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MATERIAL CIRCULARITY INDICATOR FOR THAI OIL PALM INDUSTRY

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ABSTRACT

The oil palm industry is vital in food and energy production and significantly contributes to the Thai economy. Nevertheless, the sector faces environmental management challenges, especially waste management. With an awareness of the importance of a circular economy, this study aims to utilise the material circularity indicator (MCI) to measure the material circularity in multiple products of the Thai oil palm industry and plan for sustainable improvement. The circularity measurement result shows that palm oil production is more circular than linear, with a calculated MCI of 0.5372. This shows the importance of recycling, reusing and composting of co-products, residual oil and wastes of oil palms to achieve the sustainable development of Thai agriculture. The results also show that the MCI value may be enhanced by increasing the biomass's oil extraction rate (OER) and calorific value. By improving the OER from 18% to 23%, the MCI value rises to 0.6230, explaining a better circularity of the oil palm industry. The oil palm industry, the government and related authorities may use the study results to plan for the palm oil process improvement to enhance the circularity in the long term. The study has a limitation: The data used in the analysis are from a limited number of palm oil factories. An increasing number of participating factories may enhance the study results.

Keywords: circular economy, material circularity indicator, multiple products, oil extraction rate, palm oil production.

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INTRODUCTION

Oil palm is an essential crop in Thailand in terms of agriculture, economy, and industry, as the country is the world's third-largest oil palm producer (Sowcharoensuk, 2020a). The production value of oil palm in Thailand increased by almost 2.5 times in the past 10 years (*Figure 1*). It contributes to the stability of food and energy in the country. It is grown nationwide, with dense plantation areas in Southern Thailand (Sowcharoensuk, 2020a) (*Figure 2*). From 2011 to 2019, the yield area increased by 4.63% annually. The total yield of fresh fruit bunches (FFB) increased by 4.30%/yr, with a total output of 16,408,440 t in 2019, representing an average yield of 1.81 kg/m^2/yr (*Figure 3*) (Office of Agricultural Economic [OAE], 2020; Siam Legal, 2023).

The palm oil extraction process involves five steps: 1) Reception, transfer, and temporary storage of FFBs, 2) sterilisation, 3) bunch striping, 4) digestion, and 5) extraction (Kaewmai, 2012). When FFBs go through the extraction process, they produce approximately 18%-22% of crude palm oil (CPO), which is processed into edible oil, used in energy production, such as biodiesel, and sold to palm oil refineries or biodiesel plants (Sangkharak, 2014). FFBs also produce palm kernels that are processed into palm kernel oil, and dried palm kernels are transported to palm kernel crushers. By-products and wastes, accounting for 78%-82% of FFBs, include empty fruit bunches (EFBs), palm fibres (PFs), palm kernel shells (PKSs), decanter cakes and palm oil mill effluents (POMEs) (Sangkharak, 2014).

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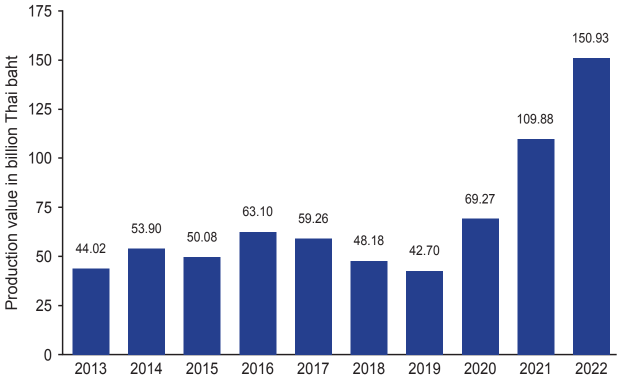
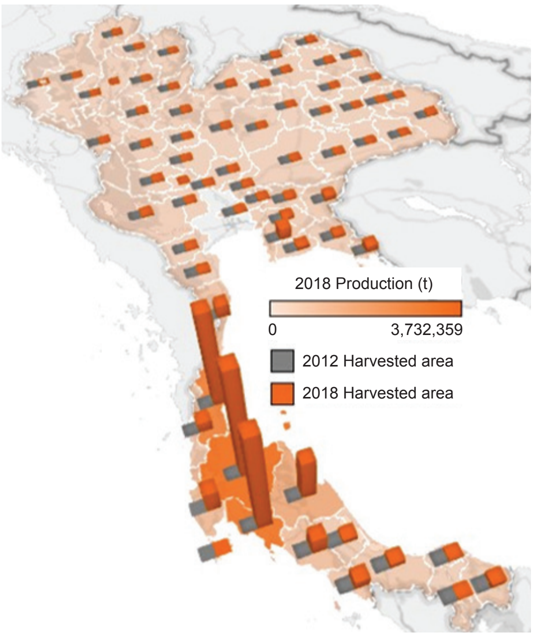


Source: Statista (2023).

Figure 1. Production value of oil palm in Thailand from 2013-2022.

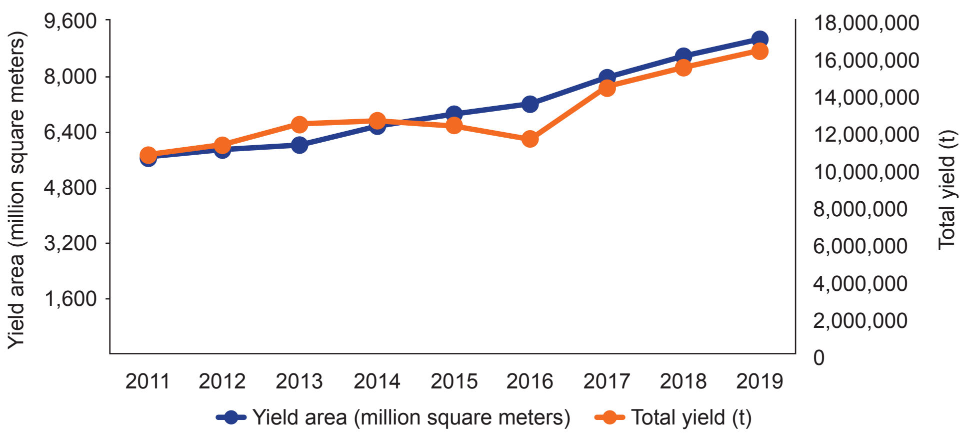


Source: Sowcharoensuk (2020a).

