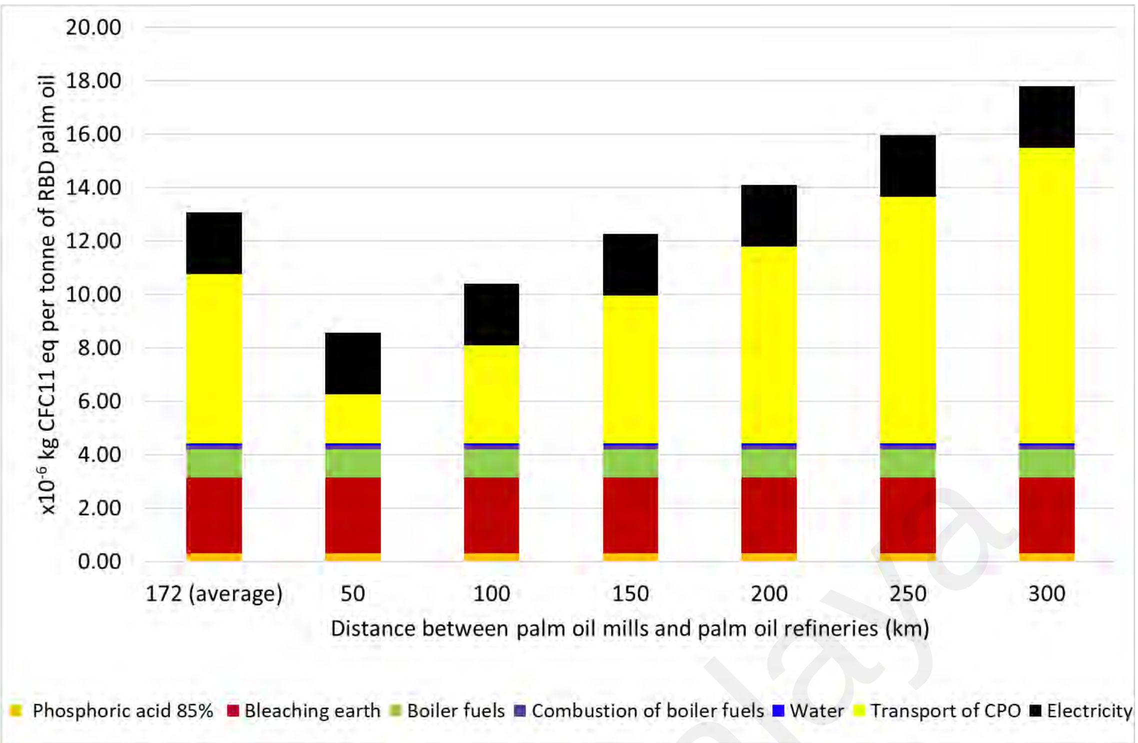


Figure 4.77: The effects of CPO transportation distance on stratospheric ozone depletion potential for gate-to-gate LCA for palm oil refining

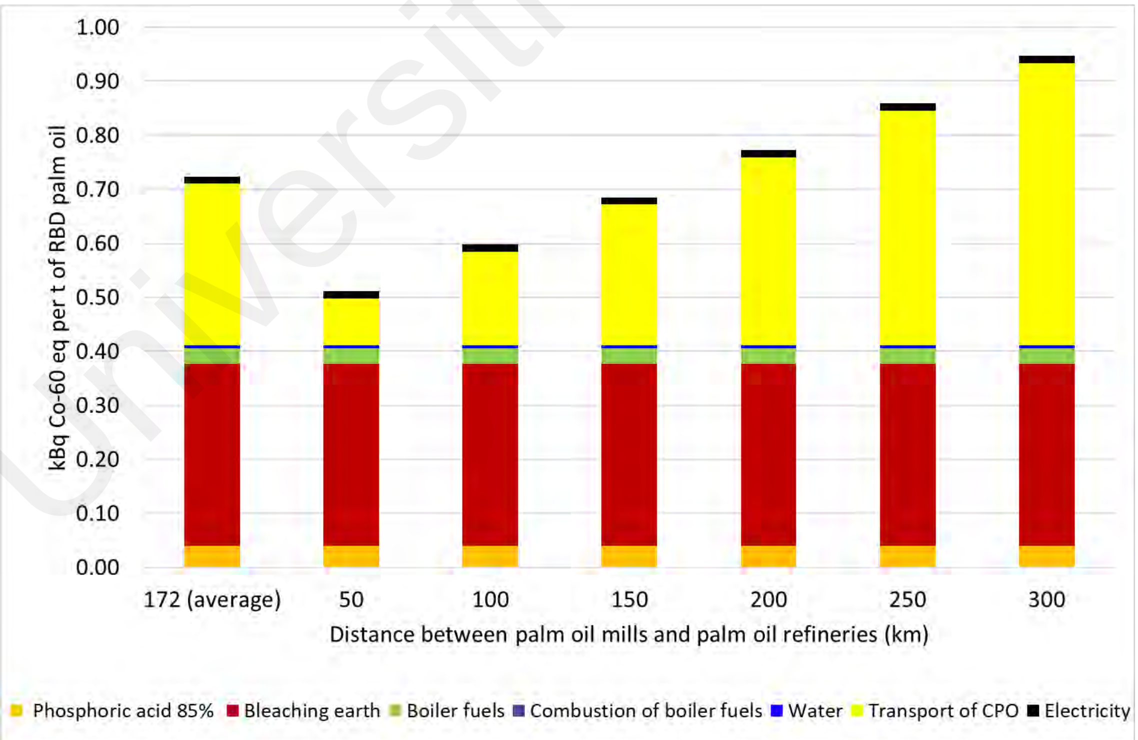


Figure 4.78: The effects of CPO transportation distance on ionising radiation potential for gate-to-gate LCA of palm oil refining

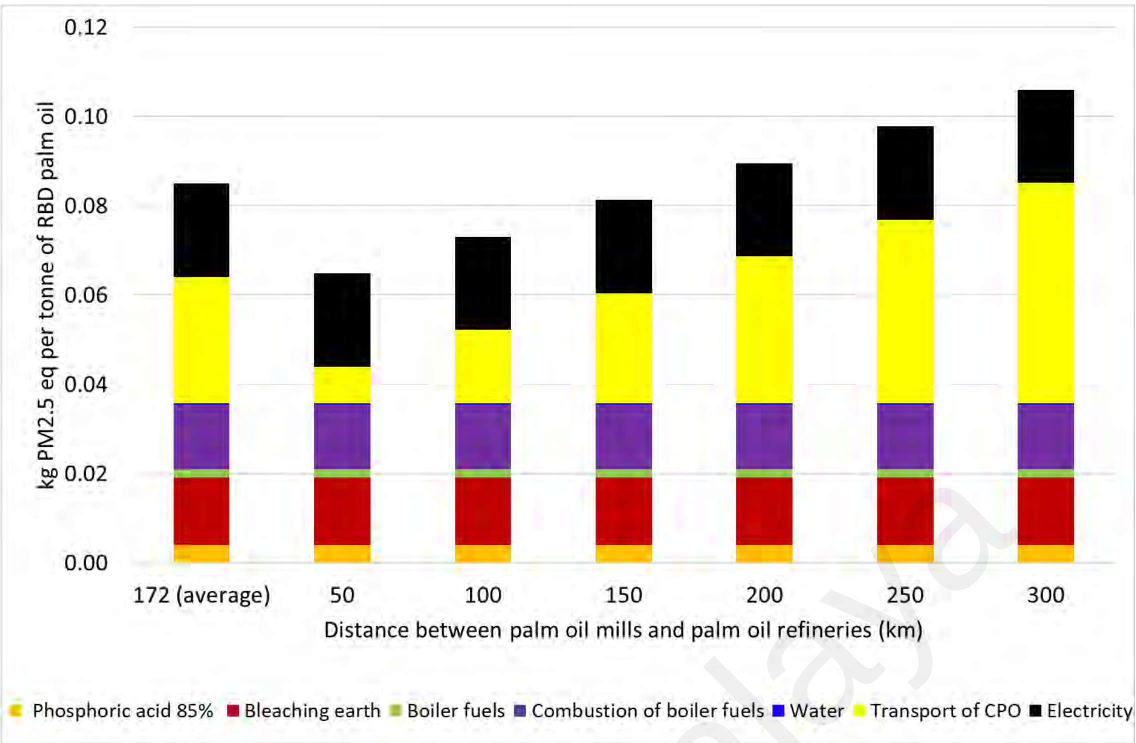


Figure 4.79: The effects of CPO transportation distance on fine particulate matter formation potential for gate-to-gate LCA of palm oil refining

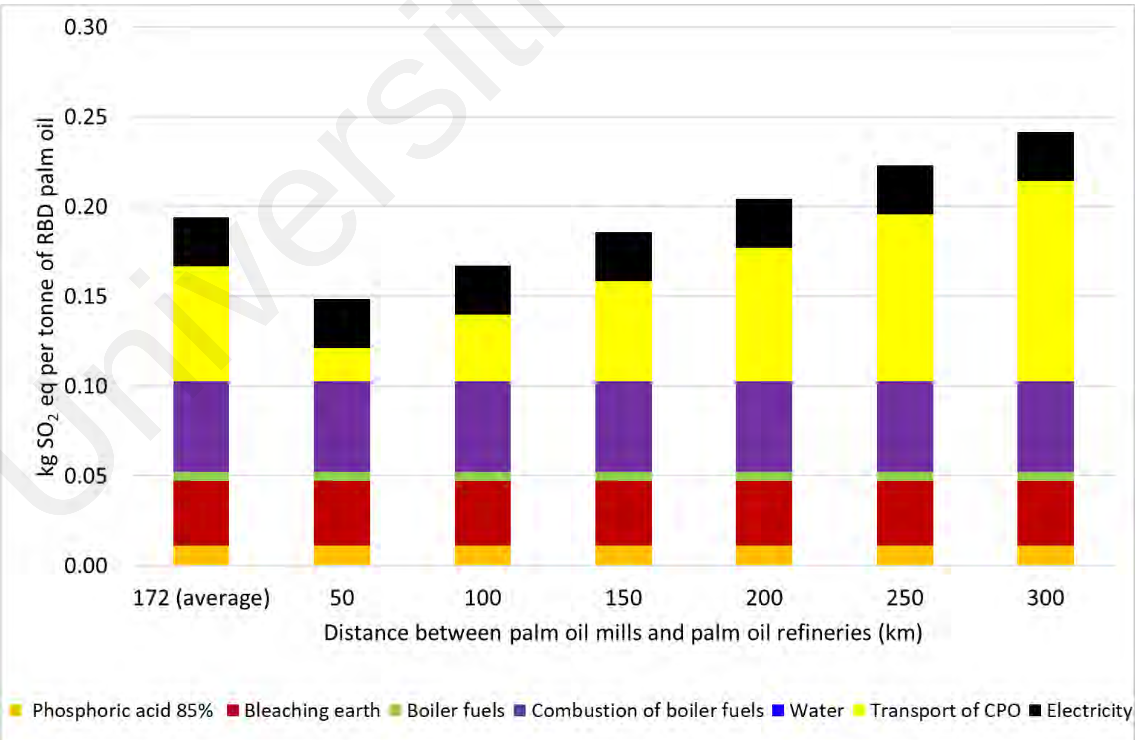


Figure 4.80: The effects of CPO transportation distance on terrestrial acidification potential for gate-to-gate LCA of palm oil refining

