THE APPLICATION OF MATERIAL CIRCULARITY MEASUREMENT IN MULTIPLE PRODUCTS OF THE OIL PALM INDUSTRY

BY

MS. MUTHITA KACHAPOCH

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING (ENGINEERING TECHNOLOGY)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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ENTITLED

THE APPLICATION OF MATERIAL CIRCULARITY MEASUREMENT IN MULTIPLE PRODUCTS OF THE OIL PALM INDUSTRY

was approved as partial fulfillment of the requirements for
the degree of Master of Engineering (Engineering Technology)

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ABSTRACT

The oil palm industry plays an important role in food and energy production. However, this industry is one of the agricultural industries with high greenhouse gas (GHG) emissions of 52.16 million tons of carbon dioxide equivalent, accounting for 14.72% of total GHG emissions. This study, therefore, assesses GHG emissions of fresh fruit bunch (FFB), which is a product from oil palm plantations and is a raw material for the palm oil extraction process. GHG emissions assessment shows that in the area with high material consumption, GHG emissions are also high. It is suggested that GHG emissions are reduced by increasing FFB yields. With the awareness of the importance of a circular economy, the material circularity indicator (MCI) is also applied in this study to measure the material circularity of multiple products in the oil palm industry. The circularity measurement results show that palm oil production is more circular rather than linear with the calculated MCI of 0.5372. The MCI value can be enhanced by increasing the fraction of recycling, reuse, and composting of the co-product, residual oil, and waste, and reducing wastes to landfills. The MCI value may also be improved by increasing the oil extraction rate and the calorific value of the biomass.

This study contributes to the reduction of GHG emissions of FFB production and supports palm oil production and the use of oil palm resources efficiently. The measure of circularity in this study serves as a baseline for the oil palm industry to effectively palm for improvement in the future by increasing the oil extraction rate, recovering and reusing the residual oil, and making the most of ash.

Keywords: Circularity, Greenhouse gas (GHG) emissions, Material circularity indicator (MCI), Multiple products, Oil palm plantations

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Ms. Muthita Kachapoch

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Terms
ARDA	Agricultural Research Development Agency (Public Organization)
CE	Circular economy
CF	Carbon footprint
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
DEDE	Department of Alternative Energy Development and Efficiency
DIT	Department of Internal Trade
DOAE	Department of Agricultural Extension
EFB	Empty Fruit Bunch
EMF	Ellen MacArthur Foundation
FFB	Fresh Fruit Bunch
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LFI	Linear Flow Index
MCI	Material Circularity Indicator
OAE	Office of Agricultural Economics
OER	Oil Extraction Rate
ONEP	Office of Natural Resources and Environmental Policy and Planning
PF	Palm Fiber
PFAD	Palm Fatty Acid Distillate
PKS	Palm Kernel Shell
POME	Palm Oil Mill Effluent

RBDPKO	Refined Bleached Deodorized Palm Kernel Oil
RBDPO	Refined Bleached and Deodorized Palm Oil
TGO	Thailand Greenhouse Gas Management Organization (Public Organization)
TVO	Thai Vegetable Oil Public Company Limited
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WDRA	Warehousing Development and Regulatory Authority
WEF	World Economic Forum

CHAPTER 1
INTRODUCTION

This chapter discusses the background and significance of the research problem, objectives, scope of the study, and research timeline.

1.1 Background and significance of the research problem

The world population tends to increase continuously. This results in increased use of resources while natural resources are limited and continuously decreasing until there is a risk that they will run out of depletion in the near future. The world's population is projected to increase to nearly 9 billion by 2030 and to reach 10 billion by 2050, resulting in increased demand for products and services (UN, 2017). As a result, the competition for land, water, and energy will intensify. Meanwhile, the impacts of climate change are likely to become more severe.

Climate change from rising global temperature is mainly due to the high levels of greenhouse gas emissions in recent years from the growth of industrial sectors around the world. For this reason, the main measure that many governments are dealing with is reducing greenhouse gas emissions (Chansin, 2020). Leaders recognized the importance of climate change and signed the Paris Climate Change Agreement in 2016, setting a fundamental goal to keep global temperature rise below 2 ºC and setting a challenge up at 1.5 ºC based on fairness principles and shared responsibility at different levels of developed and developing countries (Chucherd, 2021).

Production and consumption patterns that use more natural resources and energy causing a shortage of raw materials, as well as the problem of solid waste management. Most of the natural resources and energy used today are non-renewable and are limited. Efforts to find renewable resources that have been used up are still not enough to meet the demand. The parts that cannot be reused have not been properly disposed of or treated. Therefore, it remains in the environment and causes the ecosystem to deteriorate in the long run (TGO, 2021a).

The circular economy concept is a new alternative that can develop the country's economy towards sustainability. It is recognized and driven by governments and businesses around the world. Businesses in developed countries have begun to adopt this policy by turning their business cycles as self-sufficient as possible. The circular economy may replace the traditional linear economy based on “take make use dispose of”. Many countries worldwide, including international organizations, governments, and large businesses have adopted the circular economy concept to improve and apply it appropriately to the context of their own countries and organizations. All sectors can benefit from the economic system developed from it. It is considered a sustainable economic, social, and environmental development of the country. The World Economic Forum (WEF) states that the move towards a circular economy will create economic opportunities through innovation, create jobs and drive economic growth (WEF, 2021). This is the key to solving resource problems and long-term environmental impact. It can also respond to the United Nations Sustainable Development Goals in Section 8 Decent Work and economic growth, Section 12, Responsible consumption and production, Section 13 Climate action, and Section 15 Life on land (Naden, 2019).

A circular economy is an economic framework that focuses on the careful management of resources so that nothing is wasted. In other words, products and materials are stored, reused, remanufactured, and recycled as long as those resources are used in the most cost-effective manner (Bureauveritas, 2021). This regeneration aims to create a closed supply chain that is “designed to eliminate” wasted resources. The circular economy stimulates the economy and society. It is seen as an important tool to empower businesses and help them seamlessly manage their environmental priorities, optimize and stimulate economic growth (EMF, 2021).

Thailand has a tendency to increase greenhouse gas emissions from national development activities. The amount of greenhouse gas emissions in 2011 was 305.52 million tons of carbon dioxide equivalent (ONEP, 2016). It is estimated that GHG emissions will reach 555 million tons of carbon dioxide equivalent in 2030 (KrungthaiCOMPASS, 2021). The sector with the largest share of greenhouse gas emissions is energy, followed by agriculture, industrial process, and waste (TGO, 2020).

The oil palm industry is one of the agriculture industries important for Thailand in terms of agriculture, economy, and industry. Currently, oil palm is not only planted in the southern region of Thailand but also planted in different regions of the country.

With different management practices and spatial conditions, this makes yields in each area, as well as materials/equipment and energy usage, in the oil palm plantations different. Palm planting uses fertilizers, which are a source of nitrous oxide; one of the greenhouse gases that contribute to global warming (Ngamkalong, 2021). The transportation of raw materials to the plantation results in the combustion of fuel, generating greenhouse gas (GHG) emissions. This environmental problem is very big and needs to be solved urgently. Therefore, it is necessary to assess the environmental impact through a life cycle perspective of FFB production to identify problems and find ways to reduce GHG emissions. In addition, different management practices and spatial characteristics of oil palm plantations must be examined to minimize GHG emissions.

Recognizing the importance of a circular economy is the key to achieving Sustainable Development Goals in economic, social, and environmental dimensions. Therefore, the circular economy concept was applied in this study to measure the circularity of multiple products in the oil palm industry. When fresh fruit bunches (FFB) go through the extraction process, they produce approximately 18-22% of crude palm oil (CPO), which is further processed into edible oil, used in energy production, such as biodiesel, or sold to palm oil refineries or biodiesel plants. Palm kernel is processed into palm kernel oil for consumption or dried for sale to palm kernel oil mills. By-products and wastes account for 78-82%, including empty fruit bunch (EFB), palm fiber (PF), palm kernel shell (PKS), decanter cake, and palm oil mill effluent (POME) (Sangkharak, 2014). It can be seen that the palm oil mill produces more by-products and wastes than CPO. The utilization of the by-products and wastes supports the transition to a circular economy; a system that uses resources effectively and sustainably. This system deals with recycling, waste management, and extending the lifetime of the product. Especially, this system focuses on circulating resources in each process of production. The ability to measure and verify the circularity through evaluation tools and indicators is essential to understand the current situation and find ways to improve in the future. Therefore, it is of great interest to measure product circularity in the oil palm industry to promote efficient and sustainable palm oil production and uses of oil palm resources.

1.2 Objectives

The objectives of this research study are as below:

- To analyze and quantify the environmental impact of FFB from oil palm plantations with different management practices and spatial characteristics.
- To apply the circularity indicator to identify the level of circularity of palm oil production with multiple products.

1.3 Scope of the study

In this study, the environmental assessment covers only the greenhouse gas emissions (GHG) caused by 1 ton of FFB from oil palm plantations with different management practices and spatial characteristics according to the IPCC method. The scope of the life cycle assessment study is Gate to Gate, from the transportation of raw materials to oil palm plantations, palm plantation, and the harvesting of FFB.

The circularity measurement is performed using Material Circularity Indicator (MCI) to calculate the circularity of oil palm products. The study begins with FFBs, which contain oil that is sent to palm oil mills. They produce 18% of CPO and the rest is by-products and wastes, including palm kernel, EFB, PF, PKS, decanter cake, palm oil mill effluent, and other impurities. CPO, palm kernel, EFB, PF, and PKS are considered multiple products of the oil palm industry in this study. Decanter cake, palm oil mill effluent, and other impurities are treated as waste, so they are not included in this study. The study uses the MCI calculation of oil palm products based on the Ellen MacArthur Foundation's formula. However, it is found that the unrecoverable waste formula according to the Ellen MacArthur Foundation's formula is not suitable with oil palm products and that it is later modified. After the MCI of oil palm products is calculated, it is applied with the company level methodology to calculate the circularity of palm oil production.

The data used in this study were obtained from field data collection of two oil palm plantation areas and two palm oil mills in Thailand. In addition, fertilizer application, percentage of ash, shelf life, oil extraction rate, and heating value data, and others are obtained from literature review and data from various websites and are used to calculate GHG and circularity of oil palm products and palm oil production.

The calculations in this study are based on the following assumptions; many of which are completely mentioned elsewhere in this thesis:

- Crude palm oil is considered using at the palm oil refinery.
- The efficiency of the recycling process of the co-product is 0.9 (J&T Recycling Corporation, 2021).
- To calculate the utility, the lifetime of the product is based on the shelf life of the product, the functional unit for crude palm oil and palm kernel is determined by the oil extraction rate, and EFB, PF, and PKS are determined by heating value (Gue, Ubando, Cuello, & Culaba, 2018).

1.4 Research timeline

The research action plan consists of eight activities as shown in Table 1.1.

Table 1.1 Research timeline

Activity	Academic year 2020					Academic year 2021							
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Literature review													
Data collection													
Calculation and correction of GHG and MCI results													
Proposal and progress examination													
Manuscript preparation													
Progress examination													
Thesis writing													
Final defense													

CHAPTER 2
LITERATURE REVIEW

The overview of the oil palm industry, concepts, theories, and related literature are presented in this chapter. It consists of literature related to oil palm plantation, life cycle assessment (LCA), and carbon footprint (CF), basic information about oil palm, the structure of the oil palm industry in Thailand, oil palm wastes and their utilization, and literature on circular economy (CE) and material circularity indicator (MCI).

2.1 Literature related to oil palm plantation, LCA, and CF

Hansuek, Chucherd, and Benchasri (2021) studied the growth of oil palm under different planting areas. It consists of 3 types of planting areas, which are hill area, plain area, and swamp area. They found that oil palm plantations in the plains had the best palm oil growth and yield. The results can be used as a guideline to decide the area of oil palm plantation for good growth and high yields in the future.

Sampattagul, Nutongkaew, and Kiatsiriroat (2011) studied the environmental impacts of 1 liter of palm oil biodiesel from the Life Cycle Assessment (LCA). The study was divided into three processes: agriculture, biodiesel production, and utilization. The study area is located in Krabi Province in the south of Thailand. The study used the EDIP method and European databases in the LCA software, SimaPro, for impact calculations. The results showed that the utilization of biodiesel had the highest environmental impact caused by CO and NO_2 emissions during combustion. The major impacts include ozone formation, terrestrial eutrophication, aquatic eutrophication, and acidification. It is followed by biodiesel production as a result of the use of methanol in transesterification to biodiesel. The major impacts include soil toxicity, aquatic eutrophication, radioactive waste, and global warming. The least impact is in agriculture resulting from the use of fertilizers and pesticides. The major impacts include the release of toxic substances into the air, water, and soil, radioactive waste, and global warming.