Figure 2. Harvested areas of oil palm in Thailand.

Kaewmai (2012) mentioned that palm oil production processes generate solid waste, wastewater, and air pollution that require proper management to avoid long-term environmental problems. Improper management of these by-products and wastes can severely harm the environment. Palm oils, similar to other production and consumption patterns that use more natural resources and energy, cause a shortage of oil palms and solid waste management problems. Most natural resources and energy used are non-renewable and limited. Efforts to find renewable resources are required to meet the increasing demand. Although some of the waste generated can be recycled, their non-reusable parts must be appropriately disposed of or treated. Therefore, they remain in the environment and may cause deterioration to the ecosystem in the long run (Carbon Market, 2021).

A circular economy concept is a new alternative that can develop the country's economy towards sustainability. It is recognised and driven by governments and businesses worldwide to improve their sustainability levels (Chorolque *et al.*, 2022; De Oliveira Neto *et al.*, 2023). The circular economy is expected to replace the traditional linear economy based on the take-make-use-dispose concept (TGO, 2021). It is considered as a sustainable economy, social and environmental development of the country that creates economic opportunity through innovating ideas, creating jobs, and driving economic growth (World Economic Forum, 2014). In Thailand, the circular economy concept is applied in many agricultural-related studies. For example, Suksaroj *et al.* (2023) investigated the biogas production and circular economy perspective in the Thai oil palm industry through co-digestion of EFB pressing wastewater and POME. The results provide information on the circular economic approach to promote sustainable palm oil processing in Thailand.



Source: OAE (2020); Siam Legal (2023).

Figure 3. Yield area and total FFB yield of Thailand.

Edyvean *et al.* (2023) developed a bio-circular-green (BCG) economic solution to mitigate the effects of CO_2 emissions in the food and agricultural, medical, bioenergy, and tourism sectors in Thailand. Usapein *et al.* (2022) performed strengths, weaknesses, opportunities, and threats (SWOT) analysis of the oil palm industry to help drive the BCG economy model in Thailand.

To effectively plan for the circular economy implementation, its value must be measured and tracked through evaluation tools and indicators to support the move toward a circular economy. Various indicators may be used to assess the circularity, such as the circular economic value (CEV), material reutilisation score (MRS), product-level circularity metric (PLCM), mass recovery index (MRI), quantitative indicators and value assessment (QIVA) and material circularity indicator (MCI) (Syu *et al.*, 2022). Syu *et al.* (2022) stated that the PLCM measures circular inputs into the manufacturing process; thus, production waste and product end-of-life management only affect the score if they are closed-loop recycling pathways. The MRI, in contrast, focuses on the value output and measures the amount of material consumed that is converted into a product. The CEV and MCI can capture differences between all scenarios. Saidani *et al.* (2019) mentioned that the CEV is the indicator used in the meso-level (*i.e.*, businesses and industrial symbiosis), while the MCI is used in the micro-level (*i.e.*, products, components and materials). Kristensen and Mosgaard (2020) stated that the MCI is one of the first circular economy indicators to draw attention from practical and academic parties. It considers the amount of recycling in the product and the lifetime use of the product.

In this study, the MCI measures the circularity of the oil palm industry as it focuses on the lifetime extension, recycling and waste management perspectives (Matos *et al.*, 2023). Rocchi *et al.* (2021) commented that compared to other indicators, the MCI is one of the few that includes retention in its metric, as it considers how much an element is used in the process in terms of intensity and duration. It covers more aspects of lifespan, recycling rate, and use intensity than the MRI, QIVA, PLCM, and CEV indicators (Syu *et al.*, 2022). The product-level MCI is used to measure the circularity in multiple products of the oil palm industry and the company-level MCI of both small and large palm oil mills to determine the overall MCI value of the country and enhance the sustainability of the oil palm industry. The study results are expected to provide an indicator for the oil palm industry to plan for long-term sustainable and circular operations.

The research flow of this study is in *Figure 4*. The process of palm oil milling is explained and the by-products and wastes of oil palm are listed based on the related literature. The reuse, recycling, composting, and landfill processes are also reviewed to understand the circularity concept. Data is collected through interviews, on-site observations and secondary data from previous studies. The MCI is calculated, and different scenarios are tested to achieve suitable strategies for the sustainable development of the oil palm industry.

