

# OIL PALM ECONOMIC PERFORMANCE IN MALAYSIA AND R&D PROGRESS IN 2025

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## ABSTRACT

*The Malaysian oil palm industry recorded a strong performance in 2025, driven by productivity gains, replanting-led structural adjustments, and stabilised labour conditions. Crude palm oil (CPO) production increased by 4.9% to 20.28 million tonnes, supported by higher fresh fruit bunch (FFB) yields and improved labour efficiency, while the total oil palm area expanded marginally to 5.70 million hectares within a strictly capped land-use framework. Despite weaker export demand and elevated stock levels, sustained productivity improvements and ongoing structural reforms enhanced Malaysia's competitive position in the global market. Additionally, the advancements in research and development (R&D) continue to support the industry to remain resilient amid the rising global trade uncertainties and market volatility. This review synthesises recent industry statistics and selected literature on oil palm R&D to evaluate how current innovations address key sectoral constraints. While important progress is evident in breeding, disease management, traceability, waste management, biomass valorisation, and downstream applications, gaps remain in smallholder adoption, technology translation, and critical assessment of long-term competitiveness.*

**Keywords:** competitiveness, economic performance, resilience, value addition and sustainability.

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## INTRODUCTION

The year 2025 has been a challenging year for the global vegetable oils industry and the oil palm sector is no exception. Key challenges included uncertainties in weather conditions, fluctuations in commodity prices, as well as the dynamics of supply and demand in vegetable oils. Despite these challenges, the Malaysian oil palm industry has demonstrated resilience and maintained its competitive edge as the world's second-largest producer and exporter of palm oil. The strong fundamentals of the industry continue to drive its progress, underpinned by sustainable development practices. Malaysia remains committed to sustainable palm oil production, balancing environmental protection, biodiversity conservation and socio-economic development.

Palm oil is the most widely consumed edible oil globally and a key ingredient in a wide range of everyday products, both for food and non-food applications, due to its versatility and functional properties. The growing utilisation of palm oil and its derivatives continues to drive global demand. The extensive efforts and initiatives by Malaysia have positioned the oil palm industry as one of the most advanced sectors in terms of sustainability.

The mandatory implementation of the Malaysian Sustainable Palm Oil (MSPO) certification standard (MSPO, 2022) is one of the approaches by the industry to ensure transparency while promoting sustainable practices across the entire palm oil supply chain. Malaysia is also developing the National Traceability System (SKN) to enable full traceability, providing credible data and science-based evidence to support the sustainable production of Malaysian palm oil and its derivatives in a holistic manner. Continuous engagement and collaboration among stakeholders of the industry, including smallholders, enable the

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sector to evolve in tandem with global dynamics encompassing policy developments, contributing to both food and energy security.

Additionally, Malaysia launched the Malaysia Aviation Decarbonisation Blueprint on 5 September 2024 (Ministry of Transport, 2024), with the aim of achieving net-zero carbon emissions by 2050 for the aviation sector. This initiative presents potential for growth in the use of palm oil to produce sustainable aviation fuel (SAF) in line with the global transition to a low-carbon economy.

The oil palm industry plays a significant role in alleviating poverty, particularly among oil palm smallholders. It fosters economic growth, creates employment opportunities and facilitates the development of new industries and infrastructure. The importance of the oil palm sector has expanded beyond the two largest producing countries, Indonesia and Malaysia, with its growing presence in regions such as Latin America and Africa. This global expansion underscores the socio-economic contributions of the industry, highlighting its broader impacts on the national economy of these developing countries.

The positive growth of the oil palm industry globally has prompted the intensification of research and development (R&D) across the supply chain. These efforts have continued to progress robustly, with the focus of addressing challenges faced by the industry, including enhancing productivity, reducing greenhouse gas (GHG) emissions, developing downstream value-added palm products as well as tackling global concerns related to sustainability, nutrition and food safety, among others. The R&D is aimed at ensuring the oil palm industry continues to remain sustainable and competitive, while balancing the efforts for conservation of forest and biodiversity as well as social equity with economic growth.

Although annual reports and topic-specific studies are available, there remains limited integrative analysis linking near-term economic performance indicators with the evolving R&D landscape of the Malaysian oil palm sector. This review addresses that gap by critically evaluating how recent scientific and technological advances respond to current production, labour, trade, sustainability, and value-addition challenges. This will enable the oil palm industry to continue to make positive transformation and advancement for the benefit of the global community.

#### PERFORMANCE OF THE MALAYSIAN OIL PALM INDUSTRY

The Malaysian oil palm industry demonstrated a resilient and structurally transformative performance in 2025, amid intensifying

sustainability constraints, heightened global market volatility, and increasing demands for supply chain transparency. Operating within a tightly regulated land-use framework, the sector has shifted from expansionary growth toward a productivity-driven paradigm, whereby output, income generation, and export competitiveness are sustained through efficiency gains rather than area expansion. This transition reflects the cumulative impact of long-term structural reforms, particularly in plantation rejuvenation, labour optimisation, and the adoption of digital traceability systems, which are now yielding measurable economic outcomes.

Unlike earlier cyclical recoveries driven by favourable price dynamics or short-term yield improvements, the 2025 trajectory signals a deeper recalibration of the industry's production base. This recalibration is characterised by accelerated replanting, gradual normalisation of labour availability, and the consolidation of upstream processing and downstream value-added activities within an increasingly stringent global regulatory environment. Despite ongoing external pressures including evolving import policies, competition from alternative vegetable oils, and tightening sustainability-related market access requirements, the sector exhibits enhanced systemic efficiency and adaptive capacity.

Importantly, the industry's performance underscores a structural shift from volume-driven expansion to efficiency-driven value creation. Improvements in fresh fruit bunch (FFB) productivity, stabilisation of crude palm oil (CPO) output, and stronger downstream price realisation indicate a transition toward a more mature growth phase. However, this transformation entails trade-offs, including reduced mature acreage due to accelerated replanting, persistently high labour costs, and uneven spatial distribution of downstream value capture. Collectively, these dynamics define the sector's 2025 performance landscape, highlighting both its developmental progress and the structural constraints shaping its future trajectory.

#### Oil Palm Planted Area

In 2025, the total oil palm planted area reached 5.70 million hectares, representing a 1.6% adjustment from 5.61 million hectares in 2024 (*Table 1*). This marginal shift underscores a strategic transition towards high-precision data synchronisation in recording active cultivation areas. Concurrent with this spatial refinement, the industry witnessed a robust intensification of replanting activities, spearheaded by estate conglomerates and further catalysed by government-led initiatives, specifically those targeting independent smallholders.

Empirical data from the Malaysian Palm Oil Board (MPOB, 2026) indicates that the national replanting rate ascended from 2.0% in 2024 to 3.4% in 2025. In absolute terms, the replanted area expanded significantly from 0.11 million hectares to 0.19 million hectares, marking a substantial year-on-year increase of 67.1%.

Regional analysis reveals heterogeneous growth patterns: Sarawak recorded the most significant expansion (2.2%), followed by Peninsular Malaysia (1.6%), while Sabah demonstrated a more conservative growth trajectory (0.9%). Conversely, the national mature oil palm area contracted by 0.5%, a direct corollary of the temporary withdrawal of productive stands during the replanting phase. This contraction was most evident in Sabah, whereas Peninsular Malaysia exhibited relative stability, suggesting a more balanced age structure and a well-regulated replanting cycle. Collectively, these trends signify a deliberate, industry-wide pivot toward rejuvenating aging plantations to optimise yield potential and fortify sectoral resilience against future productivity constraints.

In 2025, private and government-owned estates continued to dominate the oil palm sector, accounting for 73.2% (4.17 million hectares) of total oil palm area, reflecting their structural advantage in capital mobilisation and large-scale replanting.

Independent smallholders comprised 15.2% (0.87 million hectares), while organised smallholders accounted for 11.6%, indicating a persistently concentrated ownership structure as shown in Figure 1.

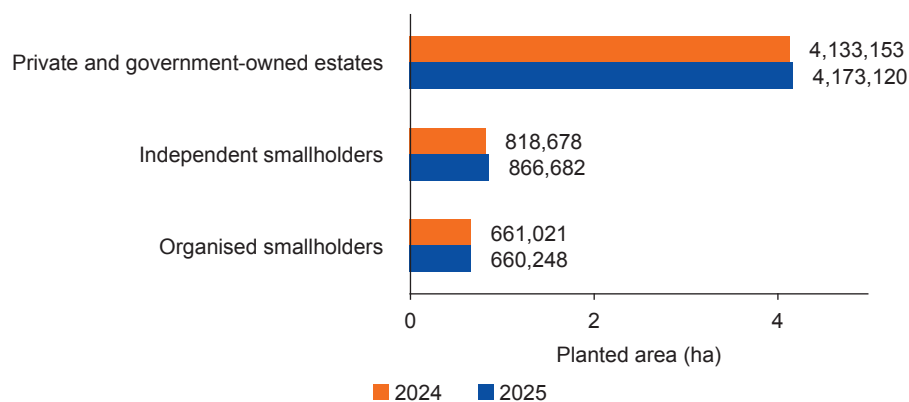
Independent smallholders recorded the fastest expansion, increasing by approximately 48,000 ha, driven by the *Budi Agrokomoditi* initiative and the rollout of the MPOB's Sawit Intelligent Management System (SIMS). SIMS requires dealers and manufacturers to record transactions, including identity card information for purchases from unlicensed independent smallholders, which has facilitated the formal recognition of previously unregistered smallholder activities and contributed to the increase in recorded acreage. In contrast, the organised smallholder segment remained broadly stable, with a marginal contraction (0.12%) likely reflecting administrative consolidation rather than a substantive sectoral exit.

Overall, the sector remains characterised by entrenched estate dominance alongside a gradual, policy-enabled rise in independent smallholder participation. However, without sustained improvements in access to finance, technology, and extension services, this expansion is unlikely to yield proportional productivity gains, limiting its contribution to long-term sectoral resilience.

TABLE 1. MALAYSIAN OIL PALM PLANTED AREA IN 2024 AND 2025

Region	Total area (ha)			Mature area (ha)		
	2025	2024	Difference (%)	2025	2024	Difference (%)
Peninsular Malaysia	2,543,636	2,504,786	1.6	2,275,822	2,268,705	0.3
Sabah	1,496,558	1,483,699	0.9	1,267,999	1,291,591	-1.8
Sarawak	1,659,857	1,624,366	2.2	1,499,656	1,506,228	-0.4
<b>Total</b>	<b>5,700,050</b>	<b>5,612,852</b>	<b>1.6</b>	<b>5,043,478</b>	<b>5,066,524</b>	<b>0.5</b>

Source: MPOB (2026).