Giama, Mamaloukakis, and Papadopoulos (2019) applied the circularity and carbon footprint indicators to the process of producing stone wool and extruded polystyrene, two types of insulating materials mostly used in the construction sector.

The use of resources is a major aspect when considering the environmental impact of building materials. The production process is the most important process, in order to achieve a high degree of circularity and a low carbon footprint. They found that the increased use of recycled materials as feedstocks in the production process can increase the material circularity indicator and reduce the linear flow index. Another point from the study was the need to reduce the distances in the transportation of both raw materials and finished products. Because transportation is a significant environmental burden.

2.2 Basic information about oil palm

Oil palm is an important plant of Thailand in terms of agriculture, economy, and industrial. Oil palm contributes to the stability of food and energy in the country. When FFBs go through the extraction process, they produce approximately 18-22% of crude palm oil (CPO), which is processed into edible oil or used in energy production, such as biodiesel or sold to palm oil refineries or biodiesel plants. Palm kernel is processed into palm kernel oil for consumption or dried for sale to a palm kernel oil mill. By-products and wastes account for 78-82%, including EFBs, PFs, PKSs, decanter cakes, and palm oil mill effluents (POMEs) (Sangkharak, 2014).

Palm oil mills produce more by-products and wastes than CPO. There are utilizations of the by-products and wastes, such as using EFB to grow mushrooms, making organic fertilizer from sludge, using PF as boiler fuel to generate steam and electricity for palm oil mills. In addition, oil palm biomass with high calorific value, such as PKS, can either be sold as fuel or processed into briquettes or pellets. These increase the revenue for the palm oil mill and make more value-added for products. In addition, the recycling of resources in the production process reduces the amount of waste going to landfills.

The yield area from 2011 to 2019 increased at an average rate of 4.63% per year. In 2019, there was a yield area of 5,662,997 rai of oil palm, an increase of 5.48% from 5,352,641 rai in 2018. Most of the oil palm plantation areas are in the southern region, followed by the central and the northeast regions. Total FFB yield increased by an average rate of 4.30% per year, with a total yield of 16,408,440 tons in 2019, representing an average yield of 2,897 kg/rai/year (OAE, 2020). Figure 2.1 shows that the yield area increases in the same direction as the total yield.

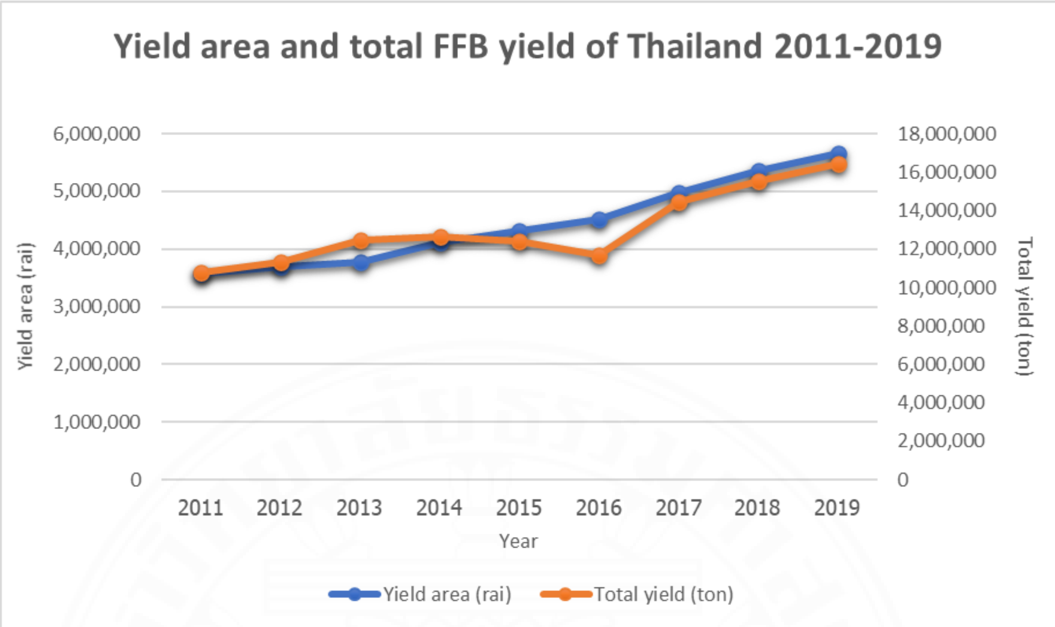

Figure 2.1 Yield area and total FFB yield of Thailand 2011-2019 (Source: Office of Agricultural Economics, 2020).

Environmental conditions that could affect the oil palm yield include rainfall, temperature, soil condition, sunlight, and transportation (ARDA, 2021; DOAE, 2012; Maneewan, Ranong, Sukkanta, Lampang, & Boonpeng, 2021).

2.3 Structure of oil palm industry in Thailand

Thailand's palm oil industry has the strength of having a fully integrated production chain (see Figure 2.2). It consists of four main parts:

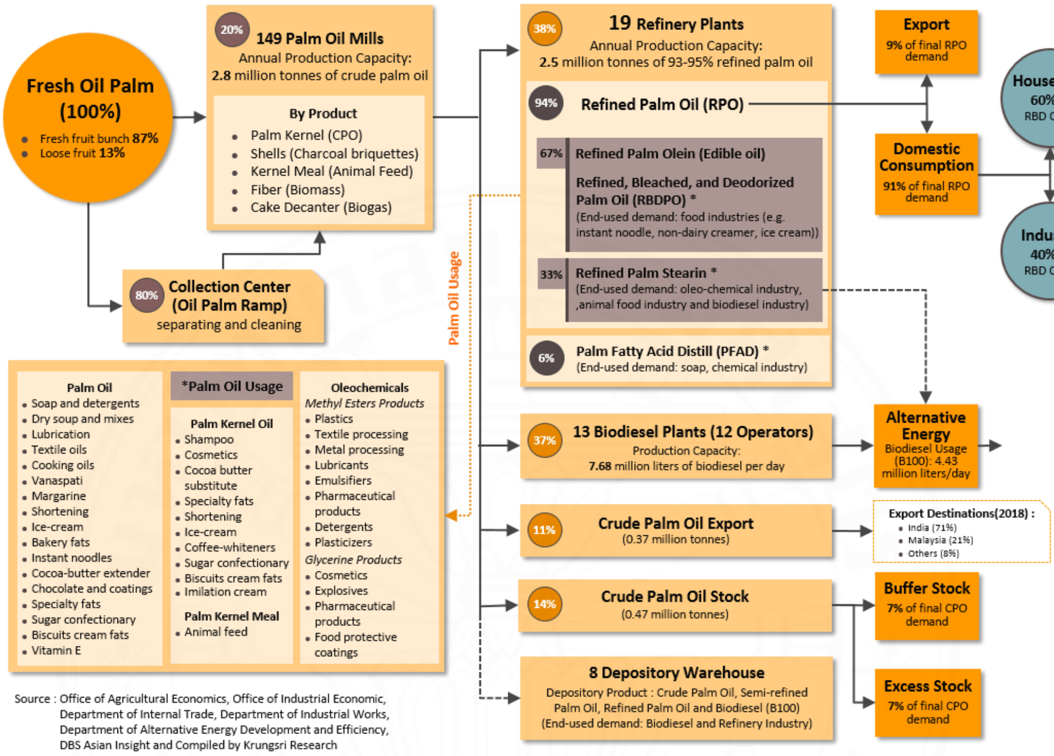

Figure 2.2 Supply chain of palm oil industry in Thailand (Sowcharoensuk, 2020).

- Oil palm cultivators (upstream): Most Thai farmers are smallholders with average planting area of 20-25 rai per person. The sale of fresh palm fruit is through middlemen or nearby palm oil fields. Due to the low production volume per person, it is not worth shipping the products directly to palm oil mills.
- Palm oil mills (midstream): It receives FFBs to make CPOs, with the oil extraction rate (OER) about 17-18% (Sowcharoensuk, 2020).
- Palm oil refineries (downstream): It receives CPOs, which is about 38% of the total CPOs. In the palm oil refining process, 94% yield of refined palm oil is achieved (67% refined palm olein + refined palm stearin 33%) and palm fatty acid distillate 6%.

- Biodiesel plants (downstream): It receives CPOs, which is about 37% of the total CPOs.

According to Sowcharoensuk (2020), the development of palm oil-related industries and the promotion of production/marketing by the authorities are found not being connected. For example, the food industry and the oleochemical industry are under the supervision of the Ministry of Industry, while the biodiesel industry is overseen by the Ministry of Energy. In addition, the production potential of crude palm oil in Thailand is still low, which is a limitation of competition in the world market. Although Thailand is the third-highest palm oil production in the world. It accounts for only 3.9% of global production, thus, it has no power in determining the price direction (Manprasert, 2020).

Approximately 75% of CPO is used for domestic consumption (see Figure 2.3), which is divided into two parts:

- 68% of domestic consumption is used as raw materials in various industries, including 1) biodiesel industries (49%), 2) food industries (16%), such as snacks, instant noodles, sweetened condensed milk, non-dairy creamer, margarine, shortened butter, ice cream, and vitamins, and 3) chemical and oleochemical industries (3%), such as soaps, cosmetics, and shampoos.
- 32% of domestic consumption is used as refined palm oil, which is a downstream palm oil processing industry (Sowcharoensuk, 2020).

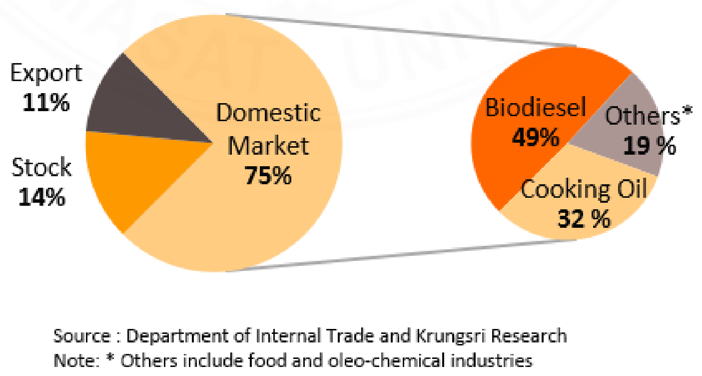

Figure 2.3 Domestic crude palm oil market in Thailand (Sowcharoensuk, 2020).

2.4 Oil palm wastes and their utilization

The oil palm industry produces a large amount of biomass. Most of them come from oil palm plantations and the crude palm oil extraction process. Biomass from oil palm plantations includes oil palm fronds and oil palm trunks. Wastes from palm oil mills include EFBs, PKSs, and PFs (Hambali & Rivai, 2017), as shown in Figure 2.4.

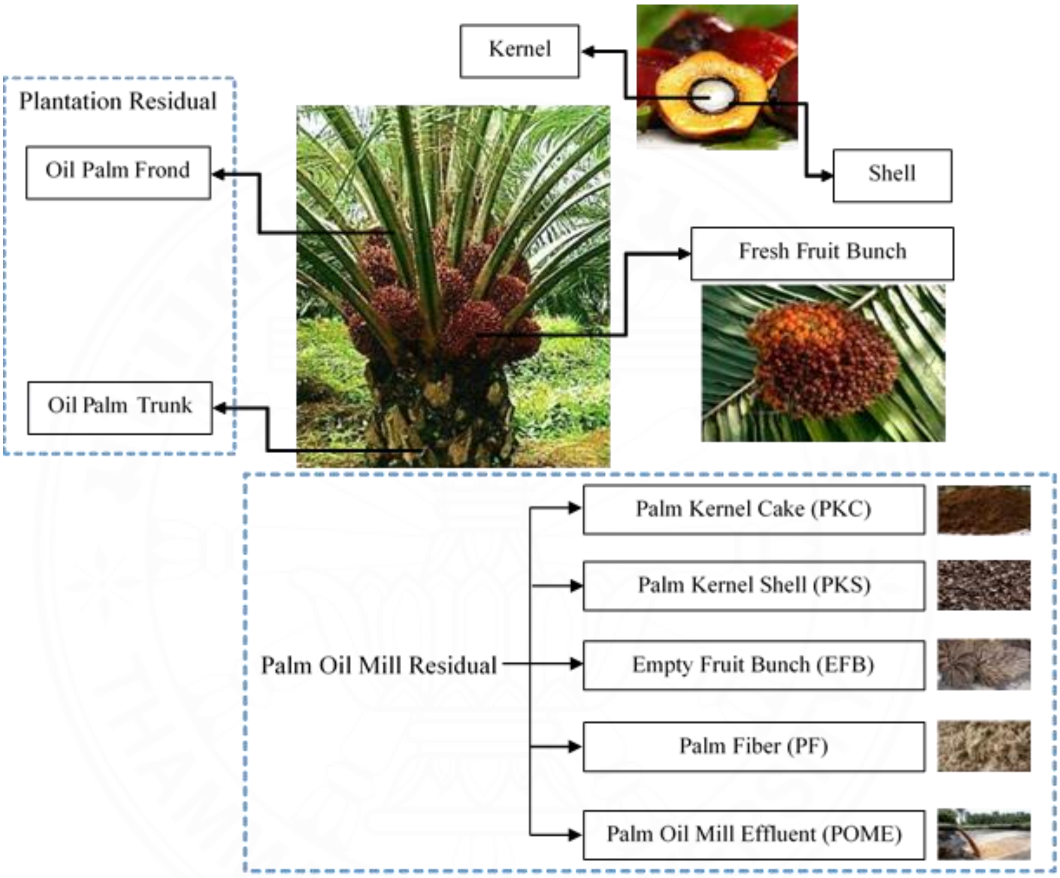

Figure 2.4 Wastes in the oil palm industry (Dungani et al., 2018).