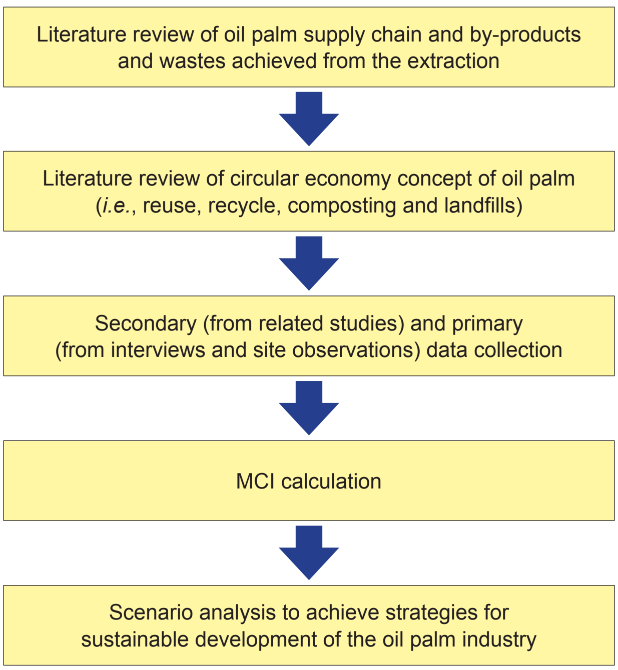


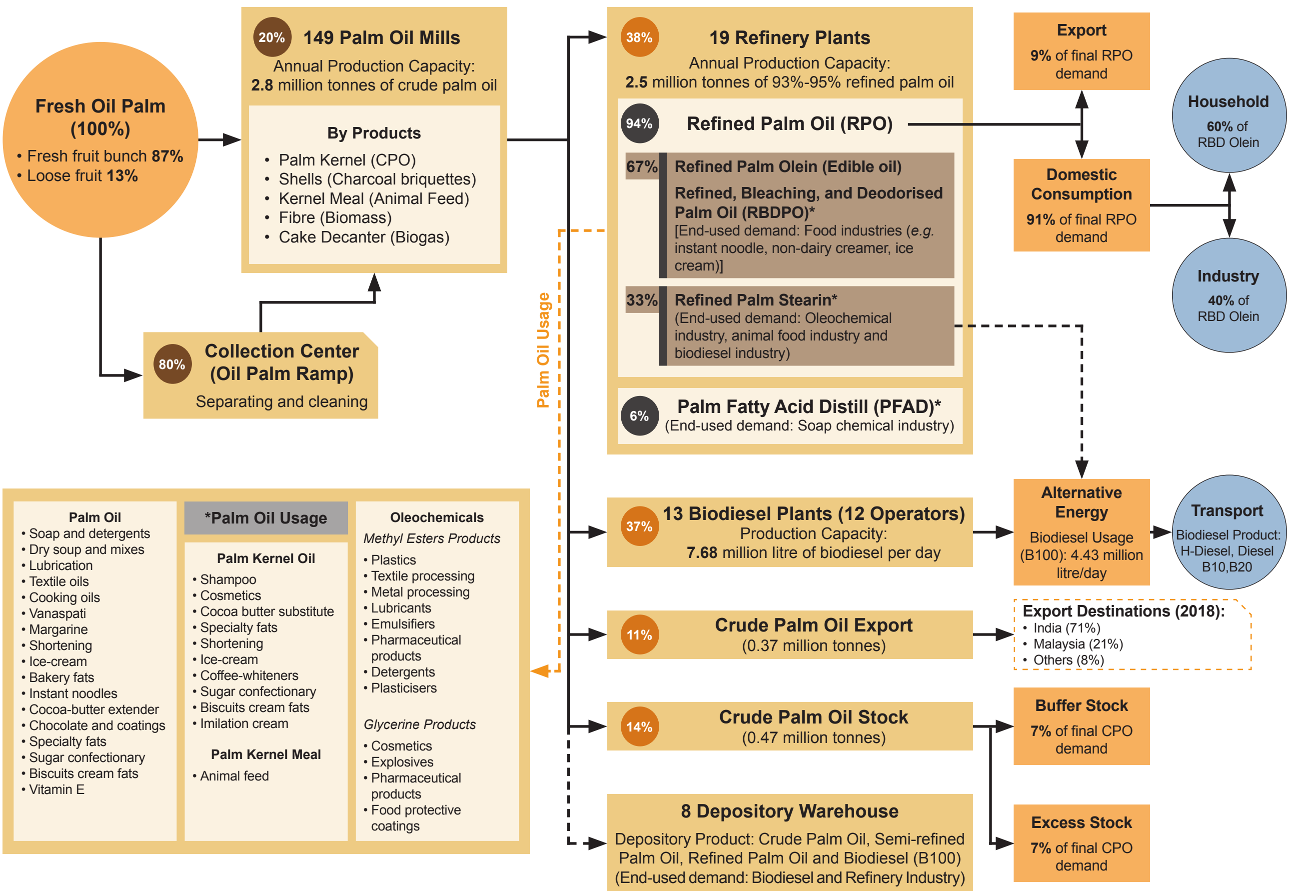
Figure 4. Research flow of the study.

Supply Chain of Oil Palm Industry in Thailand

The Thai oil palm industry has a fully integrated production chain. It consists of oil palm cultivators (upstream), palm oil mills (midstream), and palm oil refineries (downstream) (*Figure 5*). Fresh oil palms are sent to palm oil mills with an annual production capacity of 2.8 million tonnes of CPO in 2018 (Sowcharoensuk, 2020b). The oil palm trees also produce a wide range of by-products that can generate additional income, such as kernel meals used to manufacture animal feed and palm shells and fibres, which can produce biomass energy. There are 19 refinery factories in Thailand with an annual production capacity of 2.5 million tonnes of 93%-95% refined palm oils, mainly used for edible oil and biodiesel production.

By-products and Wastes of Oil Palm

The oil palm industry produces massive solid wastes (*Figure 6*). Most come from oil palm plantations and the CPO extraction process (Sukiran *et al.*, 2017). Oil palm solid wastes from oil palm plantations include palm fronds and trunks. On the other hand, oil's solid wastes from palm oil mills include EFB, PKS, and PF (Sukiran *et al.*, 2017). EFB are found to be the most widely used residues as a feedstock for composting due to their excellent organics and micronutrients. PF and PKS are, in contrast, burned in boilers to generate steam and electricity, which are then used in the CPO extraction process, thus raising the industry's sustainability. They can also be processed into solid fuel through pellets or briquettes and used as fillers for fibre-reinforced composites (Sukiran *et al.*, 2017). Trimmed and cropped oil palm leaves usually decompose naturally in the ground for soil fertiliser, erosion control, and long-term recycling of beneficial nutrients. Oil palm fronds can replace grasses in the ruminant industry and can be converted into pulp. Oil palm trunks must be specifically treated and processed to obtain fine wood for plywood and fibreboard manufacturing (Sukiran *et al.*, 2017). All of the above confirm various uses of oil palm by-products and wastes to enhance the sustainability of the oil palm industry.



Source: Sowcharoensuk (2020b).

Figure 5. The supply chain of the oil palm industry in Thailand.