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 (2026).

Figure 1. Ownership distribution of oil palm area, 2024 vs. 2025.

## Processing Facilities and Downstream Integration

At the upstream level, Malaysia's milling landscape underwent a subtle consolidation, with the total number of active palm oil mills adjusting from 453 in 2024 to 452 in 2025. Paradoxically, total installed capacity ascended from 125.40 to 126.33 million tonnes yr<sup>-1</sup> (Table 2). This divergence signifies a strategic shift from horizontal expansion toward capacity intensification and technological retrofitting of existing infrastructure. Spatially, milling activities remain intrinsically coupled with plantation distribution. Peninsular Malaysia maintains its primacy with 240 mills (64.79 million tonnes yr<sup>-1</sup>), followed by Sabah (128 mills; 34.93 million tonnes yr<sup>-1</sup>) and Sarawak (84 mills; 26.60 million tonnes yr<sup>-1</sup>). The observed stability in mill counts, juxtaposed with incremental capacity gains, suggests a trajectory of productivity optimisation within the established milling framework.

In contrast, the downstream segment exhibits a more concentrated and selectively adjusted structure. While the refinery count increased marginally from 53 to 54, aggregate refining capacity experienced a slight contraction from 26.39 to 26.15 million tonnes yr<sup>-1</sup>. This phenomenon likely reflects operational recalibration, encompassing capacity rationalisation or tactical underutilisation in response to market fluctuations. Spatially, refining activities demonstrate significant geographical inertia, heavily clustered in Peninsular Malaysia (39 refineries), which commands over 60% of national capacity (16.12 million tonnes yr<sup>-1</sup>). This highlights the critical role of industrial agglomeration, proximity to major export gateways, and sophisticated logistical ecosystems. Conversely, both Sabah and Sarawak recorded diminished refining capacities, with Sarawak experiencing a decline in refinery numbers indicative of persistent regional disparities in downstream maturation.

The palm kernel crushing sector remained structurally resilient, maintaining 43 plants nationwide. However, total capacity edged upward from 7.36 to 7.39 million tonnes yr<sup>-1</sup>. Notably, Sarawak registered a meaningful capacity surge (0.76 to 0.79 million tonnes yr<sup>-1</sup>) despite a static plant count. This underscores a pattern of selective capital deepening, where output growth is driven by asset upgrading rather than new facility establishment. Similarly, the oleochemical industry remains the most spatially polarised segment, with all 20 facilities centralised in Peninsular Malaysia. Although capacity declined slightly (2.68 to 2.63 million tonnes yr<sup>-1</sup>), its absolute absence in East Malaysia underscores the high entry barriers associated with value-added downstream activities, including specialised infrastructure requirements and the need for economies of scale.

Synthetically, these trends indicate that Malaysia's palm oil industry is undergoing a fundamental structural transition from land-based expansion to efficiency-driven optimisation. Productivity gains are increasingly derived from technological integration and facility consolidation rather than physical footprint growth. The industry exhibits a bifurcated spatial logic: Upstream processing is dispersed according to feedstock proximity, while high-value downstream and oleochemical activities gravitate toward the Peninsular to leverage agglomeration economies. While this configuration enhances global competitiveness, it also reveals a strategic window for policy interventions aimed at regional rebalancing. Encouraging downstream investment in Sabah and Sarawak remains imperative to foster a more inclusive and resilient national value chain.

## Crude Palm Oil (CPO) Production Trends

The CPO production rose by 4.9% year-on-year to 20.28 million tonnes in 2025 (Table 3), reflecting a cyclical recovery in upstream performance supported by improved FFB yields, stabilised labour availability, and incremental gains in operational efficiency.

A disaggregated analysis of regional production reveals Sarawak as the primary driver of growth in terms of percentage increase. Production in Sarawak surged by 7.8%, rising from 4.17 million tonnes in 2024 to 4.50 million tonnes in 2025. This outsized growth (323,930 t) likely reflects the maturation of newer plantings and the stabilisation of labour availability in the state's expansive plantation landscape.

Conversely, Peninsular Malaysia maintained its status as the largest contributor to national output, accounting for 56.1% of total production in 2025. The region recorded a solid growth rate of 4.5%, with an absolute volume increase of 485,428 t. Meanwhile, Sabah exhibited a more moderate growth profile at 3.2%, reaching 4.41 million tonnes. While Sabah's growth was the most conservative among the three regions, its consistent output remains vital to the national supply chain.

The synchronisation of increased CPO production across all regions, despite diverse geographical and operational challenges, underscores the sectoral resilience of the Malaysian palm oil industry. The notable increase in Sarawak's output suggests a narrowing of the productivity gap between East and Peninsular Malaysia. Overall, the 945,209 t increment at the national level provides a critical buffer for the downstream processing industry, ensuring adequate feedstock for refining and oleochemical activities while strengthening Malaysia's competitive position in the global vegetable oil market (MPOB, 2026).

**TABLE 2. NUMBER AND CAPACITIES OF PALM OIL MILLS, REFINERIES, PALM KERNEL CRUSHERS AND OLEOCHEMICAL PLANTS, 2024 AND 2025**

Region	Year	Item	Sector			
			Palm oil mill	Palm oil refinery	Palm kernel crusher	Oleochemical plant
Peninsular Malaysia	2025	Cap. number	240	39	27	20
		(Mn t yr <sup>-1</sup> )	64.79	16.12	4.61	2.63
	2024	Cap. number	240	37	27	19
		(Mn t yr <sup>-1</sup> )	64.05	15.42	4.61	2.68
Sabah	2025	Cap. number	128	10	10	-
		(Mn t yr <sup>-1</sup> )	34.93	7.44	2.00	-
	2024	Cap. number	129	10	10	-
		(Mn t yr <sup>-1</sup> )	34.99	7.88	2.00	-
Sarawak	2025	Cap. number	84	5	6	-
		(Mn t yr <sup>-1</sup> )	26.60	2.60	0.79	-
	2024	Cap. number	84	6	6	-
		(Mn t yr <sup>-1</sup> )	26.35	3.10	0.76	-
Total	2025	Cap. number	452	54	43	20
		(Mn t yr <sup>-1</sup> )	126.33	26.15	7.39	2.63
	2024	Cap. number	453	53	43	19
		(Mn t yr <sup>-1</sup> )	125.40	26.39	7.36	2.68

Note: Mn t yr<sup>-1</sup> - million tonnes yr<sup>-1</sup>, Cap - capacity.

Source: MPOB (2026).

**TABLE 3. MALAYSIAN CRUDE PALM OIL (CPO) PRODUCTION, 2024 AND 2025**

Region	2025 (t)	2024 (t)	Difference	
			Volume (t)	%
Peninsular Malaysia	11,376,845	10,891,417	485,428	4.5
Sabah	4,410,291	4,274,440	135,851	3.2
Sarawak	4,496,339	4,172,409	323,930	7.8
<b>Total</b>	<b>20,283,475</b>	<b>19,338,266</b>	<b>945,209</b>	<b>4.9</b>

Source: MPOB (2026).

### Productivity, Extraction Efficiency, and Labour Normalisation

The FFB productivity in Malaysia improved markedly in 2025, increasing by 6.4% to 17.77 t ha<sup>-1</sup>, supported by favourable weather conditions, improved agronomic practices, and more stable labour availability. Yield gains were observed across all regions, with Sarawak recording the strongest relative improvement, followed by Sabah and Peninsular Malaysia. Despite this recovery, national yields remain below theoretical potential, reflecting persistent structural constraints, including aging planting materials, soil fertility limitations, and uneven adoption of precision agriculture.

Improvements in oil extraction rate (OER) were modest, with the national average rising marginally to 19.74% (Table 4). Regional divergence suggests ongoing variability in fruit quality, harvesting

timeliness, and mill efficiency, indicating that future output growth will rely more heavily on yield enhancement and harvesting efficiency than extraction gains alone.

Labour normalisation in 2025, driven by targeted foreign worker approvals, improved harvesting execution, and raised labour productivity to 1.49 t man-day<sup>-1</sup>. While this supported output recovery, continued reliance on foreign labour exposes the sector to policy risks, underscoring the need for mechanisation and automation to sustain competitiveness.

### Trade Performance and Market Reconfiguration

A defining feature of Malaysia's palm oil trade performance in 2025 was the decoupling between export volume and export value. Total export volume declined by 7.2% to 24.75 million tonnes,

while export value increased by 2.8% to RM112.43 billion (Table 5). This divergence reflects improved unit prices and a compositional shift towards higher value-added products.

Exports of palm oil contracted sharply in volume (9.6%) yet experienced only a marginal decline in value (1.8%), suggesting partial price insulation amid weaker global demand. In contrast, palm kernel oil and oleochemicals recorded strong value growth despite lower volumes, pointing to tighter global supply conditions and sustained demand for specialised downstream derivatives. Biodiesel emerged as the most dynamic segment, with substantial increases in both export volume (38.4%) and value (48.1%), highlighting Malaysia’s growing exposure to renewable energy markets and policy-driven demand. While biodiesel exports enhance value capture, they also expose the industry to regulatory risk, as demand is closely tied to energy and climate policies in importing countries.

These patterns indicate a structural shift towards downstream value, which has partially mitigated declining bulk exports. However, the uneven performance across product categories

underscores persistent vulnerabilities, including reliance on price-sensitive markets and policy-driven demand for biofuels. Sustaining export resilience will require deepening downstream capabilities, diversifying end markets, and managing exposure to regulatory and price volatility in the global energy and chemical sectors.

Figure 2 illustrates the year-on-year changes in Malaysia’s palm oil export volumes to the top-10 destinations between 2024 and 2025. Countries are systematically ordered by their 2025 export volumes (thousand tonnes), ranging from the largest market (India) to the smallest (Tanzania), to facilitate consistent cross-country comparison. Over this period, total exports declined from 16.90 million tonnes in 2024 to 15.27 million tonnes in 2025, indicating a notable contraction in external demand. The reduction was particularly pronounced in major importing markets, including India (12.1%), China (35.1%), and the European Union (20.2%). These declines likely reflect a combination of heightened price sensitivity, evolving trade policy environments, and substitution effects within the global vegetable oil complex, where competing oils

TABLE 4. MALAYSIAN FRESH FRUIT BUNCH (FFB) PRODUCTIVITY AND OIL EXTRACTION RATE (OER), 2024 AND 2025

Region	FFB productivity (t ha <sup>-1</sup> )				OER (%)			
	2025	2024	Difference		2025	2024	Difference	
			Volume	%			Volume	%
Peninsular Malaysia	19.49	18.42	1.07	5.8	19.62	19.46	0.16	0.8
Sabah	16.76	15.74	1.02	6.5	20.31	20.53	-0.22	-1.1
Sarawak	15.98	14.89	1.09	7.3	19.51	19.37	0.14	0.7
<b>Total</b>	<b>17.77</b>	<b>16.70</b>	<b>1.07</b>	<b>6.4</b>	<b>19.74</b>	<b>19.67</b>	<b>0.07</b>	<b>0.4</b>

Source: MPOB (2026).

