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OIL PALM ECONOMIC PERFORMANCE IN MALAYSIA AND R&D PROGRESS IN 2024

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ABSTRACT

Malaysia's palm oil sector experienced significant growth in production, exports, and prices in 2024, despite a slight decrease in total planted area due to replanting initiatives. The crude palm oil (CPO) production rose in early 2024 due to improved fresh fruit bunches (FFB) yield and labour availability, but fell below 2023 levels in the last quarter due to unfavourable weather patterns. The total exports of oil palm products increased compared to 2023, primarily driven by higher demand from major importing countries, with India leading the way. Research and development (R&D) across the industry have advanced significantly, adopting innovative and interdisciplinary approaches. In the upstream sector, efforts focused on enhancing soil and plant health, conserving biodiversity, and developing high-yielding, resilient oil palm varieties. There were efforts to use mechanisation in plantations and Industrial Revolution 4.0 (IR4.0) in mills, such as Artificial Intelligence of Things (AIoT)-based fruit sorting, targeted spraying systems and mechanised harvesting in the midstream industry. The adaptability of palm oil allows for the investigation of its nutritional values for application in dietary supplements and functional meals as well as value addition in oleochemical derivatives to secure a greater share of the value chain in the downstream sector.

Keywords: biotechnology, mechanisation and automation, nutrition and value addition, smallholders, yield performance.

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INTRODUCTION

The economic performance of the oil palm industry in Malaysia has shown remarkable resilience over the past years, driven by both domestic demand and international markets. The oil palm industry continued to demonstrate its economic prowess, solidifying Malaysia's position as one of the global leaders in palm oil production and export. The oil palm sector is a vital pillar of Malaysia's economy, generating RM109.39 billion in export revenue in 2024 [Malaysian Palm Oil Board (MPOB), 2025]. With approximately 5.6 million hectares of cultivation, the industry is striving harder than ever to address issues related to sustainability and its safety put forward by global concern.

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In recent years, Malaysia has focussed on improving productivity and sustainability within the oil palm sector. Research and development (R&D) initiatives have been enhanced to address challenges such as climate change, pest management, and land-use efficiency. Innovations in agricultural techniques, pest management, and soil health are gaining traction. Enhanced genetic research is also helping to cultivate more resilient palm varieties that can withstand climate challenges and disease pressures. Simultaneously, advancements in agronomic practices and the adoption of precision agriculture technologies are expected to further boost yields while minimising environmental impact. As we envisage, integrating technology in the oil palm industry through practices like data analytics and automated harvesting systems is anticipated to transform operations. This evolution is essential for maintaining competitiveness in the global market and to cater to the increasing demand for sustainable palm oil. This shift has prompted producers to adopt more eco-friendly practices, focussing on reducing greenhouse gas (GHG) emissions and improving land use efficiency, thus enhancing market competitiveness. Collaborative initiatives between government agencies, industry stakeholders, and research institutions are vital in promoting these sustainable practices.

Meanwhile, investments in state-of-the-art milling facilities and refining processes allowed for greater efficiency, quality control, and diversification of palm-based goods, from edible oils and biofuels to oleochemicals and specialty food ingredients. This has translated to soaring export figures and remunerative returns for Malaysian palm oil stakeholders, from smallholder farmers to major conglomerates. Moreover, the Malaysian government's proactive policies to promote downstream processing and value-added palm-based products have further diversified the industry, opening new revenue streams and cementing Malaysia's status as a comprehensive palm oil powerhouse. Additionally, Malaysia remains committed to meeting international sustainability standards, which is crucial for accessing key markets. Collaborations with international bodies and adherence to certifications have bolstered Malaysia's reputation as a responsible producer.

This review provides insight into the performance of the oil palm industry as well as the R&D progress and achievements for the year 2024. The performance of the Malaysian oil palm industry will be specifically examined, followed by global R&D advancements in the upstream, midstream, and downstream segments of the oil palm industry, and finally, key areas for development and future paths for the industry's sustained expansion in the coming years.

PERFORMANCE OF THE MALAYSIAN OIL PALM INDUSTRY

The year 2024 saw the Malaysian palm oil sector as resilient and adaptive, achieving notable growth in production, exports, and prices. The total planted area decreased marginally below the 2023 level due to strategic replanting initiatives to ensure long-term productivity. The crude palm oil (CPO) production in 2024 outperformed that in 2023, supported by improved fresh fruit bunches (FFB) yield and labour availability. However, due to unfavourable weather, CPO production dropped in the last quarter of 2024 to lower levels than in the last quarter of 2023. Exports of palm oil products increased by 8.9% amidst strong demand from major markets, particularly India and China, resulting in increased revenue. Although the closing stocks of palm oil dropped by 25.3%, this helped to support the upward trend of CPO prices, which rose 9.7% year on year, especially during the last quarter of the year. The combined effect of strategic changes and robust export demand has placed Malaysia in a good position in the global palm oil market.

Oil Palm Planted Area

As of December 2024, the oil palm planted in Malaysia underwent a marginal decline of 0.70%, dropping from 5.65 million hectares in December 2023 to 5.61 million hectares (MPOB, 2025). This reduction is partly due to continuous national efforts in the replanting programme to replace ageing, less productive oil palm trees with high-yielding oil palm planting material, which is fundamental to the long-term sustainable production of Malaysia's palm oil.

At the regional level, Peninsular Malaysia and Sabah experienced a drop in planted area of 0.56% and 1.74%, respectively, while Sarawak saw an increase of 0.04%. Sarawak remains the largest oil palm planted area in Malaysia (*Table 1*). Sarawak presently accounts for 1.62 million hectares, or 28.94%, of the nation's total planted area, followed by Sabah with 1.48 million hectares (26.43%) and Pahang with 0.74 million hectares (13.20%). The industry's commitment to replanting is further demonstrated by a 1.24% reduction in the mature oil palm area, from 5.13 million hectares in 2023 to 5.07 million hectares in 2024, reflecting strategic efforts to boost yield through replanting and modernisation (McGill, 2024).

TABLE 1. MALAYSIAN OIL PALM PLANTED AREA IN DECEMBER 2024 AND 2023

Region	Planted area (ha)			Mature area (ha)		
	2024	2023	Difference (%)	2024	2023	Difference (%)
Peninsular Malaysia	2,504,786	2,518,883	-0.56	2,268,705	2,307,546	-1.68
Sabah	1,483,699	1,510,025	-1.74	1,291,591	1,316,356	-1.88
Sarawak	1,624,366	1,623,661	0.04	1,506,228	1,506,271	-0.00
Malaysia	5,612,852	5,652,569	-0.70	5,066,524	5,130,172	-1.24

Source: MPOB (2025).

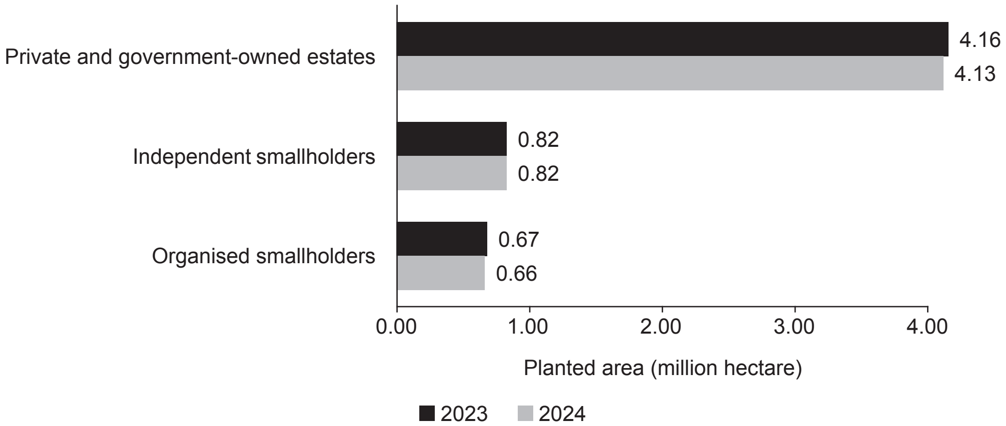
Regarding ownership, private and government-owned estates covered 4.13 million hectares, or 73.6% of the total planted area (*Figure 1*). This was followed by independent smallholders with 0.82 million hectares (14.6%) and the remaining 11.8% owned by organised smallholders. Compared to 2023, the oil palm planted area declined across all ownership categories in 2024, with the largest reduction seen in organised smallholders (1.49%), followed by private and government-owned estates (0.72%) and independent smallholders (0.00% or no change).

Status of Mills and Plants

Table 2 highlights the regional disparities of Malaysia's palm oil processing facilities in 2024. Malaysia has a total of 453 palm oil mills with a combined processing capacity of 123.46 million tonnes of FFB yr^{-1}, 53 refineries [26.39 million tonnes of CPO and crude palm kernel oil (CPKO) yr^{-1}], and 43 kernel crushers (7.36 million tonnes yr^{-1}). The milling capacity utilisation rate also rose by 2.56% in 2024, reaching 80.15% compared to 78.15% in the previous year due to a higher volume of FFB processed in 2024 as against 2023 (MPOB, 2025). Oleochemical plants are exclusively located in Peninsular Malaysia, while biodiesel plants are relatively limited nationwide, with 18 facilities having a total capacity of 2.53 million tonnes yr^{-1}. In conclusion, Peninsular Malaysia dominates in all categories, housing the highest number and capacities of palm oil mills, refineries, kernel crushers, oleochemical plants, and biodiesel plants.

CPO Production

CPO production in 2024 saw an increase of 4.2% to 19.34 million tonnes compared to 18.55 million tonnes in 2023, driven by a higher volume of FFB processed as a result of improved FFB yield. Enhanced labour availability in oil palm plantations also helped increase production levels back to a



Note: In the Malaysian context, independent smallholders are individuals who manage oil palm on their land, typically less than 40.46 ha (100 acres), without being part of any government or organised schemes.

Source: MPOB (2025).

Figure 1. Ownership distribution of oil palm planted area in 2024 vs. *2023.*

TABLE 2. NUMBER AND CAPACITIES OF MALAYSIAN PALM OIL MILLS, REFINERIES, PALM KERNEL CRUSHERS, OLEOCHEMICAL PLANTS AND BIODIESEL PLANTS IN 2024

Facility type	Peninsular Malaysia		Sabah		Sarawak		Malaysia	
	No.	Capacity (Mn t yr^{-1})	No.	Capacity (Mn t yr^{-1})	No.	Capacity (Mn t yr^{-1})	No.	Capacity (Mn t yr^{-1})
Palm oil mill	240	64.05	129	34.99	84	26.35	453	125.40
Palm oil refinery	37	15.42	10	7.88	6	3.10	53	26.39
Palm kernel crusher	27	4.61	10	1.99	6	0.76	43	7.36
Oleochemical plant	19	2.68	-	-	-	-	19	2.68
Biodiesel plant	15	2.01	2	0.30	1	0.22	18	2.53

Note: Mn t yr^{-1} - million tonnes yr^{-1}.

Source: MPOB (2025).

typical trajectory in early 2024, following only marginal production growth in 2023 (Parveez *et al.*, 2024). However, from September 2024 onwards, production performance fell below the 2023 level, largely due to unfavourable weather patterns from 2023 impacting yield in the fourth quarter of 2024. Peak CPO production for 2024 was recorded in August at 1.89 million tonnes, while the lowest was in February at 1.26 million tonnes. In Peninsular Malaysia, CPO production rose by 10.9% to 10.89 million tonnes, while CPO production in Sabah and Sarawak declined by 5.2% and 1.1%, reaching 4.27 million tonnes and 4.17 million tonnes, respectively (*Table 3*).

In 2024, FFB yield increased slightly by 5.8% to 16.70 t ha^{-1} as against 15.79 t ha^{-1} in 2023, mainly driven by better yield performance in the first eight months of the year, which was largely supported by an improved labour situation in the oil palm plantation sector (*Table 4*). Regionally, FFB yield in Peninsular Malaysia increased by 14.5% to 18.42 t ha^{-1}. Sabah's FFB yield registered a decline of 4.0% to 15.74 t ha^{-1} from 16.39 t ha^{-1}, while that of Sarawak was higher by 0.9% to 14.89 t ha^{-1} from 14.75 t ha^{-1} in 2023.