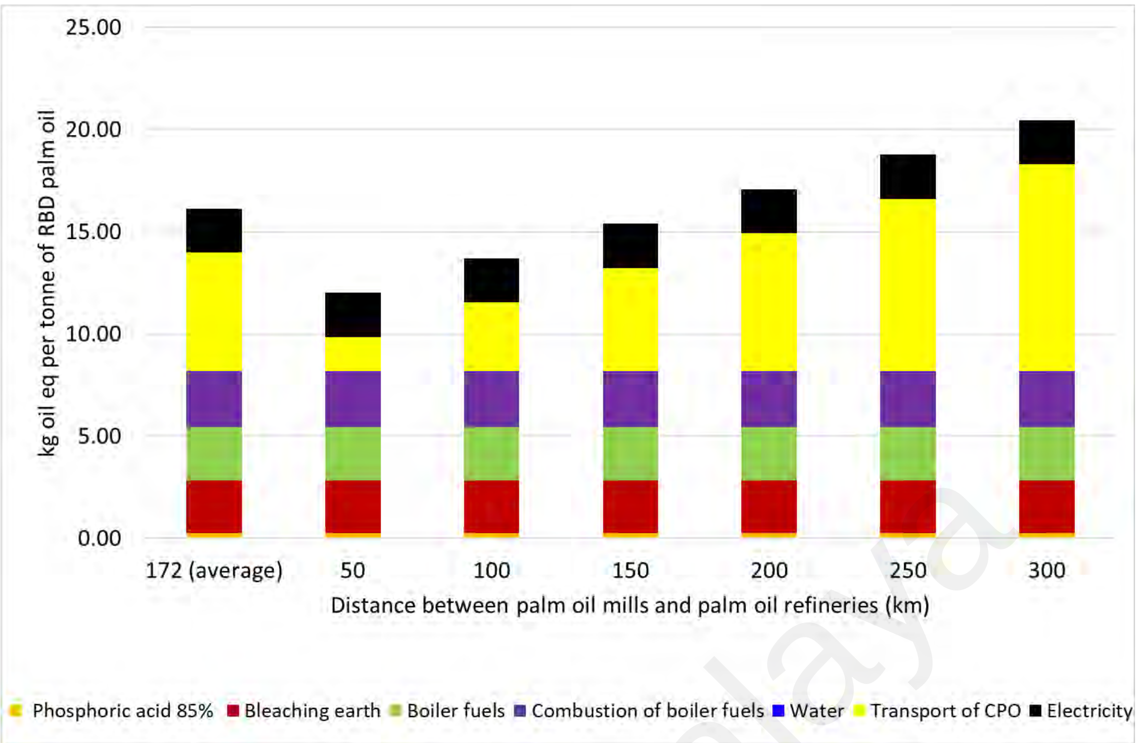


Figure 4.81: The effects of CPO transportation distance on fossil resource scarcity potential for gate-to-gate LCA of palm oil refining

The second approach is the replacement of Euro 3 with Euro 5 emissions compliant trucks. Euro 5 diesel or ultra-low sulphur diesel has been introduced to the Malaysian market as an optional diesel since 2014. The Euro 5 diesel is mandated to all petrol stations in the country starting April 2021. However, most of the trucks currently used by the transportation sector in the country are still Euro 3 emissions compliance. The replacement with Euro 5 trucks and Euro 5 diesel will lead to better exhaust emissions from vehicle tailpipes and is anticipated to provide a significant reduction in the stratospheric ozone formation (-36%) (Figure 4.82). Mild improvements in terrestrial acidification (-11%) and fine particulate matter formation (-10%) are also anticipated (Figures 4.83 & 4.84). No difference to the other impact categories such as global warming and fossil resource scarcity is observed possibly due to the reason that the same amount of transportation fuel is consumed (Figures 4.85 & 4.86). A higher impact on stratospheric ozone depletion (45%) is observed in Figure 4.87 but the absolute values are insignificant.

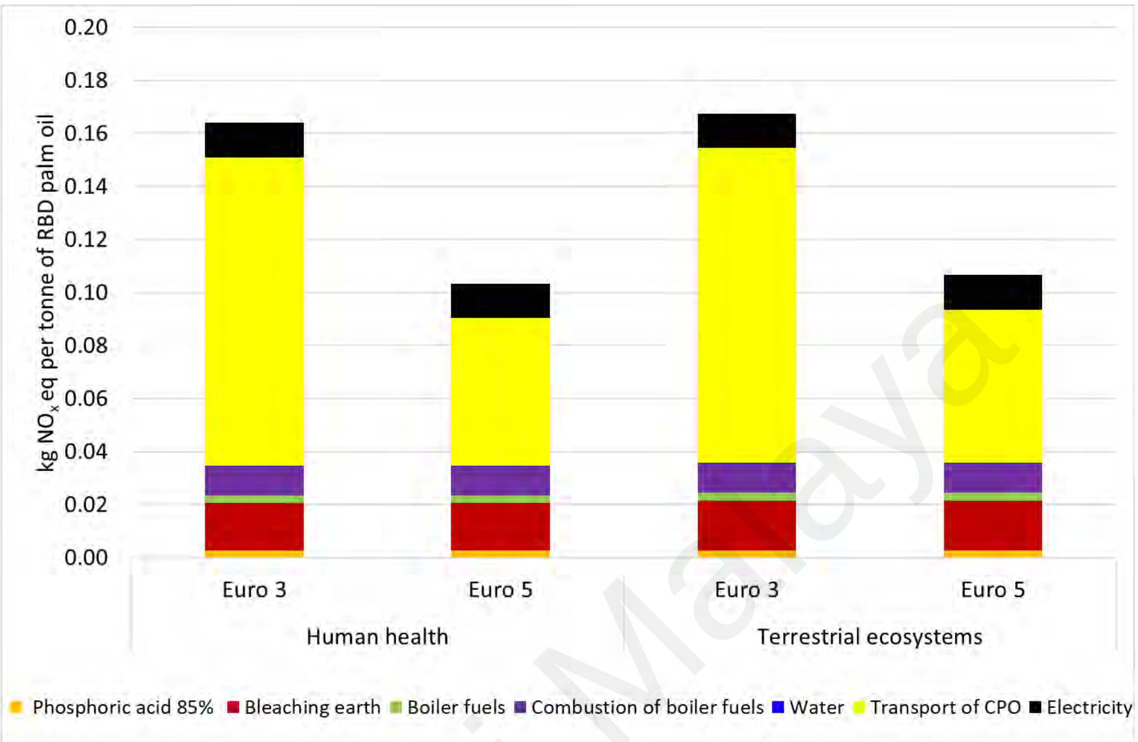


Figure 4.82: The effects of truck emission compliance on ozone formation potential for gate-to-gate LCA of palm oil refining

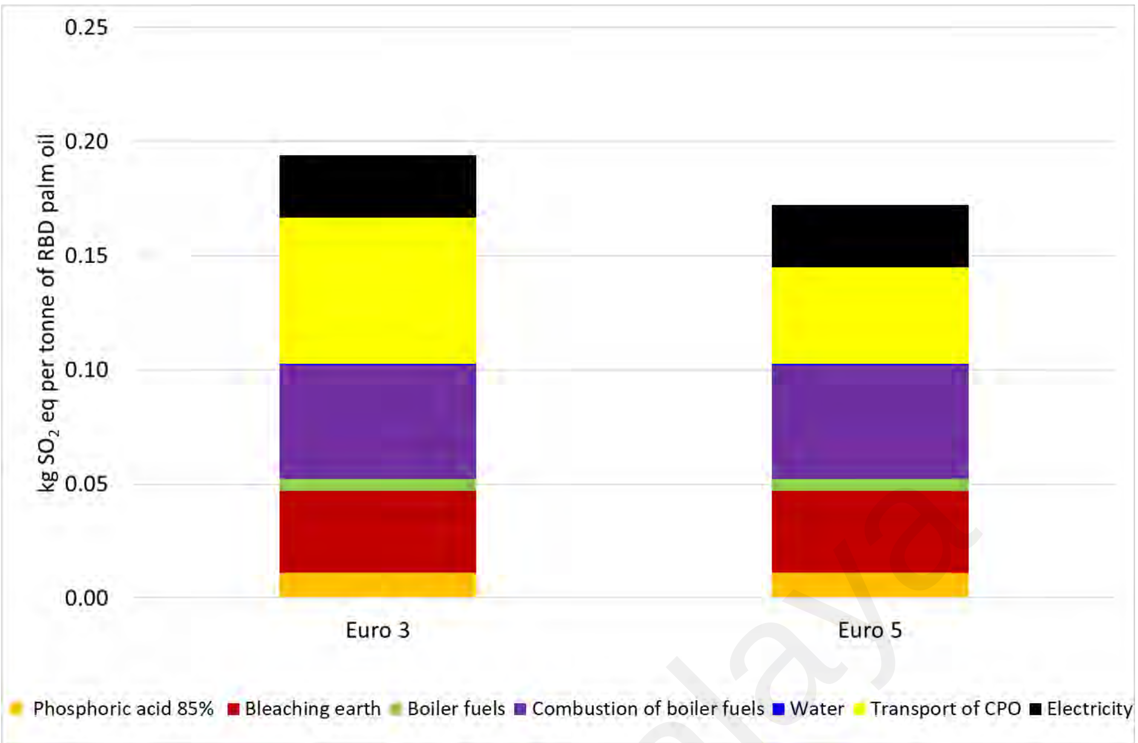


Figure 4.83: The effects of truck emission compliance on terrestrial acidification potential for gate-to-gate LCA of palm oil refining