TABLE 5. MALAYSIAN EXPORTS OF PALM OIL AND PALM-BASED PRODUCTS, 2024 AND 2025

Palm-based product	Volume (t)			Value (RM million)		
	2025	2024	Difference (%)	2025	2024	Difference (%)
Palm oil	15,272,823	16,902,595	-9.6	71,632.49	72,952.58	-1.8
Palm kernel oil	1,082,925	1,151,104	-5.9	9,209.13	6,787.45	35.7
Palm kernel cake	2,431,495	2,396,517	1.5	1,303.49	1,496.60	-12.9
Palm-based oleochemicals	2,684,938	2,993,592	-10.3	19,385.69	17,409.76	11.3
Biodiesel	353,780	255,669	38.4	1,856.18	1,253.27	48.1
Finished products	587,231	585,764	0.3	4,866.53	4,313.02	12.8
Other palm-based products*	2,337,699	2,375,206	-1.6	4,179.21	5,178.60	-19.3
<b>Total</b>	<b>24,750,892</b>	<b>26,660,448</b>	<b>-7.2</b>	<b>112,432.71</b>	<b>109,391.29</b>	<b>2.8</b>

Note: \* - sludge oil, mixed acid oil, industrial grade palm oil, residue oil/scavenger oil, lauric fatty acid distillate, used frying oil, lacto plus, spent bleaching earth, fruit waste/oil palm waste, fatty alcohol residues, empty fruit bunch (EFB), mixed vegetable acid oil, high free fatty acid (FFA) acid oil, palm oil mill effluent (POME), sodium fatty acid salt, oil palm fibre/palm fibre, palm kernel shell (PKS), empty fruit bunch pellet.

Source: MPOB (2026).

such as soybean oil (SBO) and sunflower oil (SFO) continue to exert increasing competitive pressure on palm oil demand.

Import contraction in key Asian markets has heightened volatility in Malaysia's palm oil export performance. In India, elevated domestic edible oil inventories and frequent tariff recalibrations have strengthened substitution towards SBO and SFO when relative price advantages emerge, increasing Malaysia's exposure to policy-driven demand fluctuations in its largest export destination (Jadhav & Bhardwaj, 2025; Organisation for Economic Co-operation and Development & Food and Agriculture Organization of the United Nations [OECD-FAO], 2025). China experienced the steepest decline, reflecting strong substitution towards domestically crushed SBO amid unfavourable palm oil price differentials. Such price-sensitive responses are particularly pronounced in markets with substantial domestic oilseed processing capacity, amplifying demand volatility during periods of palm oil premium pricing (OECD-FAO, 2025). Concurrently, Indonesia's biodiesel blending policies, including the proposed B50 mandate, have tightened regional supply, supported prices but also altered Malaysia's competitive positioning. Intermittent policy adjustments in 2025 eased supply pressure, intensifying competition and constraining Malaysia's export opportunities in price-sensitive markets (Reuters, 2025).

Together, the contraction in Malaysia's palm oil exports in 2025 reflects the interaction of reciprocal trade policies, substitution effects, and regional biofuel strategies rather than demand weakness alone. While emerging markets such as Tanzania and the Philippines recorded growth, these gains were insufficient to offset losses in large, policy-sensitive markets. Strengthening Malaysia's export resilience will therefore depend on managing exposure to

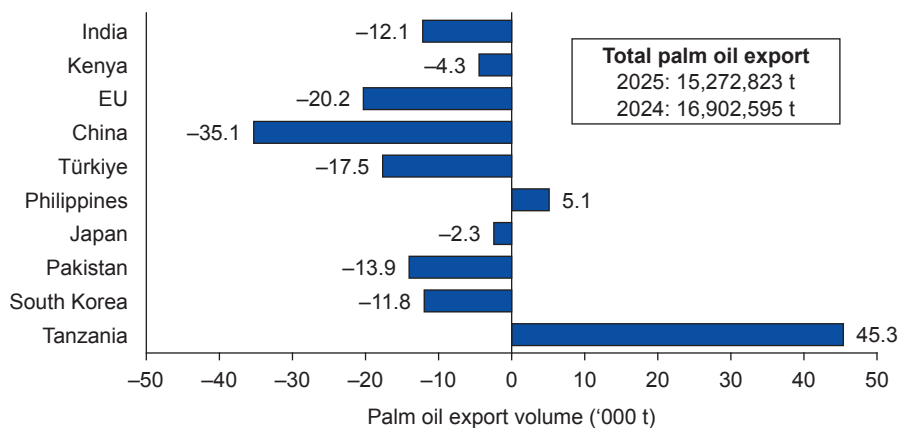
tariff volatility, enhancing price competitiveness, and deepening downstream value capture to reduce reliance on bulk commodity trade.

### Inventory Dynamics and Price Formation

Figure 3 illustrates the inverse relationship between Malaysia's palm oil stocks and CPO prices in 2025, highlighting the interaction between supply accumulation and price adjustment. Stocks were relatively tight in the first quarter (1.51–1.58 million tonnes), supporting elevated CPO prices of around RM4,700.00 t<sup>-1</sup>. From April onwards, inventories rose sharply, exceeding 2.00 million tonnes by mid-year and peaking at 3.05 million tonnes in December, reflecting seasonal production recovery and weaker export offtake.

As stocks accumulated, CPO prices declined markedly between April and May, before partially recovering in the third quarter despite continued inventory growth. This divergence suggests that price formation was influenced not only by domestic stock levels but also by expectations of downstream demand, global vegetable oil market conditions, and cost-related price floors. By year-end, prices stabilised despite historically high inventories, indicating a market adjusting to higher supply rather than experiencing a demand-driven collapse.

The 2025 price-stock dynamics underscore the continued role of inventory accumulation in shaping short-term price movements, while the observed price resilience at elevated stock levels points to structural support mechanisms that moderated downside risk. This pattern highlights the importance of managing stock build-ups through export responsiveness and downstream absorption to reduce price volatility in periods of supply expansion.



Source: MPOB (2026).

Figure 2. Year-on-year change in Malaysia's palm oil export volume to major destinations (2024 vs. 2025).

Price movements varied across product segments. The CPO prices increased modestly by 2.7% to RM4,292.50 t<sup>-1</sup>, while refined products recorded stronger gains. Palm kernel-related products experienced the largest price increases, driven by tight lauric oil supply. At the upstream level, FFB prices rose by 6.3%, improving grower incomes but reinforcing cost pressures downstream.

Stronger price gains were observed in refined products, with refined, bleached and deodorised (RBD) palm oil and palm olein increasing by 1.3% and 1.2%, respectively, reflecting sustained downstream demand and refiners' ability to pass through higher costs. In contrast, RBD palm stearin recorded a slight decline (1.6%), pointing to segment-specific demand weakness or relative oversupply.

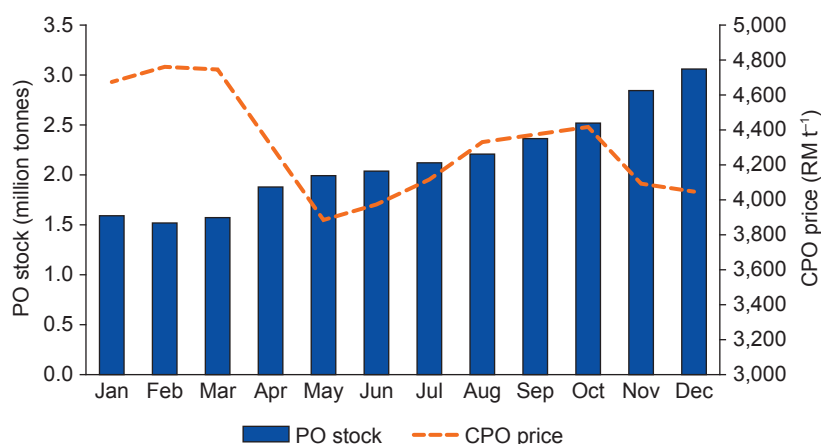
Palm kernel-related products exhibited the most pronounced price increases, with palm kernel and crude palm kernel oil (CPKO) rising by 29.4% and 33.9%, respectively, driven by tight lauric oil supply and robust demand from the oleochemical and food sectors. At the upstream level, FFB prices

increased by 6.3%, improving grower returns but also reinforcing cost pressures across the value chain.

The 2025 price structure highlights increasing differentiation across oil palm product segments, with price strength concentrated in higher value and supply-constrained products (Table 6). While this supported producer and processor margins, it also underscores growing exposure to cost inflation and segment-specific demand risks rather than broad-based market expansion.

Figure 4 compares monthly prices of CPO with SBO and SFO in 2024–2025, highlighting divergent price trajectories within the global vegetable oil complex. All three oils recorded higher prices in 2025, particularly in the first quarter, reflecting tight global supplies and strong demand. However, price increases for CPO were generally smaller than those for SBO and SFO, indicating a relative price discount for palm oil.

During the first half of 2025, CPO prices rose by 10%–28% year-on-year but remained consistently below competing oils, reinforcing



Note: PO - palm oil; CPO - crude palm oil.  
Source: MPOB (2026).

Figure 3. Palm oil stocks and crude palm oil (CPO) prices, 2025.