According to DEDE (2013), the ratio of oil palm trunk per ton of FFB is 1, the ratio of oil palm frond per ton of FFB is 1.41, the ratio of EFB per ton of FFB is 0.32, the ratio of palm fiber per ton of FFB is 0.19, and the ratio of palm kernel shell per ton of FFB is 0.04. The percentages of moisture content of oil palm biomass from the highest to the lowest are oil palm frond (78%), EFB (58.60%), oil palm trunk (48.40%), PF (38.50%), and PKS (12%), respectively. On the other hand, the calorific values from the highest to lowest are PKS (16.90 MJ/kg), PF (11.40 MJ/kg), oil palm trunk (7.54 MJ/kg), EFB (7.24 MJ/kg), and oil palm frond (1.76 MJ/kg), respectively.

The heat energy potential obtained from EFB is calculated based on Equation 2.1

$$Q_{EFB} = M_{EFB} \times HV \quad (2.1)$$

where Q_{EFB} is the heat energy potential from EFB (MJ), M_{EFB} is the amount of EFB (kg), and HV is the heating value of the EFB (MJ/kg).

The electricity production potential from heat energy potential from EFB is achieved through Equation 2.2

$$PE_{EFB} = \frac{Q_{EFB} \times Eff_{plant}}{Operating\ Hour \times 3.6 \times 1{,}000} \quad (2.2)$$

where PE_{EFB} is the electricity production potential (MW), Eff_{plant} is the efficiency of the power plant (%), and Operating Hour is the working hour of the power plant (hour/year).

The electricity production potential assessment results according to the oil palm yield target of Alternative Energy Development Plan 2015 - 2036: AEDP2015 (see Table 2.1). It is found that in 2026, there will be 217.4 MW of electricity production from EFB; an increase of 1.3 times from 2019. In 2036, there will be 299.2 MW of electricity production from EFB, or 1.8 times higher than that in 2019 (DEDE, 2014).

Table 2.1 Potential for heat and electricity production from EFB

Year	Yield quantity (Mt)	EFB quantity (Mt)	Potential of heat production (GJ)	Potential of electricity production (MW)
2015	14.34	2.87	20,764,320	145.7
2017	15.4	3.08	22,299,200	156.4
2019	16.66	3.33	24,123,680	169.2
2026	21.4	4.28	30,987,200	217.4
2036	29.46	5.89	42,658,080	299.2

Sukiran, Abnisa, Wan Daud, Abu Bakar, and Loh (2017) studied the use of oil palm residues from oil palm plantations and the CPO extraction process in Malaysia. It is found that EFB is the most widely used product in the palm oil industry (see Figure 2.5). Because of its good organics and micronutrients, it is directly used as mulch in oil palm plantations. Moreover, it is used as a feedstock for composting and for the fiber production industry. PF and PKS are burned in boilers to generate steam and electricity, which are used in the CPO extraction process and other plant applications. Palm oil mills are sustainable in terms of energy. Because these oil palm wastes can be used as fuel to produce energy for the mills. The use of PKS and PF can provide enough energy to the palm oil mill for low-pressure and relatively inefficient boilers. In addition, processing PKS and PF into solid fuel through pellets or briquettes is an attractive alternative. PF can also be used as a filler for fiber-reinforced composites.

Trimmed and cropped oil palm leaves usually decompose naturally in the ground for soil fertilizer, erosion control, and long-term recycling of beneficial nutrients. A few other applications include raw material for ruminant feed. This suggests that oil palm fronds can replace grasses in the ruminant industry. In addition, oil palm fronds can be converted into pulp. Oil palm trunks need to be especially treated and processed in order to obtain acceptable wood due to their natural properties. Oil palm trunks are also used in plywood production and they can be used as a raw material for medium density fiberboard (MDF) (Kaniapan, Hassan, Ya, Patma Nesan, & Azeem, 2021).

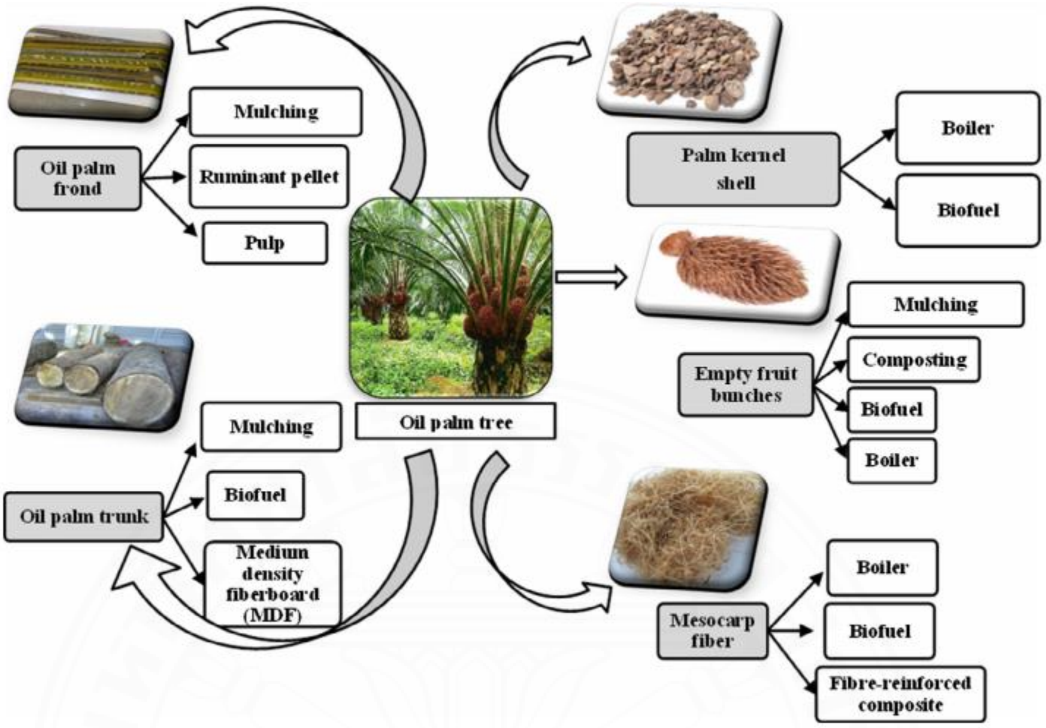

Figure 2.5 The utilization of oil palm solid wastes (Sukiran et al., 2017).

2.5 Literature related to CE and MCI

A linear economy is based on a one-way process of "Make-Use-Dispose" without being recycled and reused. It has negative impacts on the world. The circular economy, on the other hand, is the recycling of natural resources in the value chain and optimizing the management of wastes, raw materials, end-of-life products, and energy to return to circulating resources in the system through appropriate processes (SCG, 2021).

According to EMF (2019), the circular economy model distinguishes between two types of cycles:

- Biological cycle: Organic materials and products are returned to the bioeconomy in the process of regenerating natural systems.
- Technical cycle: Products, components, and materials are kept on the market in the highest possible quality and for as long as possible through repair and maintenance, reuse, refurbishment, remanufacturing and recycling.

These cycles are illustrated on the circular economy system diagram in Figure 2.6

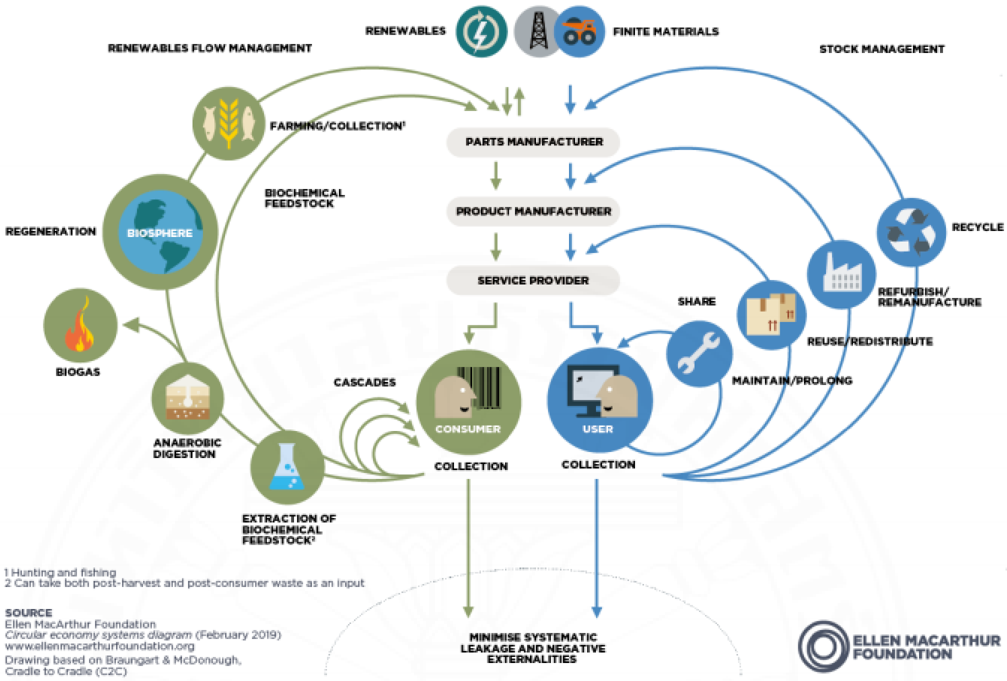

Figure 2.6 Circular economy system diagram (EMF, 2019).

With the transition to renewable energy sources. The circular model generates economic, natural and social capital based on three principles (EMF, 2019):

- Design out waste and pollution. A circular economy reveals and designs the negative impacts of economic activities that damage human health and natural systems. This includes emissions of GHGs and hazardous substances, air pollution, land and water pollution, structural wastes, such as traffic congestion, and unused assets, such as cars and buildings.
- Keep products and materials in use. The circular economy supports activities that maintain value in the form of energy, labor, and materials. This means durable design, reuse, remanufacturing, and recycling to keep products, components, and materials circulating in the economy. The circular system makes efficient use of bio-based materials by supporting many different applications before nutrients are returned to the natural system.

- Regenerate natural systems. The circular economy avoids the use of non-renewable resources as much as possible and maintains or improves renewable resources, such as returning valuable nutrients to the soil to support regeneration.

Kristensen and Mosgaard (2020) examined 30 indicators at the micro-level that clearly support a circular economy. One of the most interesting indicators is the Material Circularity Indicator (MCI), as it is one of the first circular economy indicators that attracts both practical and academic attention. This indicator is linked to the measure of product recycling, which is in ratio form. It also considers the generation of waste in the process and the utility of the product, which is determined by the actual lifetime and functionality of the product in comparison with the same industrial product. Significantly increased publications may reflect a growing awareness of the need to measure and document a circular economy in relation to products and organizations. The number of publications on micro-level indicators has been increasing since 2016, which may have begun with the development of MCI (Ellen MacArthur Foundation & Granta Design, 2015). Circular economy development has shifted from the strategic level to the operational level. This may explain the increasing focus in recent years on micro-level indicators for the circular economy.