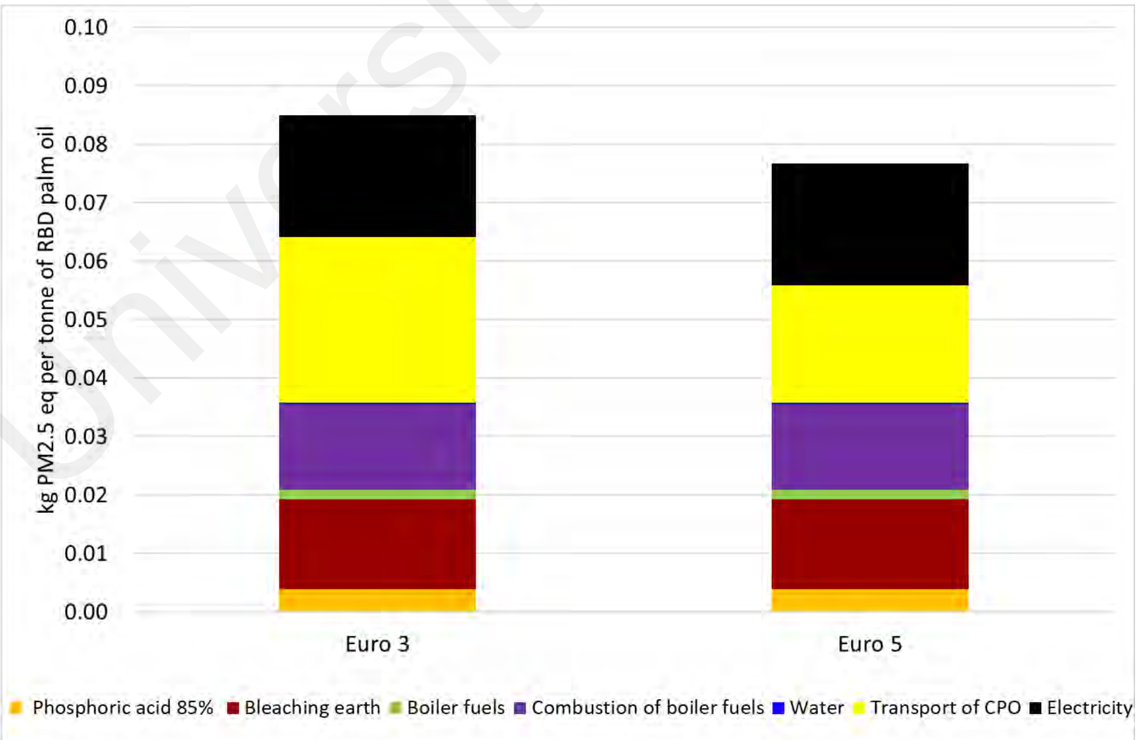


Figure 4.84: The effects of truck emission compliance on fine particulate matter formation potential for gate-to-gate LCA of palm oil refining

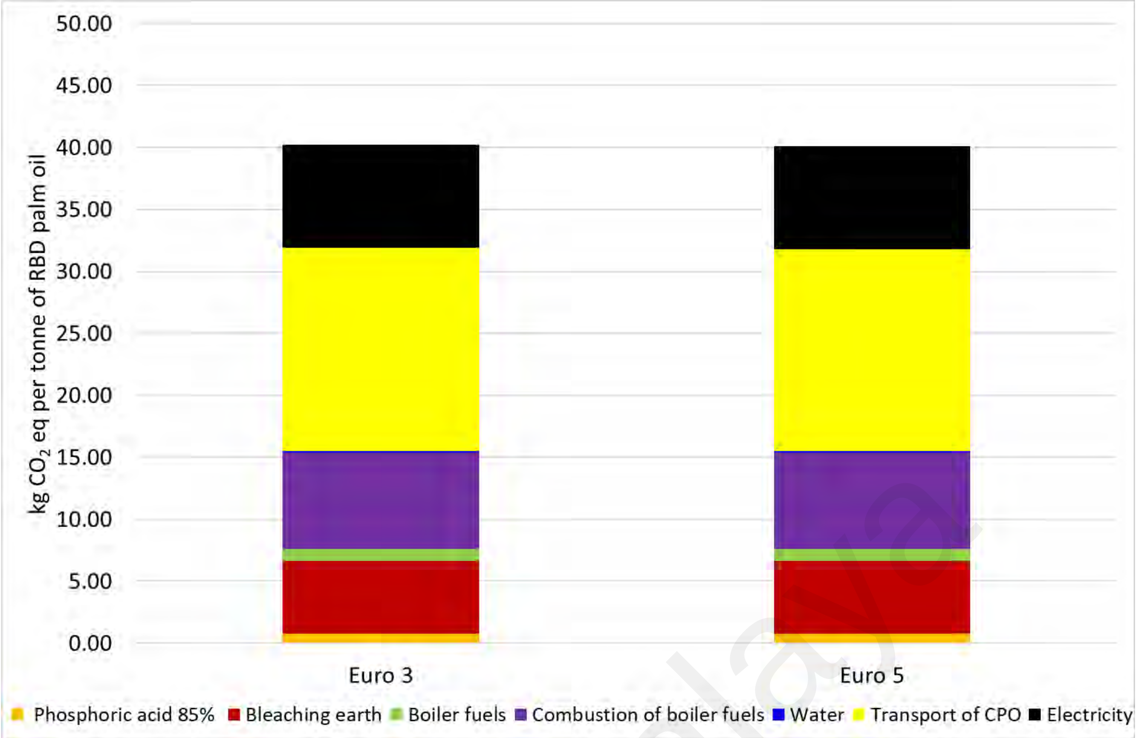


Figure 4.85: The effects of truck emission compliance on global warming potential for gate-to-gate LCA of palm oil refining

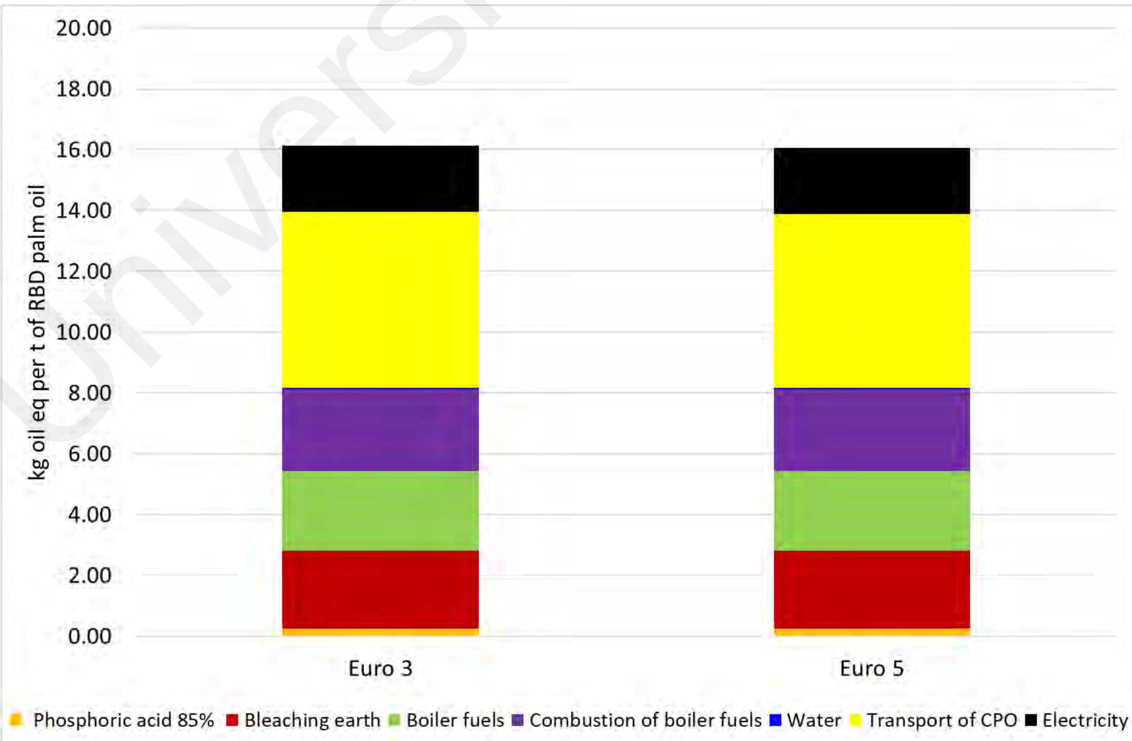


Figure 4.86: The effects of truck emission compliance on fossil resource scarcity potential for gate-to-gate LCA of palm oil refining

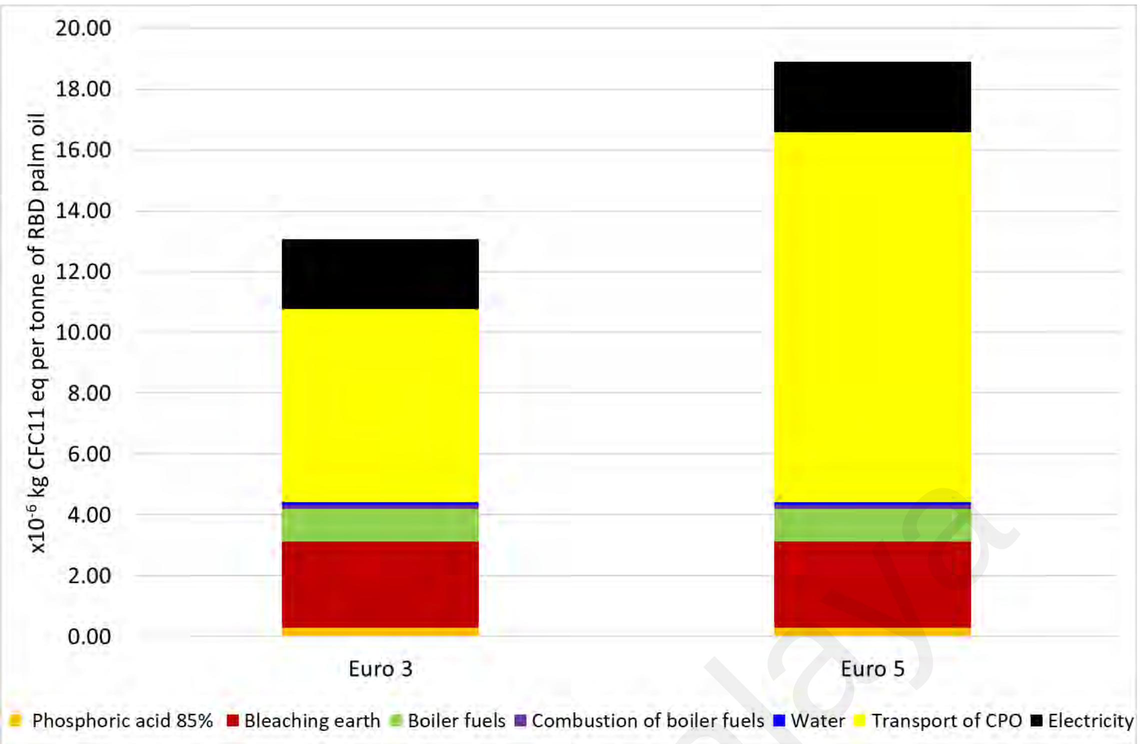


Figure 4.87: The effects of truck emission compliance on stratospheric ozone depletion potential for gate-to-gate LCA of palm oil refining

4.5.5 Sensitivity Analysis on Methanol

Methanol is the important chemical used for the production of palm biodiesel. It is typically produced via syngas conversion of fossil-based natural gas. Methanol is one of the most common chemicals supplied and transported worldwide with a total production volume exceeded 95 billion litres per annum (Hobson and Marquez, 2018). Commercial production of biomethanol has recently gained attention as seen with the construction of several commercial plants in the developed countries in Europe and North America.