TABLE 6. MALAYSIAN PRICES OF OIL PALM PRODUCTS

Item	2025 (RM t <sup>-1</sup> )	2024 (RM t <sup>-1</sup> )	Difference	
			RM t <sup>-1</sup>	%
CPO	4292.50	4179.50	113.00	2.7
RBD palm oil	4456.50	4400.00	56.50	1.3
RBD palm olein	4471.50	4417.00	54.50	1.2
RBD palm stearin	4353.50	4425.50	-72.00	-1.6
Palm kernel	3424.50	2645.50	779.00	29.4
CPKO	7329.50	5475.50	1854.00	33.9
FFB	930.00	875.00	55.00	6.3

Note: CPO - crude palm oil; RBD - refined, bleached and deodorised; CPKO - crude palm kernel oil; FFB - fresh fruit bunches.  
Source: MPOB (2026).

palm oil’s cost competitiveness in price-sensitive markets. Price convergence across oils in mid-2025 suggests active substitution effects, with buyers adjusting procurement in response to relative price movements. In contrast, towards the year-end, CPO prices weakened on a year-on-year basis, coinciding with rising inventories, while SBO and SFO prices remained supported by tighter supply conditions. This divergence underscores palm oil’s greater exposure to stock accumulation and demand volatility.

On an annual average basis, CPO prices increased by 12.7%, compared with stronger gains for SBO (17.6%) and SFO (19.6%). While this relative underperformance enhanced palm oil’s affordability and role in global food security, it also reflects structural vulnerabilities linked to inventory build-up and competitive pressures within the edible oil complex.

In 2025, the Malaysian oil palm industry demonstrated improved system-level performance, underpinned by higher yields, stabilised labour availability, and resilient price conditions. However, competitiveness remained largely price-based, underscoring the importance of sustained productivity enhancement, improved stock cycle management, and deeper downstream integration.

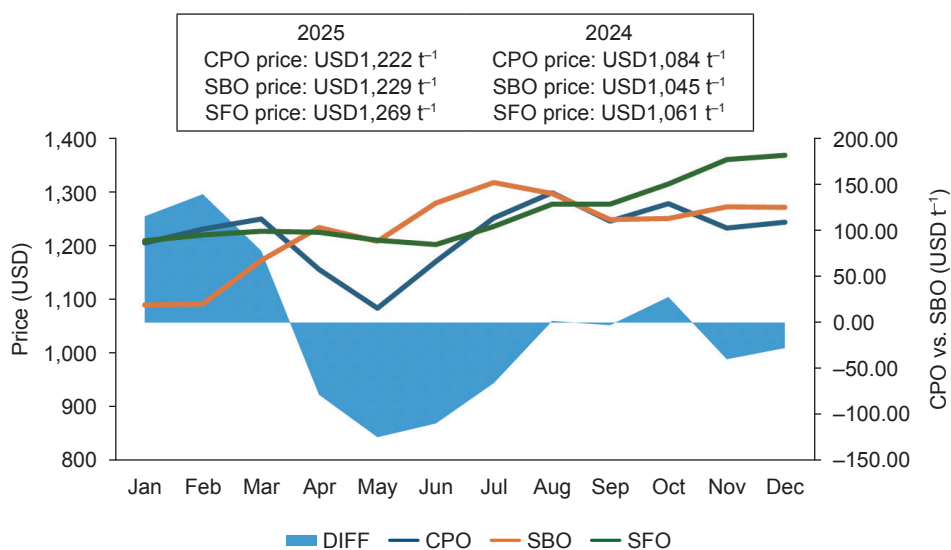
The implementation of digital monitoring systems under the stewardship of MPOB and the acceleration of replanting have established a stronger structural foundation for future growth. As cyclical recovery effects dissipate, the industry’s next growth phase will depend on its ability to generate technology-driven productivity gains, enhance climate resilience, and move decisively up the value chain.

The 2025 data suggest moderate recovery in productivity and output, supported by improved labour availability and ongoing replanting, although evidence for deeper structural transformation remains partial and uneven across regions and value-chain segments. However, some sectoral constraints have shaped and prioritised R&D efforts toward targeted, solution-driven innovations. In order to ensure the long-term resilience and competitiveness of the sector, it is crucial to accelerate the development of high-yielding breeding and elite planting materials to address replanting and declining mature areas, enhance mechanisation and automation to reduce labour dependency, strengthen downstream diversification and specialty products to mitigate trade volatility, tackle sustainability challenges through traceability, emission reduction, and low-carbon pathways along the supply chain, as well as support smallholder expansion through digital extension, affordability, and adoption-focused research. The R&D focus areas synthesise the 2025 R&D advances through the lens of productivity, sustainability, resilience, and value-chain transformation.

**RESEARCH AND DEVELOPMENT (R&D)  
FOCUS AREAS IN 2025**

**Methodology**

This review of the R&D focus areas adopted a structured narrative approach. Literature published between the end of 2024 and 2025 was identified from databases such as Scopus,



Note: SBO - soybean oil; SFO - sunflower oil; CPO - crude palm oil; DIFF - difference between CPO and SBO prices. Source: MPOB (2026).

Figure 4. Palm oil vs. other vegetable oil prices, 2025.

Web of Science, and Google Scholar using combinations of keywords including oil palm, palm oil, oil palm biomass, biofuel, sustainability, breeding, genomics, *Ganoderma*, greenhouse gas, biodiversity, tocotrienols, food safety, nutrition, and oleochemicals. Industry statistics were obtained from MPOB sources. Studies were prioritised based on relevance to Malaysian oil palm performance and innovation themes.

### Precision Breeding: Integrating with Genomics

Field evaluation of progeny and germplasm remains critical to ensure practical breeding gains. Performance assessments of AVROS and Yangambi-derived three-way crosses demonstrated significant variations in bunch yield, oil yield and vegetative traits, allowing the identification of high-performing genotypes suitable for future breeding programs (Nor Azwani et al., 2025). Broader breeding strategies emphasise the integration of mechanisation, compactness, dwarfness, and other value-added traits to enhance yield and productivity under labour constraints, while expanding the genetic base using conserved germplasm collections from multiple countries (Mohamad et al., 2025). Recent advances in molecular genetics and genomics would aid oil palm (*Elaeis guineensis*) improvement through precise breeding, effective quality control, enhanced disease diagnostics, and informed germplasm conservation. Collectively, studies across multiple breeding programmes demonstrate how simple sequence repeat (SSR) or single-nucleotide polymorphism (SNP) markers, genome-wide analyses, and high-resolution genotyping platforms are accelerating the development of elite planting materials while strengthening the genetic foundation of the crop. Marker-assisted selection has shown strong value in improving oil quality, particularly through the identification of functional SSR markers associated with lipase activity. The mEgCIR\_LIP03 marker, located in the promoter of the *EgLIP1* gene, differentiates low- and high-lipase genotypes in Ulu Remis *tenera* materials, enabling breeders to eliminate high-free fatty acid (FFA) palms and fast-track the development of low-acidity lines (Weng et al., 2025b). Genetic purity verification has also advanced with the use of SSR and SNP markers. In interspecific BC1 × BC1 populations, polymorphic SSRs successfully identified outliers and enabled full reconstruction of true parental genotypes (Serdari et al., 2025). Genomic tools also support trait improvement, particularly for canopy compactness and height, which are crucial for high-density planting and long-term harvesting efficiency. Genome-wide association studies identified significant SNPs associated with height

increment (Weng et al., 2025a) and 27 SNPs linked to compact architecture traits across diverse *tenera* families (Samsudin et al., 2025). These markers and candidate genes provide a pathway towards marker-assisted breeding for more manageable, high-yielding palms. Genomic analyses continue to highlight the importance of conserving the crop's genetic base. Genotyping-by-sequencing (GBS)-based evaluation of 478 African accessions identified over 7,000 SNPs, revealed the highest diversity and private alleles in Nigerian populations and defined a core set of 96 palms for conservation (Zolkafli et al., 2025). Complementary SSR-based assessment of Tanzanian accessions revealed moderate diversity and evidence of historical gene flow, underscoring the need for broader germplasm collection to strengthen future breeding (Masanja et al., 2025).

On an industry-wide scale, deoxyribonucleic acid (DNA) testing of smallholder fields using the *Shell* gene array revealed extensive contamination with low-yielding non-*tenera* palms, showing that the systematic "screen-then-plant" DNA verification approach could dramatically increase smallholder income and mill productivity (Maskromo et al., 2025). A complementary innovation involving mixed-pollen controlled crosses was also introduced. Multiple paternal sources are applied simultaneously, and progenies are later assigned using a 108-SNP panel. This novel approach increases breeding efficiency, reduces dependency on flowering cycles, and provides accurate parentage resolution (Yaakub et al., 2025). Pollen from multiple paternal sources was combined and used to hybridise a female flower from a single maternal palm. The subsequent progenies could be assigned to specific families (paternal source) using MPOB's True-to-Type platform. This genomic platform achieved >99.4% accuracy in parentage assignment and improved legitimacy detection across diverse genetic backgrounds, offering robust quality control for breeding, seed gardens, nurseries, and tissue culture operations (Ting et al., 2025).

Somatic embryogenesis remains a cornerstone for clonal propagation, with studies showing that even virescent off-type plantlets, previously discarded due to abnormality concerns, can develop into normal fruiting palms, thereby improving the efficiency of seedling production (Karyanti et al., 2025). However, tissue culture-derived palms can still exhibit floral and fruit abnormalities such as thin/thick coat, squirrel tail, and mantling, which underscores the need for careful morphological screening and selection (Sari & Sari, 2025). Complementing traditional tissue culture, monitoring epigenetic changes such as those observed in the Karma transposable element and other heritable modifications can potentially enhance oil palm resilience and trait

stability, particularly when coupled with priming strategies and epigenome editing tools (Sarpan & Ooi, 2025). Genome editing and transformation technologies are increasingly applied to accelerate oil palm improvement. The development of CRISPR/Cas9 ribonucleoprotein (RNP)-mediated editing of embryogenic calli allows transgene-free modifications with higher efficiency and reduced regeneration time (Norfaezah et al., 2025). Progress in *Agrobacterium*-mediated transformation and biolistic delivery systems, including optimised particle bombardment parameters, further supports functional genomics and targeted trait modification such as oil yield, plant height, fruit colour, and stress resistance (Hanin et al., 2025; Nurfahisza et al., 2025). These molecular approaches, combined with mixed-pollen strategies and SNP-based fingerprinting, allow breeders to assign progenies accurately to paternal sources and efficiently manage breeding populations (Nurfahisza et al., 2025). Together, these studies highlight the integration of biotechnology, genome editing, epigenetics, and traditional breeding as complementary approaches for sustainable oil palm improvement. This integrated approach is key to establishing the foundations of a modern precision breeding era for the oil palm industry.