Several studies have applied the MCI to assess product-level circularity. Saidani, Yannou, Leroy, and Cluzel (2017), for example, presented three tools that can be used to measure product performance following the circular economy concept, namely MCI, Circular Economy Toolkit (CET), and Circular Economy Indicator Prototype (CEIP). MCI is proposed by Ellen MacArthur Foundation (2015). It is a tool for European companies to evaluate the performance of the products and business models in the circular economy. The indicator is last revised to cover biomaterials and address some of the challenges associated with the combination of biological and technical materials. It also identifies risk-based complementary metrics for biomaterials and defines energy recovery conditions as part of a circulating strategy (EMF, 2019). On the other hand, CET is a question-and-answer assessment tool used to identify the improvement of product circularity. CEIP is a question-weighted assessment divided into five stages of the life cycle. It is scored in percentage terms and has a diagram showing the total score for each stage in the life cycle (Cayzer, Griffiths, & Beghetto, 2017). Gue et al. (2018) proposed a framework of MCI to assess the circularity of microalgae biodiesel. They also compared it with Jatropha biodiesel, which is a reference feedstock because of its similar popularity. In addition, they also used the life cycle assessment (LCA) framework to assess the environmental impact of products. The results showed that Jatropha had less environmental impact than microalgae in all three impact categories, including Resource Depletion, Bulk Waste, and Global Warming Potential. MCI of microalgae biodiesel was 0.04 higher than that of Jatropha biodiesel. This means that microalgae biodiesel has better material circularity. Razza, Briani, Breton, and Marazza (2020) modified the MCI calculation formula for use with bio-based and biodegradable (BB) products and applied it to BB mulch film. The results showed that considering the proportion of 30% bio-based and 70% fossil-based, MCI of BB mulch film was calculated as 0.37, it is less than 0.5 indicates linearity related to the bio-based feedstock content. Rocchi, Paolotti, Cortina, Fagioli, and Boggia (2021) proposed a modification of MCI formula for use with the biological cycle. The modified MCI is applied to poultry production, the mass of virgin raw material is related to animals and their feed. They also considered feed conversion rate (FCR), which is the ratio between input (feed) and output (meat) involved in production. The utility is calculated using the utility conversion factor, which is calculated from the mortality rate. The result shows a modified MCI value of 0.4872. Values below 0.5 may be considered linear rather than circular. As a result, intensive broiler production was confirmed mostly linear production with high resource consumption. Pavlovic et al. (2020) applied a company-level MCI to a company in the Republic of Serbia that focuses on the production of paper and cardboard packaging and cupcake liner. This study used the normalizing factor as the mass of the product and concluded that the circular economy was not total newness because the obtained MCI was 0.47. This means that the company operates according to the economic model, which is between linear and circular.

CHAPTER 3
RESEARCH METHODOLOGY

This study uses GHG emissions assessment of 1 ton of FFB from oil palm plantations with different plantation management practices and spatial characteristics and a measure of the circularity of palm oil production in which many products are produced. The study assesses GHG emissions by IPCC methodology and measuring the circularity using the MCI from Ellen MacArthur Foundation.

3.1 Life cycle assessment

Life Cycle Assessment (LCA) is a tool for analyzing and quantifying the environmental impact of products, production processes, and activities. It is considered throughout the life cycle, covering raw material acquisition, manufacturing process, transportation, distribution, use, and end-of-life product disposal, which can be said to consider the product from birth to death (Cradle to Grave). It indicates the amount of energy and raw materials used and the pollution released to the environment, as well as environmental impact assessment in order to find ways to improve products and production processes to reduce environmental impacts (Sampattagul, 2012).

LCA consists of four main steps, including 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (see Figure 3.1).

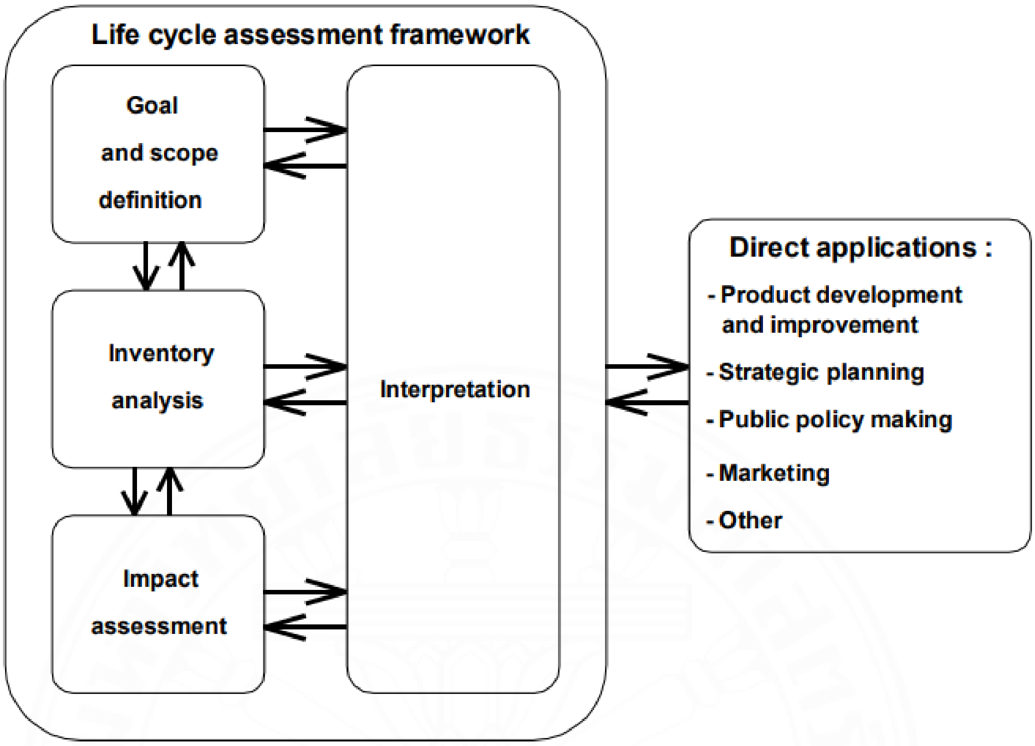

Figure 3.1 Components of LCA (Jungbluth, 2020).

Step 1: Goal and scope definition step, this step identifies the purpose of the study and the manner in which the results of the study are applied, as well as the scope of the study. How much the results are achieved will depend on the setting of the goal and the scope of the study.

Step 2: Once the goal and scope definition step is completed, the second step of LCA is to create a database. For this step, a list of life cycle inventory (LCI) is made and the data related to the product life cycle is collected. Data collected are incoming data (raw materials, energy, processing chemicals) and outgoing data (product, co-product, emissions to air, water, soil, and waste).

Step 3: Impact assessment is the third step of LCA. It is categorized and compared the significance of each type of impact. Its purpose is to convert the inventory data obtained from the collection of the incoming and outgoing substances of the production system from the inventory analysis step into an environmental impact indicator to indicate its capacity to cause the environmental impact.

Step 4: Interpretation is a step for analyzing the data outcomes and proposing solutions or improving environmental impacts throughout the life cycle to reduce the overall quantity and severity of the issue of interest. Analysis and summary of results, limitations, and recommendations are finally achieved through results interpretation (Jungbluth, 2020).

Life Cycle Inventory (LCI) is one step of LCA, which is the most time-consuming and difficult. This leads to the collection of environmentally relevant data from the process that objectives and goals have been set in the first step, as well as the modeling of the product system for calculating the amount of incoming and outgoing substances. The flow diagram of energy, raw materials, waste, and pollutants entering and leaving the system as a whole as the resources and energy used or the emissions into the air, water, and soil. These data are used to determine the environmental impact throughout the product life cycle. Data collection should be in a format that is easy to understand, corresponding to the process flow stream.

Allocation can be used in the case that data must be allocated when doing LCA. It may be that our system is difficult and complex, making data collection or data reference difficult. It, therefore, requires data allocation, which may be achieved by increasing the scope of the system. To make it able to collect more data or allocate the impact more match what we study. For example, if we want to analyze the impact caused by the use of electricity. Electricity generation comes from many sources, each of which causes different environmental impacts, thus requiring allocation. This way it is better to go to increase the scope of the system. The allocation is the division of the incoming and/or outgoing substances of a process or system of the studied product to the target product and other products occurring in the product system. Allocation takes place in the case that there are multiple products in the same period and utilities are shared between the products. There are several types of allocations, but the most common are the considerations based on mass, volume, energy, and economic value (sales price or net cost) and considering based on the number of finished products.

After the inventory analysis step is completed, the next step is Life Cycle Impact Assessment (LCIA). The purpose of LCIA is to assess the environmental impact of the system studied from the resource utilization and emissions data obtained from the inventory analysis step by classifying, grouping, and comparing the impacts in order to prepare data for interpreting the environmental impact of product systems. However, there are many methods that can be used to assess environmental impacts, either by calculating manually or relying on software assessments.

3.2 GHG emissions assessment

Greenhouse gas (GHG) is a gas that has the ability to absorb heat radiation or infrared radiation well. These gases are necessary to maintain the temperature in the earth's atmosphere. If the earth's atmosphere does not have the GHGs in the atmosphere, then daytime temperatures are very hot, and nighttime is very cold. Because these gases absorb heat radiation during the day and then gradually emit heat at night, the temperature in the earth's atmosphere does not change abruptly (TGO, 2020).

There are many gases that have the ability to absorb radiation and are classified as GHGs. They are both naturally occurring gases and produced by human activities. Major GHGs are water vapor, carbon dioxide, ozone, methane and nitrous oxide, and Chlorofluorocarbon (CFC). However, only seven GHGs are regulated by the Kyoto Protocol including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbon (PFC), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). On the other hand, GHG produced by human activities is CFC, which is used as a refrigerant and in foam production; though, it is not defined in the Kyoto Protocol but in the Montreal Protocol (TGO, 2020).

Calculation of GHG emissions is based on recommendations in the calculation guide of the Intergovernmental Panel on Climate Change (2006 IPCC Guidelines for National Greenhouse Gas Inventories) and referred to the potential to cause Global warming (Global Warming Potential: GWP) where carbon dioxide (CO_2) equal to 1, methane (CH_4) equal to 25, and nitrous oxide (N_2O) equal to 298 (IPCC, 2007; TGO, 2020). The amount of GHG emissions is given by Equation 3.1.

$$CO_2\ equivalent\ of\ each\ process\ =\ Activity\ Data\ \times\ Emission\ Factor \qquad (3.1)$$

where Emission factor is a value that shows the amount of GHG emissions per unit. ($kgCO_2eq$/unit)

The conversion of GHGs to CO_2 equivalents is multiplied by the GWP of each GHG (see Equation 3.2).

$$GHG\ emissions = Amount \times GWP \tag{3.2}$$

Calculation of nitrous oxide from N fertilizer application is given by Equation 3.3.

$$N_2O\ (kg) = Amount\ of\ N\ in\ fertilizer\ (kg) \times Emission\ Factor \times 44/28 \tag{3.3}$$

where Emission factor is 0.01 (Default emission factor to estimate direct N_2O emissions from managed soils) according to IPCC.

The amount of GHG emissions (transportation) is achieved through Equation 3.4.

$$GHG\ Emissions = Amount \times Distance \times Transport\ Factor \tag{3.4}$$

3.3 Material circularity indicator

Material Circularity Indicator (MCI) is proposed by Ellen MacArthur Foundation, which is a tool using to assess material circularity performance. It considers product recycling, including the wastes generated by the manufacturing process (Kristensen & Mosgaard, 2020). It also takes into account the utility of the product through its lifetime and the functional units compared to the same industrial product. It is represented in a numeric form, ranging from 0-1, where 1 indicates fully circular product and 0 means no circulating of material (fully linear product) (EMF, 2019). A diagram of parameters used for the calculation of product-level MCI is as shown in Figure 3.2.