Despite the increase in FFB yield, the oil extraction rate (OER) in 2024 experienced a slight decline of 1.00% to 19.67% compared to 19.86% recorded in 2023. This reduction was primarily attributed to the lower quality of FFB processed in palm oil mills, which was adversely affected by prolonged rainfall and flooding in oil palm areas, especially during the northeast monsoon season in the second half of 2024. Also, the washing of CPO to reduce contamination and lower the levels of 3-monochloropropane-1,2-diol esters (3-MCPDE) further contributed to this decline.

Table 4 also suggests a negative relationship between FFB yield and OER across regions. For instance, Peninsular Malaysia recorded a 14.5% increase in FFB yield, but OER fell by 0.9%. Similarly, Sarawak recorded a slight increase in yield accompanied by a 2.3% reduction in OER. This inverse relationship may be due to the trade-off between higher fruit yields and oil content, which means an increase in fruit production may lead to the processing of lower-quality fruits, thus, reducing oil extraction efficiency. Balancing efforts to enhance yield while maintaining OER remains a critical challenge for the industry.

OER performance in 2024 generally fell across most regions, apart from Sabah, compared to the previous year. Specifically, the OER in Peninsular Malaysia and Sarawak dropped by 0.90% to 19.46% and 2.30% to 19.37%, respectively (*Table 4*).

Trade Performances of Oil Palm Products

Total exports of oil palm products in 2024 reached 26.66 million tonnes, representing an 8.9% increase from 24.49 million tonnes recorded in 2023 (*Table 5*). This growth was driven by a rise in exports across various oil palm products, including palm oil itself and its by-products. Palm oil exports alone rose notably by 11.7%, amounting to 16.90 million tonnes, compared to 15.14 million tonnes in the previous year, driven by a substantial 15.0% increase in processed palm oil (PPO) exports, while CPO exports recorded a modest rise of 0.9%. This surge in exports was largely due to higher demand from

TABLE 3. MALAYSIAN CRUDE PALM OIL PRODUCTION

Region	2024 (t)	2023 (t)	Difference	
			Volume (t)	%
Peninsular Malaysia	10,891,417	9,825,140	1,066,277	10.9
Sabah	4,274,440	4,507,460	-233,020	-5.2
Sarawak	4,172,409	4,219,350	-46,941	-1.1
Total	19,338,266	18,551,950	786,316	4.2

Source: MPOB (2025).

TABLE 4. MALAYSIAN FRESH FRUIT BUNCH PRODUCTIVITY AND OIL EXTRACTION RATE

Region	FFB productivity (t ha^{-1})				OER (%)			
	2024	2023	Difference		2024	2023	Difference	
			Volume	%			Volume	%
Peninsular Malaysia	18.42	16.09	2.33	14.5	19.46	19.64	-0.18	-0.9
Sabah	15.74	16.39	-0.65	-4.0	20.53	20.40	0.13	0.6
Sarawak	14.89	14.75	0.14	0.9	19.37	19.83	-0.46	-2.3
Total	**16.70**	**15.79**	**0.91**	**5.8**	**19.67**	**19.86**	**-0.19**	**-1.0**

Source: MPOB (2025).

major importing countries, reflecting the resilience of global demand despite fluctuating commodity markets.

Besides, Malaysia's palm kernel oil (PKO) exports recorded the highest growth rate at 17.2% to 1.15 million tonnes, up from 0.98 million tonnes in 2023. The major demand for Malaysian PKO came from the European Union (EU), China, and India, where it is used extensively in both food and non-food industries. Meanwhile, Malaysia's exports of palm kernel cake rose modestly by 3.7%. Palm-based oleochemicals and biodiesel exports grew by 4.5% and 4.4%, respectively. Finished products showed an 11.1% increase, while exports of other oil palm products experienced a slight decline of 2.0%. These results reflect a strong demand for palm oil and its derivatives in the global market, with significant contributions from value-added products.

In addition to the impressive export performance, the export revenue of Malaysian palm oil and oil palm products in 2024 saw significant growth of 15.1% from RM94.95 billion in 2023 to RM109.39 billion in 2024. The largest contributor to this growth was palm oil. Palm oil export revenue rose 16.4% to RM72.95 billion, compared to RM62.60 billion in 2023. This increase reflects higher export volume and improved prices, driven by strong global demand for palm oil. Furthermore, the revenue from PKO showed remarkable performance, with a 35.9% increase in export revenue to RM6.79 billion, reflecting strong global demand. Meanwhile, palm-based oleochemicals grew by 8.8%, while finished products recorded an impressive 19.7% increase, reaching RM4.31 billion. Biodiesel exports experienced a declining growth of 4.4%, while other products increased by 8.4%. This higher growth in export revenue compared to volume indicates improved prices together with strong demand for premium and value-added products in the global market.

Malaysian palm oil exports in 2024 were predominantly directed to traditional markets. India led the way with an increase of 185.46 thousand tonnes, followed by the EU with 227.00 thousand tonnes and Kenya with 345.27 thousand tonnes (*Figure 2*). Other key markets included China, which remained one of Malaysia's top importers despite a decline of 77.95 thousand tonnes, as well as Iran (252.51 thousand tonnes), the Philippines (245.21 thousand tonnes), South Korea (42.78 thousand tonnes), Japan (53.71 thousand tonnes), Pakistan (83.65 thousand tonnes) and Türkiye (21.02 thousand tonnes). Together, these top 10 importing countries accounted for 63.7% of Malaysia's total palm oil exports in 2024 with a combined year-on-year increase of 1.46 million tonnes.

India strengthened its position as the largest Malaysian palm oil importer in 2024, with a notable 6.5% increase in imports, reaching 3.03 million tonnes, up from 2.84 million tonnes in 2023. This shift was due to a 12.4% decline in Indonesian palm oil imports, which fell from 5.10 million tonnes in 2023 to 4.47 million tonnes in 2024. The reduction in Indonesia's exports was primarily due to increased domestic consumption driven by a higher biodiesel blending mandate and a slight decrease in production. Meanwhile, China's imports fell by 5.3% due to increased soybean imports from Brazil by 4.2% to 75.45 million tonnes (ISTA Mielke GmbH, 2025).

The EU saw a significant 21.3% increase in Malaysian palm oil imports to 1.29 million tonnes in 2024, driven by a sharp drop in Indonesian supply by 48.4% to 99,000 t in January-November 2024. Moreover, Kenya also boosted imports by 37.7% to 1.26 million tonnes in 2024, as it reduced imports of Indonesian palm oil by 41.9% in January-November 2024.

Palm Oil Closing Stocks and Prices

The palm oil closing stocks in December 2024 declined by 25.3% reaching 1.71 million tonnes *vis-à-vis* 2.29 million tonnes recorded in December 2023. The lower closing stocks were mainly

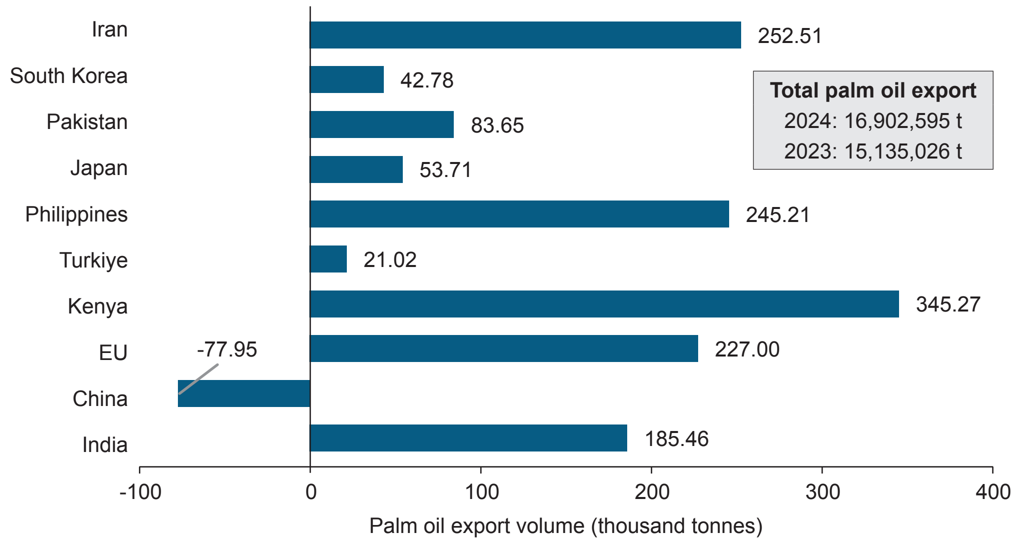
TABLE 5. MALAYSIAN EXPORTS OF PALM OIL AND OIL PALM PRODUCTS

Item	Volume (t)			Value (RM million)		
	2024	2023	Difference (%)	2024	2023	Difference (%)
Palm oil	16,902,595	15,135,026	11.7	72,952	62,601	16.4
Palm kernel oil	1,150,105	981,800	17.2	6,789	4,993	35.9
Palm kernel cake	2,396,517	2,311,506	3.7	1,497	1,667	-10.2
Palm-based oleochemicals	2,993,592	2,864,004	4.5	17,410	15,999	8.8
Biodiesel	255,669	244,793	4.4	1,253	1,310	-4.4
Finished products	585,764	527,013	11.1	4,313	3,602	19.7
Other oil palm products	2,375,206	2,422,905	-2.0	5,179	4,776	8.4
Total	**26,660,448**	**24,487,045**	**8.9**	**109,391**	**94,949**	**15.1**

Source: MPOB (2025).

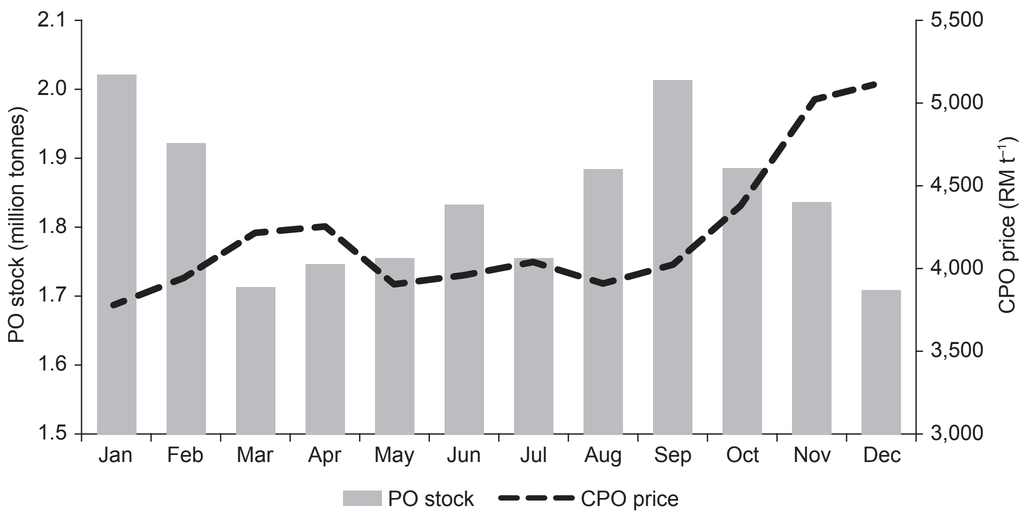
caused by 71.8% lower imports, equivalent to 0.65 million tonnes, and 11.7% increase in palm oil exports. The higher export volume was driven by stockpiling activity among importing countries coupled with lower CPO production, particularly in the fourth quarter of 2024. The palm oil closing stocks comprised 52.0% CPO and 47.4% PPO. All regions recorded declines in palm oil stocks ranging between 21.0% and 30.9%. The significant low stocks compared to the preceding year had a stronger effect on CPO prices throughout 2024, with the average price increasing by 9.7% to RM4,179.50 t^{-1}, in contrast to the recorded RM3,809.50 t^{-1} in 2023 (*Figure 3*).

The highest traded CPO price in 2024 occurred in December at RM5,119.50 t^{-1}, while the lowest was in January at RM3,783.50 t^{-1}. Despite starting the year lower, CPO prices generally trended upward, particularly in the last quarter of 2024. The average CPO price in the first half of 2024 rose marginally by 2.3% to RM4,010.50 t^{-1} compared to the same period in 2023. However, in the second half of 2024, the average CPO price continued to increase, rising remarkably by 18.1% to RM4,414.00 t^{-1} compared to the same period in 2023, mainly due to the sentiment factor of Indonesia's plans to implement B40 biodiesel programme in January 2025 as well as stronger demand from major importing countries.



Source: MPOB (2025).

Figure 2. Year-on-year change in Malaysia's palm oil export volume to major destinations (2024 vs. *2023).*



Note: PO - palm oil; CPO - crude palm oil.