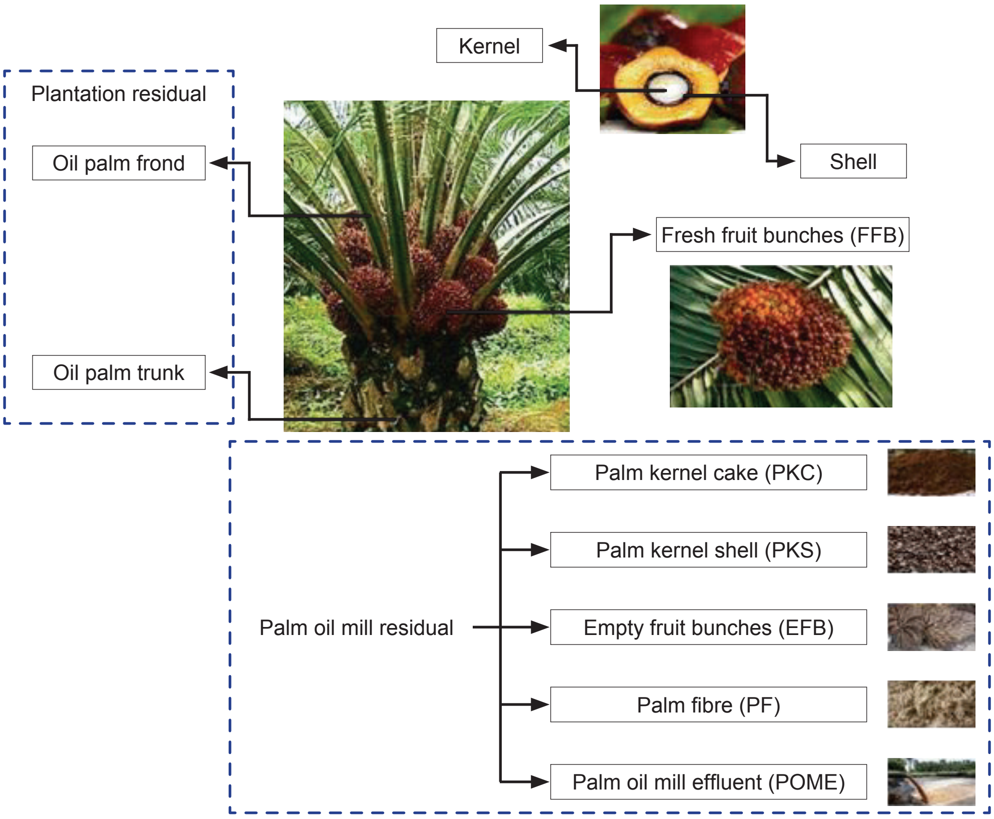


Figure 6. *Waste in the oil palm industry.*

MATERIALS AND METHODS

Material Circularity Indicator (MCI)

MCI is proposed by the Ellen MacArthur Foundation (EMF) as a tool to assess product and business model performance. It considers product recycling, including waste generated by the manufacturing processes. It considers the product's utility throughout its lifetime and the functional units compared to the same industrial product (Bejarano *et al.*, 2022; Kristensen & Mosgaard, 2020). It covers biomaterials and addresses challenges associated with combining biological and technical materials. It also identifies risk-based complementary metrics for biomaterials and defines energy recovery conditions as part of a circulating strategy. It has been applied in various studies to assess product-level circularity. For example, Gue *et al.* (2018) proposed an MCI framework to determine the circularity of microalgae biodiesel. Due to its similar popularity, they also compared it with *Jatropha* biodiesel, a reference feedstock. In addition, they also used the life cycle assessment (LCA) framework to assess the environmental impact of products. The results showed that *Jatropha* has less environmental impact than microalgae in all three impact categories, including resource depletion, bulk waste and global warming potential. MCI of microalgae biodiesel is 0.04 higher than that of *Jatropha* biodiesel, meaning that microalgae biodiesel has a better material circularity.

The scale of MCI ranges from 0-1, where 1 indicates a full circular product, and 0 represents a full linear product (*i.e.,* no circularity). A diagram of the parameters used for product-level MCI calculation in this study is in *Figure 7*. In this study, the mass of virgin feedstock (V), FFBs, is sent to the palm oil mills and refineries to achieve the products (M), such as edible oil, biodiesel and beauty products. Once the products are consumed, they produce unrecoverable waste (W_0) that is disposed of in landfills. The components that can be reused (C_U) are collected and sent back to the plants as the reuse feedstock (F_U) for further processes. Similarly, the recyclable components (C_R) are returned to the plants as recycled feedstock (F_R) for processing. The unrecoverable waste from the recycling process (W_C) and the recycled feedstock (W_F) is sent to landfills.

MCI Calculation

To calculate the MCI, several steps are performed. The first parameter to be calculated is the virgin feedstock (V). This parameter links to recycling, reuse and biological material in the virgin raw material, as shown in Equation (1), where M is the mass of the final product, F_R is the

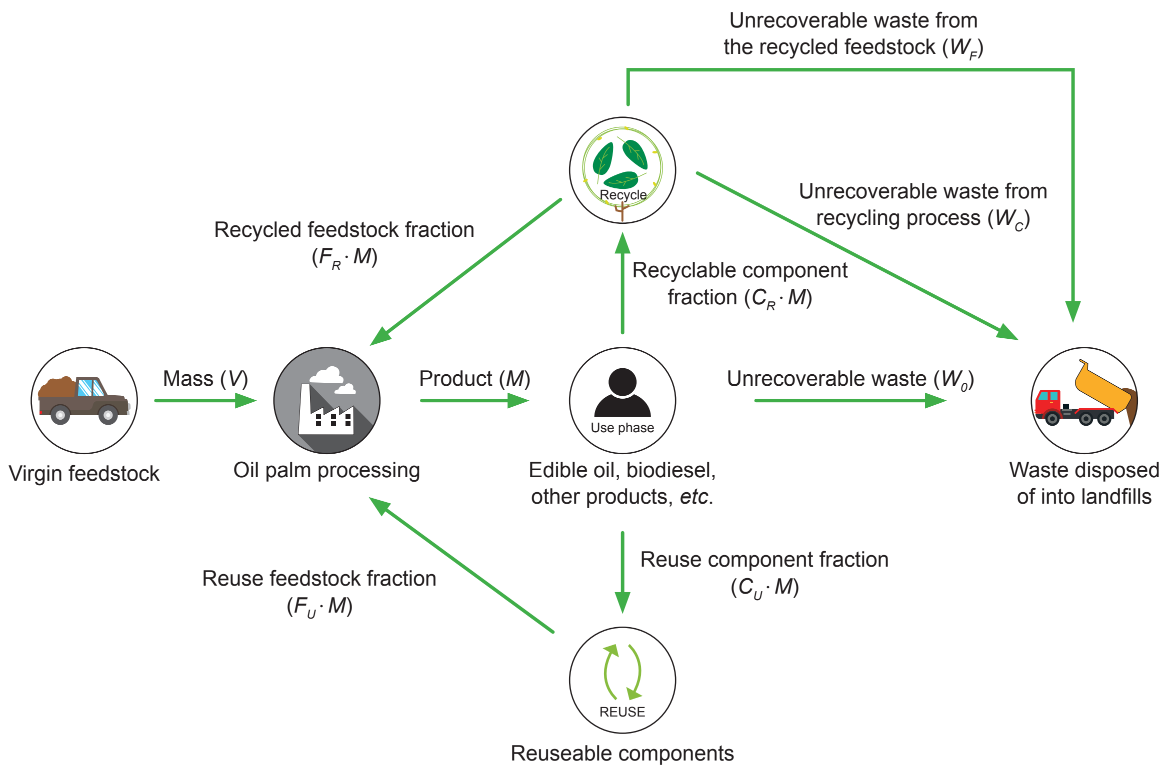


Figure 7. Parameters used to calculate product-level MCI.