Methanol has a significant impact on all the midpoint impact categories evaluated, in particular, global warming, stratospheric ozone depletion, ozone formation for both impacts on human health and terrestrial ecosystems, mineral resource scarcity and fossil resource scarcity. More than 40% of the impact are due to methanol (Figure 4.27).

As the single major contributor to the total GHG emissions, 72.91 kg CO_2 eq per tonne of palm biodiesel produced or 48% of the overall emissions are due to methanol (Figure 4.28). Replacement of fossil-based methanol with bioethanol or biomethanol was previously suggested to reduce the environmental impacts to the global warming impact categories (Sampattagul et al., 2011; Noorazah et al., 2017). However, no detailed analysis is presented thus far.

Replacement of fossil-based methanol with biomethanol is evaluated in this study. Three scenarios are simulated, namely (1) biomethanol produced from biomass in Switzerland (Ecoinvent 3.6 database) and shipped to Malaysia, (2) biomethanol produced in Malaysia, modified from scenario (1) with Malaysian utilities and (3) biomethanol produced from biogas by replacing fossil-based natural gas with bio-compressed natural gas (bio-CNG) produced from biogas trapped in palm oil mills.

For scenario 1, although the production of biomethanol from biomass could significantly lower the global warming effect, the long-distance transportation of biomethanol to Malaysia has offset some of the GHG savings (Figure 4.88). Net GHG emissions of 129.46 kg CO_2 eq per tonne of palm biodiesel produced is recorded. This is equivalent to a 15% saving compared to the fossil-based methanol scenario. No significant change is observed for scenario 2, mainly due to higher carbon emissions utilities in Malaysia compared to those in Switzerland. Scenario 3 contributes to the highest reduction in GHG emissions among the three simulated scenarios. A saving of 28.87 kg CO_2 eq or 19% for every tonne of palm biodiesel produced is anticipated. This is assumed that the bio-CNG is an environmental-friendly chemical and does not carry any environmental burden from the upstream processes.

Biogas capturing in the palm oil mills has been previously identified as an important solution to lower the overall GHG emissions of the palm oil industry (Choo et al., 2011). The biogas captured is typically used for power and heat generation for consumption in palm oil mills or grid connections. Purification of the biogas captured for the production of bio-CNG is one of the emerging utilisations in recent days (Nasrin et al., 2020). Furthermore, the replacement of fossil-based methanol with biomethanol is also anticipated to eliminate the carbon emissions contributed by the fossil-based methanol as explained in Section 4.3.10. Further reduction in the cradle-to-grave GHG emissions of 4.02 g CO_2 eq per MJ of palm biodiesel is anticipated.

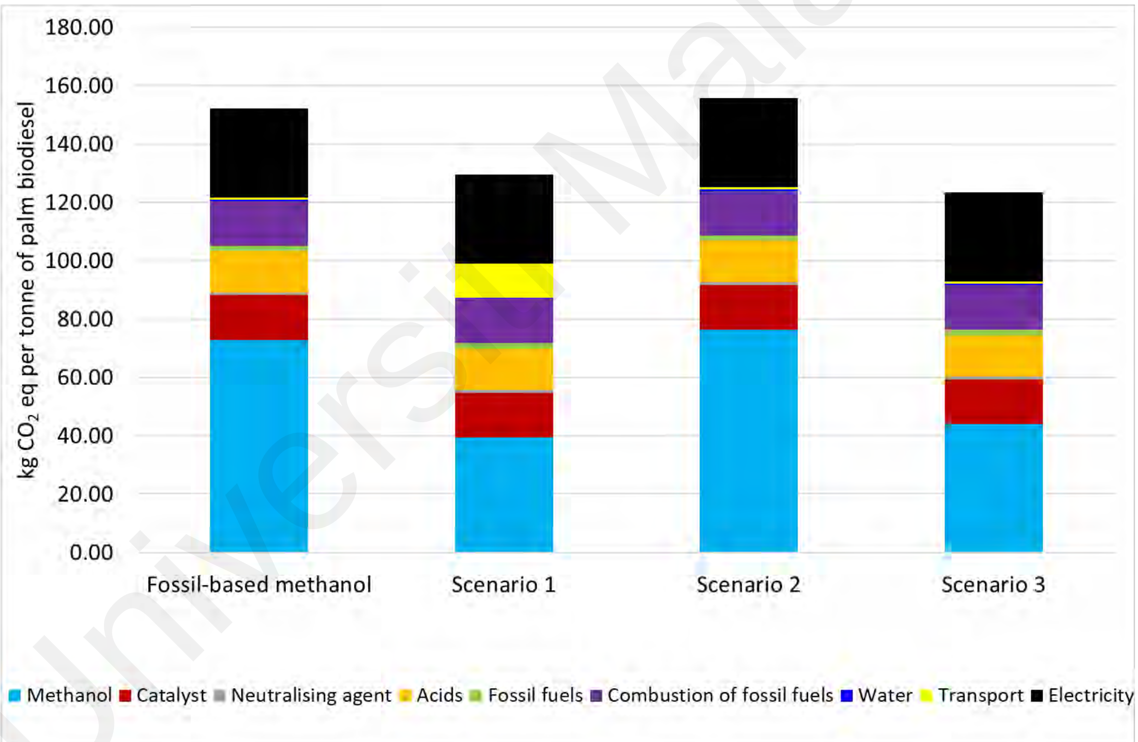


Figure 4.88: The effects of biomethanol on global warming potential for gate-to-gate LCA of palm biodiesel production

No improvement is observed for the biomethanol to the stratospheric ozone depletion impact category in scenarios 1 and 2 (Figure 4.89). For scenario 3, a 30% reduction is observed but the absolute value is however negligible.

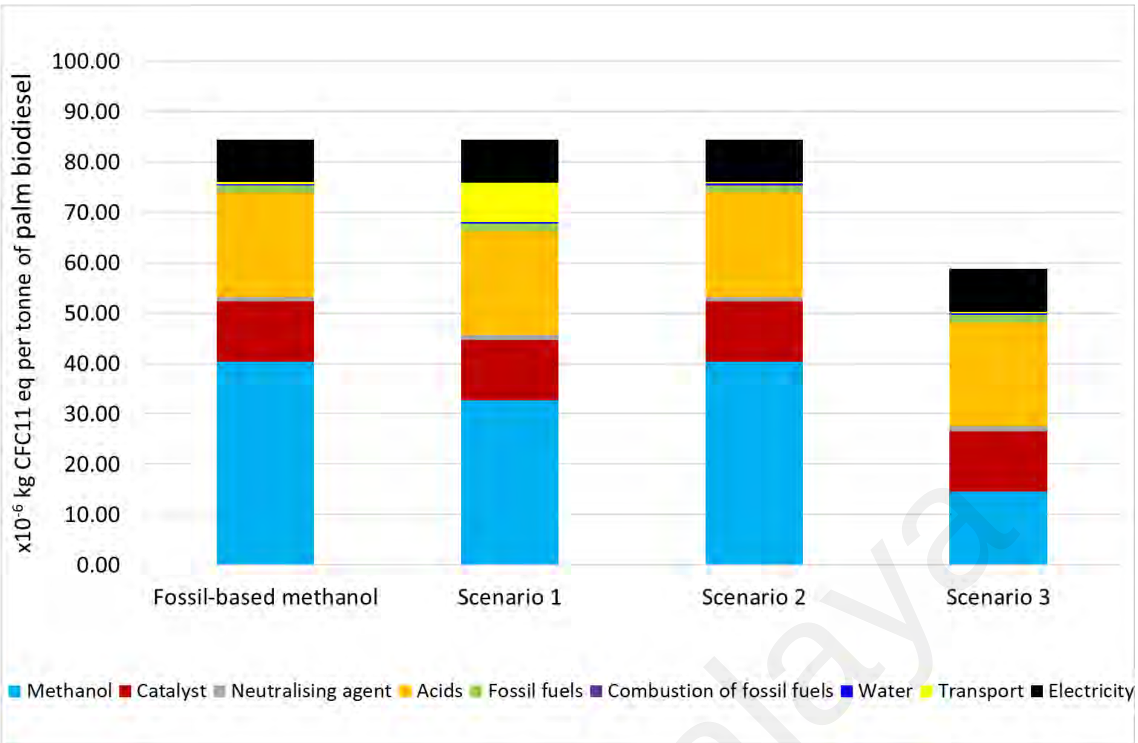


Figure 4.89: The effects of biomethanol on stratospheric ozone depletion potential for gate-to-gate LCA of palm biodiesel production

On the other hand, it is observed that the impact on ionising radiation is 4.3 times higher if fossil-based methanol is replaced by biomethanol in scenario 1 (Figure 4.90. This is possibly due to the use of nuclear-based electricity for the production of syngas from biomass and subsequently biomethanol production. A simulated biomethanol production using local Malaysian utilities as for scenario 2 significantly lower the ionising radiation impact. However, the contribution of biomethanol in scenario 2 is 2.8 times higher than the fossil-based methanol due to the background process for conversion of biomass to syngas according to the dataset in the Ecoinvent 3.6 database. The contribution of biomethanol is reduced significantly in scenario 3, 28.5% reduction to the overall ionising radiation impact.

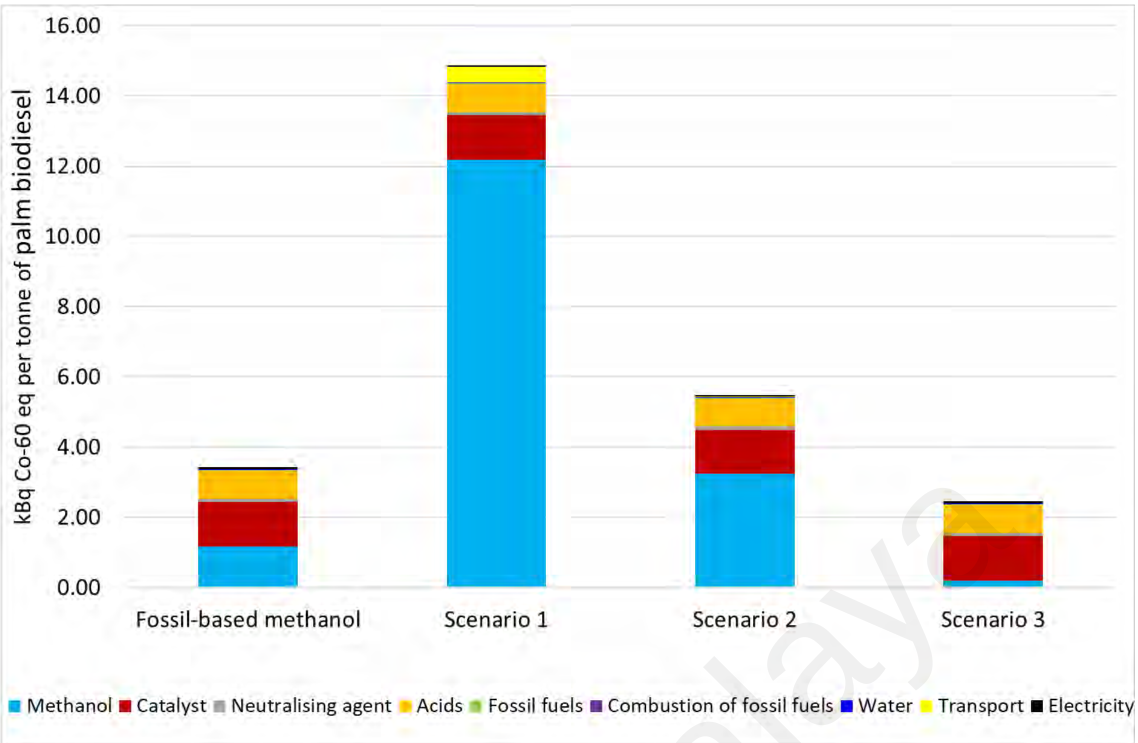


Figure 4.90: The effects of biomethanol on ionising radiation potential for gate-to-gate LCA of palm biodiesel production