### Multi-Omics Perspective

Recent advances in functional genomics, metabolomics, and molecular breeding have substantially deepened our understanding of the biological processes governing oil palm (*E. guineensis* and *E. oleifera*) productivity, oil quality, abiotic stress resilience, and metabolic regulation. Collectively, findings from eight studies highlight the expanding role of integrative omics, promoter characterisation, and gene-function validation in accelerating genetic improvement of this globally important crop. Oleic acid biosynthesis remains a central target for improving palm oil quality due to its oxidative stability and health benefits. Multi-omics analyses comparing seedless and *tenera* palms across fruit developmental stages identified key genes including *SAD*, *FabD*, *LACS6*, *BC*, *FabB*, and *FabI*, as positive regulators of oleic acid accumulation, whereas *LACS9* showed negative associations (Xu et al., 2025). These results reveal distinct regulatory mechanisms shaping fatty acid synthesis across genetic backgrounds, providing actionable targets for high-oleic breeding. Promoter biology also continues to advance, with the MSP-C7 promoter showing tissue-specific functionality in oil palm mesocarp and transgenic tomato. A 2.1 kb promoter fragment (MSP-C7-F1) was sufficient to drive expression in monocot and dicot systems, highlighting its utility for genetic engineering strategies aimed at fruit-specific transgene

deployment (Badai et al., 2025). Complementing this, functional dissection of the EgPAL5 promoter uncovered strong responsiveness to developmental cues, osmotic stress, and transcriptional regulation by AtMYB58, pinpointing essential *cis*-elements that modulate phenylpropanoid metabolism and drought induction (Yusuf et al., 2025). At the protein level, the mesocarp lipase PLA1-3 was successfully cloned, expressed, and partially purified, demonstrating notable catalytic activity (210.1 U mg<sup>-1</sup>). This work enables future biochemical characterisation of lipases affecting innate oil quality and offers prospects for industrial biocatalysis (Safiudin et al., 2025).

Abiotic stress responses were further explored through transcription factor (TF) analysis. Twenty TFs belonging to MYB, HD-ZIP, NF-Y, and HSF families exhibited coordinated induction under both drought and salinity stress. Promoter and homology studies support their conserved roles in stress regulatory networks, with qRT-PCR validating most RNA-Seq patterns. These candidates form a foundation for engineering multi-stress-tolerant cultivars, though functional validation remains essential (Salgado et al., 2025). Genetic variation in key lipid biosynthesis genes also offers future breeding opportunities. Sequence analysis of the *SAD* gene across *E. guineensis*, *E. oleifera*, their hybrids, and various fruit forms identified 15 SNPs across intronic, exonic, and UTR regions. Derived SNP markers exhibited diversity across 50 accessions, indicating their potential use in selecting lines with improved oleic acid profiles (Rismayanti et al., 2025).

### Biodiversity in Oil Palm Landscapes

Studies on biodiversity in oil palm landscapes are pivotal for balancing the maximisation of palm oil productivity with sustainable development, with new findings providing insights into the positive development in the protection of biodiversity. For example, in oil palm ecosystems, the most diverse bird families with important ecological roles include Ardeidae, Cuculidae, Nectariniidae, and Cisticolidae. However, further studies are needed to investigate the interactions between dominant insectivorous birds and their arthropod prey within these ecosystems, to better understand their roles in regulating ecosystem balance (Amit et al., 2025). In the Central Kalimantan, Indonesia, observation of the White-throated kingfisher, *Halcyon smyrnensis*, in an oil palm plantation has proven that species exhibiting high adaptive behavioural capacity to the agricultural and urban development will increase their distribution range and colonise new areas. The species that was initially occasional visitor has now become a resident breeder and consequently, expanded its distribution range (Silmi et al., 2025).

## Progress in Effective Management of Pests and Diseases

*Ganoderma boninense*, a basidiomycete fungus that causes basal stem rot (BSR) disease, remains a major threat to the industry, leading to substantial economic losses (Hamid et al., 2025). This has driven continued studies in addressing the concern, including the development of various methodologies for its detection and curative control. Improved detection methodologies have been developed with the potential for management of the disease. These included qPCR primer for detection in soil (Tung et al., 2025), object-based image analysis from drone for detection in oil palm (Izzuddin et al., 2025) and a recombinase polymerase amplification-lateral flow assay (RPA-LFA) for onsite and early detection at the asymptomatic phase (Lakshmi et al., 2025).

Transmission of BSR disease primarily occurs through root-to-root contact in the soil. However, the role of *Ganoderma* basidiospores in the transmission process has often been overlooked. A study conducted at five plantations in Sabah, Malaysia, found that at least 55 arthropod species were associated with *Ganoderma* basidiocarps. Among the insects identified in the study carrying the basidiospores, the handsome fungus beetle, *Eumorphus* spp., was found to have the greatest potential for transmitting the basidiospores, showing the potential sporadic spread of BSR and upper stem rot (USR) incidences in the field (Syarif et al., 2025).

Chemical control of *G. boninense* has been proven to be ineffective and thus, prompted the exploration of microbial-based biocontrol, with potential synergistic effect of fungal isolates as biocontrol agents and bioformulations in suppressing the fungus (Anuar et al., 2025). Alternatively, *Trichoderma* isolates from the rhizosphere soil of oil palm seedling plantations have shown potential as biological control of *G. boninense* (Lisnawita et al., 2025), while *Pseudomonas aeruginosa* and *T. asperellum* exhibit potential in promoting plant growth and suppression of the disease infestations in oil palm (Muniroh et al., 2025). A combination of organic fungicide, biofungicide, endophytic bacteria and biostimulant has been effective in curative control of various stages of infection (Eris et al., 2025). Interestingly, the volatile organic compounds (VOCs) from *Fusarium foetens* can inhibit *G. boninense* growth by up to 60% (Lutfia & Rupaedah, 2025). Four key VOCs were identified, with two compounds, 2,3-pyrazinedicarboximide and indolylmethyl thiohydroximate, exhibiting binding affinities similar to the standard antifungal agent hexaconazole.

Improved tools for analysing pathogenic interactions were demonstrated through pathway

analysis of *G. boninense* metabolomics data (Nurazah et al., 2026). Enrichment of starch and sucrose metabolism, branched-chain amino acid degradation, and tricarboxylic acid (TCA) cycle pathways across temporal stages highlighted key metabolic shifts supporting fungal growth. These insights improve our understanding of pathogen biology and may inform integrated disease management.

Pests such as rodents and insects have impacted the productivity of the oil palm industry. Rodents cause significant financial losses in the oil palm industry, highlighting the critical need for effective pest management. Understanding the habitat requirements of rodents in oil palm plantations is crucial for effective population control (Asrif et al., 2025). The presence and genetic characterisation of *Bartonella* in small mammals, particularly rodents, were assessed to evaluate the zoonotic risk (AbdulHalim et al., 2025). The study identified the predominant rodent species, *Rattus tanezumii* (R3 mitotype) and *R. tiomanicus*, as hosts for *Bartonella phoceensis*. Although the zoonotic potential of this bacterium remains unconfirmed, these findings highlight the need to adopt precautionary measures to protect workers from potential infection. Moreover, they emphasise the need for continuous monitoring of host-pathogen interactions and the mitigation of risks associated with emerging zoonotic diseases.

## Technological Advancement in Enhancing Productivity

The impact of climate change on oil palm plantations has become a critical concern. A systematic review was conducted to examine the effects of climate change on oil palm productivity and plantation physical conditions (Wulandari et al., 2025). The study provided insights into the roles of relevant stakeholders in developing effective adaptation strategies to mitigate the impacts of climate change on oil palm plantations and recommended various measures to sustain productivity and enhance industry resilience. In addition, the impacts of applying advanced technologies associated with the Fourth Industrial Revolution (IR4.0) including artificial intelligence (AI), blockchain, the Internet of Things (IoT), big data analytics and remote sensing, in the oil palm industry were assessed (Zaki et al., 2025). The findings indicated that these technologies can positively improve palm oil production by offering innovative solutions, enhancing operational efficiency and reducing environmental impacts.

Mapping of oil palm plantations and individual trees across Malaysia using the Single Tree Extraction Method-Oil Palm (STEM-OP) with sub-meter visible-light satellite imagery (RGB bands)

was conducted in 2022. The study estimated that Malaysia had 5.25 million hectares of oil palm plantations, with approximately 572.6 million trees (Zhang et al., 2025). The method achieved over 90% accuracy for mapping plantation extent and 80% accuracy for counting individual trees.

A study produced a 10–30 m oil palm extent map and a pixel-wise stand-age layer using a multi-sensor remote sensing approach, which integrated 38 years (1987–2024) of Landsat data with 2024 Sentinel optical-synthetic-aperture radar (SAR) composites in a cloud-native workflow (Weerakitikul et al., 2025). This combined approach provides nationally relevant data on plantation area, supporting policy-making decisions and commercial applications. However, future work should focus on expanding field validation, refining age-detection thresholds, and integrating age maps with yield and carbon models.

A dataset of FFB images from commercial plantations in Central Kalimantan, Indonesia, was compiled, covering five different maturity stages: Unripe, underripe, ripe, flower and abnormal (Suharjito et al., 2025). The images were captured using smartphone video from multiple angles under varying conditions, then frame-extracted and annotated. The dataset is validated using a digital census approach, with the aim of supporting the development of deep learning models for FFB detection and classification. These images will support the monitoring of harvest times, predicting yield, and optimising resource allocation.

A non-destructive method combining near-infrared (NIR) spectroscopy with chemometric analyses using Empirical Wavelet Transform and Gaussian Process Regression was developed for the multi-parameter prediction of oil palm fruit quality (Nanda et al., 2025). These parameters predicted included water content, oil content and FFA, which facilitate the optimisation of harvest timing and enhancement of productivity.

Nutrient management plays a crucial role in enhancing palm oil productivity. The growing interest in the development of organic fertilisers has led to increased research on the impacts of fertilisers on palm oil production. A comprehensive assessment of various commercial fertilisers used in oil palm plantations in Indonesia was conducted (Sukarman et al., 2025). The study highlighted the prevalence of counterfeit and non-conforming fertilisers, which negatively impact the productivity and sustainability of oil palm plantations in the country. The findings emphasise the need to use authentic, high-quality fertilisers to ensure the long-term productivity and sustainability of the oil palm industry.

A combination of visible-NIR spectroscopy with advanced statistical analyses has been shown to provide enhanced precision in monitoring

and detecting nutrient levels in oil palm plants, compared to traditional methods (Zahir et al., 2025). The red-edge band (660–770 nm) yielded the best results for identifying nutrient-stressed conditions. The study also highlighted that the application of 0.8 g of NPK fertiliser every two weeks significantly improves plant nutrient conditions, as indicated by the spectral index calculation.