fraction of recycled feedstock, F_U is the fraction of reused feedstock, and F_S is the fraction of biological feedstock from sustainable production.

$$V = M(1 - F_R - F_U - F_S) \quad (1)$$

The unrecoverable waste after use to landfill (W_0) is next calculated in Equation (2). C_R is the fraction of the mass of the product collected for a recycling process, which produces the waste from the recycling process (W_C). This waste depends on the efficiency of the recycling process used to recycle the product (E_C) and C_R, as shown in Equation (3). C_U is a fraction of the mass of the product collected for reuse. At the same time, C_C is a fraction of the mass of the product collected for the composting process and C_E is a fraction of the product collected for energy recovery.

$$W_0 = M(1 - C_R - C_U - C_C - C_E) \quad (2)$$

$$W_C = M(1 - E_C)C_R \quad (3)$$

There is also waste generated from recycled feedstock (W_F) production. This waste depends on the efficiency of the recycling process used to produce the recycled feedstock (E_F), as shown in Equation (4). The overall amount of unrecoverable waste (W) can then be obtained from Equation (5).

$$W_F = M\frac{(1 - E_F)F_R}{E_F} \quad (4)$$

$$W = W_0 + \frac{W_F - W_C}{2} \quad (5)$$

Linear flow index (LFI) indicates the linearity of the product, which is calculated by Equation (6). This value ranges from 0-1, where 1 represents full linearity and 0 represents nonlinearity.

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \quad (6)$$

The utility factor, $F(X)$, is 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 (7) and (8), where L represents the actual average lifetime of a product, L_{av} represents the average lifetime of the same industry average 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 industry average product.

$$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right) \quad (7)$$

$$F(X) = \left(\frac{0.9}{X}\right) \quad (8)$$

The MCI of the product (MCI_P) is then calculated using Equation (9), and the MCI of the company (MCI_C) is finally computed using Equation (10). It is based on the weighted average of MCI_P, where N_C is the sum of the normalising factor used, N_P is the normalising factor of each product, and MCI_P is the MCI value of each product.

$$MCI_P = 1 - LFI \cdot F(X) \quad (9)$$

$$MCI_C = \frac{1}{N_C}\sum_{\alpha}(N_{P(\alpha)} \cdot MCI_{P(\alpha)}) \quad (10)$$

Many studies modify the Ellen MacArthur Foundation's formula to suit their products (Anastasiades *et al.*, 2023; Moller *et al.*, 2023). For example, Razza *et al.* (2020) modified the MCI calculation formula for 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, the MCI of BB mulch film is 0.37, which is less than 0.50, indicating the linearity related to the bio-based feedstock content. Rocchi *et al.* (2021) proposed a modification of the MCI formula to be used with the biological cycle of poultry production by adding the feed conversion rate (FCR), which is the ratio between input (feed) and output (meat) in production. The utility is calculated using the utility conversion factor, which is calculated from the mortality rate. The results showed a modified MCI value of 0.49, representing low circularity. Phimphakarn *et al.* (2021) proposed a modification of MCI to the biological cycle of broiler feed production. The results showed an MCI value of 0.68, representing high circularity. Pavlovic *et al.* (2020) applied a company-level MCI to paper and cardboard packaging and cupcake liners in the Republic of Serbia. The normalising factor is used as the mass of the product, and the results concluded the MCI of 0.47, representing the middle point between linear and circular economies.

For oil palm products, the MCI formula is also required to be modified. When considering CPO as a product, M becomes the mass of CPO. CPO use occurs at a palm oil refinery when it is transformed into refined bleached and deodorised palm oil (RBDPO). A co-product, the palm fatty acid distillate (PFAD), can be used for soap and oleochemical industries. Bleaching earth, on the other hand, is sent to landfills.

Using the traditional MCI formula, the amount of unrecoverable waste from the oil palm industry is very high, meaning many CPOs are sent to landfills. This is inaccurate as CPOs can be transformed into RBDPOs, which are not considered unrecoverable wastes. Therefore, the formula must be modified to suit oil palm products in the unrecoverable waste section. The unrecoverable waste after use (W_0) is modified [Equation (11)], where M^* is the sum of the mass of the co-products, wastes, and residual oil. C_R is the fraction of the mass of the co-products, wastes, and residual oil collected for the recycling process, which produces the waste from the recycling process (W_C). This waste depends on the efficiency of the recycling process used to recycle the co-products, wastes, and residual oil (E_C) [Equation (12)]. C_U is the fraction of the co-products, wastes, and residual oil collected for reuse. At the same time, C_C is the fraction of the co-products, wastes, and residual oil collected for the composting process. C_E is the fraction of the co-products, wastes and residual oil collected for energy recovery.

$$W_0 = M^* (1 - C_R - C_U - C_C - C_E) \quad (11)$$

$$W_C = M^* (1 - E_C)C_R \quad (12)$$

Data Collection

Both secondary and primary data are used in this study. Primary data are obtained from two oil palm plantations (*Figure 8*) and two palm oil mills in Thailand with different operations and production capacities. The first palm oil mill performs palm oil extraction with a production capacity of 30 t CPO/hr. The second palm oil mill, on the other hand, conducts palm oil extraction and palm oil refining at a production rate of 120 t CPO/hr. Both factories operate 24 hr/day and 330 day/yr. The proportions of multiple products obtained from the two factories are in *Table 1*. The data used in MCI calculations are collected through direct fieldwork and secondary sources. The circularity measurement in this study considers five oil palm products at palm oil mills, including; 1) CPO, 2) palm kernel, 3) EFB, 4) PF, and 5) PKS that are used for several purposes (*Figure 9*).