Approximately 50% of the impact on ozone formation impacts on human health and terrestrial ecosystems are due to fossil-based methanol (Figure 4.91). Replacing fossil-based methanol with biomethanol in scenario 1 raises the total impact to 1.8 times higher than that using fossil-based methanol. The increase is mainly contributed by the long-distance transportation of biomethanol from Switzerland to Malaysia. Simulated biomethanol produced locally in scenario 2 is also anticipated to have a higher impact on ozone formation compared with the fossil-based methanol scenario. This is possibly due to the local utilities and also the energy required for the production of syngas from biomass. Replacement of fossil-based natural gas with bio-CNG shows a reduction of approximately 22%.

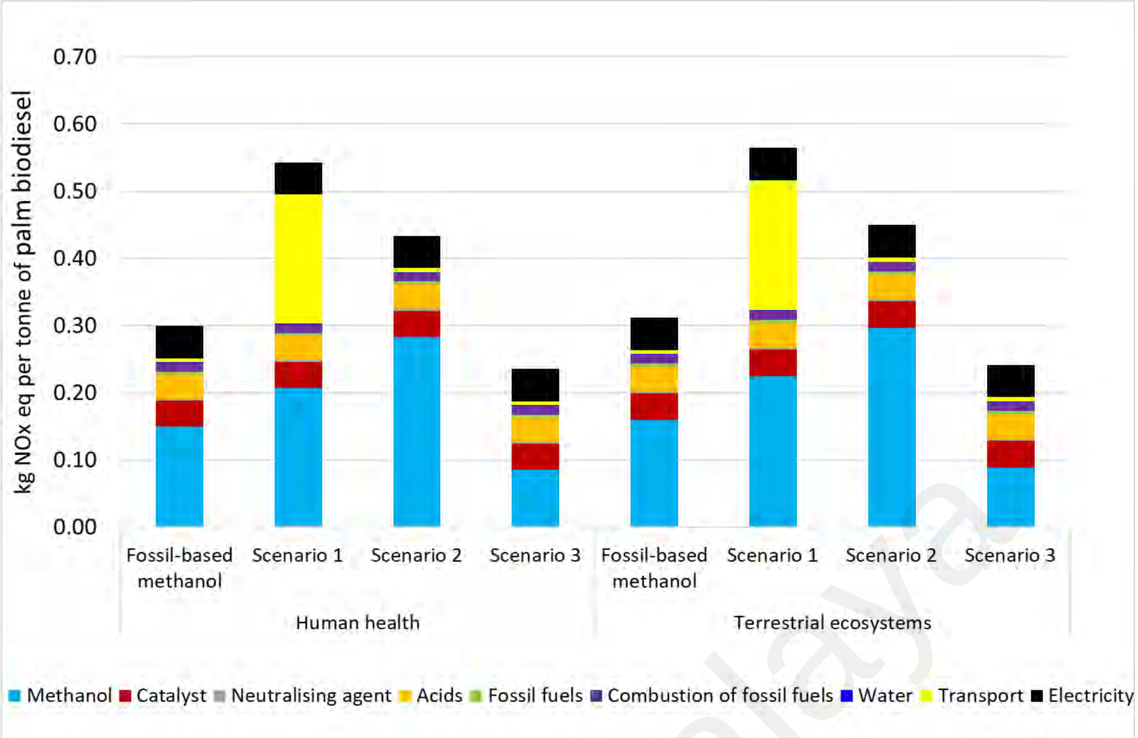


Figure 4.91: The effects of biomethanol on ozone formation potential for gate-to-gate LCA of palm biodiesel production

A similar trend is observed for terrestrial acidification and water consumption impact categories (Figure 4.92 & 4.93). Scenario 1 has the highest impact, follows by scenario 2. Scenario 3 has the lowest impact due to the replacement of fossil-based natural gas with bio-CNG in the production of biomethanol. The highest impact for scenario 1 in terrestrial acidification is once again due to the long-distance transportation of biomethanol while the higher impact for scenario 2 is due to the Malaysian utilities i.e. electricity, for the production of biomethanol. Water consumed in background processes for the production of biomethanol in scenarios 1 and 2 is the reason for overall higher water consumption. Replacement of fossil-based methanol with biomethanol produced from bio-CNG has no significant effect on the total water consumption impact category.

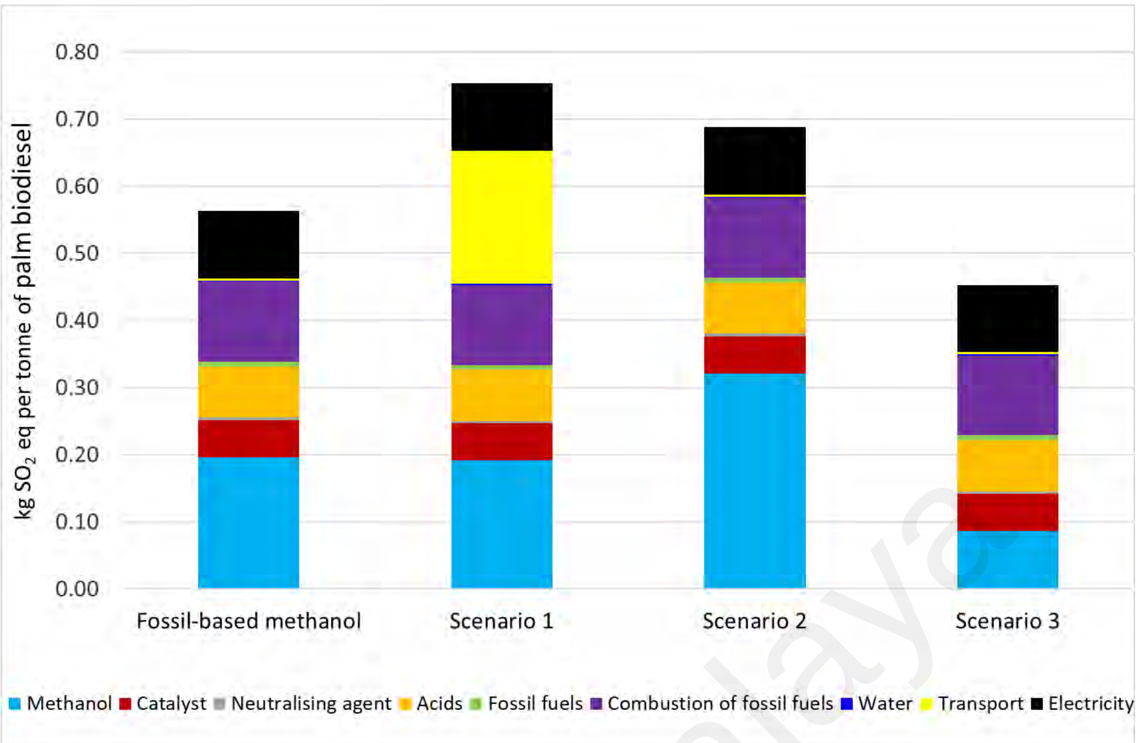


Figure 4.92: The effects of biomethanol on terrestrial acidification potential for gate-to-gate LCA of palm biodiesel production

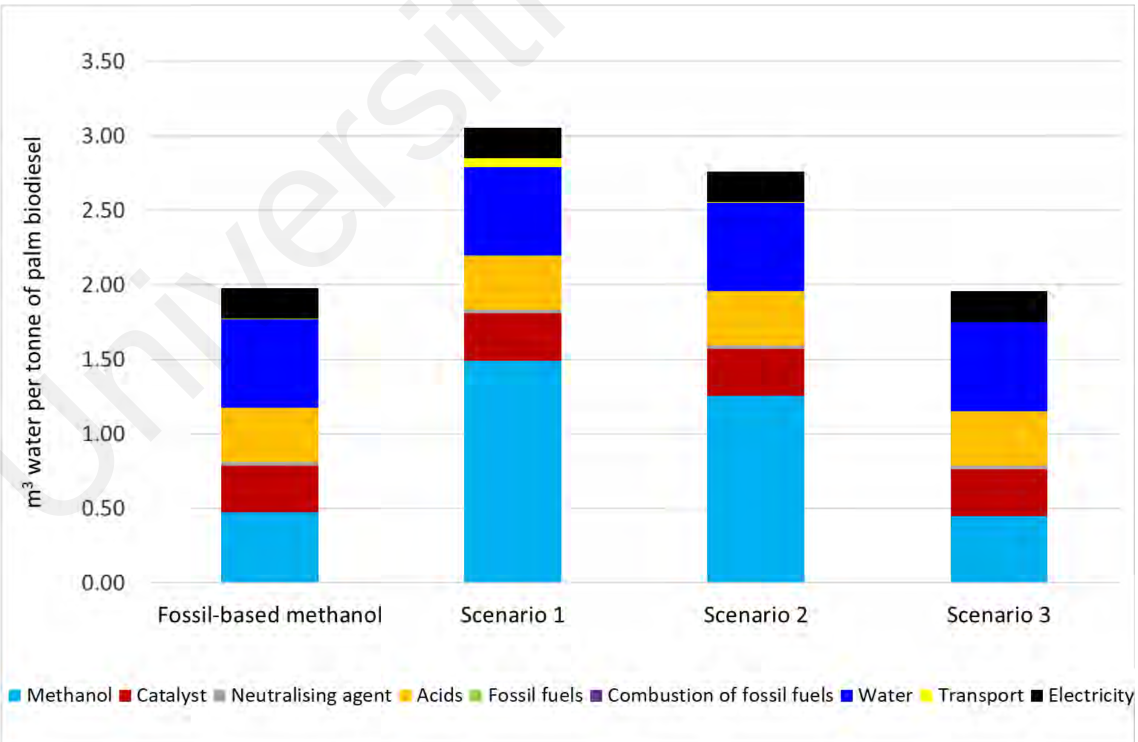


Figure 4.93: The effects of biomethanol on water consumption potential for gate-to-gate LCA of palm biodiesel production

A similar trend is observed for fine particulate matter formation, freshwater eutrophication, marine eutrophication and mineral resource scarcity impact categories (Figure 4.94 to 4.97). Scenario 2 has the highest impact. It is followed by scenario 1 and the fossil-based methanol scenario. Scenario 3 has the lowest impact among the scenarios evaluated. Figure 4.94 clearly shows that higher fine particulate matter formation in scenario 1 is mainly due to the long-distance transportation while the higher impact in scenario 2 is due to the local utilities i.e. electricity mix in the country. Higher impacts on freshwater eutrophication, marine eutrophication and mineral resource scarcity for scenarios 1 and 2 are observed due to the background process for the production of biomethanol (Figures 4.95 to 4.97).