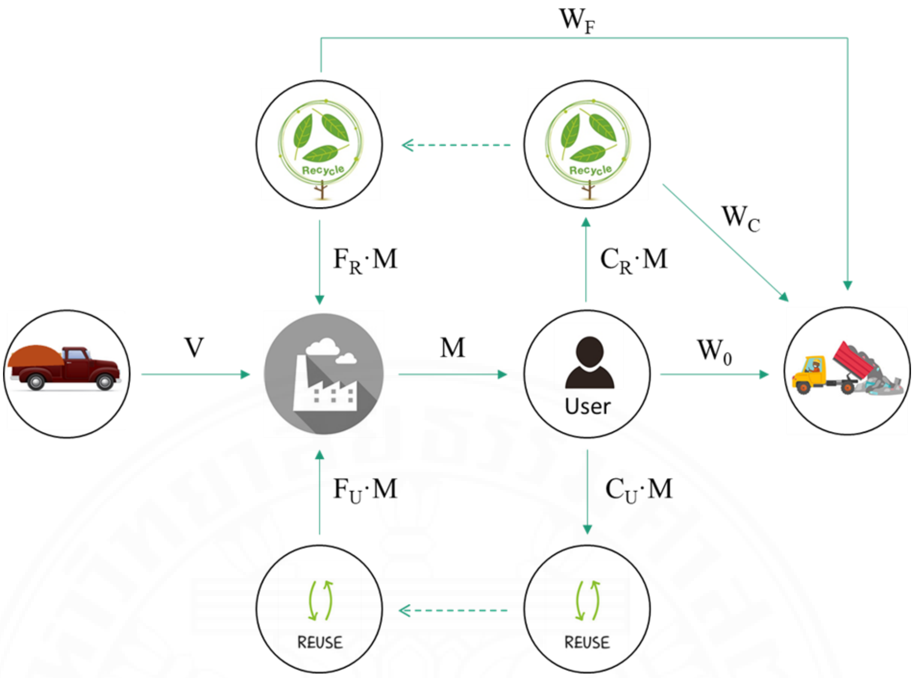

Figure 3.2 Diagram showing the parameters used to calculate the product-level circularity based on Ellen MacArthur Foundation.

To calculate the MCI, a number of steps are conducted. The first parameter to be calculated is virgin feedstock (V). This parameter links to recycling, reuse, and biological material in the virgin raw material (see Equation 3.5).

$$V = M(1 - F_R - F_U - F_S) \tag{3.5}$$

where M is the mass of the final product, F_R is the fraction of recycled feedstock, F_U is the fraction of reused feedstock, and F_S is the fraction of biological feedstock from sustainable production. The unrecoverable waste going to landfill or energy recovery (W_0) is next calculated in Equation 3.6. C_R is the fraction of the co-product, waste, and oil loss collected for a recycling process, which produces the waste from the recycling process (W_C). C_U is the fraction of the co-product, waste, and oil loss collected for reuse, C_C is the fraction of the co-product, waste, and oil loss collected for the composting process, and C_E is the fraction of the co-product, waste, and oil loss collected for energy recovery.

W_C depends on the efficiency of the recycling process (E_C) and C_R, as shown in Equation 3.7.

$$W_0 = M(1 - C_R - C_U - C_C - C_E) \quad (3.6)$$

$$W_C = M(1 - E_C)C_R \quad (3.7)$$

There is also waste generated from the production of recycled feedstock (W_F). This waste depends on the efficiency of the recycling process used to produce the recycled feedstock (E_F), as shown in Equation 3.8.

$$W_F = M\frac{(1-E_F)F_R}{E_F} \quad (3.8)$$

In contrast to the equation for W_C (Equation 3.7), the equation for W_F (Equation 3.8) has the recycling efficiency E_F in the denominator. This is because $M \cdot F_R$ in the derivation of W_F is the mass of material leaving the recycling process. To produce this amount $M \cdot F_R$ of recycled material, a mass $(M \cdot F_R)/E_F$ of material entering the recycling process is needed.

For example, M = 100; F_R = 0.8; E_F = 0.4:

Recycled material from recycling process = 100*0.8 = 80

Material entering the recycling process = (100*0.8)/0.4 = 200

Waste generated from recycled feedstock process = 100*(1-0.4)*0.8/0.4 = 120

In calculating the overall amount of unrecoverable waste (W), it is important to consider both W_C and W_F. In general, however, if W_C and W_F are added together, this would double count some or all of the waste generated during two recycling processes.

This problem is most easily explained by a closed-loop example, where E_C and E_F both refer to the same recycling process. Consider a product made from 50% recycled material (F_R = 0.5), collected entirely for recycling at the end of its use (C_R = 1), and used for new product manufacture such that E_C = E_F = 0.5.

For example, M = 100 and using the definitions above, it now follows that W_C = 100*(1-0.5)*1 = 50 is equal to W_F = 100*(1-0.5)*0.5/0.5 = 50. Considering both W_C and W_F in full would clearly double count the waste from the recycling process.

A 50:50 approach is therefore used, such that W_C and W_F are given equal emphasis. This approach assigns 50% of W_F to the product that the recycled feedstock came from, and 50% of W_C to the product that will use the collected and recycled material.

The overall amount of unrecoverable waste (W) can then be obtained from Equation 3.9.

$$W = W_0 + \frac{W_F + W_C}{2} \quad (3.9)$$

Linear Flow Index (LFI), which indicates the linearity of the product, is next calculated (see Equation 3.10). This value ranges from 0-1, where 1 represents full linearity and 0 represents nonlinearity.

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \quad (3.10)$$

The utility factor F(X) is also calculated based on the lifetime of the product and the functional unit of the product, which are combined to create the utility (X), see Equations 3.11 and 3.12.

$$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right) \quad (3.11)$$

$$F(X) = \frac{0.9}{X} \quad (3.12)$$

where L represents the actual average lifetime of a product, L_{av} represents the average lifetime of the same industrial product, U is the actual average number of functional units of the product, and U_{av} is the average number of functional units of the same industrial product.

The MCI of the product (MCI_P) is finally calculated using Equation 3.13.

$$MCI_P = 1 - LFI \cdot F(X) \quad (3.13)$$

The MCI of the company (MCI_C) is also calculated using Equation 3.14. It is based on the weighted average of MCI_P.

$$MCI_C = \frac{1}{N_C} \sum_{\alpha} (N_{P(\alpha)} \cdot MCI_{P(\alpha)}) \quad (3.14)$$

where N_C is the summation of the normalizing factor used, N_P is the normalizing factor of each product, and MCI_P is the MCI value of each product.

However, it is found that the unrecoverable waste formula according to Ellen MacArthur Foundation's formula is not suitable with oil palm products and that it is later modified. The reason for the need to modify the unrecoverable waste formula can be explained in the example below. Considering CPO as a product, so M is the mass of CPO. The use of CPO takes place at a palm oil refinery. CPO is transformed to Refined Bleached and Deodorized Palm Oil (RBDPO). There is also a co-product, Palm Fatty Acid Distillate (PFAD) that can be used for soap and oleochemical industry and waste, Bleaching Earth that is sent to landfills. There is also an oil loss from the refining process that can be reused at a palm oil refinery.

For example, $M = 18$; $M_{Co\text{-}product} = 0.92$; $M_{Oil\ loss} = 0.015$; $M_{Waste} = 0.18$

So, $C_R = 0.92/18 = 0.0511$, $C_U = 0.015$

$W_0 = 18*(1-0.0511-0.015) = 16.8102$

This shows that the amount of unrecoverable waste is very high, which can mean a large amount of CPO is sent to landfills. This is not true because CPO has already transformed into RBDPO.

The modification of formulas is performed in the unrecoverable waste part to suit oil palm products. The diagram of parameters for the modified MCI calculation of oil palm products is as shown in Figure 3.3.

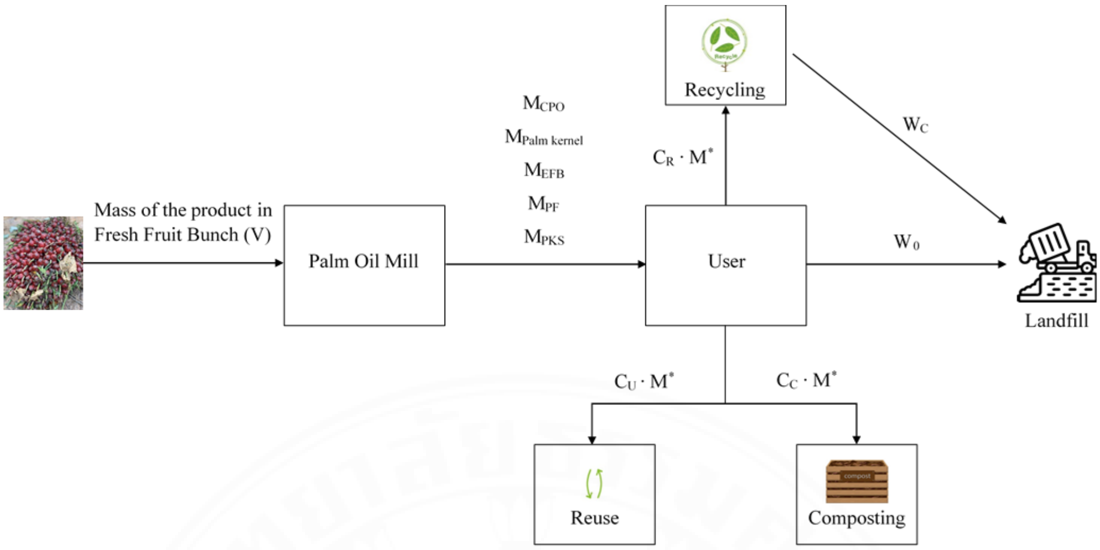

Figure 3.3 Diagram showing the parameters used to calculate the product-level circularity based on the modified unrecoverable waste formula.

The calculation formula of the unrecoverable waste after use (W_0) was modified for use with oil palm products as follows:

$$W_0 = M^*(1 - C_R - C_U - C_C - C_E) \quad (3.15)$$

where M^* is the sum of the mass of the co-product, waste, and oil loss. C_R is the fraction of the co-product, waste, and oil loss collected for the recycling process, C_U is the fraction of the co-product, waste, and oil loss collected for reuse, C_C is the fraction of the co-product, waste, and oil loss collected for the composting process, and C_E is the fraction of the co-product, waste, and oil loss collected for energy recovery.

The amount of waste generated in the recycling process used to recycle the co-product, waste, and oil loss is expressed as W_C. This waste depends on the efficiency of the recycling process used to recycle the co-product, waste, and oil loss (E_C). This waste is determined by:

$$W_C = M^*(1 - E_C)C_R \quad (3.16)$$

When considering CPO as a product (see Figure 3.4), the calculation based on the modified unrecoverable waste formula is shown in the example below.

For example, M = 18; $M_{Co\text{-}product}$ = 0.92; $M_{Oil\ loss}$ = 0.015; M_{Waste} = 0.18

So, $M^{*} = 0.92+0.015+0.18 = 1.115$, $C_R = 0.92/1.115 = 0.8251$, $C_U = 0.0135$

$W_0 = 1.115*(1-0.8251-0.0135) = 0.18$

This makes sense since the unrecoverable waste after use that is sent to landfills is equal to the mass of the waste, Bleaching Earth.

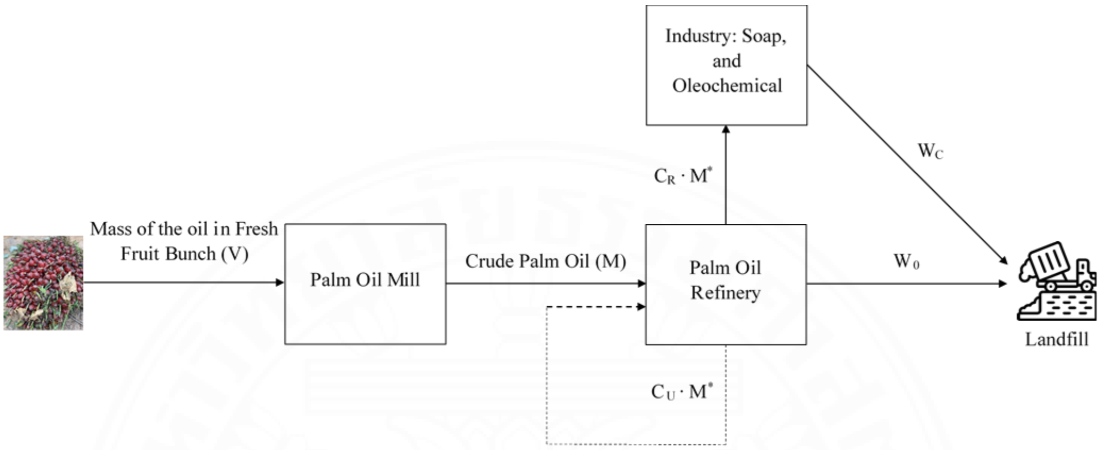

Figure 3.4 Diagram showing the parameters used for MCI calculation of CPO based on the modified unrecoverable waste formula.

As the palm oil mill produces multiple products, the company-level MCI (MCI_C) is also applied. It is obtained as a weighted average of MCI_P. In order to combine MCI_P, a normalizing factor is used to determine a weighted average of MCI_P.

The next chapter presents the results of LCA, the results of an assessment of GHG emissions of FFB from two case studies, the results of the circularity measurement of oil palm products, and the results of the circularity measurement at the company level.

CHAPTER 4
RESULT AND DISCUSSION

This research assesses the GHG emissions of one ton of FFB from two sites in Thailand with different management practices and spatial characteristics according to the IPCC method. Regarding the importance of the circular economy, the circularity of multiple products in the oil palm industry is measured using MCI. The results are explained in this chapter.