The CPO is refined at a palm oil refinery. CPO should be stored for a maximum of a year. The estimated shelf life of CPO, when kept at 20°C-25°C in the dark, is approximately 6 months (De Almeida *et al.*, 2019). Based on *Table 1*, the oil extraction rate (OER) of CPO is 18.00%. This extraction rate is typical for the palm oil mill that operates with the nut-separated palm oil extraction process. Palm oil is extracted from FFBs and loose palm fruits as raw materials, with an extraction rate of about 18 kg of oil per 100 kg of raw materials (Ministry of Industry, 2019). The 18.00% OER of CPO comprise RBDPO 16.90%, the co-product of palm fatty acid distillate (PFAD) 0.92% and the waste bleaching earth 0.18%. PFAD can be considered as the fraction of co-product collected for the recycling process as it is used in the animal feed, soap, and oleochemical industries.

The use of palm kernels takes place at a palm kernel crusher. The 6.00% palm kernel comprises crude palm kernel oil (CPKO) 2.50%, the co-product of palm kernel meal 3.20% and the waste, which is other impurities 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. Dried palm kernels should be stored for up to seven days. Oil palm biomass products, including EFB, PF, and PKS, are used as fuel for electricity generation. The shelf lives of EFB, PF, and PKS are five days, three months, and one year, respectively (Zafar, 2022). Burning oil palm biomass produces ash that can be used to increase the FFB yield. The average ash contents of EFB, PF, and PKS are 3.97%, 4.89%, and 3.68%, respectively. The heating values of PF, PKS and EFB are 20.24, 18.90, and 18.90 MJ/kg, respectively. The residual oil is a fraction of the residual oil collected for reuse. The average residual oils in EFB and PF are 8.00% and 6.00%, respectively, while there is no residual oil in PKS.

Figure 8. Two oil palm plantations.

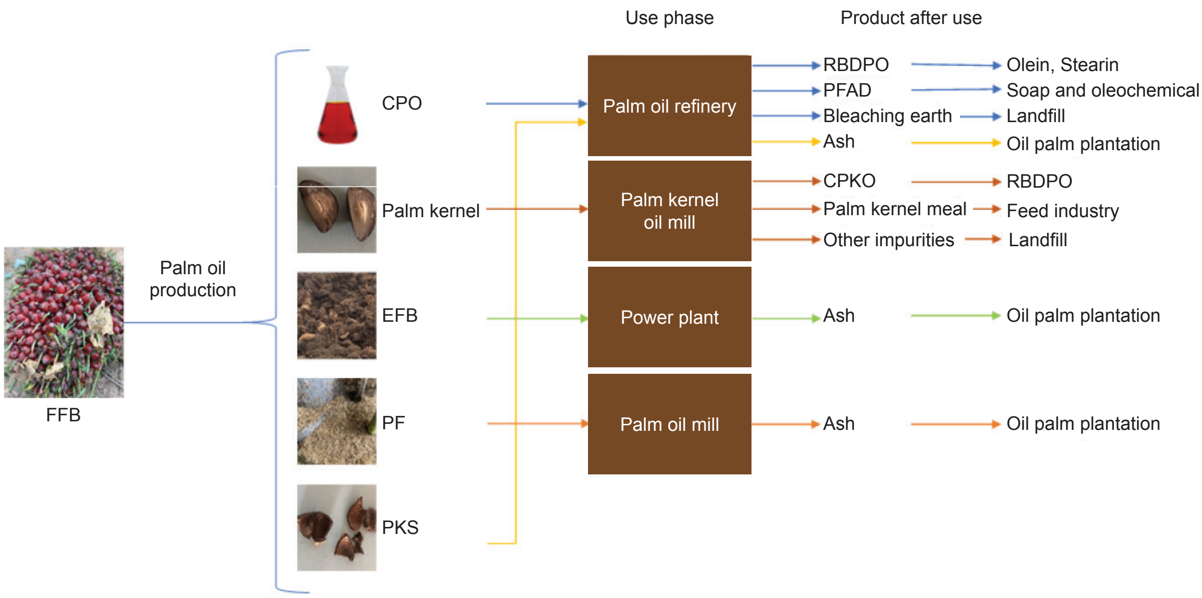


Figure 9. The use of multiple products in the oil palm industry.

TABLE 1. THE PROPORTION OF MULTIPLE PRODUCTS FROM TWO PALM OIL MILLS IN THAILAND

Data	Product	The proportion of multiple products (%)	
		1st factory (mill)	2nd factory (mill and refinery)
Input	FFB	100.0	100.0
Output	CPO	18.0	18.0
	Palm kernel	6.0	6.0
	EFB	23.0	20.0
	PF	13.0	14.0
	PKS	6.0	6.0
	Decanter cake	2.5	4.0
	POME	21.5	21.0
	Other impurities	10.0	11.0
	Total	**100.0**	**100.0**

RESULTS AND DISCUSSION

Results of Circularity Measurement

To calculate MCI and define the circularity of the oil palm industry, the process begins with FFBs, which are sent to palm oil mills. They produce CPO, palm kernel, EFB, PF, PKS, which are considered multiple products, and decanter cakes, palm oil mill effluent and other impurities, which are considered wastes and are not included in this study. The modified formula assesses the overall circularity of palm oil production. The quantity used in the MCI calculation is in t/yr (*Table 2*). It is then converted to t/t CPO by dividing the quantity of CPO. As the data are collected from two palm oil mills, the weighted average using the capacity ratio is used to obtain the average quantity of each product.

This study uses the OER as the product's functional unit of CPO and palm kernel, while the heating value is the functional unit of EFBs, PFs, and PKSs. The results of MCI calculation for multiple products are in *Table 3*. The MCI calculation of the CPO is provided as an example. As palm oil production does not have recycling and reuse processes and has no biological material of virgin feedstock, V is equal to M in all multiple products. M^* of the CPO is the sum of the co-products, wastes, and residual oil mass and is 0.0611 t (based on interviews). About 83.64% of the CPO products can be recycled, leading to the $W_0 = 0.01$ [Equation (13)]. The efficiency of the recycling process of the CPO (E_C) is 90.00%, leading to W_C of 0.0051 [Equation (14)].

$$W_{0,CPO} = M_{CPO}{}^*(1 - C_{R,\,CPO} - C_{U,\,CPO} - C_{C,\,CPO} - C_{E,\,CPO}) \\ = 0.0611(1 - 0.8364 - 0 - 0 - 0) = 0.01 \quad (13)$$

$$W_{C,CPO} = M_{CPO}{}^*(1 - E_{C,\,CPO})C_{R,\,CPO} \\ = 0.0611(1 - 0.9)(0.8364) = 0.0051 \quad (14)$$

There is no fraction of recycled feedstock; W_F is then 0. The overall amount of the CPO's unrecoverable waste (W) is then calculated [Equation (15)]. The *LFI* of CPO is then calculated [Equation (16)].