For the fossil resource scarcity impact category, significant savings of fossil resources, i.e. natural gas, is recorded for all scenarios when fossil-based methanol is replaced by biomethanol (Figure 4.98). Savings of more than 50% of fossil resource is anticipated for all three biomethanol scenarios.

Based on the impact assessment results, changing feed materials from fossil-based to biological resources may not always resolve all the associated environmental impacts. A thorough investigation is needed to evaluate the effects of the proposed options. Results from the current study clearly show that biomethanol produced from bio-CNG is the best option with the lowest environmental impacts in the impact categories evaluated.

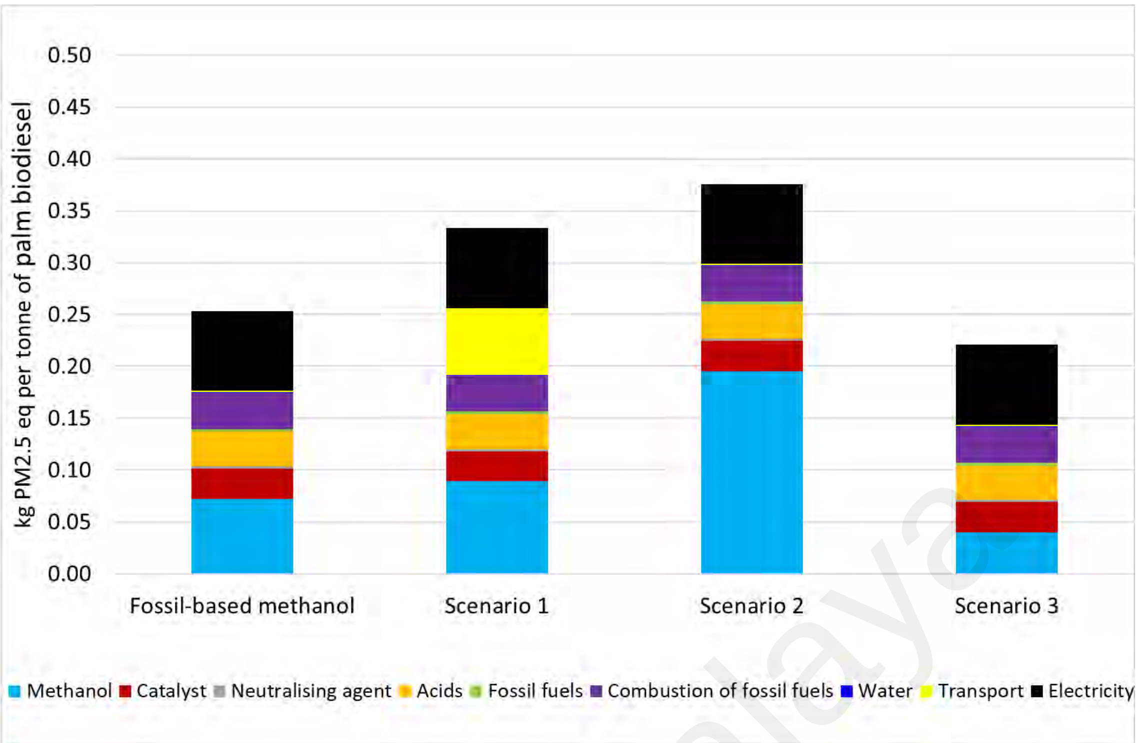


Figure 4.94: The effects of biomethanol on fine particulate matter formation potential for gate-to-gate LCA of palm biodiesel production

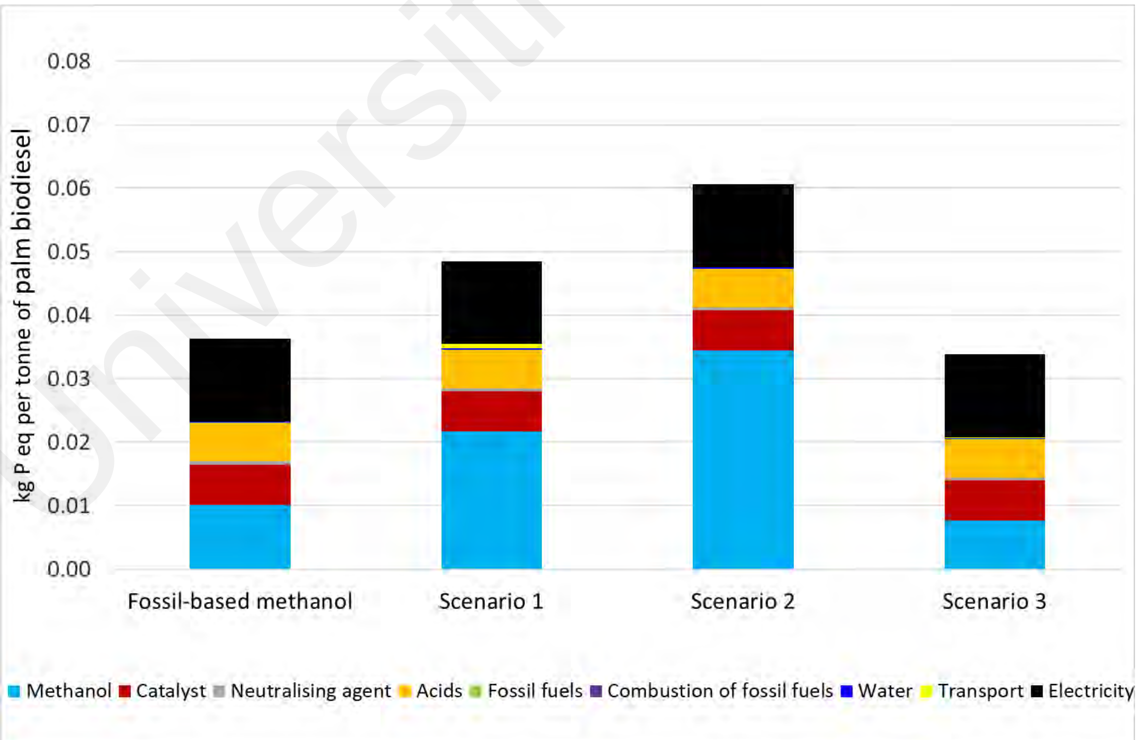


Figure 4.95: The effects of biomethanol on freshwater eutrophication potential for gate-to-gate LCA of palm biodiesel production

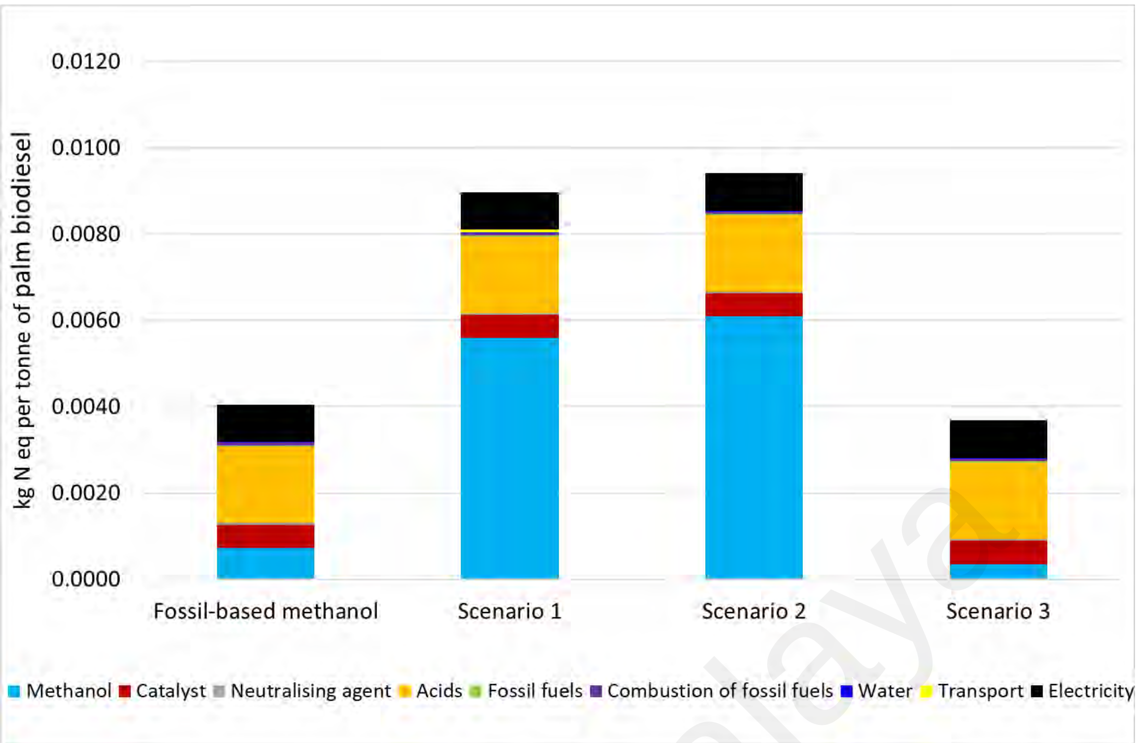


Figure 4.96: The effects of biomethanol on marine eutrophication potential for gate-to-gate LCA of palm biodiesel production