4.1 Results of LCA

4.1.1 Goal and Scope

- The goal of the study is to assess the environmental impact only of GHG emissions, considering FFB production from oil palm plantation areas with different plantation management practices and spatial characteristics.
- Functional unit: This study assesses GHG emissions caused by 1 ton of FFB.
- The scope of the LCA study covers the transportation, plantation, and harvesting stages (Gate to Gate), as shown in Figure 4.1.

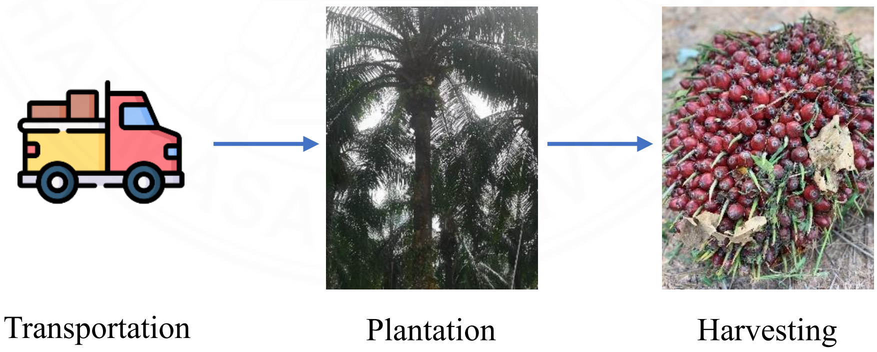

Figure 4.1 Scope of the LCA study.

4.1.2 Inventory Analysis

Analyze each stage of FFB production before collecting data in order to obtain complete data. When knowing each stage then collect the incoming and outgoing substance data in each stage, as shown in Figure 4.2. Primary data are collected from two oil palm plantation areas. Some data, such as fertilizer application is achieved through secondary data as shown in Table 4.1.

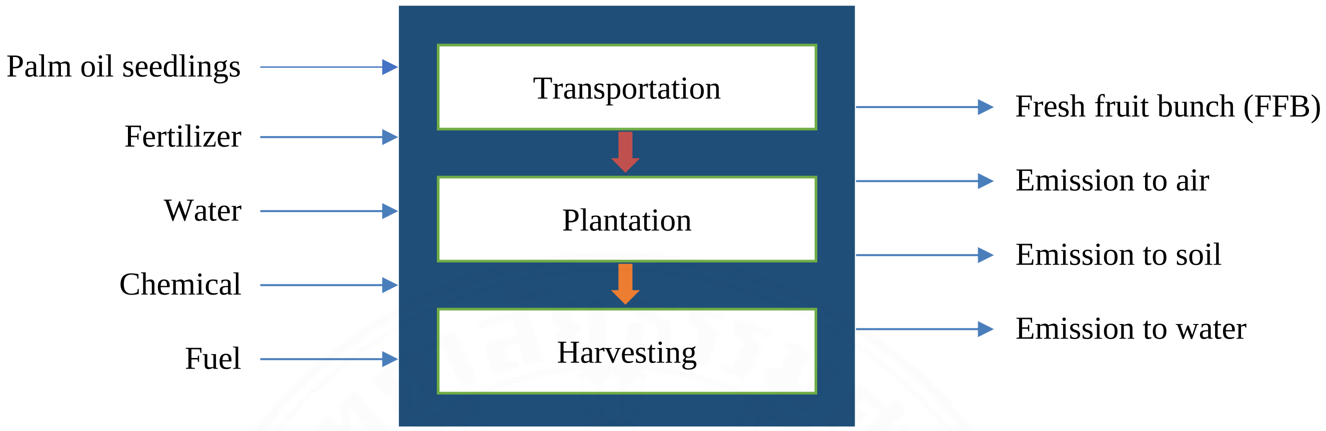

Figure 4.2 Incoming and outgoing substances of oil palm plantations.

Table 4.1 Collecting data used in GHG assessment

Primary data	**Secondary data**
Ask directly from farmers Case 1 Collecting field data from three farmers Case 2 Collecting field data from one oil palm plantation	Search from reliable sources. It can be obtained from the following reference sources: • Oil palm plantation management from RD Kasetpattana Co., Ltd. • Emission factor from Thailand Greenhouse Gas Management Organization (Public Organization) • Research papers published international, national, and thesis • Agricultural production data from Office of Agricultural Economics

For the palm plantation, it is found that 1 rai can be planted with 22 trees, and the average age of one palm tree is about 25 years. The palm tree starts to produce palm fruit at the age of three years and can be harvested every 15-20 days, or two times a month, or three times every two months. The case study of oil palm plantations with different management practices and spatial characteristics is as shown in Figure 4.3.

Case 1 Case 2

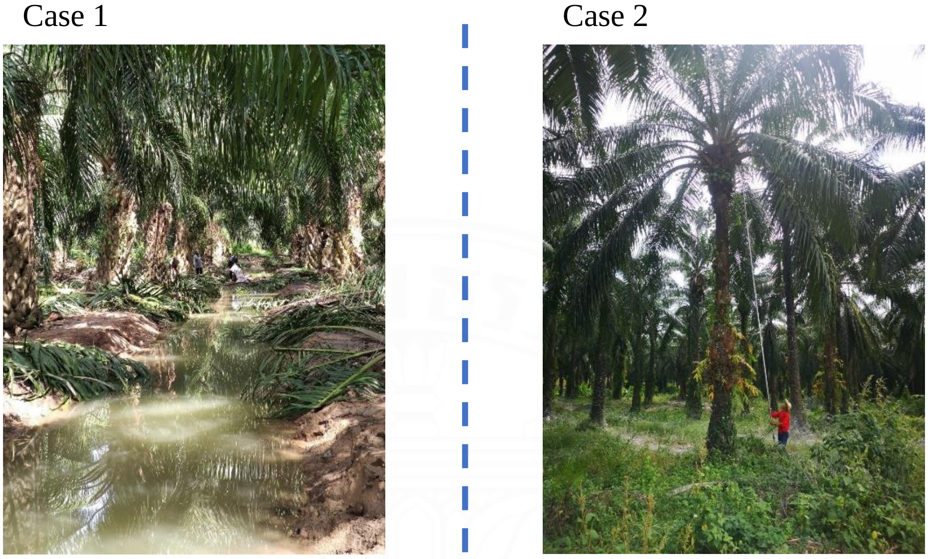

Figure 4.3 Two case studies of oil palm plantations.

Case 1 is an oil palm plantation on an area with a trench of water. This area was used to grow oranges in the past. It has poor soil quality and farmers have to use large amounts of fertilizers. In the palm harvesting process, FFBs are loaded onto boats and channeled along the trench to the conveyor belts. They are conveyed through the belts up to the pickup truck. The boat does not use fuel, while the conveyor belt is powered by gasoline. For Case 1, data are collected from three farmers. The number of rai, the age of palm trees, and the yields are not the same (see Table 4.2). Data collected are managed in units per rai per year. It is then converted to units per ton FFB per year by dividing by FFB yields. Because the data collected come from three farmers, the amount of material used by each farmer is not the same. Therefore, a weighted average using the number of rai is needed to obtain an average quantity of material used that is representative of this area.

Table 4.2 Data collection from three farmers

No.	Number of rai	Age of palm trees	FFB yields (ton/rai/year)
1	60	Palm trees are 13 years, 10 years, and 6 years.	4.50
2	17	Palm trees are only 4 years.	2.25
3	6	Palm trees are 15 years but have a problem with tree dying.	1.50

Case 2 is an oil palm plantation on the plain area. The yield from this area is relatively low as palm trees in this area are all mature, almost 25 years old. In the palm harvesting process, FFBs are loaded onto a palm tractor. Then they are transported to the pickup truck. The palm tractor is powered by diesel fuel. For case 2, data are collected from only one oil palm plantation area with FFB yields of 2.70 ton/rai/year, so in this case, no weighted average is needed. Data collected are managed in units per rai per year. It is then converted to units per ton FFB per year by dividing by FFB yields.

Life cycle inventory (LCI) of 1 ton of FFB production of cases 1 and 2 are as shown in Tables 4.3 and 4.4, respectively.

Table 4.3 List of incoming substances of oil palm plantations for Case 1

Incoming substance	Unit	Amount
Raw material		
Palm seedlings	kg	2.60
Energy		
Gasoline	L	0.20
Fertilizer and chemical		
Fertilizer N	kg	10.01
Fertilizer P	kg	5.49
Fertilizer K	kg	19.28
Fertilizer Mg	kg	0.42
Fertilizer B	kg	0.04
Paraquat	L	0.82

Table 4.4 List of incoming substances of oil palm plantations for Case 2

Incoming substance	Unit	Amount
Raw material		
Palm seedlings	kg	3.21
Energy		
Diesel	L	2.00
Fertilizer and chemical		
Fertilizer N	kg	9.64
Fertilizer P	kg	0.80
Fertilizer K	kg	19.04
Fertilizer Mg	kg	10.02
Fertilizer B	kg	1.14
Paraquat	L	0.22

From the preliminary analysis, this is because the data collected in Case 1 came from three farmers, each farmer used unequal materials due to the age of the oil palm, and their practices are different. Three farmers had unequal FFB yields. Therefore, a weighted average is required to obtain the amount of material used for this area. It was found that the area in Case 1 used more fertilizers and chemicals than that in Case 2 due to poor soil conditions and some farmers had problems with tree dying, weeds, and insects. On the other hand, Case 2 had higher fuel consumption. It leads to high fuel production and fuel combustion, resulting in high emissions.

4.1.3 Impact Assessment

- Using LCI collected to assess GHG emissions
- Calculation of GHG emissions is based on the IPCC guidelines.

4.1.4 Interpretation

- Analyze which stage has the most GHG emissions. This will lead to solutions and improvements to reduce GHG emissions that occur in the future.

4.2 Results of GHG emissions assessment

The results show in Case 1, the GHG emission is 102.57 kg CO_2eq, while in Case 2, the GHG emission is 97.50 kg CO_2eq. It can be seen that Case 1 has more emissions than Case 2 because Case 1 uses high amounts of N-fertilizer and the chemical in the plantation stage. Whereas, Case 2 uses higher fuel than Case 1 in the harvesting stage, which results in high emissions. The use of the N-fertilizer in Case 1 is slightly more than that in Case 2, resulting in the N_2O of Case 1 is slightly higher than that in Case 2. In addition, Case 1 uses higher chemicals than that in Case 2. These make the total emissions in the plantation stage of Case 1 higher than those in Case 2. This may be because the area in Case 1 is originally used for orange plantation. Once it is switched to palm plantations, with poor soil quality, the area needs large amounts of N fertilizer. A summary of the calculation results of GHG emissions by stages is as shown in Table 4.5 and a comparison of GHG emissions by stages in percentage is as shown in Figure 4.4.

Table 4.5 Results of the calculation of GHG emissions by stages

Stage	**GHG emission (kg CO_2eq)**	
	Case 1	**Case 2**
Plantation	101.63	90.82
Harvesting	0.50	6.08
Transportation	0.44	0.60
Total	**102.57**	**97.50**

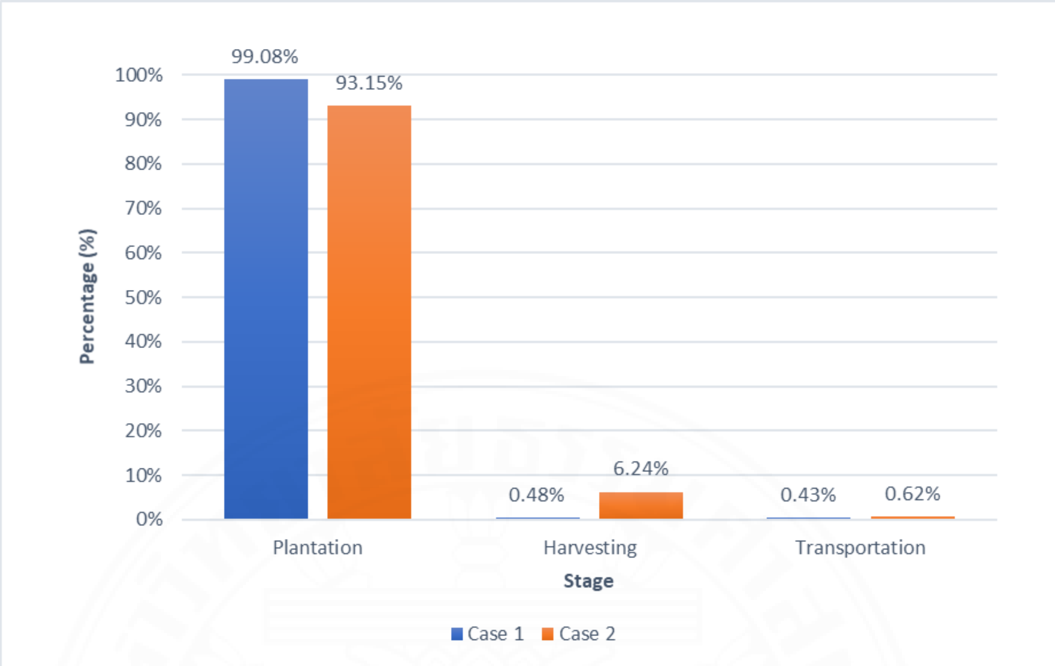

Figure 4.4 Comparison of GHG emissions by stages in percentage.