Source: MPOB (2025).

Figure 3. Palm oil stocks and crude palm oil prices, 2024.

In the domestic market, alongside the increase in CPO prices, other oil palm products also traded higher in 2024 as against 2023. The highest percentage rise was observed in CPKO (40.5%), followed by palm kernel (PK) (31.2%) and RBD palm stearin (14.9%) (*Table 6*).

The surge in CPKO prices in 2024 aligned with the rise in global PKO and coconut oil prices, which increased by at least 40.0% compared to 2023. Additionally, the average FFB price in 2024 was up by 13.0% to RM875.00 t^{-1}, reflecting the higher CPO and PK prices.

Figure 4 shows the difference between CPO prices and other vegetable oil prices traded in the international market. CPO price was traded higher by 12.4% to USD1,084.00 t^{-1} in 2024 as against USD964.00 t^{-1} in 2023. Meanwhile, sunflower oil (SFO) was traded higher at USD1,061.00 t^{-1}, up by 5.4%, while soybean oil (SBO) price was traded lower at USD1,045.00 t^{-1} in 2024 as against USD1,124.00 t^{-1} in 2023. Although CPO, SBO and SFO prices continued to move in tandem, the CPO price premium against SBO was at USD39.00 t^{-1} in 2024, compared to a wide discount of USD160.00 t^{-1} in 2023. In the case of SFO, the CPO price premium against the former was at USD23.00 t^{-1} *vis-à-vis* a discount of USD43.00 t^{-1} in 2023. The price gap between CPO and SBO, as well as SFO, narrowed in 2024. The premium in CPO price against other vegetable oil prices was mainly attributed to the supply disruption in the global market, which resulted in less competitiveness of CPO price as against SBO and SFO (McGill, 2025).

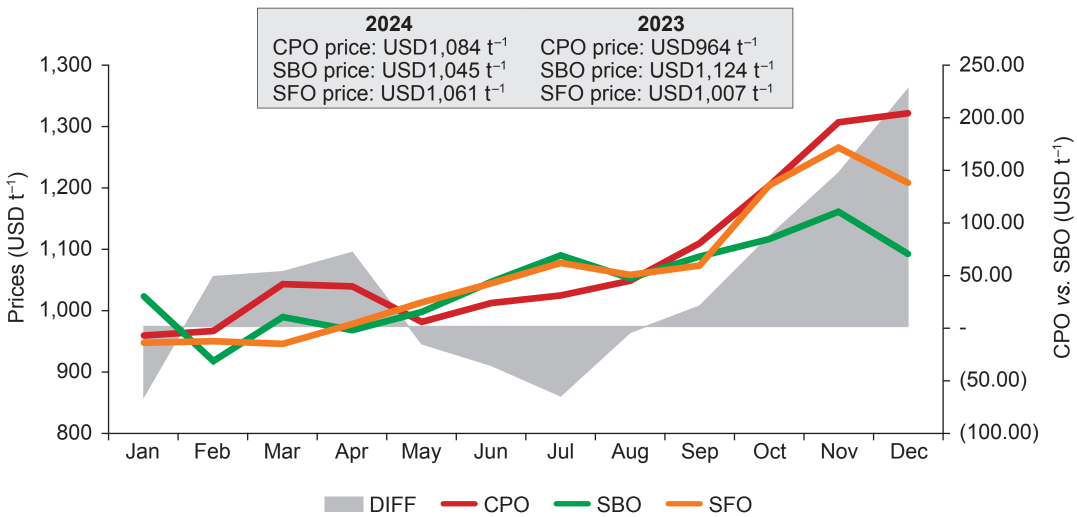
Moving forward to 2025, the CPO price is expected to strengthen, averaging between RM4,000.00 t^{-1} and RM4,300.00 t^{-1} compared to RM4,179.50 t^{-1} in 2024, primarily driven by a tightening global palm oil supply. The

TABLE 6. MALAYSIAN PRICES OF OIL PALM PRODUCTS

Item	2024 (RM t^{-1})	2023 (RM t^{-1})	Difference	
			RM t^{-1}	%
CPO	4,179.50	3,809.50	370.00	9.7
RBD palm oil	4,296.50	3,989.00	307.50	7.7
RBD palm olein	4,359.50	4,055.00	304.50	7.5
RBD palm stearin	4,402.50	3,833.00	569.50	14.9
Palm kernel	2,645.50	2,016.00	629.50	31.2
CPKO	5,475.50	3,896.00	1,579.50	40.5
FFB	875.00	774.00	101.00	13.0

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

Source: MPOB (2025).



Note: SBO - soybean oil; SFO - sunflower oil; CPO - crude palm oil; DIFF - difference between CPO and SBO prices.

Source: MPOB (2025).

Figure 4. Prices of palm oil vs. *other vegetable oils in 2024.*

implementation of the B40 biodiesel (a blend of 40% palm oil and 60% regular diesel) mandate in Indonesia is expected to further reduce the availability of global palm oil for export, as a significant portion of production will be allocated for domestic use. Additionally, biodiesel demand in the USA is anticipated to rise and Malaysia's palm oil stocks are projected to remain below 2.00 million tonnes, contributing to price stabilisation and further tightening the global supply of palm oil (Parveez, 2025).

R&D FOCUS AREAS IN 2024

Climate Change Mitigation and Carbon Sequestration in Oil Palm Plantations

Climate change significantly impacts oil palm cultivation in terms of soil moisture, unpredictable weather changes, and monsoon patterns, thus causing heat stress (Tey & Brindal, 2024). According to the 2018 Intergovernmental Panel on Climate Change (IPCC) report, global average temperatures will increase by 1.5°C to 2.0°C between 2030 and 2050, which will reduce yields and increase costs, threatening the oil palm's productivity and subsequently its sustainability (Abubakar *et al.*, 2023). Tey and Brindal (2024) emphasised that accelerating climate change adaptation for oil palm necessitates effective dissemination of mechanisation advancements, focussing on plant breeding and bio-fertiliser technologies, accentuating the need to enhance resilience and yield stability. It is therefore recommended that a model should be developed to mitigate emerging adverse effects, including optimising agronomic practices such as planting density, irrigation, fertilisation, pruning, pest, and disease control; developing resilient palm varieties that are drought-tolerant, disease-resistant, and pest-resistant; improving land use strategies; utilising hyperspectral imaging drones for early disease detection; promoting intercropping and agroforestry systems; and implementing an early weather monitoring system.

The global carbon cycle balance has deteriorated over the last century, as carbon sequestration has failed to keep pace with anthropogenic CO_2 emissions, causing climate instability and jeopardising future food security. Rising CO_2 levels may promote photosynthesis, but biogeochemical considerations, notably nitrogen (N) availability, may impede fruit development (Beringer *et al.*, 2023). Rebalancing the carbon flux and minimising GHG emissions requires lowering net emissions and increasing carbon sequestration activities. As such, the development of high-sequestration systems, such as natural forests, coastal wetlands, and tropical croplands, should be prioritised (Murphy, 2024). The study recommended that recovering degraded lands, producing high-yield agricultural genotypes, and attaining net-zero carbon objectives should be adopted. The African oil palm (*Elaeis guineensis*) is well recognised for its high carbon absorption capability, especially in agroforestry systems where intercropping increases carbon uptake. A carbon sequestration study in India discovered that the overall carbon storage capacity across eight planting sites with 1,015 standing palms was 345.1 t yr^{-1}, underscoring a significant contribution to carbon capture (Lalawmpuia *et al.*, 2023). However, the planters need to be guided on sustainable management practices, such as how to treat degraded lands for intercropping activities, to reduce negative environmental effects and maximise oil palm carbon sequestration potential while balancing the need for climate change mitigation with forest preservation.

Good Practices and Biodiversity in Oil Palm Cultivation

Good oil palm planting materials are essential for maximising yield and palm oil production under optimised planting density. Afandi *et al.* (2024) demonstrated that the PS1 trait provided characteristics that are ideal for planting at higher densities of 160 palms ha^{-1} through shorter rachis length and lower height increment. However, long-term evaluations revealed that planting at 140 palms ha^{-1} density provided yields with the highest cumulative and average FFB at 427.0 and 24.2 t ha^{-1} yr^{-1}, respectively. No significant interactions were observed among planting density, N, and progeny lineage. Furthermore, significant N_2O flows and N losses have been discovered in several locations, especially following fertiliser application (Zawawi *et al.*, 2024). A study by Chen *et al.* (2024) proposed that precision agriculture through controlled-release fertilisers to manage soil may reduce N_2O flux. However, oscillations in N_2O emissions between fertilisations reflect changes in N dynamics throughout the year, suggesting a need for further research using stable isotope tracers to monitor N fertiliser and comprehensive sampling to estimate its total emissions (Zawawi *et al.*, 2024).

Additionally, fertiliser created from biochar generated from oil palm biomass (OPB), such as mesocarp fibre and empty fruit bunches (EFB), enhances fertiliser efficiency, seedling development, and soil health, establishing it as a sustainable solution for oil palm cultivation in Malaysia (Tugiman *et al.*, 2024). In some cultivation areas, high aluminium toxicity levels cause acidic soil, impeding root growth and nutrient uptake by oil palm seedlings (Husein *et al.*, 2024). Among the four varieties evaluated, Ulu Remis Deli *dura* x Ulu

Remis *tenera* seedlings appeared more tolerant to aluminium toxicity with no significant effects on bole width, chlorophyll content, or biomass. Mobile apps may be used to optimise oil palm fertilisation practices, as demonstrated in this study on the Oil Palm Fertiliser Infographic Mobile Application, also known as *Baja Sawit* (Ishak *et al.*, 2024). The app encourages efficient fertilisation techniques among smallholders with a simple, user-friendly design based on Mayer's 12 Principles of Multimedia Learning, as well as straightforward infographics, real-time crop monitoring, and artificial intelligence integration to increase oil palm production and sustainability.

Biodiversity in oil palm plantations is crucial for preserving ecosystem balance, boosting pollination, encouraging pest and disease control, and ensuring long-term agricultural sustainability while minimising negative environmental consequences (Dalheimer *et al.*, 2024). Biodiversity flourishes in oil palm smallholdings because smaller field sizes and staggered replanting practices generate ecosystems that promote ecological equilibrium. Smallholders can contribute to local biodiversity conservation by fostering spatial heterogeneity and crop diversification while large plantations can adjust replanting strategies (Azhar *et al.*, 2023).

Sustainable Development for Smallholders

Malaysia has introduced the Malaysian Sustainable Palm Oil (MSPO) certification to encourage sustainable practices in the palm oil sector. One critical factor for enhancing smallholders' participation in MSPO involves addressing their attitudes and perceived behavioural control (Majid *et al.*, 2023). Abidin *et al.* (2024) further reported that awareness and knowledge gaps among smallholders regarding certification benefits and requirements need to be addressed. Besides addressing social and environmental concerns, the MSPO standards provide smallholders with guidance on Good Agricultural Practices (GAP), including waste management (Hamid *et al.*, 2024).

The adoption of GAP is important for the sustainable management of oil palm cultivation among smallholders. MPOB, through its extension services, provides training to smallholders on various GAP designed to optimise oil palm management and yields. Adoption of GAP, such as improved harvesting and nutrient management, leads to an increase in yields (Lim *et al.*, 2024b; Ramachandran *et al.*, 2024). Sham *et al.* (2024) emphasised the importance of reducing nutrient leaching from fertilisers and promoting sustainable agricultural practices, encouraging smallholders to adopt strategies that minimise nutrient losses and mitigate environmental impacts. Another study by Ahmad *et al.* (2024a) recommended selecting suitable soil types to increase oil palm production without compromising high-value tropical forests. This approach promotes sustainable practices while maintaining productivity in oil palm cultivation.

There is a greater need to accentuate the crucial role of Information and Communication Technology (ICT) in empowering oil palm smallholders to adapt to climate change and improve their livelihoods (Peng *et al.*, 2024). As stated earlier, Ishak *et al.* (2024) have developed a user-friendly mobile application platform (*Baja Sawit*) for farmers to access current information, thereby enhancing productivity and supporting informed decision-making. MPOB has embarked on developing ICT tools to enhance the monitoring of oil palm product transactions, ensuring greater transparency and traceability throughout the supply chain [MPOB, 2023; MSPO & the European Forest Institute (EFI), 2024].