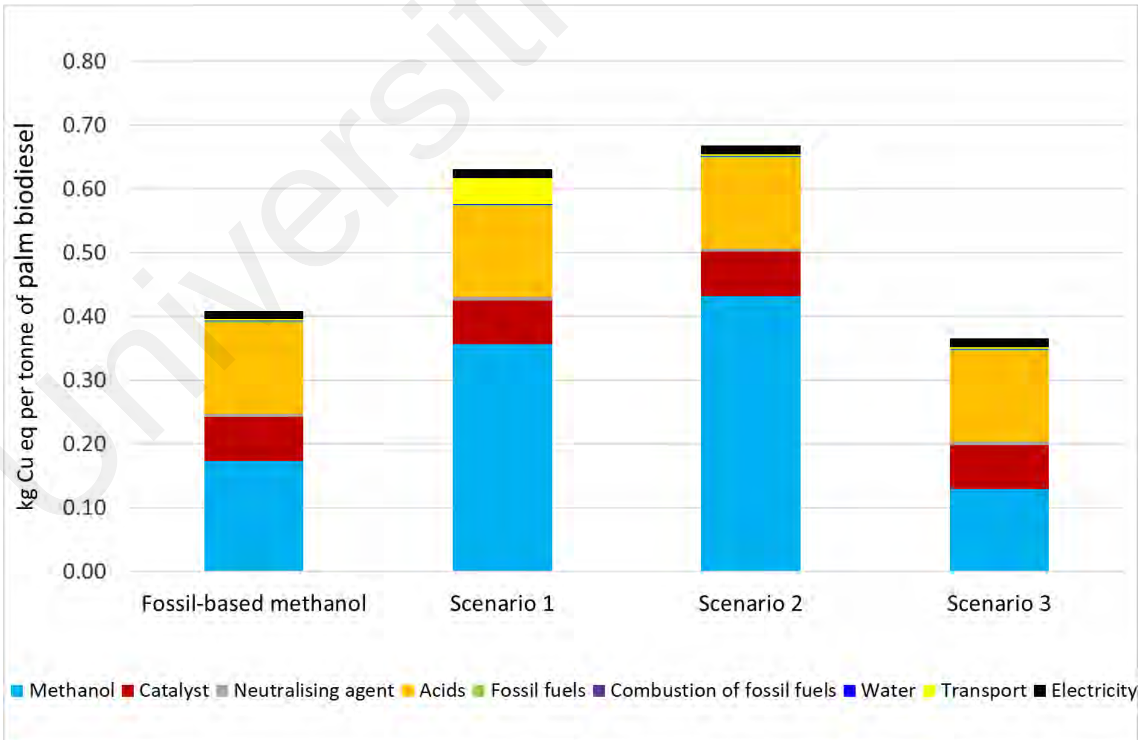


Figure 4.97: The effects of biomethanol on mineral resource scarcity potential for gate-to-gate LCA of palm biodiesel production

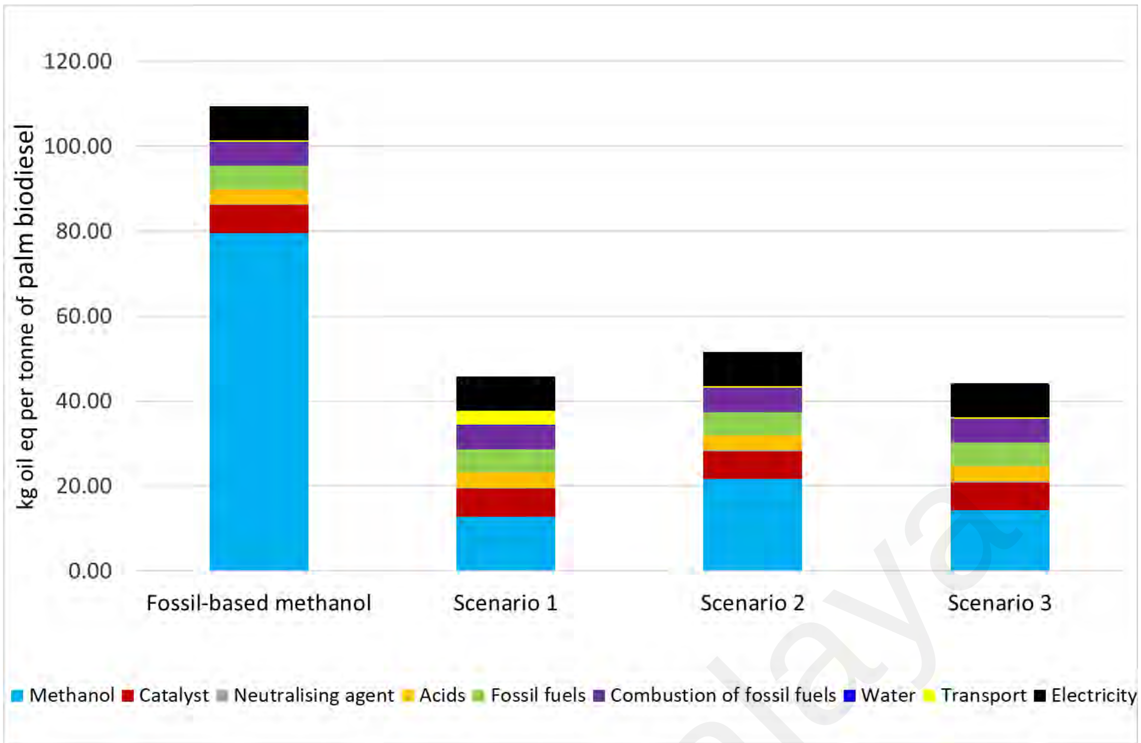


Figure 4.98: The effects of biomethanol on fossil resource scarcity potential for gate-to-gate LCA of palm biodiesel production

4.5.6 Sensitivity Analysis on Biogas Capture

In the previous section, it has been reported that the palm oil mills subsystem is the main contributor to the global warming impact category for cradle-to-gate LCA of palm oil refining, fractionation, biodiesel and biofuels production. Also, it has been reported in the previous study that the biogas produced from the palm oil mill effluent dominates the GHG emissions in palm oil mills (Choo et al., 2011).

In this study, scenarios are simulated for 0%, 50%, 75% and 100% biogas capturing facilities in Malaysia comparing with the current status of 28% (Loh et al., 2019). For the no biogas capturing facilities scenario, the cradle-to-gate global warming potential per tonne of RBD palm oil produced is recorded at 1396.36 kg CO_2 eq, 16% higher than the current scenario (Figure 4.99). Reductions in the total GHG emitted of 13%, 28% and 42% are anticipated for scenarios with 50%, 75% and 100% biogas captured. The total RBD palm oil produced in 51 palm oil refineries across Malaysia in 2019 was recorded at 16.4 million tonnes (MPOB, 2020a). Thus, this translates to an absolute GHG savings of 3.24 million tonnes CO_2 eq for the current Malaysia status compared to no biogas capturing effort in the palm oil mills.

A similar trend is observed for the cradle-to-gate and cradle-to-grave LCA of palm biodiesel as shown in Figures 4.100 and 4.101. Greater reduction in total GHG emissions is anticipated for the combination of biogas captured, upgrading to bioCNG and conversion to biomethanol for the transesterification process.

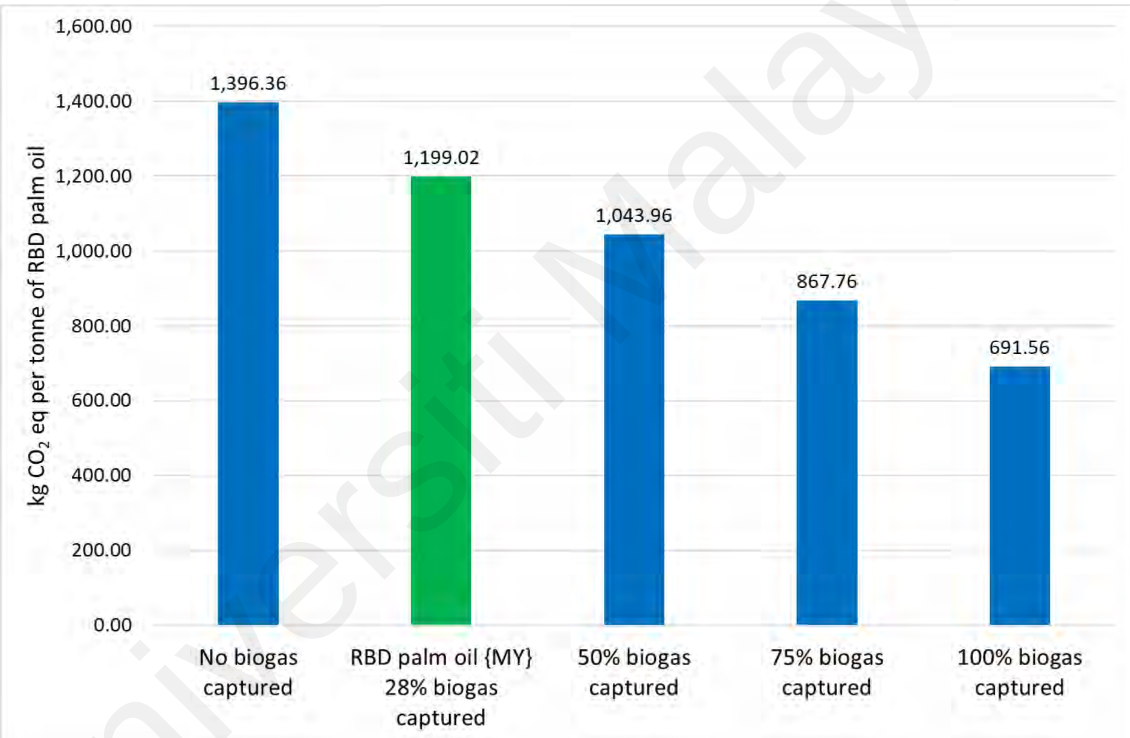


Figure 4.99: The effects of biogas capturing at palm oil mills subsystem on global warming potential for cradle-to-gate LCA of palm oil refining