$$W_{CPO} = W_{0,CPO} + [(W_{F,CPO} + W_{C,CPO})/2] \\ = 0.01 + [(0 + 0.0051)/2] \\ = 0.0126 \quad (15)$$

$$LFI_{CPO} = (V_{CPO} + W_{CPO}) / \{2M_{CPO} + [(W_{F,CPO} - W_{C,CPO})/2]\} \\ = (1 + 0.0126)/\{2(1) + [(0 - 0.0051)/2]\} \\ = 0.5069 \quad (16)$$

The utility of CPO (X_{CPO}) is calculated based on the lifetime and the average lifetime of CPO of half a year (*i.e.*, L and $L_{av} = 0.5$) [Equation (17)]. The functional units of the CPO (U and U_{av}) are represented by an oil extraction rate of 18.00% (based on the interviews). The $F(X)$ and the product-level MCI of CPO are then achieved in Equations (18) and (19).

$$X_{CPO} = (L_{CPO}/L_{av,\,CPO})(U_{CPO}/U_{av,\,CPO}) \\ = (0.5/0.5)(0.18/0.18) = 1 \quad (17)$$

$$F(X)_{CPO} = 0.9/X_{CPO} = 0.9/1 = 0.9 \quad (18)$$

$$MCI_{CPO} = 1 - [(LFI_{CPO})(F(X)_{CPO})] \\ = 1 - [(0.5069)(0.9)] = 0.5438 \quad (19)$$

Table 3 shows that PF has the highest MCI value of 0.6159, followed by EFB, CPO, PKS, and palm kernel. The high MCI value of PF relates to its use in biodiesel production. This is consistent with

TABLE 2. THE AVERAGE QUANTITY OF EACH PRODUCT PER TONNES OF CPO

Output	Quantity (t/yr)		Quantity (t/t of CPO)		Average quantity (t/t of CPO)
	1st factory (mill)	2nd factory (mill and refinery)	1st factory (mill)	2nd factory (mill and refinery)	
FFB	237,600	950,400	5.5556	5.5556	5.5556
CPO	42,768	171,072	1.0000	1.0000	1.0000
Palm kernel	14,256	57,024	0.3333	0.3333	0.3333
EFB	54,648	190,080	1.2778	1.1111	1.1444
PF	30,888	133,056	0.7222	0.7778	0.7667
PKS	14,256	57,024	0.3333	0.3333	0.3333
Decanter cake	5,940	38,016	0.1389	0.2222	0.2056
POME	51,084	199,584	1.1944	1.1667	1.1722
Other impurities	23,760	104,544	0.5556	0.6111	0.6000

Bejarano *et al.* (2022) that palm fibre is favourable for incineration in boilers to obtain energy. Yeo *et al.* (2020) stated that oil palm biomass in Malaysia favours the linear over the circular economies in terms of profitability; however, the reduction in imported resources in electricity production raises the circularity implementation.

To further calculate the company-level MCI, sales revenue is used as the normalising factor, with the product price data obtained from the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy, and the Department of Internal Trade, Ministry of Commerce (DEDE, 2023). The MCIs of multiple products are then summarised and the company-level MCI is achieved as 0.5372, in which the CPO contributes the highest portion, followed by palm kernel, PKS, PF and EFB, respectively (*Table 4*).

Results of Circularity by Improving OER

The MCI value of 0.5372 in *Table 4* comes from the OER of 18.00%. However, the OER may be increased by 5.00% (or 23.00% OER) based on the highest OER of Indonesia's OER value in 2020 (IJM Corporation Berhad, 2021). Calculating the MCI value based on the higher OER of 23.00% yields a better MCI value, as in *Table 5* and *6*. *Table 5* shows that CPO, PF and EFB have the highest MCI values. It is clear that when the percentage of OER is increased by 5.00%, from 18.00% to 23.00%, the company-level MCI increases by 15.97%, from 0.5372 to 0.6230.

In summary, the product-level circularity measurement at 18.00% OER shows that PF has the highest MCI value among the five oil palm products (*Table 4*), as PF is utilised in the plant. It also has residual oil collected for reuse and ash collected to be used in oil palm plantations to increase FFB yields. The company-level MCI, when using the sales revenue as the normalising factor, is 0.5372. This is greater than 0.5000, meaning Thailand's current palm oil production is circular rather than linear. Moreover, when the % OER increases to 23.00%, the company-level MCI value rises to 0.6230, indicating that a higher % OER brings a higher MCI value.

TABLE 3. MCI OF MULTIPLE PRODUCTS

Parameter	CPO	Palm kernel	EFB	PF	PKS
M	1.0000	0.3333	1.1444	0.7667	0.3333
V	1.0000	0.3333	1.1444	0.7667	0.3333
$M_{Co\text{-}product}$	0.0511	0.1778	0.1391	0.1711	0.1286
M_{Waste}	0.0100	0.0167	-	-	-
$M_{Residual\ oil}$	-	-	0.0806	0.0593	-
M^*	0.0611	0.1944	0.2196	0.2303	0.1286
W_0	0.0100	0.0167	-	-	-
C_R	0.8364	0.9143	-	-	-
C_U	-	-	0.3669	0.2573	-
C_C	-	-	0.6331	0.7427	1.0000
C_E	-	-	-	-	-
W_C	0.0051	0.0178	-	-	-
E_C	0.9000	0.9000	-	-	-
W_F	-	-	-	-	-
E_F	-	-	-	-	-
W	0.0126	0.0256	-	-	-
L	0.5000	0.0194	0.0139	0.2500	1.0000
L_{av}	0.5000	0.0194	0.0139	0.2500	1.0000
U	18.00%	41.67%	18.9000	20.2400	18.9000
U_{av}	18.00%	43.00%	17.4600	17.2800	20.4000
X	1.0000	0.9690	1.0823	1.1714	0.9267
F(X)	0.9000	0.9288	0.8315	0.7683	0.9712
LFI	0.5069	0.5456	0.5000	0.5000	0.5000
MCI	0.5438	0.4932	0.5842	0.6159	0.5144

Note: The efficiency of the co-product recycling process (E_C) is 0.9.