In addition to the challenges smallholders face in managing oil palm cultivation, they also struggle with global regulations, such as the European Union Deforestation Regulation (EUDR). The EUDR is the latest regulation from the EU aimed at addressing deforestation-related concerns. The EU's focus on ensuring palm oil traceability to its specific plantation origin poses challenges, especially for smallholders, who may find it difficult to comply with these requirements [Malaysian Palm Oil Council (MPOC), 2024]. Smallholder producers may face challenges in meeting traceability requirements, which could exclude them from global supply chains (Nadras *et al.*, 2024). Solidaridad Network (2023) suggests acknowledging the initiatives that promote the sustainable development of palm oil in producing countries. These include mandatory sustainability frameworks like the MSPO and the Indonesian Sustainable Palm Oil (ISPO), which are vital tools for promoting adherence to national regulations and laws. Therefore, continuous communication of reliable and accurate information about Malaysia's efforts in sustainable practices is crucial for addressing and clarifying any misconceptions about the palm oil industry (Naidu *et al.*, 2024).

The use of technologies, especially machinery, in oil palm cultivation is often limited for smallholders due to economies of scale. This limitation suggests the need for forming groups of smallholders to leverage collective resources and benefits (Ahmad *et al.*, 2023). To address this, the government, through the MPOB, introduced a cooperative structure to empower smallholders to better manage their resources collectively. Various forms of financial and management assistance have been provided to cooperatives to engage in business ventures, such as establishing FFB collection centres. This enables smallholders to sell FFB directly to mills, thereby enhancing economic development. In addition, the establishment of cooperatives among indigenous oil palm smallholders could provide substantial benefits to the indigenous community (Chin *et al.*, 2023).

Effective Pest and Disease Management Strategies

Several vertebrate and invertebrate pests were found to be potential threats to oil palm plantations. The bagworm *Metisa plana* (Lepidoptera: Psychidae) causes significant leaf defoliation, especially in Peninsular Malaysia (Ahmad *et al.*, 2024b). Management strategies utilising palm-based sticky glue, neem oil (*Azadirachta indica* A. Juss) and Quad trap have been successfully implemented to reduce bagworm incidence in plantations (Ahmad *et al.*, 2024b; Kamarudin *et al.*, 2024; Sattar *et al.*, 2024). Another pest, the mealybug, has had a substantial impact on oil palm plantations in Sabah, particularly in Tawau and Lahad Datu, by spreading the sooty mould disease (Miwil, 2024). This disease obstructs the photosynthesis of oil palm fronds, resulting in stunted growth and a 5.6% annual decline in FFB production between 2018 and 2023. Treatments such as trunk injections and chemical sprays have the potential to manage outbreaks effectively. Meanwhile, to address rodent infestation, artificial hunting perch spots strategically positioned within oil palm plantations are ideal in attracting predatory birds, in this case barn owls (*Tyto alba*), as a natural solution for pest control and thus reducing dependency on chemical pesticides (Tohiran *et al.*, 2024).

Aside from pests, oil palm disease is a serious threat to Malaysian oil palm plantations, with the most prevalent being basal stem rot (BSR) caused by *Ganoderma boninense,* which may cause economic losses of up to 80.0% (Zakaria, 2023). During the 37-month observation period, BSR progressed significantly faster in oil palms planted in peat soil, with 93.8% reaching critical infection (Stage 4) compared to 62.5% in mineral soil, most likely due to higher organic matter and nutrient deficiencies, such as copper and zinc, in peat soil (Virdiana *et al.*, 2024). A genomic study of *G. boninense* isolates from three Malaysian oil palms revealed seven haplotypes with modest genetic variation (0.1%-0.9%), indicating low genetic recombination and strong population similarity (Roslan *et al.*, 2024). In addition, Syarif *et al.* (2025) identified 53 arthropod species (Coleoptera) and *Eumorphus* sp. beetle associated with *Ganoderma* basidiocarps in oil palm plantations as probable vectors of BSR disease.

Detection strategies, such as deep learning techniques and dedicated drone cameras through hyperspectral image processing, have significantly improved *Ganoderma* infection detection in oil palm canopies, with accuracy rates ranging from 70.0% to 92.5% (Izzuddin *et al.*, 2024). Simultaneously, employing nanotechnology to enhance azole-based fungicide delivery provides a game-changing solution for managing BSR disease in oil palm plantations, increasing fungicide efficacy by up to 75% compared to earlier techniques (Asmawi *et al.*, 2024). The incorporation of fungal biocontrol agents (BCA) into integrated disease management (IDM), especially BSR, represents a significant advancement in sustainable agriculture by utilising natural microbial communities for safe disease control, reducing synthetic chemical impacts, improving plant health and yield, and supporting United Nations Sustainable Development Goals (UNSDG) (Sundram *et al.*, 2023). Recent advances in early detection and resistance breeding highlight the need for integrated approaches that combine cultural practices, biological management, and resistant varieties to promote plant health and sustainability in oil palm plantations (Karunarathna *et al.*, 2024).

In Malaysia, the integrated pest management (IPM) and IDM are designed to provide a sustainable approach to pest and disease control. However, concerns persist regarding pesticide, herbicide, and fungicide residues in oil palm and its extracted oils, such as CPO and PKO. Fortunately, most pesticides used in oil palm plantations degrade quickly, minimising the risk of groundwater contamination. Analysing pesticides in palm oil matrices presents significant challenges, particularly in multi-component analyses. Ping and Maurad (2024) provided an overview of recent advancements in analytical methods for detecting pesticides in CPO and PKO, ensuring food safety and regulatory compliance. The high lipid content and diverse fatty acid profiles of palm oil and PKO can create substantial matrix effects, complicating pesticide extraction and detection.

Malaysia has addressed the challenges facing the industry by establishing long-term solutions balancing economic growth, environmental preservation, biodiversity conservation, and social welfare (Ali *et al.*, 2024). The adoption of modern technologies in management practices, harvesting, and productivity activities, as well as infrastructure improvements and the implementation of supportive government funding and enforcement policies, such as primary forest conservation for local inhabitants and biodiversity, have all contributed to the industry's positive growth. Shehu and Salleh (2024) agreed that Malaysia serves as an example for other countries, including Nigeria, which might benefit from its approach to revitalising the sustainable palm oil industry.

Biotechnology: Key Solutions for Sustainable Future

The MPOB-Angola oil palm germplasm provided a high level of genetic variability within the selected *dura* and *pisifera* parental lines, which could effectively broaden the genetic base of the current parental lines used for commercial seed production. The potential of the MPOB-Angola germplasm to further improve oil yield, in addition to its other useful secondary characteristics, provides breeders with a good source of new genetic material for breeding and selection (Norziha *et al.*, 2024). An exotic germplasm from Nigeria that demonstrated a high level of genetic variability for all yield-related traits has also been introduced into existing breeding populations to develop new high-yielding planting materials (Malike *et al.*, 2024).

One of the main challenges facing the oil palm industry is the abnormal fruits observed in clonal palms, including the mantled somaclonal variant, which can lead to a reduced oil yield. Karma-EgDEF1 methylation was shown to alter upon clonal propagation, resulting in high mantling rates upon recloning (Ooi *et al.*, 2024). The application of the single nucleotide polymorphism (SNP) array demonstrated in a quantitative trait locus (QTL) study involving a selfed Nigerian oil palm family (T128) allowed the identification of the genomic region associated with the compactness trait, including candidate genes with the QTL regions (Ting *et al.*, 2023).

The selection of ideal planting materials that are resistant or tolerant to BSR could also be expedited with the availability of genomics and molecular tools, including an RNAi-mediated gene silencing approach. A study involving the manipulation of the *lanosterol 14α-demethylase* (*GbERG11*) gene of *G. boninense* via RNAi-mediated gene silencing showed a reduction in both fungal growth and gene expression, as well as a loss of ergosterol production, an important cell membrane sterol in fungal pathogenicity (Lim *et al.*, 2024a).

Secondary metabolism in different oil palm fruit tissues at the ripening stage was also explored using the proteomics and metabolomics approaches (Hassan *et al.*, 2024). Several enzymes and metabolites associated with stilbenoid biosynthesis were determined through profiling of the proteomes and metabolomes of the tissues. The presence of stilbenoids, along with other proteins and metabolites in oil palm fruit, indicates their potential as candidate compounds for improving oil palm yield and quality. Selecting and breeding oil palm varieties rich in natural antioxidants will enhance the safety of oil palm products and improve the health benefits associated with palm oil consumption.

Efforts to improve oil palm planting materials through *Agrobacterium*-mediated genetic engineering were pursued by constructing new and efficient transformation vectors carrying different genes, promoters, and backbones and testing them in oil palm tissues (Hanin *et al.*, 2024). Recently, Norfaezah *et al.* (2024) reported the first breeding innovations through the DNA-free clustered regularly interspaced short palindromic repeats/associated protein 9-ribonucleoproteins (CRISPR/Cas9-RNPs) genome editing in oil palm protoplasts. Oil palm breeding advancements using this platform could accelerate the targeted development of desirable traits in the oil palm. In addition, genetic manipulation of multiple transgenes for the production of high oleic palm oil using the MSP-C6 promoter deployment strategy may also accelerate the development of planting material with improved nutritional quality (Badai *et al.*, 2023).

Mechanisation and Automation

Industry Revolution 4.0 (IR4.0) enhances efficiency, productivity, and precision while reducing costs and environmental impact. However, its implementation requires significant financial and technical support. Key initial steps include centralising data through big data and cloud computing and integrating automation and the Internet of Things (IoT), which improve decision-making with real-time insights and boost productivity by enabling early problem detection and optimising equipment efficiency.

There have been several advancements in R&D focused on mechanisation and automation. Hexa IoT developed an AIoT solution, Luxio-AI, to aid workers in determining palm fruit harvest readiness with ease. The solution can automatically sort palm fruit harvest readiness by visual means. IoT solutions also include Pandora software that aids in various stages of the plantation process, *i.e.*, to accurately determine upcoming weather conditions and detect soil quality (Wong & Koo, 2024). Furthermore, a LiDAR sensor-based spraying system has the potential to reduce chemical usage by 25% through targeted spraying, subsequently leading to an overall reduction in the amount of chemicals used. This system integrates traceability via IoT, which enhances productivity and reduces the need for labour (Bakri *et al.*, 2023).

While robotic solutions for harvesting show promise, their high cost and complexity currently limit widespread adoption. Therefore, an innovative lifting device has been developed to aid in loading FFB in the palm oil industry. This device utilises a simple hydraulic tipping system and can handle 400 kg in just 40 s, resulting in a 35% reduction in loading time. A comparative study of various FFB harvesting methods revealed that the manual method is the least efficient, with a labour-to-land ratio of 1:21 ha, even though it has the lowest capital and operational expenses. The mechanised cutters, such as CANTAS (RZTech Resources Sdn. Bhd., Malaysia), are more efficient, with a labour-to-land ratio of 1:35 ha, albeit with higher initial costs. Despite their high upfront costs, mid-size harvesting machines cover the most land for each worker involved, with a labour-to-land ratio of 1:86 ha, ultimately reducing operational expenses due to increased efficiency (Ramli *et al.*, 2023). Despite these challenges, these advancements represent significant strides towards increasing productivity and sustainability in Malaysia's palm oil industry.

Biomass, Bioenergy and Biorefinery

The country's palm bioenergy potential could reach 63.5 million tonnes of oil equivalent, fulfilling 64% of the primary energy demand. Optimising second-generation feedstocks could unlock an additional 31.7 million tonnes, increasing the renewable energy share to 38% and reducing GHG emissions by up to 57% from 2005 levels (Gourich *et al.*, 2023).

At the heart of this transformative shift is a cutting-edge technology: The Novel-Lignoripper Snipper (Hur Far Engineering Works Sdn. Bhd., Malaysia) press machine, which efficiently transforms OPB into short fibres suitable for renewable energy feedstock. Biopellets made from OPB using this machine in combination with a pelletising unit meet international quality standards (Fazliana *et al.*, 2024).

Palm-pressed mesocarp fibre (PPMF), having approximately 11% residual oil, could be diversified to produce hydrogels from its holocellulose component using citric and acetic acids as cross-linkers (Teh *et al.*, 2024). Additionally, ferulic acid, a low-toxicity compound with various health benefits, can be extracted from EFB using a deep eutectic solvent made from choline chloride and acetic acid, with the process allowing for recycling of the solvent to enhance yields with each extraction (Ng *et al.*, 2024).