The effect of various types of fertilisers on the growth of oil palm in Indonesia, with a focus on root morphology and nutrient uptake was investigated (Wahyudin et al., 2025). The modification of root morphology through root pruning enhances plant nutrient uptake, as root cutting can stimulate the growth of new roots at the cut ends. The study found that plants aged seven years showed the best response in terms of stem circumference and stem diameter, compared to plants aged 12 and 16 years. Additionally, an analysis of variance (ANOVA) revealed a significant difference in the normalised difference vegetation index (NDVI) across plants of different ages, with the highest NDVI value observed in plants aged seven years. No significant difference in NDVI was found between plants aged 12 and 16 years.

The application of slow-release fertiliser to promote growth in oil palm seedlings was investigated (Harahap et al., 2025). The study found that a slow-release fertiliser dose of 75% resulted in the greatest increase in oil palm seedling growth, with an agronomic effectiveness value exceeding 95%, compared to doses of 50% and 150%. Additionally, the use of organic fertilisers and biochar produced from empty fruit bunches (EFB) significantly reduces the need for synthetic fertilisers (F. R. Yusuf et al., 2025). The utilisation of organic fertilisers not only reduces GHG emissions, improving the environmental impact of the oil palm industry, but also lowers the input costs associated with synthetic fertilisers.

### **Sustainable Development for Smallholders**

Sustainable palm oil continues to be a growing global demand. Consumers who increasingly recognise their purchasing power play an important role in increasing the demand for sustainable palm oil as they become more aware of the environmental and social impacts of palm oil. This shift in consumer behaviour underpins Malaysia's strong commitment to the MSPO certification, positioning it as a national priority for sustainability, market credibility, and industry accountability (Rahami, 2024). MSPO serves as a proven mechanism, driving the adoption of best agronomic practices and introducing shared standards that align smallholders' operations with industry expectations. In addition, in an effort to strengthen MSPO outcomes, the Social Impact

Assessment procedure was enforced in June 2025 to enhance compliance and elevate the overall certification standard.

Recent empirical studies, supported by extensive field data, highlight the challenges faced by smallholders (Charlotte & Oliver, 2025; Hong et al., 2025) and evaluate the effectiveness of MSPO certification in strengthening operational compliance and sustainability outcomes (Supriatna et al., 2025). Meanwhile, smallholders continue to face significant barriers to achieving sustainability certification such as financial strain, limited knowledge, and a high dependence on the extension services. Therefore, sustaining smallholders' participation in MSPO ultimately depends on whether independent certified smallholders receive a premium price for their produce, as a direct incentive and reward for implementing the practices (Ansah et al., 2025).

Smallholders are encouraged to adopt crop or livestock integration as a practical path toward income diversification. Recent findings show that oil palm fronds are a viable and cost-efficient substitute for conventional roughage, showing equivalent impacts on livestock performance (Mat Rodi et al., 2025). This allows smallholders to cut feed costs while extracting greater value from existing oil palm resources. Controlled grazing within farm plots naturally returns organic nutrients to the soil, reducing dependence on chemical fertilisers and improving input efficiency without sacrificing yield performance. Although nature-based land management improves soil health and sustainability over time, smallholders' adoption is primarily held back by high upfront costs and the slow impact (Sibhatu et al., 2025).

A robust traceability system is essential to ensure that sustainably produced palm oil reaches the intended consumers and provides verifiable origin claims (Lai et al., 2025). As environmental and economic pressures intensify, the oil palm industry is compelled to increase productivity, strengthen sustainability, and expand transparency throughout its supply chain. Evidence shows that AI technologies can significantly improve production, elevate supply chain visibility, and reinforce environmental compliance (Judijanto, 2025b). The Malaysian oil palm industry is undergoing a steady yet high-stakes transition toward stronger environmental sustainability, propelled by regulatory demand, market forces, and the rising awareness of long-term economic value (Hong et al., 2025).

### **Sustainable Palm Oil Mill Effluent (POME) Treatment and Biogas Recovery**

The palm oil milling sector plays a vital role in the palm oil production and processing supply chain but faces growing challenges such as stagnant

efficiency, stringent environmental regulations and increasing sustainability demands. A key focus area in the milling sector relates to the management of palm oil mill effluent (POME). Sustainable treatment of POME is crucial for preserving the environment while supporting the commitment to sustainable development.

In recent years, POME treatment technology has advanced significantly beyond just conventional ponding systems. Innovations such as the POMEVap technology (Alfa Laval Malaysia Sdn. Bhd., Malaysia) have introduced an efficient, compact and environmentally friendly alternative for managing POME. This technology applies evaporation-based separation to recover reusable water and solid concentrate, enabling zero liquid discharge and reducing raw water consumption through internal reuse. Its closed-loop, methane-free design minimises GHG emissions, while its forced-circulation plate evaporator ensures high turbulence and a self-cleaning effect, thereby attenuating fouling and maintenance needs (Nasrin et al., 2025).

Continuous adsorption system (CAS) of POME using palm kernel shell (PKS) activated carbon offers a cost-effective and high-performance approach for polishing final discharge. The system consistently achieves significant reductions for crucial pollutant indicators, including biochemical oxygen demand (BOD) (by up to 85%), suspended solids (by approximately 70%), chemical oxygen demand (COD) (by approximately 80%), and colour removal reaching zero ADMI units, thereby producing effluent that nearly meets drinking water standards. Beyond its superior pollutant-removal efficiency, the CAS is also cost-effective, which warrants a lower capital cost than membrane-based systems. In keeping with the principles of a circular economy, the CAS further generates economic value through annual water-reclamation savings and the conversion of saturated activated carbon into bio-fertilisers (N. H. Zainal et al., 2025).

Another emerging technology in POME polishing is the photocatalytic degradation of anaerobically-treated POME with green-synthesised zinc oxide-lemongrass nanoparticles. This eco-friendly approach has demonstrated remarkable reductions in pollutant metrics, such as turbidity (by 85.6%), COD (by 97.0%), and colour (by 50.9%), thus yielding treated effluents that meet the Malaysian Department of Environment's (DOE) discharge standards. The enhanced performance is attributed to the small nanoparticle size and lemongrass-based capping, which improve photocatalytic activity and stability (Sidik et al., 2025).

The use of pre-treated EFB as a co-substrate in POME anaerobic digestion has gained increasing attention due to its ability to improve biodegradability and methane generation.

Pre-treatment methods such as chemical, hydrothermal, bacterial and subcritical water-based means are used to delignify EFB by breaking down its lignocellulosic structure. This not only improves the accessibility of cellulose but also reduces the resistance of the biomass. These pre-treatment approaches therefore facilitate a greater release of fermentable compounds and improve the overall digestibility, leading to more efficient co-digestion with POME. When integrated into modern high-rate anaerobic systems, these approaches can strengthen process stability, accelerate degradation and maximise renewable energy recovery, making them promising pathways for advancing biogas production from POME (Hamzah et al., 2025).

Additionally, a conductive carbon brush (CB) has emerged as a promising material for enhancing acetoclastic methanogenesis in POME. CB promotes direct interspecies electron transfer between microorganisms, leading to faster and more stable electron flow, thus accelerating organic matter degradation and improving methane production. By improving electron transfer, CB also stabilises pH levels, mitigating typical acidification issues and leading to more consistent and efficient biogas recovery. CB can potentially be integrated into existing anaerobic POME pond or digester tanks without major structural changes (Ngatiman et al., 2025).

Another promising approach involves the synergistic impact of biochar and torrefied products from oil palm biomass to optimise biodegradability and methane production. Biochar enhances anaerobic digestion by providing a favourable microbial habitat, reducing the methanogenic lag phase, and boosting methane production, leading to improved sustainability and efficiency in biogas recovery (Yan et al., 2025). Similarly, torrefaction of oil palm frond (OPF) before its co-digestion with POME significantly increases methane yield due to structural and chemical changes that enhance biodegradability. Co-digestion with torrefied OPF also leads to high removal efficiencies for COD, volatile solids and total nitrogen of POME (Milicevic et al., 2025). Combining biochar and torrefied biomass as co-feeds offers a sustainable, energy-efficient solution to enhance POME treatment and resource recovery by the oil palm industry.

Biogas capture facilities can reduce energy costs, generate revenue by selling power to the grid, and potentially benefit from carbon credit mechanisms. In addition, biogas can be upgraded to biomethane for use in vehicles or injected into the natural gas grid. Moreover, the use of POME treatment and biogas capture technology can support the achievement of the Nationally Determined Contribution targets for GHG reduction and promote energy transition and the use of green technologies as outlined in the

National Energy Transition Roadmap (NETR) and National Agricommodity Policy 2021–2030 (DAKN 2030) (Kementerian Perusahaan Perladangan dan Komoditi, 2021).

### **Biomass and Bioenergy Innovation**

The transition towards a low-carbon economy is gaining momentum in Malaysia through innovative uses of oil palm biomass. Lignocellulosic materials of oil palm biomass predominantly contain a mixture of cellulose, hemicelluloses (polyose), and lignin (a complex phenolic polymer). This biomass holds significant potential as a sustainable source of fuels, bio-products, and chemicals due to its abundance, renewability, low cost, and non-competing food sources.

Oil palm trunk (OPT) has been estimated to constitute approximately 5% of the total oil palm biomass, with quantities reaching up to 75 t ha<sup>-1</sup> during the replantation period (Norhazimah et al., 2025). Currently, only a small portion of the felled OPT is utilised for plywood manufacturing or sold to interested buyers, while the majority is typically shredded and mulched in the fields to decompose naturally for nutrient recycling (Uke et al., 2021). Thus, there is growing interest in studying alternative ways to fully exploit and tap the potential of underutilised OPT. The enzymatic hydrolysis of lignocellulose from OPT has been identified as a potential alternative for the production of fermentable sugars. Utilisation of surfactant significantly improves the enzymatic hydrolysis performance of OPT at increasing solid loadings by enhancing glucose yields, and maintaining higher conversion efficiencies compared to non-supplemented systems (Bukhari et al., 2025).

Oil palm fibres possess promising characteristics for composite applications. However, their hydrophilic nature, residual oil content, and high lignin composition present challenges in composite fabrication, affecting fibre-matrix adhesion and overall performance. To overcome these limitations, exploration of hybridisation with other synthetic or natural fibres, as well as nano-integration using nanomaterials, has been studied to enhance the structural integrity of the composite. A combination of oil palm fibres with other reinforcements has led to enhanced mechanical, thermal, and durability properties, making the composites suitable for various engineering applications (Aisyah et al., 2026). Meanwhile, due to the presence of sugars and starches in their tissues, oil palms have an exceptionally low natural resistance to fungi, making them susceptible to contamination. Therefore, palm oil-based particle board shows susceptibility to fungal attack, especially from

*Aspergillus* sp., *Trichoderma* sp., and *Paecilomyces variotii*. Additional treatments to control or prevent fungal growth were required to increase the commercial value of particleboard (Idris et al., 2025).