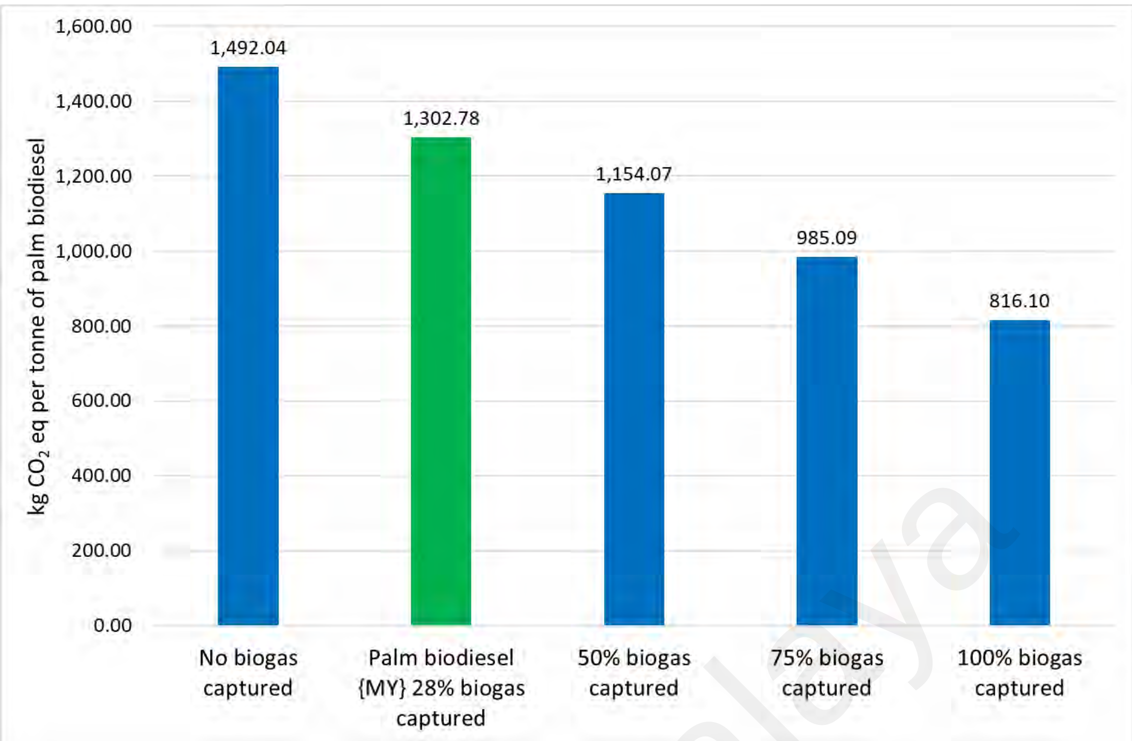
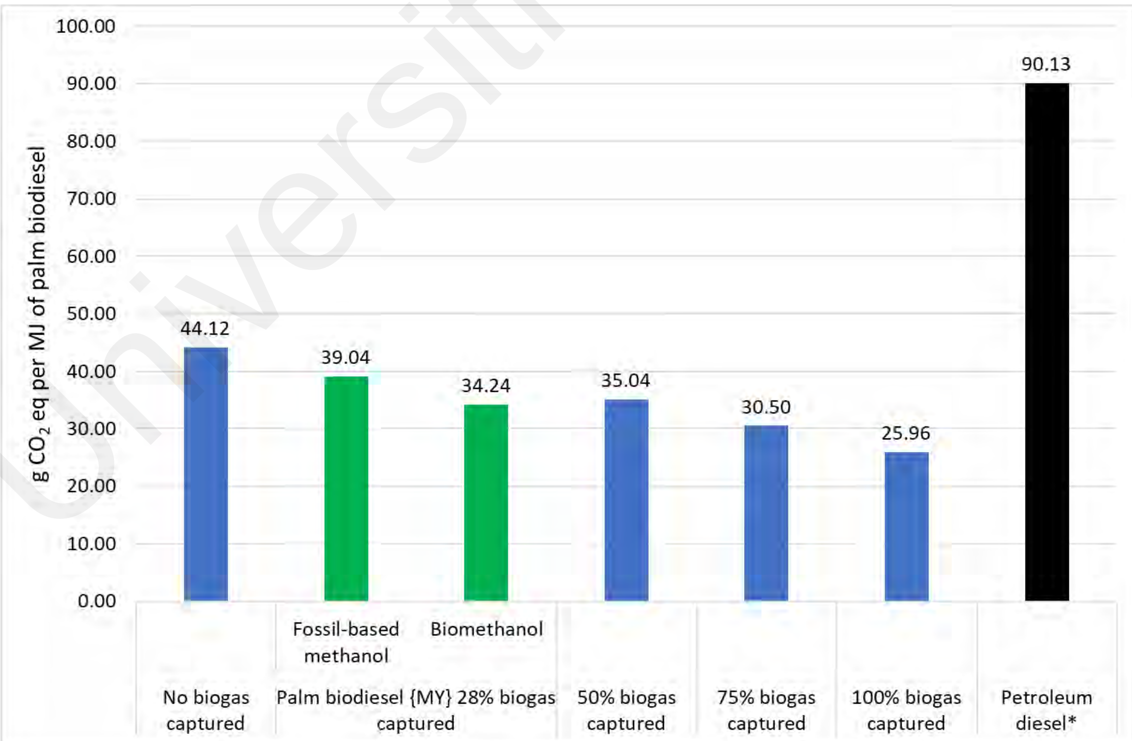


Figure 4.100: The effects of biogas capturing at palm oil mills subsystem on global warming potential for cradle-to-gate LCA of palm biodiesel production



Note: *Skone and Gerdes, 2008

Figure 4.101: The effects of biogas capturing at palm oil mills subsystem on global warming potential for cradle-to-grave LCA of palm biodiesel

4.6 Consistency Check

The objective of a consistency check is to determine whether the assumptions, methods and data used are consistent with the goal and scope of the LCA study (ISO, 2006b). In the present study, the assumptions, inventory data and its quality used in different palm subsystems are consistent with the goal and scope described in Chapter 3. Impact assessment of the gate-to-gate and cradle-to-gate LCA has been carried out consistently. The allocation has been performed consistently to all subsystems with co-products. System boundaries have been applied consistently to the subsystems for the impact assessment evaluation.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

For the gate-to-gate system boundary, bleaching earth and transportation of CPO play significant roles in contributing to the environmental impacts of palm oil refining and fractionation. The amount of bleaching earth used by the refineries is within the recommended minimum requirement, 1.05% of the CPO refined. Hence, no further improvement was proposed for the bleaching earth used. From the transportation angle, refineries should source CPO from nearby palm oil mills to reduce the environmental impacts caused by the distance between mills and refineries. Also, improving the transport vehicles to a better emission standard coupled with good fuel quality had a noticeable improvement in global warming, ozone formation, terrestrial acidification and fine particulate matter formation.

Methanol, transesterification catalyst (sodium methoxide) and acids are the main contributors to the environmental impacts of the biodiesel production subsystem. Replacement of fossil-based methanol with biomethanol can lower the overall environmental impacts. However, not all biomethanol sources would have a positive contribution to all the environmental impacts evaluated. Biomethanol produced from bio-CNG (biogas from POME) is preferred as it has the most positive contribution to the environment, in particular, global warming and fossil resource scarcity impact categories. Furthermore, savings of 4.02 g CO_2 eq per MJ of biodiesel combusted is anticipated in the cradle-to-grave LCA when the fossil-based methanol is replaced by biomethanol.

Hydrogen and electricity are the main contributors to the environmental impacts of the production of hydroprocessed biofuels. Comparing the production of HRD and HRJ, HRJ production has higher environmental impacts simply due to higher energy and hydrogen requirements for the isomerisation process to achieve desired properties in particular the freezing point. From a technical perspective, all the refined palm products are suitable feed materials for the production of hydroprocessed biofuels. From the environmental angle, PFAD is preferable since fewer environmental burdens are inherited from PFAD compared to RBD palm oil, olein and stearin. Furthermore, PFAD is not an edible oil. There is no food versus fuel concern for PFAD to be used as starting material for biofuels production. However, the production volume of PFAD is a limiting factor since it is a co-product of the refining stage. The typical refining process is tuned to produce RBD palm oil (main product) at the maximum output while PFAD is at a minimum level for maximum profitability of the refinery. Due to the same reason, the percentage of free fatty acids in CPO is well managed by the palm oil millers to stay below 5% upon reaching the refineries.

Allocation based on mass value does not reflect the actual difference of the products and co-products in palm oil refining, fractionation and biodiesel production. Allocation based on economic value was found suitable for the refining, fractionation and biodiesel production subsystems since the products and co-products significantly differ in terms of product quality and they are traded commercially at different prices in the open market. Sensitivity analysis shows no difference between the allocation based on energy content and mass value for the refining and fractionation stages due to the similar energy values of the products and co-products. Since the use of crude glycerol as a fuel substitute is not common, allocation based on energy content is not suitable for the biodiesel subsystem. Energy allocation is however suitable for the hydroprocessing subsystem since the products (HRD or HRJ) and co-products (naphtha and propane mix gas) are generally use as energy products.

Evaluation on the prices movement of the main products and co-products in refining, fractionation and biodiesel subsystems displays consistent allocated environmental impacts per mass (functional) unit of the main products i.e. per tonne of RBD palm oil, olein, stearin and palm biodiesel produced. Insignificant variation (<3%) is observed for prices movement evaluated in the sensitivity analyses. However, a wider variation on the environmental impacts per mass unit of the co-products is also observed, in particular, crude glycerol in the biodiesel subsystem. This is mainly due to the fluctuation of the prices of both palm biodiesel and crude glycerol in the commercial market.

The cradle-to-gate characterised LCA for palm oil refining, fractionation and biodiesel production highlight the importance of biogas capturing activity to the global warming impact category. As shown in the simulated scenarios, a significant reduction in the global warming impact is anticipated for the expansive implementation of biogas capturing in the palm oil mill subsystem. A similar outcome is also expected for the production of hydroprocessed palm biofuels i.e. HRD and HRJ.

In conclusion, the present study has evaluated the environmental impacts of palm oil refining, fractionation and biofuels production with a special focus on the activities in these subsystems, within the system boundaries of the study as illustrated in Chapter 3. Activities that occur outside the system boundaries are omitted in the gate-to-gate LCA study. Reference to the published data available was conducted for the cradle-to-gate and cradle-to-grave LCA. The present study also successfully demonstrated that allocation based on the economic or market values of the products and co-products of the refinery (refining and fractionation) and biodiesel subsystems are a suitable option comparing to the mass allocation and energy allocation procedures.

The present study further shows that the LCA is a useful tool for the evaluation of potential environmental impacts of a product or system. Besides providing an overview of environmental evaluation for the whole life cycle, it also provides useful information on the actual performance of a single stage or a subsystem. The information in the macro and micro level are critical in enabling the evaluation of potential environmental improvement while supporting the corporate strategy, research and development programme and also the improvement in product or system design, of a particular industry or sector.

5.2 Recommendations for Future Works

5.2.1 Continuous Improvement Exercise

Life cycle assessment is a continuous improvement exercise. Evaluation of the environmental impacts should be conducted periodically and particularly when there is a change of process in the subsystems of interest. Also, re-evaluation of the environmental impacts is highly recommended when there is a major revision of the impact assessment methodology. This is to avoid the use of obsolete or superseded methodology which are no longer valid. Hence, it is the responsibility of the LCA practitioner to follow closely the latest development of LCA studies, methodologies, software and relevant ISO standards.

5.2.2 Activities at Oil Palm Plantations and Palm Oil Mills Subsystems

Results from the cradle-to-gate and cradle-to-grave LCA show that most of the environmental impacts are due to the upstream activities in the oil palm plantation and palm oil mills subsystems. Hence, a thorough evaluation of these two important subsystems with the latest inventory data is crucial in identifying new environmental hotspots (if any) and evaluating the potential improvements to the environmental impacts. The allocation procedures practised for the palm oil mill subsystems should also be re-evaluated. Allocation procedures based on mass value, energy content e.g. calorific value, and economic value should be studied and compared thoroughly.

5.2.3 Production of hydroprocessed palm biofuels

LCA for the production of hydroprocessed palm biofuels conducted for the current study is based on limited confidential pilot plant data. The results presented serve as a snap shot of the potential environmental impacts of such activity. It is recommended that a thorough study be conducted when the commercial activity is available in the country to reflect the real situation.

5.2.4 Other impact categories

LCA is a holistic evaluation of various environmental impact categories based on the scientific knowledge available. It is not only a single footprint analysis focussing on carbon or water footprint. Evaluation of other impact categories is equally important for a comprehensive LCA study although global warming is the main international agenda in the present day.

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