Biodiesel blends, typically composed of 5% to 35% biodiesel mixed with conventional diesel, have uncertain impacts on emissions and fuel consumption. A study on six VOLVO FM400 I-Shift trucks using B10 and B20 revealed that engine oil quality met manufacturer standards within the 30,000 km service interval without significant maintenance differences (Daryl Jay *et al.*, 2024). The palm oil industry could potentially contribute to the reduction of carbon emissions and enhance sustainability, encouraging other sectors to adopt biodiesel by using higher blends like B20 or B100, which can also help to meet local demand and reduce import dependency (Yung *et al.*, 2024). While palm biodiesel is well-established in the lowlands, its performance in the highlands is uncertain. A trial in a highland, *i.e.*, Cameron Highlands, showed that Euro 2M blends work well at 15°C for B20 and 20°C for B30, while Euro 5 blends up to B30 have no startability issues. On-road tests confirmed that diesel vehicles using the three blends up to B30 are suitable for Malaysia's highlands with no technical problems encountered (Nursyairah *et al.*, 2024).

A renewable diesel with 73% C16 hydrocarbon content that can meet Ultra Low Sulphur Diesel (ULSD) specifications, making it compatible with existing engines, was successfully prepared (Nur Azreena *et al.*, 2024). In addition to biodiesel, there is a growing effort to diversify palm biodiesel into bio-lubricants by utilising high-oleic palm methyl ester (HO-PME) and trimethylolpropane (TMP) as substrates for enzymatic transesterification. Recent research has identified TMP and HO-PME as competitive inhibitors of the lipase enzyme (Novozyme 435) used in this process, providing critical insights for large-scale production of biodegradable lubricants that offer improved biodegradability and lower toxicity compared to conventional lubricants (Wafti *et al.*, 2023). Furthermore, OPB is being explored as a feedstock for furfural production, a versatile biorefinery platform chemical for biofuels and fuel additives. A collaborative effort between MPOB and Tsinghua University, China has developed a non-isothermal kinetic model that predicted a 71% yield of furfural from EFB through intermittent steam discharge. This integrated process not only enhances sustainability and green chemistry but also promotes responsible waste management, supporting a circular economy by incentivising millers to improve milling efficiency (Ouyang *et al.*, 2023).

Additionally, certifying residual oils from palm oil mills offers significant environmental and economic benefits for sustainable fuel production. The International Sustainability and Carbon Certification (ISCC) includes feedstocks like EFB, palm oil mill effluent (POME), and PPMF. Malaysia could potentially recover 0.7 million tonnes of waste oil annually for biofuel under ISCC. By utilising biomass and residual oils, mills can diversify their product portfolios, minimise environmental impact, and support the transition to a low-carbon economy. This globally recognised certification ensures that such oils are sustainably sourced and processed into biodiesel and other biofuels that meet stringent standards (Lau *et al.*, 2024).

Palm Oil and Its Nutritional Benefits

Palm oil is known for its distinctive reddish-orange colour due to its high carotenoid content. One characteristic of palm oil is its comparatively balanced fatty acid composition. Saturated and unsaturated fatty acids have the same compositional makeup (Arias *et al.*, 2023), making them suitable for various food product applications. The relatively low linoleic acid (C18:2, 10%-11%) and higher palmitic acid (C16:0, 44%-45%) content in palm oil increases its heat stability and makes it more resistant to oxidative deterioration during food and food product preparation (Loganathan *et al.*, 2022) compared to other vegetable oils with high polyunsaturated fats. Polyunsaturated oils such as SFO, SBO and corn oil are particularly susceptible to oxidation and are therefore less suitable for prolonged cooking. Palm oil or its blends are preferable for prolonged cooking as they help to maintain oil quality and delay lipid oxidation. It was found that the presence of antioxidants can increase the oxidative stability of the oil, but their effectiveness decreases with improper storage and prolonged exposure to heat (Loganathan *et al.*, 2022).

The World Health Organization (WHO) recently conducted an overview of systematic reviews highlighting the significant impact of palm oil intake on cardiovascular health, particularly concerning cardiovascular disease (CVD), a major cause of mortality worldwide, and it is particularly prevalent in low- and middle-income countries (WHO, 2024). CVD is often characterised by dyslipidaemia, an imbalance of blood lipids such as cholesterol, with elevated levels of non high-density lipoprotein (HDL) and low-density lipoprotein (LDL) cholesterol associated with an increased risk of CVD. Keeping these cholesterol levels low has been shown to be associated with a reduction in CVD risk. Dietary factors also play a crucial role in determining CVD risk. The health effects of palm oil consumption have attracted considerable attention worldwide due to its saturated fat content. The literature search was performed in March 2021 and was conducted again in January 2022 in various databases. The overview provides pooled analyses of the data from the individual clinical trials by evaluating the results of these studies based on eligibility criteria and statistical analyses. The authors extracted data for comparisons between the consumption of palm oil and other vegetable oils, including a subgroup analysis of PUFA-rich and MUFA-rich oils. The results of the systematic reviews that used a pairwise meta-analysis were reported. The risk of bias in each clinical trial included in the systematic reviews was also determined using validated instruments. The results showed varying effects on lipid profiles, with palm oil intake showing trivial to minimal effects on total cholesterol, LDL cholesterol, HDL cholesterol, and triglycerides.

Further to the above, a recent review has updated and summarised the health effects of consumption of various vegetable oils, including rapeseed, peanut, olive, flaxseed, sesame, rice bran, coconut, and palm oils (Voon *et al.*, 2024). The study synthesised evidence from systematic reviews and meta-analyses to evaluate the health outcomes associated with different types of vegetable oils. The study was conducted across 12 databases until 31 July 2023, and identified studies examining the association of various vegetable oils with health outcomes in adults. The review article included 48 studies, and 206 meta-analyses reported that oils rich in monounsaturated and polyunsaturated fatty acids, such as canola, virgin olive, and rice bran oils, moderately reduce serum total cholesterol (TC) and LDL cholesterol concentrations, while palm oil and coconut oil positively influence lipid profiles by raising the good cholesterol (HDL) levels even though they are also found to raise TC and LDL cholesterol levels (Voon *et al.*, 2024). In addition, palm oil was found to have a neutral effect on i) lipid profile (total/HDL cholesterol, triglycerides, apolipoprotein A1, apolipoprotein B), ii) glycemic outcomes (fasting glucose and insulin), and iii) body weight changes. The review suggested that all vegetable oils included in the study, including palm oil, offer different health benefits, particularly lipid parameters. Therefore, the recommendation for palm oil intake must be carefully examined, particularly when it is used in a balanced diet in tropical populations.

A healthy diet could provide a favourable environment that allows essential bacteria to grow and ferment beneficial metabolites, short-chain fatty acids (SCFA), through various metabolic pathways. SCFA, including linear and branched-chain SCFA (BSCFA), is important for regulating energy, haemostasis, inflammation and appetite. Malaysian dietary guidelines are in line with global recommendations for a healthy diet and emphasise the consumption of fruits and vegetables. However, there is limited research on the gut microbiota and SCFA profiles associated with the Malaysian diet, particularly in relation to palm oil consumption. Acetate, propionate and butyrate are the most abundant SCFAs, with Firmicutes and Bacteroidetes being the predominant phyla and *Faecalibacterium* and *Prevotella* being the major SCFA-producing genera (Yap *et al.*, 2024). Given the uniqueness of Malaysian cuisine prepared with palm oil, there is potential to create a favourable environment for the gut microbiota and improve SCFA production to promote gut health. Therefore, the incorporation of palm oil into the diet may also provide holistic benefits for digestive health. These findings highlight palm oil's potential in functional foods targeting gut health and suggest a need for further research to confirm these effects across different populations in dietary contexts.

Red palm olein contains a high level of carotenoids (rich in beta-carotene, a precursor to vitamin A) in the oil, which plays a role in vision and immune function. Tan *et al.* (2024) studied red palm olein biscuit supplementation to help control vitamin A deficiency (VAD), aiming to prevent childhood morbidity and mortality in developing countries. A significant improvement in retinol and retinol-binding protein-4 levels was observed.

The blood alpha- and beta-carotenes, iron levels, and haematological parameters were increased and thus contributed to a reduction in the prevalence of microcytic anaemia and inflammation. In addition, the control group (palm olein biscuits) was also found to have higher improvements in retinol levels among those with marginal VAD.

A study by Teng *et al.* (2024) on 143 adults with central obesity who consumed red palm olein, virgin olive oil, and virgin coconut oil for 12 weeks revealed that the red palm olein group had higher levels of alpha- and beta-carotenes (P<0.05) compared to the extra virgin olive oil and extra virgin coconut oil groups, which corresponds to the high carotenoid content in the red palm olein. The three diets were found to have comparable effects on cardiometabolic biomarkers, lipid profile, and bone mineral density. Therefore, similar to the well-accepted virgin olive oil and virgin coconut oil, it was suggested that red palm olein is suitable for use in food preparation, especially as a salad dressing, preserving its antioxidant effects.

In addition to carotenoids, palm oil also contains a variety of phytonutrients, notably tocotrienols and tocopherols. These compounds have antioxidant properties that help protect cells from oxidative stress, a factor linked to aging and chronic diseases (Fatah & Tee, 2024).

New Developments in Palm Oleochemical Applications

Grand View Research (2024) projects a 7.0% compound annual growth rate (CAGR) in revenue growth for the global oleochemicals market between 2024 and 2030. Demand growth can be attributed to a shift toward sustainable chemicals. Traditional applications of oleochemicals, such as surfactants, personal care products, and food additives, have been extended to new applications in segments such as biosurfactants, lubricants, and polymers in recent years, which offer substantial prospects for companies in the long run.

A noteworthy advancement has been in the circular economy and waste-to-wealth concept for the development of sustainable building materials by utilising OPB and polyurethanes (PU) (Poopalam *et al.*, 2024). Conventional building materials are manufactured using energy-intensive materials that degrade the environment and contribute to increased GHG emissions. By prioritising eco-friendly building materials and practices, sustainable construction helps to preserve ecosystems, conserve natural resources, and reduce energy consumption. Consequently, this leads to a decrease in GHG emissions and a lower carbon footprint for the construction industry. In addition, Ismail *et al.* (2024) revealed that the incorporation of palm-based dihydroxystearic acid (DHSA) as a co-polyol to synthesise rigid PU foams significantly affects the PU cell matrix. Open cell content notably increased from 6.83% to 90.99% when the DHSA content was increased from 0.00% to 50.00%. This opens up the potential applications of rigid PU foams as sound absorption materials. This not only fosters environmentally sustainable materials but also contributes to long-lasting solutions for the sustainable construction sector.

Similarly, the lubricant and grease sector has embraced the unique qualities of palm oleochemicals. Fajar *et al.* (2024) have begun tapping into the lubricating power of palm-based bio-lubricant formulations for diesel engines using machine learning and experimental techniques to enhance thermal-oxidative stability and lubricity. The bio-lubricant formulation combines various modified base stocks to meet SAE-30 and SAE-40 diesel lubricant specifications. This study underscores the effectiveness of integrating chemical modifications, machine learning predictions, and blending palm-based stocks to optimise bio-lubricant formulations without the need for prior synthesis or modification of palm olein and palm methyl ester.

Polyglyceryl polyricinoleate (PGPR), an emulsifier for food, cosmetics, and personal care products, is commercially produced by the esterification of polyricinoleic acid and polyglycerol. Since polyricinoleic acid is expensive compared to other polymerised forms of fatty acids, Hoong *et al.* (2024) attempted to produce an analogue made from less costly fatty acids by converting oleic acid to polyhydroxy estolide (*Figure 5*) and using it as a substitute for polyricinoleic acid to produce PGPR analogues. By tailoring the synthesis parameters and using specific fatty acids, a spectrum of emulsifiers can be produced, each with different properties suitable for diverse emulsion formulations.

Triglycerides from plant oils provide a sustainable alternative for ultraviolet (UV)-curable coatings, which can be used in electronics, inks, coatings, and adhesives. However, the alkene group of unsaturated fatty acids in the triglyceride structure is insufficiently reactive for various polymerisation processes. A bio-based resin was obtained by replacing part of a petroleum-based resin with natural plant oil via UV curing technology, which has key attributes such as low temperature, fast curing, and solvent-less processes (Cheong *et al.*, 2024a).