Mesocarp fibre is a by-product generated from the palm oil mill, which has been highly used as a boiler fuel, containing 5%–6% of residual oil (dry basis). However, it has a lot of potential to be used as a dietary fibre with many health benefits, especially for lowering blood sugar levels and improving gut health. The physicochemical and functional properties of mesocarp fibre suggest that it could serve as an alternative source of dietary fibre and functional ingredient for mitigating the risk of dietary fibre deficiency-related diseases (Teh & Lau, 2025).

The increasing demand for clean and renewable energy storage has driven studies into cutting-edge battery materials using oil palm biomass. EFB is identified as a potential material for producing activated carbon for battery electrodes based on its carbon properties. The production of the material was carried out by chemical activation using NaOH and KOH, followed by physical activation using varying temperatures. High activation temperature (900°C), long soaking time (18 hr) in a 2 M concentration of KOH resulted in the highest surface area, specific capacitance, and potential (Triana et al., 2025). Meanwhile, PKS has the potential to produce SiO<sub>2</sub>/hard-carbon-like nanocomposites for applications in dual carbon sodium-ion batteries. The pyrolysis temperature has been found to have a significant effect on the structural, chemical, and electrochemical properties of the resulting materials. High-quality hard carbons are produced at 700°C with a combination of high specific capacitance, balanced defect density, graphitic ordering, and hierarchical porosity, enhancing Na<sup>+</sup> ion adsorption and charge transfer. The pores produced by PKS hard carbon-like have great potential as sodium ion intercalation sites for sodium batteries (Mas'udah et al., 2025). In addition, pellet-form graphitic carbon (PGC) for use in supercapacitor applications was successfully synthesised from OPF using a one-step carbonisation process without the use of chemicals for activation. High-quality graphitic carbon products were produced with characteristics such as optimal specific capacitance (334 F g<sup>-1</sup>) for the PGC electrode in 1 M H<sub>2</sub>SO<sub>4</sub> electrolyte, as well as the fabrication of a symmetric supercapacitor that achieved an energy density of 18.86 Wh kg<sup>-1</sup> and a power density of 1,386 W kg<sup>-1</sup>. The use of redox enhancers, especially hydroquinone, further improved the specific capacitance (Ullah et al., 2025).

Palm biodiesel has been introduced into the Malaysian market by blending it with petroleum

diesel to produce a more environmentally friendly fuel. However, its use may be limited in cold climates and highland areas because biodiesel can thicken in cold weather due to its feedstock composition. Palm-based additives can help reduce the cold filter plugging point of biodiesel blends, making them more suitable for cold conditions. These additives improve the cold flow properties of the fuel, especially when combined with higher levels of monoglycerides (Nursyairah et al., 2025). The use of 10% biodiesel and 90% petroleum diesel (B10) and 20% biodiesel and 80% petroleum diesel (B20) palm biodiesel in heavy-duty diesel vehicles on the road showed positive effects. The two biodiesel blends did not show significant differences in fuel economy and maintenance intervals. In addition, the B20 sample showed almost the same degradation as B10. However, the total base number and iron content in the engine oil of the B20 group showed changes that had a positive effect on the condition of the engine oil (Thaddeus et al., 2025).

The SAF or biojet is a hot topic discussed by researchers recently. The use of raw materials from the palm oil industry to produce SAF is also being actively pursued. Refined palm oil was used as a feedstock to produce SAF range hydrocarbons using a hydrogen-free hydrothermolysis process and a Ni/AC-Al<sub>2</sub>O<sub>3</sub> catalyst. The study conducted shows that an economical and environmentally friendly approach for the production of biojet without using hydrogen offers an alternative to traditional processes (Ahmad et al., 2025). Palm fatty acid distillate (PFAD), by-product of the physical refining of CPO, is also a suitable raw material to produce biojet due to its free fatty acids content, primarily palmitic acid (C16). PFAD through hydrogen-free and solventless deoxygenation reaction using a bimetallic NiCo/SBA-15-NH<sub>2</sub> catalyst has successfully produced biojet, achieving the highest hydrocarbon yield (C8–C20) of 83% and biojet selectivity of 88% (Derawi et al., 2025). In addition, PFAD can be extracted to produce squalene, one of the bioactive compounds that has various applications in the food, cosmetic, and pharmaceutical industries (Nor Faizah et al., 2025). *Table 7* presents a comprehensive overview of recent innovations in oil palm biomass utilisation, highlighting the diversity of biomass sources, conversion approaches, and value-added products developed for bioenergy, advanced materials, and industrial applications.

### Food Safety and Quality Research

Adulteration in food is a widespread issue with global implications. Being a common oil used in food preparation, fraudulent activities involving

TABLE 7. SUMMARY OF RECENT INNOVATIONS IN OIL PALM BIOMASS UTILISATION FOR BIOENERGY, ADVANCED MATERIALS AND VALUE-ADDED PRODUCTS

Material/product	Biomass source	Description	Key findings	Reference
Fermentable sugars	Oil palm trunk	Enzymatic hydrolysis with surfactant	Improved glucose yield and conversion efficiency	Bukhari et al. (2025)
Hybrid composites	Oil palm fibre	Hybridisation and nano-integration	Enhanced mechanical and thermal properties	Aisyah et al. (2026)
Particleboard	Oil palm biomass	Lignocellulosic board material	Susceptible to fungi; requires treatment	Idris et al. (2025)
Dietary fibre	Mesocarp fibre	Functional food ingredient	Improves gut health and blood sugar control	Teh & Lau (2025)
Activated carbon	Empty fruit bunches	Chemical + physical activation	High surface area and capacitance	Triana et al. (2025)
Hard carbon composite	Palm kernel shell	SiO <sub>2</sub> /hard carbon nanocomposite	Enhanced Na <sup>+</sup> storage for batteries	Mas'udah et al. (2025)
Graphitic carbon	Oil palm frond	One-step carbonisation	High-energy-density supercapacitor	Ullah et al. (2025)
Biodiesel additive	Palm-based	Cold flow improver	Reduced cold filter plugging point (CFPP) in biodiesel blends	Nursyairah et al. (2025)
Biojet fuel (SAF)	Palm oil/palm fatty acid distillate	Catalytic conversion	High hydrocarbon yield (C8–C20)	Ahmad et al. (2025); Derawi et al. (2025)
Squalene	Palm fatty acid distillate	Bioactive compound extraction	High-value product for pharma/cosmetics	Nor Faizah et al. (2025)

Note: SAF - sustainable aviation fuel; SiO<sub>2</sub> - silica.

palm oil, such as dilution with cheaper oils, addition of dyes/chemicals, and mixing with used cooking oil, pose serious health threats and economic risks. Conventional chemical tests, such as fatty acid composition, have limitations in detecting these adulterations. Therefore, newer approaches such as metabolomics in combination with chemometric tools shall offer a comprehensive method to identify fraudulent additions in cooking oil (Sulaiman et al., 2025).

Similarly, in order to address the possible negative impacts on oil quality and investigate strategies to reduce the production of pollutants across the supply chain, it is crucial to study the processing of underripe and overripe fruit. A study by Ramli et al. (2025) reported that the ripeness of FFB affects both chemical contaminants, such as 3-monochloropropane-1, 2-diol esters (3-MCPDE) and refined oil colour stability, making proper harvesting and processing crucial for ensuring high-quality and safe palm oil. FFB are classified as unripe, underripe, ripe or overripe, with optimal ripeness at 20–22 weeks after anthesis. Processing of under-ripe fruits leads to low oil content, resulting in lower OER, inferior CPO quality, and low kernel extraction rate (KER). Meanwhile, ripe fruits yield CPO with lower chlorophyll, higher deterioration of bleachability index (DOBI), and higher carotene contents, which are the indications of high-quality CPO. Therefore, in order to preserve the quality of CPO, the authors recommend that underripe fruit processing should be avoided.

## Nutrition and Health

Palm oil is used globally as cooking oil, including in baked and processed food, cosmetics, as well as biofuels. However, the nutritional aspects of the oil are commonly debated. However several reviews and meta-analyses conducted in recent years have systematically analysed the literature and shown positive nutritional benefits of incorporating palm oil in diet (Judijanto, 2025a; Parveez et al., 2025; Voon et al., 2024).

A recent systematic review reported the outcomes from 22 papers published from 2020 to 2025 aimed to discuss the nutritional attributes of palm oil and the contribution of the palm bioactives in achieving beneficial outcomes (Judijanto, 2025a). The strategic predomination of palmitic acid at the *sn*-1 and *sn*-3 positions of the glycerol molecules selectively reduces the atherogenic effect of the palm oil. In addition to the saturated fatty acids, the unsaturated fatty acids composition in palm oil also contributes to cardiovascular neutrality reported in several clinical studies. Palm oil is concluded as a nutritionally rich oil if it is consumed in minimally processed conditions within the recommended dietary guidelines.

Additionally, a pilot randomised crossover study in 10 healthy young men compared the postprandial effects of high-fat meals rich in palmitic acid from palm olein and lard with virgin olive oil (Nagapan & Teng, 2025). After consuming 50 g of each test fat, blood samples were collected

over 4 hr to assess endothelial dysfunction biomarkers. All three fats led to significant reductions in plasminogen activator inhibitor-1 (PAI-1) and soluble CD40 ligand (sCD40L), with no notable effects on other pro-inflammatory markers (monocyte chemoattractant protein-1 [MCP-1], E-selectin, soluble vascular cell adhesion molecule-1 [sVCAM-1]). Overall, palmitic-acid-rich diets showed minimal impact on endothelial dysfunction biomarkers postprandially, indicating the need for larger studies to confirm these findings. The authors reported that the findings may not be applicable to females due to different physiological make-up between the genders that may affect metabolic processes, while also acknowledging the sample size was relatively small to observe a significant outcome (Nagapan & Teng, 2025).