Figure 4.4 shows that more than 90% of GHG emissions in both cases come from the plantation stage. The plantation stage uses a lot of materials in particular N-fertilizer and the chemical. N-fertilizer causes N_2O emission, which is one of the GHGs affecting global warming. The harvesting and transporting stages have very low GHG emissions compared to the plantation stage. In Case 2, the harvesting stage has high fuel consumption. This results in high fuel production and fuel combustion. In both cases, GHG emissions can be reduced by increasing FFB yields as the higher the FFB yield, the lower the GHG emissions per unit of FFB yield.

4.3 Results of circularity measurement at the product-level

The circularity measurement is performed using MCI to calculate the circularity of multiple products of the oil palm industry. The study begins with FFBs, which are sent to palm oil mills. They produce CPO, palm kernel, EFB, PF, PKS, decanter cake, palm oil mill effluent, and other impurities. CPO, palm kernel, EFB, PF, and PKS are considered as the multiple products of the oil palm industry in this study. Decanter cake, palm oil mill effluent, and other impurities are treated as waste, so they are not included in this study. The circularity of multiple products in the oil palm industry is calculated using the parameters and equations for calculating MCI based on the modified unrecoverable waste formula.

The quantity data of multiple products consists of FFB and multiple products are obtained from two palm oil mills in Thailand with different production capacities. Data used to calculate MCI are collected through direct fieldwork and secondary sources as shown in Table 4.6.

Table 4.6 Collecting data used in MCI calculation

Primary data	**Secondary data**
Ask directly from two palm oil mills	Search from reliable sources. It can be obtained from the following reference sources: • Announcement of Ministry of Industry • Research papers published international • Report of Cluster of Edible Oil Industries in Krishnapatnam Port area, SPSR Nellore district, Andhra Pradesh • Department of Alternative Energy Development and Efficiency, Ministry of energy

The general information of the two palm oil mills is as follows:

- A small palm oil mill has a production capacity of 30 tons per hour. It operates 24 hours a day and 330 day a year.
- A large palm oil mill has a production capacity of 120 tons per hour. It operates 24 hours a day and 330 day a year.

The proportion of multiple products obtained from the palm oil mill is as shown in Table 4.7.

Table 4.7 Proportion of multiple products from palm oil mills

Input	Proportion (%)	
	Small palm oil mill	Large palm oil mill
FFB	100.00%	100.00%
Output	**Proportion (%)**	
	Small palm oil mill	**Large palm oil mill**
CPO	18.00%	18.00%
Palm kernel	6.00%	6.00%
EFB	23.00%	20.00%
PF	13.00%	14.00%
PKS	6.00%	6.00%
Decanter cake	2.50%	4.00%
POME	21.50%	21.00%
Other impurities	10.00%	11.00%

Data are managed in units per year. It is then converted to units per ton CPO per year by dividing by the quantity of CPO. Because data are collected from two palm oil mills, the quantity of each product obtained from both palm oil mills is not the same. Therefore, a weighted average using the quantity of FFB is needed to obtain an average quantity of each product as shown in Figure 4.5.

List	Unit	Unit/year		Unit/ton/year		Avg
		Small	Large	Small	Large	
Fresh fruit bunch	ton	237600	950400	5.5556	5.5556	5.5556
Crude palm oil	ton	42768	171072	1.0000	1.0000	1.0000
Palm kernel	ton	14256	57024	0.3333	0.3333	0.3333
Empty fruit bunch	ton	54648	190080	1.2778	1.1111	1.1944
Palm fiber	ton	30888	133056	0.7222	0.7778	0.7500
Palm kernel shell	ton	14256	57024	0.3333	0.3333	0.3333
Decanter cake	ton	5940	38016	0.1389	0.2222	0.1806
Palm oil mill effluent	ton	51084	199584	1.1944	1.1667	1.1806
Other impurities + Moisture	ton	23760	104544	0.5556	0.6111	0.5833

Figure 4.5 Data obtained from the weighted average.

The circularity measurement in this study considers five oil palm products at palm oil mills, including CPO, palm kernel, EFB, PF, and PKS. Oil palm products are used in various ways, as shown in Figure 4.6.

- CPO is used at a palm oil refinery. It is transformed into Refined Bleached and Deodorized Palm Oil (RBDPO). The co-product is Palm Fatty Acid Distillate (PFAD), and waste is Bleaching Earth. There is also oil loss in the refining process at about 1.5% (National Green Tribunal, 2015). PFAD can be used in the animal feed, soap, and oleochemical industries. The oil loss in the refining process can be reused in the palm oil refinery. Crude palm oil should not be stored longer than one year. The estimated shelf life of CPO, when stored at 20-25°C in the dark, is approximately six months (Almeida, Viana, Costa, Silva, & Feitosa, 2019; WDRA, 2010). According to Ministry of Industry, Thailand (2019), in the case of operating a palm oil mill with Nut-Separated Palm Oil Extraction, which uses palm bunches and fallen palm fruit produced by cutting and transporting palm bunches as raw materials, the palm oil must extract using the aforementioned raw materials in a ratio of 100 kilograms and can extract not less than 18 kilograms of oil (or 18%).
- Palm kernel is used at a palm kernel oil mill. It is transformed into Crude Palm Kernel Oil (CPKO). The co-product is palm kernel meal, and waste is other impurities. Palm kernel meal can be used in animal feed production. Dried palm kernels should not be stored for longer than seven days.
- EFB, PF, and PKS are used as fuels in heat and electricity production. The burning of oil palm biomass produces ash, which is used to increase FFB yield in oil palm plantations. The ash content of EFB is 3.97%, the ash content of PF is 4.89%, and the ash content of PKS is 3.68%. The heating value of the PF is the highest, followed by PKS and EFB, which are 20.2440, 18.90, and 18.90 MJ/kg respectively. Oil loss in oil palm biomass includes EFB (8%) and PF (6%), while there is no oil loss in PKS. The shelf life of EFB is until decomposed, which is about five days (Zafar, 2020). PF, on the other hand, can be stored for up to three months (UNFCCC, 2006). The shelf life for PKS is 12 months.

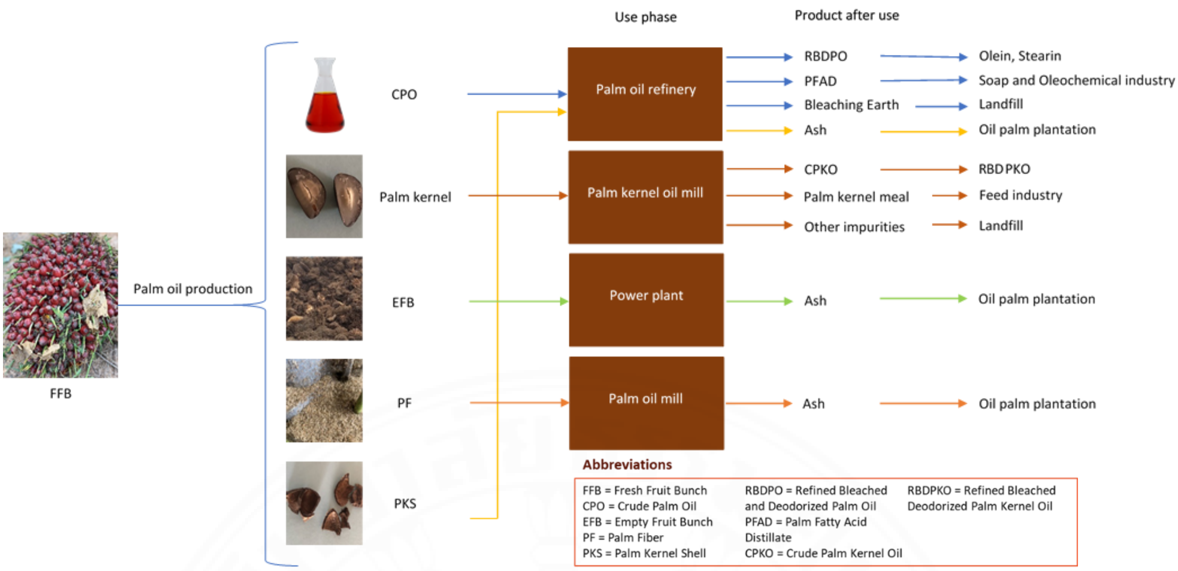

Figure 4.6 The use of multiple products in oil palm industry.

As palm oil production is no recycled and reused, and there is no biological material of virgin feedstock, V is equal to M in all five oil palm products and W_F is 0.

The use of CPO takes place in a palm oil refinery. It transforms CPO to RBDPO at 16.90%, while the co-product is PFAD at 0.92%, and the waste is Bleaching Earth at 0.18%. There is also an oil loss in the refining process at 1.5%. PFAD can be considered as the fraction of co-product collected for the recycling process as it is used in animal feed, soap, and oleochemical industries. Oil loss can be considered as the fraction of the oil loss collected for reuse. The use of palm kernels takes place in the palm kernel oil mill. It transforms the palm kernel to CPKO at 2.50%, the co-product is palm kernel meal at 3.20%, and the waste is other impurities at 0.30%. Palm kernel meal can be considered as the fraction of co-product collected for the recycling process as it is used in the animal feed industry. Oil palm biomass products including EFB, PF, and PKS are used as fuel for heat and electricity generation. The combustion of biomass fuel produces ash, which is used for increasing FFB yields in oil palm plantations. In addition, there is an oil loss in EFB and PF, with oil loss in EFB of 8% and PF of 6%. This oil loss is considered as the fraction of the oil loss collected for reuse.

The lifetimes of the products in this study are: CPO is 6 months, palm kernel is dried and stored for no more than 7 days, EFB is 5 days, PF is 3 months, and PKS is 1 year. In this study, the product's functional unit uses the oil extraction rate for CPO and palm kernel, while EFB, PF, and PKS use the heating value. The results of the MCI calculation of oil palm products are as shown in Table 4.8.

Table 4.8 MCI of oil palm products

Parameter	CPO	Palm kernel	EFB	PF	PKS
M	1	0.3333	1.1944	0.75	0.3333
V	1	0.3333	1.1944	0.75	0.3333
$M_{Co\text{-}product}$	0.0511	0.1778	0.1391	0.1711	0.1286
M_{Waste}	0.0100	0.0167	0	0	0
$M_{Oil\ loss}$	0.0150	0	0.0806	0.0593	0
M^*	0.0761	0.1944	0.2196	0.2303	0.1286
W_0	0.0100	0.0167	0	0	0
C_R	0.6715	0.9143	-	-	-
C_U	0.1971	-	0.3669	0.2573	-
C_C	-	-	0.6331	0.7427	1
C_E	-	-	-	-	-
W_C	0.0051	0.0178	-	-	-
E_C	0.9	0.9	-	-	-
W_F	-	-	-	-	-
E_F	-	-	-	-	-
W	0.0126	0.0256	0	0	0
L	0.5	0.0194	0.0139	0.25	1
L_{av}	0.5	0.0194	0.0139	0.25	1
U	18.00%	41.67%	18.90	20.24	18.90
U_{av}	18.00%	43.00%	17.46	17.28	20.40
X	1	0.9690	1.0823	1.1714	0.9267
F(X)	0.9	0.9288	0.8315	0.7683	0.9712
LFI	0.5069	0.5456	0.5	0.5	0.5
MCI	0.5438	0.4932	0.5842	0.6159	0.5144

4.4 Results of circularity measurement at the company-level

After the MCIs of five oil palm products are obtained, the circularity at the company-level is calculated. The normalization factor is used as sales revenue. Product price data is obtained from the Department of Internal Trade, Ministry of Commerce, and an article on Biomass Energy Potential from Oil Palm: A Case Study of the Empty Fruit Bunch of the Department of Alternative Energy Development and Efficiency, Ministry of Energy (DEDE, 2014; DIT, 2021). The combination of oil palm product MCIs is summarized in Figure 4.7.