The synthesis of sulphonated carbon heterogeneous acid catalyst from glycerol pitch is an emerging field exploring the utilisation of this waste resource of the oleochemical industry. A study by Armylisas *et al.* (2024) highlights the synthesis of a sulphonated carbon catalyst from glycerine pitch. Glycerine pitch is a feasible carbon source due to its high organic content, being renewable

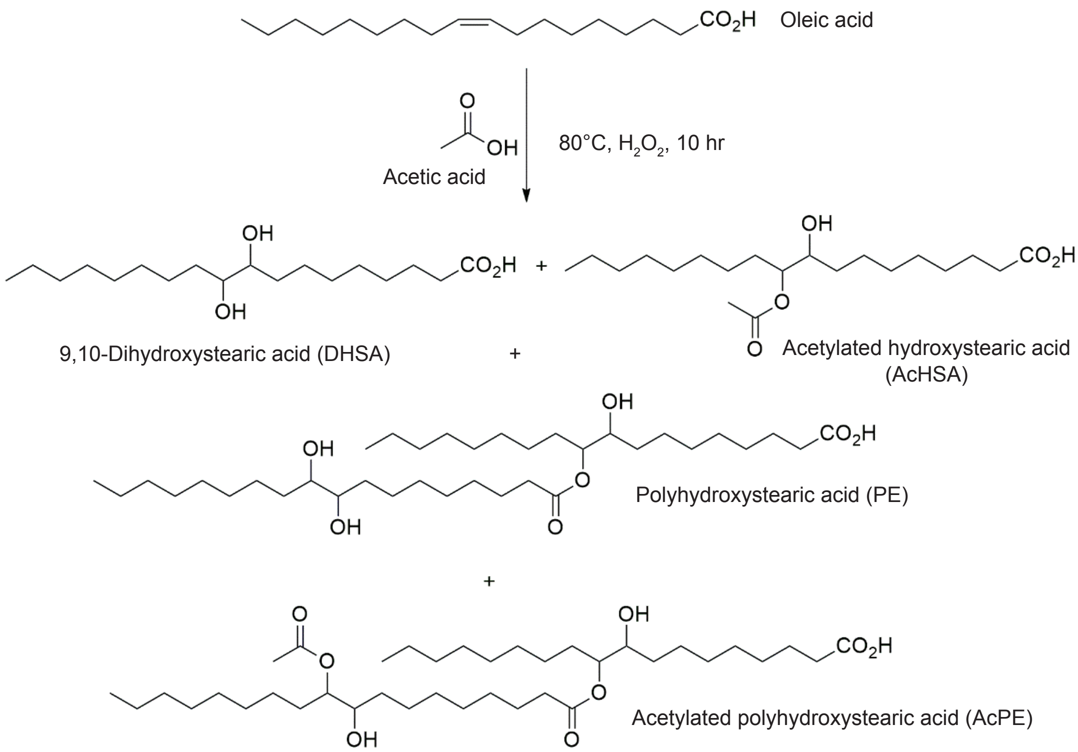


Figure 5. Synthesis of polyhydroxy estolide mixture from oleic acid.

and cost-effectiveness. The catalysts can be used in applications such as hydrolysis, esterification, and transesterification of triglycerides, glycerol acetylation and acetalisation, hydrolysis, and dehydration of biomass into value-added chemicals. This approach simplifies the production process, making it greener by minimising wastewater generation, decreasing energy consumption in biodiesel purification, and reducing production costs.

Aziz *et al.* (2024) investigated the heterogeneous transesterification of palm methyl ester and N-methyldiethanolamine, an alkanolamine feedstock, to produce biobased esterquats. The esterquats provide high di-ester content and resolve all limitations related to the hydrophobicity effect. They offer good biodegradability, with similar chemical and physical properties to commercial esterquats, which make them greener alternatives to conventional petrochemical- and tallow-based surfactants.

Levulinic acid is a promising renewable building block chemical that can be produced from biomass, such as oil palm fronds, oil palm EFB, and oil palm mesocarp fibre, with various applications in pharmaceuticals and cosmetics. The partition and distribution behaviour of the compound are key parameters used for assessing environmental fate, risk assessment, and toxicity in these applications. Understanding the partitioning processes of a compound is important for numerous applications, such as the development of drug delivery system design and the extraction of the compound in a separation process. The octanol-water system is commonly used to determine the partition coefficient, which is defined as the concentration of a compound in the octanol and water phases after distribution and equilibration. Ramli *et al.* (2024) established a simple procedure for the determination of the distribution coefficient of levulinic acid in octanol based on the OECD 107 method, which reflected the preference of levulinic acid for an aqueous phase (hydrophilic environment) rather than the hydrophobic environment, which may enhance the understanding of its use in product formulation and design as well as assessing the environmental fate.

Meanwhile, the hydrophilic–lipophilic deviation (HLD) concept, which was initially applied in enhanced oil recovery to produce ultra-low interfacial tensions in surfactant/ester oil/water (SOW) systems, is now being used to prepare microemulsions for topical application (Cheong *et al.*, 2024b). The HLD method provides a practical guide for general emulsion formulation of most cosmetic and personal care products. The SOW system exhibits many useful properties and is universally used in various consumer goods, industrial formulas, and crude oil extraction for enhanced oil recovery.

Life cycle assessment (LCA) has long been used as a tool for environmental evaluation of products or services to promote sustainable production.

Several LCA studies have addressed sustainability and environmental issues in the oil palm industry. A cradle-to-gate LCA for the production of palm-based fatty acids in Malaysia was performed (Zolkarnain *et al.*, 2024). The environmental hotspots identified can be used to establish baseline information on the environmental profile, especially the carbon footprint, of fatty acids and assist manufacturers in taking steps to mitigate the environmental impacts. They may explore process improvement using alternative energy sources, energy efficiency technology, biogas, and cogeneration and heat integration systems to reduce dependency on fossil fuels.

CONCLUSION

The Malaysian oil palm industry has been a significant contributor to Malaysia's GDP and export earnings. Market conditions in 2024 indicate a favourable outlook, with rising global demand for palm oil. Malaysia's oil palm sector continues its upward trajectory, benefiting from advancements in agricultural practices and sustainable techniques and capitalising on technological advancements and strategic investments in plantation management and infrastructure. Sustainability remains a priority, with increasing pressures from consumers and regulatory bodies. The increasing demand for sustainable palm oil has prompted producers to improve productivity and sustainability by adopting eco-friendly practices, reducing GHG emissions, and improving land use efficiency, thereby enhancing their market competitiveness.

Meanwhile, the research community is exploring new frontiers, leveraging cutting-edge technologies and interdisciplinary approaches to address evolving needs. Novel cultivation practices, breeding strategies to produce higher-yielding and disease-resistant varieties, IR4.0, biodiesel strategy, product development, and value addition are the main strategies for the industry to remain competitive. The oil palm sector is expected to attain self-sufficiency despite ongoing challenges related to environmental, economic, and welfare issues. It is evident, time and again, that by immersing ourselves in new technologies and employing them routinely, both in research and field practices, we will expedite the transformation of the oil palm industry into a more resilient industry when facing the challenges of the future. As Malaysia navigates the complexities of international trade and competition, continued investment in R&D is crucial in ensuring the industry's competitiveness and long-term viability. Although significant efforts are still needed to remain viable and sustainable, the industry remains committed to face the challenges ahead and thrive for excellence.

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REFERENCES

Abidin, M. N. Z., Fatah, F. A., Noor, W. N. W. M., & Aris, N. F. M. (2024). A review on adoption of the Malaysian sustainable palm oil (MSPO) certification scheme. *IOP Conference Series: Earth and Environmental Science*, *1397*, 012035. https://doi.org/10.1088/1755-1315/1397/1/012035

Abubakar, A., Gambo, J., & Ishak, M. Y. (2023). Navigating climate challenges: Unraveling the effects of climate change on oil palm cultivation and adaptation strategies. In M. J. Cohen (Ed), *Advances in Food Security and Sustainability* (pp. 95-116). Elsevier.

Afandi, A. M., Norliyana, Z. Z., Nordiana, A. A., Marhalil, M., Meilina, O. A., Farawahida, M. D., & Halimatul, S. A. (2024). Effect of planting density, progeny lineage and nitrogen fertiliser on oil palm performance on alluvial soil. *Journal of Oil Palm Research*. https://doi.org/10.21894/jopr.2024.0031

Ahmad, M. J., Ismail, R., Kamarulzaman, N. H., & Ghani, F. A. (2024a). Socio-economic impacts of oil palm plantations in Malaysia: A review of economic and environmental perspectives. *Advanced International Journal of Business, Entrepreneurship and SMEs*, *6*(20), 319–330. https://doi.org/10.35631/aijbes.620026

Ahmad, M. R., Bakri, M. A. M., Ramli, A. S., Mustapha, N. K., Thadeus, D. J., Ibrahim, A., & Jusoh, M. J. (2023). Mechanisation technology for small-scale oil palm plantations. *Advances in Agricultural and Food Research Journal*, *4*(2), a0000406. https://doi.org/10.36877/aafrj.a0000406

Ahmad, S. N., Kamarudin, N., Mohamad, S. A., Sulaiman, M. R., Syarif, M. N. Y., Asib, N., & Masri, M. M. M. (2024b). Effects of neem oil, *Azadirachta indica* A. Juss on growth and survival of bagworm, *Metisa plana* (Lepidoptera: Psychidae) larvae. *Serangga*, *29*(2), 13–25. https://doi.org/10.17576/serangga-2024-2902-02

Ali, M. S., Vaiappuri, S. K. N., & Tariq, S. (2024). Malaysian oil palm industry: A view on the economic, social, and environmental aspects. In C. R. G. Popescu, J. Martínez-Falcó, B. Marco-

Lajara, E. Sánchez-García, & L. A. Millán-Tudela (Eds.), *Economics and Environmental Responsibility in the Global Beverage Industry* (pp. 268-284). IGI Global Scientific Publishing.

Arias, A., Patron, A. R., Simmons, S., Bell, H., & Alvarez, V. (2023). Palm oil and coconut oil saturated fats: Properties, food applications, and health. *World Journal of Food Science and Technology*, *7*(1), 9–19. https://doi.org/10.11648/j.wjfst.20230701.12

Armylisas, A. H. N., Hoong, S. S., Ismail, T. N. M. T., & Chan, C. H. (2024). Efficient biodiesel production by sulfonated carbon catalyst derived from waste glycerine pitch via single-step carbonisation and sulfonation. *Waste Management*, *189*, 34–43. https://doi.org/10.1016/j.wasman.2024.08.011

Asmawi, A. A., Adam, F., Azman, N. A. M., & Rahman, M. B. A. (2024). Advancements in the nanodelivery of azole-based fungicides to control oil palm pathogenic fungi. *Heliyon*, *10*(18), e37132. https://doi.org/10.1016/j.heliyon.2024.e37132

Azhar, B., Oon, A., Lechner, A. M., Ashton-Butt, A., Yahya, M. S., & Lindenmayer, D. B. (2023). Large-scale industrial plantations are more likely than smallholdings to threaten biodiversity from oil palm replanting spatial disturbances. *Global Ecology and Conservation*, *45*, e02513. https://doi.org/10.1016/j.gecco.2023.e02513

Aziz, H. A., Yusoff, R., Cheng, N. G., Idris, Z., & Ramli, N. A. S. (2024). Optimization and kinetic study of N-methyldiethanolamine-based esterquats production. *Journal of Surfactants and Detergents, 28*(2), 277–291. https://doi.org/10.1002/jsde.12797

Badai, S. S., Rasid, O. A., Masani, M. Y. A., Chan, K. L., Chan, P. L., Shaharuddin, N. A., Abdullah, M. P., Parveez, G. K. A., & Ho, C. L. (2023). Functional characterization of the MSP-C6 promoter as a potential tool for mesocarp-preferential expression of transgenes. *Journal of Plant Physiology*, *289*, 154080. https://doi.org/10.1016/j.jplph.2023.154080

Bakri, M. A. M., Ahmad, M. R., & Aris, A. (2023). Sensor-based system for mechanised oil palm herbicide spraying. *Advances in Agricultural and Food Research Journal*, *4*(2). https://doi.org/10.36877/aafrj.a0000414

Beringer, T., Müller, C., Chatterton, J., Kulak, M., Schaphoff, S., & Jans, Y. (2023). CO_2 fertilization effect may balance climate change impacts on oil palm cultivation. *Environmental Research Letters*, *18*(5), 054019. https://doi.org/10.1088/1748-9326/accbd5

Chen, G., Veldkamp, E., Damris, M., Irawan, B., Tjoa, A., & Corre, M. D. (2024). Large contribution of soil N_2O emission to the global warming potential of a large-scale oil palm plantation despite changing from conventional to reduced management practices. *Biogeosciences*, *21*(2), 513–529. https://doi.org/10.5194/bg-21-513-2024

Cheong, M. Y., Ahmad, N., Lim, W. H., & Yusof, Y. A. (2024a). A hydrophilic-lipophilic deviation model in formulating microemulsion for topical application. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *703*, 135271. https://doi.org/10.1016/j.colsurfa.2024.135271

Cheong, M. Y., Lim, W. H., & Hasan, Z. A. A. (2024b). Synthesis of radiation curable trimethylolpropane epoxy acrylate. *Journal of Photopolymer Science and Technology*, *37*(1), 115–127.