TABLE 4. COMPANY-LEVEL MCI USING SALES REVENUE AS THE NORMALISING FACTOR

Product	Sales revenue ($)	Sales revenue contribution (%)	Calculated MCI	Company-level MCI with the sales revenue as the normalising factor
CPO	809.6	81.93	0.5438	0.8193 × 0.5438 = 0.4455
Palm kernel	126.6	12.81	0.4932	0.1281 × 0.4932 = 0.0632
PKS	36.9	3.73	0.5144	0.0373 × 0.5144 = 0.0192
PF	12.7	1.29	0.6159	0.0129 × 0.6159 = 0.0079
EFB	2.4	0.24	0.5842	0.0024 × 0.5842 = 0.0014
Total	**988.2**	**100.00**	**-**	**0.5372**

TABLE 5. MCI OF MULTIPLE PRODUCTS AT 23.00% OER

Parameter	CPO	Palm kernel	EFB	PF	PKS
M	1.0000	0.2609	0.8957	0.6000	0.2609
V	1.0000	0.2609	0.8957	0.6000	0.2609
$M_{Co\text{-}product}$	0.0511	0.1391	0.1391	0.1711	0.1286
M_{Waste}	0.0100	0.0130	-	-	-
$M_{Residual\ oil}$	-	-	0.0846	0.0622	-
M^*	0.0611	0.1522	0.2237	0.2333	0.1286
W_0	0.0100	0.0130	-	-	-
C_R	0.8364	0.9143	-	-	-
C_U	-	-	0.3783	0.2667	-
C_C	-	-	0.6217	0.7333	1.0000
C_E	-	-	-	-	-
W_C	0.0051	0.0139	-	-	-
E_C	0.9000	0.9000	-	-	-
W_F	-	-	-	-	-
E_F	-	-	-	-	-
W	0.0126	0.0200	-	-	-
L	0.5000	0.0194	0.0139	0.2500	1.0000
L_{av}	0.5000	0.0194	0.0139	0.2500	1.0000
U	23.00%	41.67%	18.9000	20.2400	18.9000
U_{av}	18.00%	43.00%	17.4600	17.2800	20.4000
X	1.2778	0.9690	1.0823	1.1714	0.9267
F(X)	0.7043	0.9288	0.8315	0.7683	0.9712
LFI	0.5069	0.5456	0.5000	0.5000	0.5000
MCI	0.6429	0.4932	0.5842	0.6159	0.5144

Note: The efficiency of the co-product recycling process (E_C) is 0.9.

TABLE 6. COMPANY-LEVEL MCI USING SALES REVENUE AS THE NORMALISING FACTOR AND 23.00% OER

Product	Sales revenue ($)	Sales revenue contribution (%)	Calculated MCI	Company-level MCI with the sales revenue as the normalising factor
CPO	809.60	85.28	0.6429	0.8528 × 0.6429 = 0.5483
Palm kernel	99.10	10.44	0.4932	0.1044 × 0.4932 = 0.0515
PKS	28.90	3.04	0.5144	0.0304 × 0.5144 = 0.0156
PF	10.00	1.05	0.6159	0.0105 × 0.6159 = 0.0065
EFB	1.90	0.20	0.5842	0.0020 × 0.5842 = 0.0011
Total	**949.50**	**100.00**	**-**	**0.6230**

CONCLUSION

This study applies the product-level MCI to multiple products of the oil palm industry and the company-level MCI to obtain the overall MCI that represents the circularity of a country's palm oil production. It is essential to measure the circularity of oil palm products because this industry is related to the food and energy security of the country, with approximately 75% of the CPO being used for domestic consumption. Waste from the oil palm industry requires crucial attention to reduce the environmental impacts. This is consistent with Cheah *et al.* (2023) that full ranges of biowaste management, such as waste-to-energy, waste treatment, and waste valorisation for by-products productions, are required for the oil palm industry in Malaysia to enhance the sustainability in environmental, social, and economics aspects.

This study applies the modified unrecoverable waste formula to calculate the circularity of multiple products in the oil palm industry. Rocchi *et al.* (2021) agreed that the modified MCI should be applied to the agricultural sector to reflect its biological cycles. The overall MCI of palm oil production is greater than 0.5000 (*i.e.,* 0.5372), indicating the high circularity of palm oil production. This is consistent with Falcone *et al.* (2022) that MCI values for agricultural products range between 0.4600-0.6800 due to the reuse of the co-products obtained in both agriculture and extraction phases and lower production of unrecoverable waste.

CPO is found to represent the highest contribution to the company-level MCI. As 75% of CPO is used for domestic consumption, especially in the biodiesel and refined palm oil industries, the circularities of palm oil as biodiesel and for cooking palm oil production should be further studied. The oil palm industry should also focus on improving the quality of palm oil and investing in new technology to enhance the CPO extraction processes, as the results show an improvement of MCI values from 0.5372 to 0.6230 when the extraction rate improves by 5.00%. This is consistent with Anyaoha and Zhang (2023), that a low CPO extraction rate affects greenhouse gas emissions, and that research is required to achieve a greener economy for the oil palm industry in Nigeria. Usapein *et al.* (2022) suggested strategies to enhance the bio-circular-green economy of the oil palm industry in Thailand. They include developing regulations to manage the oil palm industry systematically, evolving smart innovation to improve harvesting technologies, raising palm biomass consumption rate, and increasing CPO value-added. Lim *et al.* (2021) suggested using new technologies, such as spray drones and modified drones with smart spectrometers, to enhance the circular economy of the oil palm industry in Malaysia.

This study contributes to the oil palm industry. The use of by-products and proper waste management of oil palm raise the environmental standard of the industry, making it compatible to compete in the global market. The company-level MCI using the sales revenue as the normalising factor proves the circularity of the reuse and recycling of oil palms. The government and related agencies may provide training on new knowledge and technologies to enhance the OER to increase the circularity. Such training should focus on the CPO and PF to enhance the biodiesel and edible oil production processes.

This study has some limitations. Primary data used in the analysis are from two palm oil mills in Thailand. An increasing number of data may yield more accurate results. Moreover, secondary data are retrieved from the literature not limited to Thai literature. The use of secondary data must be adjusted to suit the working culture.

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