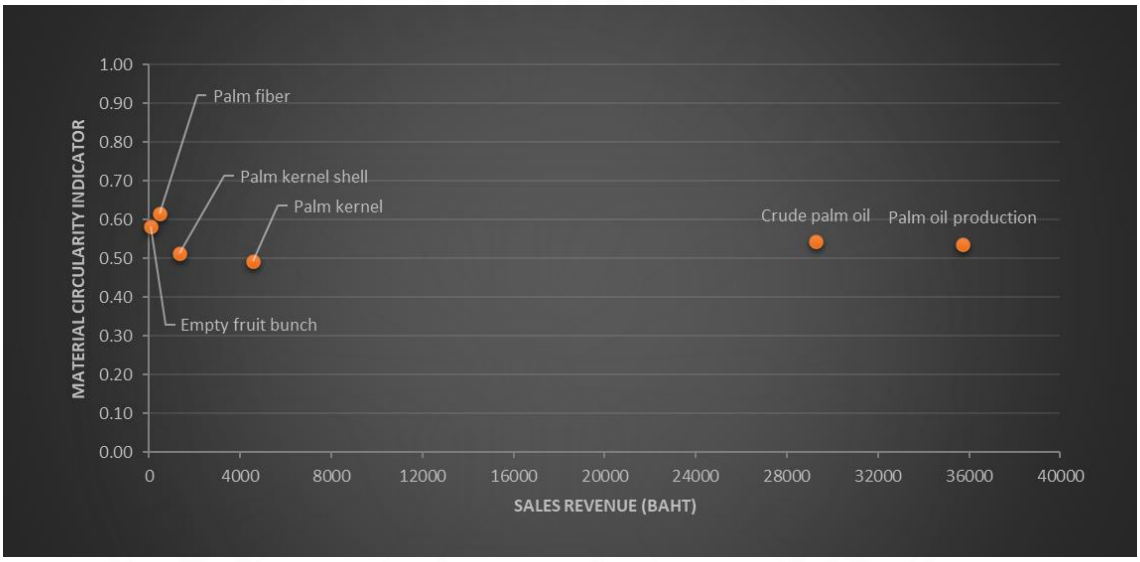

Figure 4.7 Combining oil palm products using sales revenue as the normalizing factor.

By using sales revenue as the normalizing factor, the company-level's MCI is 0.5372; high-value products "CPO" dominates the final result.

4.5 Discussion

Research findings from the GHG emission assessment show that the area with high material consumption leads to high emissions. The production and utilization of fertilizers, chemicals, and fuels emit GHG emissions that contribute to global warming. It is suggested that GHG emissions be reduced by improving FFB yields.

Compared with FFB's carbon footprint, the average of Thailand, the obtained GHG is higher than the country's average, which is 71.7 kg CO_2eq (TGO, 2021b). The country's average carbon footprint is calculated based on the majority of oil palm plantation areas in the south of Thailand with a planting area of 5,234,137 rai, yielding areas of 4,883,014 rai, the total yield of 14,784,987 tons, yield per rai of 3,028 kg/rai/year, which is a region that produces a higher yield per rai than other regions. 90% of the country's produce comes from the southern regions. This is because the southern region has a more suitable environment for oil palm planting than other regions, and farmers have more experience in oil palm plantation management as the southern region is the region where oil palm is planted before other regions of the country. The southern region has a suitable climate for oil palm planting. Because it has abundant and consistent rainfall throughout the year (1,800-2,200 mm), high humidity, and strong sunlight. Area conditions, most of the soil is well-structured soil suitable for oil palm plantation. The soil is weakly acidic, pH 4.0 - 6.0. The slope is not more than 12%, the area is not flooded. It has good to moderate drainage. In 2019, Thai's average oil palm yield is 2,897 kg/rai/year while in this study, the yields of Case 1, the oil palm plantation on an area with a trench of water are collected from three farmers 1) 4,500 kg/rai/year, 2) 2,250 kg/rai/year, 3) 1,500 kg/rai/year, and the yield of Case 2, the oil palm plantation on the plain area is 2,700 kg/rai/year. For Case 1, most farmers have low FFB yield that is less denominator, the GHG emissions are higher. When the yields of the three farmers are averaged, the yield is 3,822 kg/rai/year, which is higher than the national average. The denominator is higher, but GHG is still higher than the national average as a result of the area's high levels of fertilizers and chemicals due to poor soil conditions, tree dying, and problems with weeds and insects. For Case 2, the yield is low because the oil palm plantation area is full of mature palms. The denominator is less, resulting in higher GHG than the national average carbon footprint.

Compared with Malaysia's carbon footprint, the obtained GHG is lower than Malaysia's carbon footprint, which is 119 kg CO_2eq (Choo et al., 2011). Malaysia’s oil palm yield is 20.7 t FFB/ha, which equals 3,312 kg/rai. For Case 1 considering low-yielding farmers and in Case 2 have a small denominator, the calculated GHG is less than Malaysia's carbon footprint. When considering the average yield of Case 1, which is higher than that of Malaysia. The calculated GHG is less because the average yield of this area is greater. Malaysia's high GHG may be due to high energy and material consumption. They also considered transporting the FFB to the mill and emissions to the air, soil, and water.

Calculating MCI based on Ellen MacArthur Foundation found that MCI is not suitable for products that the product's mass changes from production to end of use. This means that there is some or all of the product is 'consumed' for example eaten or burned during its use. In this study, palm oil production is an example of a case where MCI should not be applied directly to the product due to the presence of multiple products and each product being used differently. Moreover, the product is transformed into a new product and there is a mass change from production to end of use. Therefore, the formula must be modified to suitably before use.

Research findings from the circularity measurement at the product level show that the PF has the highest MCI among the five oil palm products due to its utilization. PF has the oil loss itself, which is collected for reuse, and the ash that is collected for use in oil palm plantations to increase FFB yields. At the company level using sales revenue as a normalization factor, the calculated MCI is in line with the CPO as it is the highest-value product. The 0.5372-MCI is greater than 0.5, meaning that palm oil production is more circular than linear. Increasing the MCI value may be achieved by increasing the fraction of recycling and reuse, composting of the co-product, waste, and oil loss, reducing the unrecoverable waste going to landfills, and increasing the utility of the products.

According to ZERO and Rainforest Foundation Norway (2016), PFAD is used as feedstock for many different products for animal feeds, laundry soaps, the oleochemical industry, and combustion for local power/process heat.

According to Schmidt (2007), oil mixed with bleaching earth is sent to landfills along with bleaching earth, and the oil loss from deodorization is discharged with effluent.

According to Pattani Green Company Limited (2020) encourages people in the area to use ash as raw material for making bricks and blocks. If people contact to request ash, the project will randomly analyze the chemical composition before allowing people to use it. But if there are ashes leftover from making bricks and blocks or no one asks for the ashes, the authorized agency will be contacted for disposal.

According to Yunos et al. (2015), residual oil from oil palm empty fruit bunches should be recovered and reused as feedstock for industrial use, stimulating the oil extraction rate (OER) in the palm oil industry.

When calculating based on supported data, the oil loss mixed with bleaching earth and the bleached earth are sent to landfills, oil loss from deodorization is waste to treatment, and the ash from EFB, PF, and PKS is sent for disposal. The newly calculated MCI is at 0.5252, down from 0.5372. However, the new MCI value is still circular consistent with the calculations in this study.

CHAPTER 5
CONCLUSION AND SUGGESTIONS

5.1 Conclusion

This research assesses the GHG emissions of 1 ton of FFB from oil palm plantations with different management practices and spatial characteristics according to IPCC method. This study also applies the product-level MCI to multiple products in the oil palm industry and the company-level MCI to palm oil production.

The study results show that in Case 1, the GHG emissions are greater than those in Case 2 because data for Case 1 were collected from 3 farmers with different yields. The oil palm plantation area is a trench of water. Most farmers have low FFB yields, resulting in high GHG emissions. When the yields of the three farmers were averaged. The yield is higher than the national average yield. Despite higher yields, GHG remains above the national average as a result of high levels of fertilizer and chemical use in the area. Due to poor soil conditions, tree mortality, and weed and insect problems. While data for Case 2 was collected from one oil palm plantation, which is a plain area. The yield of Case 2 is low because the oil palm plantation area is full of mature palms. With lower yields, GHG is higher than the national average. It can be concluded that compared to the FFB's carbon footprint, the average of Thailand, both cases showed higher GHG emissions than the national average. This is because the national average is based on the Thai oil palm plantation area, which is mainly in the southern part of Thailand. The southern region has a suitable climate for oil palm planting. It has abundant and consistent rainfall throughout the year about 1,800-2,200 millimeters per year, high humidity, and strong sunlight. The area condition is well-structured soil suitable for oil palm plantation, non-flooding area, and good to moderate drainage.

This study is of great importance in contributing to the transition to the circular economy of the country. It is important to measure the circularity of oil palm products. Because this industry is related to the food and energy security of the country. Approximately 75% of the CPO is for domestic consumption, where the main consumption is divided into two industries: the biodiesel industry and the cooking oil industry. The circularity measurement in this study is a good step to apply the circularity indicator to products of the oil palm industry. MCI based on Ellen MacArthur Foundation is interesting because it is a tool for measuring product circularity with a small amount of input data and calculating it as a single value in the 0-1 range. If complete data is available, circularity can be easily calculated. The disadvantage is that the calculation formula is designed for products that have a constant mass and do not transform to a new product after use. Although MCI is not suitable for edible products. However, in this study, the unrecoverable waste formula is modified for calculating the circularity of multiple products in the oil palm industry and palm oil production. MCI of palm oil production is greater than 0.5, indicating more circular than linear. The calculated level of circularity represents the current situation of palm oil production, a process that produces multiple products. The study provides a figure indicating the level of circularity of palm oil production and promotes the efficient production and use of oil palm resources. The MCI obtained in this study serves as the baseline data for the oil palm industry for future improvements by increasing the oil extraction rate, recovering and reusing the residual oil, and making the most of ash.

5.2 Suggestions

This study modified the unrecoverable waste formula to suit with oil palm industry. MCI based on Ellen MacArthur Foundation is not suitable for use with products that the product's mass changed or product that transformed into a new product from production to the end of use such as consumable or edible products. Therefore, the formula must be modified to suitably before use. Conversely, MCI is better suited to a product that after its use the mass of the product remains the same and does not transform into a new product such as furniture.

This study calculated the circularity of palm oil production, which produces intermediate products. In order to support the comprehensive circularity of the palm industry, it is suggested to calculate the circularity of palm oil biodiesel production and cooking palm oil production. According to Sowcharoensuk (2020), approximately 75% of CPO is used for domestic consumption. Thailand’s domestic CPO consumption is for two main downstream industries: the biodiesel industry (49%) and the refined palm oil industry (32%). Considering edible vegetable oil, soybean oil is the main competitor of palm oil both in the international and domestic markets. However, oil palm plantations can produce palm oil about 4.16 tons per hectare while each hectare of soybeans can produce 0.5 tons less oil. This is the main reason that palm oil holds the largest market share for the domestic vegetable oil market. The average palm oil market share is about 60%-70% while soybean oil holds a market share of 20%-30%. In 2020, palm oil share accounted for 56% of total vegetable oils for domestic consumption, down from in 2019, at 64% while soybean oil share accounted for 40% of total vegetable oils for domestic consumption, up from 31% in 2019. During the competitive conditions in 2020, soybean oil can steal market share from palm oil. This was because the domestic palm oil price level increased at the same level as the soybean oil prices. Therefore, many customers turn to soybean oil instead of palm oil. It is expected that in 2021 if the inventory level of palm oil remains low and palm production remains low, this will cause the price of palm oil to remain high. This will result in customers turning to purchase more soybean oil (TVO, 2020). It is, therefore, recommended to calculate the circularity of soybean oil production to compare with palm oil production.

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APPENDIX

APPENDIX A
PALM OIL MILL DATA COLLECTION FORM FOR CALCULATING OF MCI OF PALM OIL PRODUCTION

Data collection form for calculating the MCI of palm oil production

Input-output

Raw material	Quantity/proportion	unit
Fresh fruit bunch		
Energy		
Water		

Main Products/By-Products/Residual Materials/Waste	Quantity/proportion	unit	Management practices/Utilization
Crude palm oil			
Palm kernel			
Empty fruit bunch			
Palm fiber			
Palm kernel shell			
Palm oil mill effluent			
Decanter cake			
Ash			

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