Chin, Y. W., Enh, A. M., Abdullah, A., Yusoff, N. H., & Kong, S. M. (2023). Indigenous oil palm farmers in Peninsular Malaysia: A collective enterprise approach to socioeconomic sustainability. *Akademika*, *93*(3), 157–168. https://doi.org/10.17576/akad-2023-9303-12

Dalheimer, B., Parikoglou, I., Brambach, F., Yanita, M., Kreft, H., & Brümmer, B. (2024). On the palm oil-biodiversity trade-off: Environmental performance of smallholder producers. *Journal of Environmental Economics and Management*, *125*, 102975. https://doi.org/10.1016/j.jeem.2024.102975

Daryl Jay, T., Nursyairah, J., Lau, N. L. N. & Ng, H. K. (2024). A vehicle fleet study to investigate the effect of B20 and B10 usage on engine oil degradation. *Key Engineering Materials*, *974*, 93–102. https://doi.org/10.4028/p-Vvtd0c

Fajar, R., Ma'ruf, M., Yubaidah, S., & Nurfadillah, A. (2024). Optimizing palm-based bio-lubricant formulations for diesel engine using machine learning and experimental techniques. *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, *11*(3), 2438–2446.

Fatah, M. A., & Tee, V. P. (2024). *In vitro* studies on palm phytonutrients: A nutrigenomic review. *Journal of Oil Palm Research*, *36*(1), 16–26. https://doi.org/10.21894/jopr.2023.0007

Fazliana, A. H., Nahrul Hayawin, Z., & Noorshamsiana, A. W. (2024). A novel-ligno snipper press for the pelletising of oil palm biomass (OPB) as an environmental solution for bioenergy. *Palm Oil Engineering Bulletin, 143,* 19–23.

Gourich, W., Song, C. P., Qua, K. S., & Chan, E. (2023). The potential of palm bioenergy in achieving Malaysia's renewable energy target and climate ambition in line with the Paris Agreement. *Energy for Sustainable Development*, *76*, 101296. https://doi.org/10.1016/j.esd.2023.101296

Grand View Research (2024). *Market analysis report: Oleochemicals market size, share & trends analysis report by product (specialty esters, fatty amines), by application (personal care & cosmetics, consumer goods), by region, and segment forecasts, 2024-2030*. https://www.grandviewresearch.com/industry-analysis/oleochemicals-industry

Hamid, S. R., Arzaman, A. F. M., Razali, M. A., Yasin, N. I., Masrom, N. R., Sabri, N. A. A., & Margono, M. (2024). The deployment of the Malaysian sustainable palm oil standard in the agriculture sector. *Multidisciplinary Science Journal*, *6*(7), e2024115. https://doi.org/10.31893/multiscience.2024115

Hanin, A. N., Masani, M. Y. A., Rasid, O. A., & Parveez, G. K. A. (2024). Vector construction and transient evaluation in oil palm calli via *Agrobacterium*-mediated transformation. *Journal of Oil Palm Research*, *36*(2), 210–223. https://doi.org/10.21894/jopr.2023.0016

Hassan, H., Tahir, N. I., Rozali, N. L., Lau, B. Y. C., Othman, A., Weckwerth, W., & Ramli, U. S. (2024). Integrative tissue-resolved proteomics and metabolomics analysis of oil palm (*Elaeis guineensis* Jacq.) fruit provides insights into stilbenoid biosynthesis at the interface of primary and secondary metabolism. *Biocatalysis and Agricultural Biotechnology*, *60*, 103308. https://doi.org/10.1016/j.bcab.2024.103308

Hoong, S. S., Zan, A. M., Din, N. S. M. N. M., Hassan, N. A. A., Tang, S. W., Ahmad, N., Ismail, T. N. M. T., & Hasan, Z. A. A. (2024). Synthesis and emulsification properties of polyglyceryl estolides prepared from fatty acids. *Tenside Surfactants Detergents*, *61*(5), 424–434. https://doi.org/10.1515/tsd-2024-2583

Husein, A. G., Bacho, N., & Kassim, N. Q. B. (2024). Aluminium toxicity tolerance of different varieties of oil palm (*Elaeis guineensis* L. Jacq.) seedlings. *Journal of Oil Palm Research*. https://doi.org/10.21894/jopr.2024.0034

Ishak, A., Murdi, A. A., Hashim, K., Muhammed, A., Rahmat, M., Shahrani, S., Rahman, R. A., Zainal, N. F. A., & Aziz, N. A. (2024). Cultivating knowledge: Design and development of the infographic (*baja sawit*) mobile application to enhance oil palm fertilization practices among smallholders. *Engineering Journal*, *28*(7), 27–40. https://doi.org/10.4186/ej.2024.28.7.27

Ismail, T. M. N. T., Lee, K. W., Adnan, S., Ban, Z. H., Hasan, Z. A. A., & Siwayanan, P. (2024). Investigating the potential of dihydroxystearic acid as feedstock for rigid polyurethane foam. *Industrial Crops and Products*, *209*, 118067. https://doi.org/10.1016/j.indcrop.2024.118067

ISTA Mielke GmbH. (2025, January 31). *OIL WORLD weekly: World supply, demand and price forecasts for oilseeds, oils and meals, Vol. 68, No. 4*.

Izzuddin, M. A., Hamzah, A., Nisfariza, M. N., & Idris, A. S. (2024). Object-based image analysis (OBIA) on hyperspectral imagery from drone for *Ganoderma* basal stem rot disease detection in oil palm. *Journal of Oil Palm Research*. https://doi.org/10.21894/jopr.2024.0025

Kamarudin, N., Ahmad, S. N., Ahmad, M. N., Keni, M. F., Napiah, N. R. A. M. A., Bakeri, S. A., Sulaiman, M. R., & Masri, M. M. M. (2024). Quad trap: An alternative approach to increase trapping efficiency of the male bagworm, *Metisa plana* walker. *Serangga*, *29*(2), 177–188. https://doi.org/10.17576/serangga-2024-2902-13

Karunarathna, S. C., Patabendige, N. M., Lu, W., Asad, S., & Hapuarachchi, K. K. (2024). An in-depth study of phytopathogenic *Ganoderma*: Pathogenicity, advanced detection techniques, control strategies, and sustainable management. *Journal of Fungi*, *10*(6), 414. https://doi.org/10.3390/jof10060414

Lalawmpuia, Lalruatsanga, H., Lalnunmawia, F; Lalbiakdika, & Ngamlai, E. V. (2023). Oil palm plantation: Carbon sequestration potential and effective carbon management within Serchhip, Mizoram, India. *Ecology, Environment and Conservation*, *29*(1), 96–101. https://doi.org/10.53550/eec.2023.v29i01.014

Lau, H. L. N., Teh, S. S., Yung, C. L. Y., Wafti, N. S. & Nursyairah, J. (2024). Harnessing International Sustainability and Carbon Certification (ISCC) feedstocks at palm oil mills: A sustainable approach to biofuel production. *Palm Oil Engineering Bulletin*, *146*, 23–25.

Lim, F., Rasid, O. A., Idris, A. S., As'wad, A. W. M., Vadamalai, G., Parveez, G. K. A., & Wong, M. (2024a). Gene silencing of *Ganoderma boninense lanosterol 14α-demethylase* (*GBERG11*) affects ergosterol biosynthesis and pathogenicity towards oil palm. *Scientia Horticulturae*, *332*, 113198. https://doi.org/10.1016/j.scienta.2024.113198

Lim, K. E., Ramachandran, V., Ata, A., Ratnam, M., Mohamad, R., Azahar, S., Hashim, A., Tat, C. S., & Mansor, H. (2024b). *Insights from GAP execution for yield intensification among independent smallholder farmer for oil palm. Working Paper Series 02/2024.* Kuala Lumpur: Asia School of Business. Creative Commons Attribution CC BY 3.0.

Loganathan, R., Tarmizi, A. H. A., Vethakkan, S. R., & Teng, K. (2022). A review on lipid oxidation in edible oils. *Malaysian Journal of Analytical Sciences*, *26*(6), 1378–1393.

Majid, N. A., Ramli, Z., Awang, A. H., & Sum, S. M. (2023). Independent smallholders behaviour towards complying with Malaysian Sustainable Palm Oil (MSPO) Certification. *International Journal of Academic Research in Business & Social Sciences*, *13*(2), 634–643. https://doi.org/10.6007/IJARBSS/v13-i2/16222

Malaysian Palm Oil Board (MPOB) (2023, September 30). *Media release: Prime minister launches MPOB's SIMS*. https://mpob.gov.my/wp-content/uploads/2024/02/Media-Release-SIMS-.pdf,

Malaysian Palm Oil Board (MPOB) (2025). *Malaysian Oil Palm Statistics 2024, 44th edition.*

Malaysian Palm Oil Council (MPOC) (2024). *EUDR challenges needs to be collectively addressed with the EU as uncertainties still looms*. Retrieved September 30, 2024, from https://www.mpoc.org.my/eudr-challenges-needs-to-be-collectively-addressed-with-the-eu-as-uncertainties-still-looms/

Malaysian Sustainable Palm Oil (MSPO) and the European Forest Institute (EFI) (2024). *Joint gap assessment of the EUDR information needs and information availability from the Malaysian sustainable palm oil (MSPO) certification*. Retrieved September 30, 2024, from https://efi.int/sites/default/files/files/flegtredd/KAMI/MSPO_Joint_Gap_Assessment.pdf.

Malike, F. A., Shamsudin, N. A. A., Amiruddin, M. D., Marjuni, M., & Yaakub, Z. (2024). Development of new high-yielding planting material based on performance of 38 oil palm (*Elaeis guineensis* Jacq.) *Dura* × *Pisifera* families. *Euphytica*, *220*(73). https://doi.org/10.1007/s10681-024-03333-2

McGill, J. (2024, December 29). *EUDR, global economic outlook and price of palm oil in 2025* [Paper presentation]. 20th Indonesian Palm Oil Conference and 2025: Price Outlook "Seizing Opportunities Amidst Global Uncertainty", Bali, Indonesia.

McGill, J. (2025, January 14). *Industry outlook and price forecast* [Paper presentation]. Palm Oil Economic Review and Outlook Seminar 2025: Enhancing Palm Oil Competitiveness through Green Economic Initiatives. Kuala Lumpur, Malaysia.

Miwil, O. (2024, September 11). Government taking action to tackle spread of sooty mold disease in Sabah oil palm plantations. *New Straits Times*, p. 2.

Murphy, D. J. (2024). Carbon sequestration by tropical trees and crops: A case study of oil palm. *Agriculture*, *14*(7), 1133. https://doi.org/10.3390/agriculture14071133

Nadras, S., Mazlan, R., Hussain, H., & Shah, I. M. (2024). The European Union deforestation-free regulation (EUDR): Assessing impacts and strategies for Malaysian and the global oil palm industry. *Journal of Sustainability Science and Management*, *19*(6), 54–74. https://doi.org/10.46754/jssm.2024.06.005

Naidu, L., Huda, M. I. M., & Moorthy, R. (2024). Trade competitiveness and sustainability policies of Malaysian palm oil in the European Union: Strategic responses by stakeholders agencies. *Malaysian Journal of History, Politics & Strategic Studies*, *51*(1), 21–36. https://doi.org/10.17576/jebat.2024.5101.02

Ng, M. H., Nu'man, A. H., & Hasliyanti, A. (2024). Recycling of deep eutectic solvent in the extraction of ferulic acid from oil palm empty fruit bunch. *Journal of Separation Science*, *47*(4), 2300842. https://doi.org/10.1002/jssc.202300842

Norfaezah, J., Masani, M. Y. A., Fizree, M. D. P. M. A. A., Bahariah, B., Shaharuddin, N. A., Ho, C. L., Rasid, O. A., & Parveez, G. K. A. (2024). DNA-free CRISPR/Cas9 genome editing system for oil palm protoplasts using multiple ribonucleoproteins (RNPs) complexes. *Industrial Crops and Products*, *208*, 117795. https://doi.org/10.1016/j.indcrop.2023.117795

Norziha, A., Zamri, Z., Zulkifli, Y., Fadila, A. M., & Marhalil, M. (2024). Selection criteria of MPOB-Angola germplasm collection for yield improvement of the oil palm. *Oil Crop Science*, *9*(1), 20–28. https://doi.org/10.1016/j.ocsci.2023.12.003

Nur Azreena, I., Asikin-Mijan, N., Lau, H. L. N., Hassan, M. A., Izham, S. M., Kennedy, E., Stockenhuber, M., Yan, P., & Taufiq-Yap, Y. H. (2024). Hydro-processing of palm fatty acid distillate for diesel-like hydrocarbon fuel production using La-zeolite beta catalyst. *Industrial Crops & Products*, *218*, 118907. https://doi.org/10.1016/j.indcrop.2024.118907

Nursyairah, J., Lau, H. L. N., & Rifqi, I. A. J. (2024). Can high biodiesel blends be used in cold highlands environment? *Palm Oil Engineering Bulletin*, *146,* 15–19.

Ooi, S., Choo, C., Sarpan, N., Wong, C., & Wong, W. (2024). *Karma-EgDEF1* methylation in *Elaeis guineensis* clonal mother palms that produced high mantling rates in the second clonal generation. In Vitro *Cellular & Developmental Biology - Plant*, *60*(2), 176–182. https://doi.org/10.1007/s11627-023-10394-w

Ouyang, D., Liu, T., Astimar, A. A., Lau, H. L. N., Teh, S. S., Nursyairah, J., Liu, D., & Zhao, X. (2023). Model-based process intensification of dilute acid pre-hydrolysis of oil palm empty fruit bunch biomass for pretreatment and furfural production. *Bioresource Technology*, *372,* 128626. https://doi.org/10.1016/j.biortech.2023.128626

Parveez, G. K. A. (2025, January 14). *Malaysian palm oil industry performance 2024 & prospect for 2025* [Paper presentation]. Palm Oil Economic Review and Outlook Seminar 2025: Enhancing Palm Oil Competitiveness through Green Economic Initiatives. Kuala Lumpur, Malaysia.

Parveez, G. K. A., Leow, S., Kamil, N. N., Madihah, A. Z., Ithnin, M., Ng, M. H., Yusof, Y. A., & Idris, Z. (2024). Oil palm economic performance in Malaysia and R&D progress in 2023. *Journal of Oil Palm Research,* 171–185. https://doi.org/10.21894/jopr.2024.0037

Peng, T. S., Lyndon, N., Taib, H. M., Basaruddin, N. H., Aman, Z., Gan, S., & Tahir, Z. (2024). How does information and communication technology (ICT) affect oil palm agricultural practices? *Malaysian Journal of Society and Space*, *20*(3), 99–121. https://doi.org/10.17576/geo-2024-2003-07

Ping, B. T. Y. & Maurad, Z. A. (2024). Progress in analytical methods for pesticide detection in palm oil and palm kernel oil matrices, and pesticide fate studies in oil palm plantations. *Journal of the American Oil Chemists' Society*, *102*(2), 261–278. https://doi.org/10.1002/aocs.12885

Poopalam, K. D., Ismail, T. N. M. T., Hanzah, N. A., Alias, A. H., Wahab, N. A., Ibrahim, Z., Subramaniam, V., Armylisas, A. H. N., & Idris, Z. (2024). Utilization of oil palm biomass and polyurethanes as sustainable construction materials: A review. *Developments in the Built Environment*, *17*, 100380. https://doi.org/10.1016/j.dibe.2024.100380

Ramachandran, V., Donough, C., Soontat, C., Ratnam, M., Mohamad, R., Azahar, S., Hashim, A., Teh, K. S., Mansor, H., Oberthür, T., & Ata, A. (2024). Improving livelihoods for independent smallholders by yield intensification through good agricultural practices. *IOP Conference Series: Earth and Environmental Science*, *1308*, 012062. https://doi.org/10.1088/1755-1315/1308/1/012062

Ramli, A. S., Bakri, M. A. M., Ahmad, M. R., Mustaffa, N. K., Khalid, M. R. M., & Azaman, I. H. (2023). Performance comparison of harvesting performance of different harvesting methods in oil palm plantation. *Advances in Agricultural and Food Research Journal*, *4*(2), a0000410. https://doi.org/10.36877/aafrj.a0000410

Ramli, N. A. S., Rania, H., Roslan, N. A., & Abdullah, A. (2024). Evaluation of distribution and partition coefficients of levulinic acid in octanol-water system at 298.15 K. *Journal of Solution Chemistry*, *53*(3)**,** 471–485. https://doi.org/10.1007/s10953-023-01345-5

Roslan, N. D., Azni, I. N. A. M., Angel, L. P. L., Sirajuddin, S. A., & Sundram, S. (2024). Analysis of haplotype on single nucleotide polymorphism in internal transcribed spacers (SNPs-ITS) of *Ganoderma boninense* collected from oil palm plantations. *Malaysian Journal Of Biochemistry & Molecular Biology, Special Issue: 15th Malaysia International Genetics Congress (MiGC15),* 105–111.

Sattar, M. N., Ismail, T. N. M. T., Palam, K. D. P., Masri, M. M. M., Hasan, Z. A., & Idris, Z. (2024). *Palm-based sticky glue for household and plantation pest control.* MPOB Information Series, MPOB TT No. 687. MPOB.

Sham, I. N., Yap, C. K., Nulit, R., Peng, S. H. T., & Chai, E. W. (2024). Nutrient leaching in oil palm plantation: A review on special reference to fertilization application. *Pakistan Journal of Life and Social Sciences*, *22*(2), 855–877. https://doi.org/10.57239/pjlss-2024-22.2.0062

Shehu, S., & Salleh, M. A. (2024). The palm oil industry in Nigeria and Malaysia: Decline and economic sustainability. *International Journal of Oil Palm*, *6*(2), 1–12. https://doi.org/10.35876/ijop.v6i2.105

Solidaridad Network (2023). *Briefing paper: Implications of the EU Deforestation Regulation (EUDR) for oil palm smallholders.* Retrieved September 30, 2024, from https://www.solidaridadnetwork.org/wp-content/uploads/2023/04/Briefing-paper-EUDR-and-palm-oil-smallholders.pdf

Sundram, S., Naidu, Y., Mohamed-Azni, I. N. A., Aripin, S. S., Nur-Rashyeda, R., Mohamed, M., & Rusli, M. H. (2023). Fungi in biological management of plant diseases: Current and future perspective. *Journal of Oil Palm Research*, *35*(3), 375–390. https://doi.org/10.21894/jopr.2022.0061

Syarif, M. N. Y., Sundram, S., Ahmad, S. N., Masri, M. M. M., & Seman, I. A. (2025). Insect community associated with *Ganoderma* basidiocarps in oil palm plantations of Sabah. *Journal of Oil Palm Research, 37*(1), 96–109. https://doi.org/10.21894/jopr.2024.0005

Tan, P. Y., Loganathan, R., Teng, K T., Johari, S. N. M., Lee, S. C., Selvaduray, K. R., Ngui, R., & Lim, Y. A. L. (2024). Supplementation of red palm olein-enriched biscuits improves levels of provitamin A carotenes, iron, and erythropoiesis in vitamin A-deficient primary schoolchildren: A double-blinded randomised controlled trial. *European Journal of Nutrition*, *63*(3), 905–918. https://doi.org/10.1007/s00394-023-03314-6

Teh, S. S., Lau, H. L. N., & Mah, S. H. (2024). Production of oil palm mesocarp fiber-based hydrogel using selected cross-linking acids. *Pure and Applied Chemistry*, *96*(11), 1683–1692. https://doi.org/10.1515/pac-2024-0208

Teng, K., Loganathan, R., Chew, B. H., & Khang, T. F. (2024). Diverse impacts of red palm olein, extra virgin coconut oil and extra virgin olive oil on cardiometabolic risk markers in individuals with central obesity: A randomised trial. *European Journal of Nutrition*, *63*(4), 1225–1239. https://doi.org/10.1007/s00394-024-03338-6

Tey, Y. S., & Brindal, M. (2024). Patent landscape review on modern oil palm climatic adaptation strategies: Gaps and opportunities. *Journal of Oil Palm Research, 36*(4), 547–559. https://doi.org/10.21894/jopr.2024.0011

Ting, N., Chan, P., Buntjer, J., Ordway, J. M., Wischmeyer, C., Ooi, L. C., Low, E. T. L., Marjuni, M., Sambanthamurthi, R., & Singh, R. (2023). High-resolution genetic linkage map and height-related QTLs in an oil palm (*Elaeis guineensis*) family planted across multiple sites. *Physiology and Molecular Biology of Plants*, *29*(9), 1301–1318. https://doi.org/10.1007/s12298-023-01360-2

Tohiran, K. A., Omar, R. Z. R., Khasim, N., Kadir, I. F., Nasir, M. D. M., Moslim, R., & Sharif, B. A. M. (2024). *Oil palm pest and rodent biocontrol service.* MPOB Information Series, TS No. 195. MPOB.

Tugiman, E. S., Yusoff, M. Z. M., Hassan, M. A., Samad, M. Y. A., Farid, M. A. A., & Shirai, Y. (2024). Assessing the efficacy of utilizing biochar derived from oil palm biomass as a planting medium for promoting the growth and development of oil palm seedlings. *Biocatalysis and Agricultural Biotechnology*, *58,* 103203. https://doi.org/10.1016/j.bcab.2024.103203

Virdiana, I., Forster, B. P., & Zakaria, L. (2024). Basal stem rot of oil palm: Disease development in mineral and peat soils. *IOP Conference Series: Earth and Environmental Science*, *1308*, 012025. https://doi.org/10.1088/1755-1315/1308/1/012025

Voon, P. T., Ng, C. M., Ng, Y. T., Wong, Y. J., Yap, S. Y., Leong, S. L., Yong, X. S., & Lee, S. W. H. (2024). Health effects of various edible vegetable oil: An umbrella review. *Advances in Nutrition*, *15*(9), 100276. https://doi.org/10.1016/j.advnut.2024.100276

Wafti, N. S. A., Choong, T. S. Y., Lau, H. L. N., Yunus, R., Abd-Aziz, S., & Raof, N. A. (2023). Kinetic study on the production of biodegradable lubricant by enzymatic transesterification of high oleic palm oil. *Process Biochemistry*, *131,* 91–100. https://doi.org/10.1016/j.procbio.2023.06.011

Wong, L., & Koo, A. (2024). Enhancing efficiency and sustainability of the oil palm plantation industry with artificial intelligence of things (AIoT). *Palm Oil Engineering Bulletin*, *142*, 12–14.

World Health Organization (WHO) (2024). *A rapid overview of systematic reviews on the effects of palm oil intake compared with intake of other vegetable oils on mortality and cardiovascular health in children and adults* (Licence: CC BY-NC-SA 3.0 IGO). https://iris.who.int/bitstream/handle/10665/376122/9789240088344-eng.pdf

Yap, S., Voon, P., & Selvaduray, K. R. (2024). Diets and health benefits of gut microbiota-fermented short-chain fatty acids: A perspective of the Malaysian diet containing palm oil. *Journal of Oil Palm Research, 36*(4), 547–559. https://doi.org/10.21894/jopr.2024.0023

Yung, C. L., Lau, H. L. N., & Loh, S. K. (2024). Fuel quality of B10 and B20 diesel from petrol stations. *Palm Oil Engineering Bulletin*, *143*, 33–38.

Zakaria, L. (2023). Basal stem rot of oil palm: The pathogen, disease incidence, and control methods. *Plant Disease*, *107*(3), 603–615. https://doi.org/10.1094/PDIS-02-22-0358-FE

Zawawi, N. Z., Khoon, K. L., Murdi, A. A., & Arn, T. Y. (2024). Quantifying the effect of fertiliser application on nitrous oxide pulses in oil palm plantation. *Journal of Oil Palm Research*. https://doi.org/10.21894/jopr.2024.0032

Zolkarnain N., Maurad, Z. A., Subramaniam, V., & Ghazali, R. (2024). Environmental assessment of fatty acids production from palm oil using life cycle approach. *Journal of Oil Palm Research*. https://doi.org/10.21894/jopr.2024.0049