Red palm olein (RPO) is recognised as the most prolific natural botanical source of carotenoids, predominantly comprising almost equal amounts of alpha-carotene and beta-carotene. Since the 1930s, RPO has garnered scholarly interest as a therapeutic agent for xerophthalmia, and its supplementation has been studied as a preventive strategy for xerophthalmia among vitamin A-deficient (VAD) primary schoolchildren, with several trials indicating significant benefits. A recent randomised controlled trial in Malaysia found that a 6-month supplementation with RPO-enriched biscuits led to a significantly higher prevention rate of xerophthalmia and conjunctival xerosis compared to the control group. Although the findings were not significant for an improved resolution rate of xerophthalmia between the two groups, it was reported that children receiving RPO were about five times less likely to develop xerophthalmia as compared to the control group (Tan et al., 2025a). In addition, another intriguing result published by the investigators showed a positive correlation between alpha-carotene, beta-carotene, alpha-tocopherol, and haematological outcomes in children receiving RPO-enriched biscuits and significant reductions in alpha diversity indices and increased abundance of potentially beneficial gut bacteria (Tan et al., 2025b). RPO supplementation is a promising, food-based preventive solution for xerophthalmia and VAD in at-risk children, with additional benefits for iron status and inflammation. Incorporation of RPO into the nutritional programs may help to address these health issues in vulnerable populations.

Fuelled by interesting outcomes from pre-clinical studies of tocotrienols, an intervention study with tocotrienol-rich fraction (TRF) was conducted in patients with rheumatoid arthritis (RA), an autoimmune disease predominantly caused by inflammation, by Z. Zainal et al. (2025). Following a 6-month of supplementation

with 400 mg of TRF day<sup>-1</sup> with the conventional disease-modifying anti-rheumatic drugs (cDMARDs), a significant drop in the Disease Activity Score-28 (DAS28), a standard measure of RA activity was reported. Patients also experienced less knee pain, improved physical function, reduced joint stiffness, swelling (edema), and discomfort. Therefore, TRF was found to be a well-tolerated adjunct that can effectively lower RA disease activity and improve patients' quality of life. Meanwhile, two preceding papers were also published on the anti-tumour potentials of tocotrienols in pre-clinical models. A study by Hafid et al. (2025) shows that combining TRF from palm oil with dendritic cell (DC) vaccines significantly improves anti-tumour immune responses and tumour control in mouse models of breast cancer. TRF acts as an adjuvant, boosting the effectiveness of DC-based cancer vaccines. Meanwhile, in acute myeloid leukaemia (AML) cell lines, the combination of TRF and cytarabine, a leukaemic drug, inhibited cell growth with a profound elevation of caspase activities, indicating the pro-apoptotic activities of the treatment (Iran et al., 2025).

Oil palm phenolics (OPP), obtained from the by-products of oil palm fruit processing, are a source of bioactive polyphenols with valuable nutraceutical properties. Numerous studies have demonstrated the physiological properties of this water-soluble bioactive. In line with this, based on a phase one clinical trial, the supplementation of encapsulated OPP in healthy individuals remarkably lowered blood pressure after 60 days and improved total antioxidant capacity following 30 days of supplementation. The authors recommended that the findings from this phase one trial serve as a strong foundation for longer intervention studies in the population with a clinical condition (Fairus et al., 2025).

### Food and Feed Studies

A robust quantification method for identifying the major phenolic acids was recently developed and published using ultra-high-performance liquid chromatography with ultraviolet/photodiode array detection (UPLC-UV/PDA). The method showed excellent specificity, linearity, accuracy, precision, and robustness. When applied to water-soluble palm fruit extract (WSPFE) samples from Malaysian and Mexican facilities, the quantified phenolic contents were comparable and aligned with results from Folin-Ciocalteu and 2,2-diphenyl-1-picrylhydrazyl (DPPH) antioxidant assays. Overall, the validated method provides a reliable tool for consistent quality control of WSPFE in supplement and functional food industries (Leow et al., 2025).

Growing concerns on food sustainability, animal welfare, and the increasing global population shifted attention towards plant-based meat analogues (PBMA), with palm oil emerging as a noteworthy potential. Approximately 6% of saturated fat was required to achieve realistic texture and palatability in PBMA. Incorporation of palm oil in PBMA has indeed shown promising outcomes in achieving the taste while having lesser saturated fats, unlike meat products (Wazir et al., 2025). Apart from this, the usage of RPO was further explored in RPO-based candies, which are easy to consume and to cater to the health-conscious consumer population. The formulation was optimised using RPO powder, erythritol as the sweetener, and gum arabic as the binding agent (Tang et al., 2025). The resulting candies were found to achieve the desired quality with moderate hardness and reduced friability.

In recent times, there has been an increased interest in organogelation techniques using vegetable oils. Despite showing increased hardness, the palm-based monoacylglycerol oleogels showed a complicated pattern of crystalline and amorphous behaviour with big crystals and voids, which led to reduced stability. This information improves our comprehension of superolein oleogel behaviour, which is crucial for their use in a variety of sectors (Saw et al., 2024).

Apart from this, in the broiler feed industry, agricultural by-products present an affordable way to lessen dependency on traditional feed grains. The effect of newly developed feed formulation incorporated with CPO and palm kernel meal in comparison with commercial feed in mixed gender Ross 308 broiler chicks fed for 35 days was evaluated (Wan Mohamed et al., 2025). The broilers fed with newly formulated feed had higher weight gain despite lower intake of feed as compared to the broilers fed with conventional feed. The higher feed conversion ratio was another promising output from this study, with the authors recommending partial substitution of imported feed ingredients with CPO and PKO to achieve comparable meat quality. Similarly, another feeding intervention was carried out in beef cattle in Malaysia. This study compared an oil palm by-product (OPB) feed pellet with a commercial pellet in 42 beef cattle over 90 days. Both pellets had similar protein and energy content. Cattle fed with OPB pellets showed comparable growth to those on the commercial pellet, although the OPB group had a slightly higher average daily gain and a marginally better feed conversion ratio (9.59 vs. 9.98). Meat from OPB-fed cattle also had significantly higher redness and yellowness, suggesting better visual quality. Overall, the OPB feed pellet provided complete nutrition and performed on par with commercial pellets in supporting cattle growth (Ibrahim et al., 2025).

## Oleochemical Innovations in Non-Food Products

In 2025, the Malaysian oleochemical industry is categorised by steady growth, strong global demand, and a strategic focus on sustainability and value-added products. The key trends include a rise in eco-conscious consumption that drives demand for natural products. Oleochemical innovations focused on developing sustainable alternatives and green technologies over petrochemical products. The key innovations include the use of oleochemicals derived from CPO and CPKO into bio-based non-food products such as bio-lubricants, specialty chemicals, surfactants, and agrochemicals, to meet the rising demand for eco-friendly solutions.

One of the highlighted innovations is the development of bio-lubricants derived from palm-based oleochemicals. A high-performance estolide ester (2-ethylhexyl ester of lauric acid-esterified estolide [2EHLaPE]), a lubricant base oil produced from PFAD and oleic acid (OA), was developed, with its lubricating properties comparable to those of commercial bio-lubricants (Hoong et al., 2025). During the reaction, peracetic acid was generated *in situ* through the reaction between hydrogen peroxide and acetic acid. This peracetic acid subsequently reacted with the alkene groups in the PFAD-OA mixtures, converting them into epoxide groups. The newly formed epoxide groups were then ring-opened by the carboxylic acid groups of the fatty acids, resulting in the formation of the desired estolide products. A higher proportion of OA in the PFAD-OA blend used as the starting material increased the kinematic viscosity, and the incorporation of OA also improved the cold flow properties of the 2EHLaPE. This innovation has emerged as a promising alternative to mineral-based lubricants due to its non-toxic nature and high biodegradability. Optimisation of the types and compositions of base stocks and additives was involved in the development of lubricant formulation. Tribology additives are one of the crucial elements in ensuring optimum lubrication performance, and investigating the tribological behaviours of these additives is essential.

A comprehensive thermodynamic modelling approach was used to determine the optimal lubrication and synergistic additives combination, even when the evaluated lubricants exhibited comparable outcomes in tribological assessments (Chan et al., 2026). The model employs a dissipative coefficient of the lubrication as a reliable assessment parameter, providing insights into the lubrication ability to minimise wear and sustain tribological operations effectively.

Drilling fluid used in the oil and gas industry acts as a lubricant, reducing friction and heat between the drill bit, drill string, and borehole wall. A newly developed ester blend, combining

2-ethylhexyl palm fatty acid distillate (2EH-PFAD) and commercial esters that meets the requirements for drilling fluid base oils and is formulated into an ester-blended drilling fluid (EBDF) (Pauzi et al., 2025). PFAD, used in the EBDF, is a cost-effective and sustainable resource. The developed EBDF demonstrated enhanced rheological properties, reduced fluid loss, and excellent electrical stability.

The R&D innovations for oleochemical derivatives also extended to the development of environmentally friendly, cost-effective, and high-performance bio-based corrosion inhibitors. Mohd et al. (2025) had synthesised imine-based compounds from palm-based fatty hydrazide and evaluated the inhibition efficiency of different alkyl chain lengths of the imine-based organic inhibitors on carbon steel in hydrochloric acid solution. Performance test results revealed that these compounds significantly reduced corrosion, with the highest inhibition effectiveness observed at C12 chain length. The alkyl chain length affects solubility in the acid solution, whereby longer chain length prevents further improvements in inhibition efficiency. The study also reported steric hindrance associated with longer alkyl chains, which may reduce the accessibility of polar head groups to the steel surface, thereby lowering inhibitor performance.

The demand for renewable and sustainable chemical innovations extends to insecticide formulations. A new water-based insecticide formulation, comprising solvents and surfactants derived from palm-based materials, with deltamethrin as the active ingredient, was developed to control dengue outbreaks and minimise the environmental impact of vector control (Mohsin et al., 2025). The formulation is naphtha-free and uses palm oil as feedstock, resulting in a cost-effective product. It offers comparable efficacy to the commercial naphtha-based formulation. Field trials using both cold and thermal fogging methods showed no significant differences in droplet size between the two formulations, although cold fogging generally performed better in terms of knockdown and mortality rates. This innovation highlights the potential of biodegradable palm-based ingredients, particularly palm methyl ester solvent and palm-based surfactants, leveraging the locally abundant renewable raw material, palm oil.

Innovations in analytical methods are also important for safeguarding the quality of oleochemical products. A method for detecting and quantifying unreacted dimethyl sulphate (DMS) in fabric softeners containing vegetable and tallow-based esterquats has been developed (Ping & Aziz, 2025). Active ingredients in fabric softener formulations, such as esterquats, have been widely used to replace the conventional

distearyldimethylammonium chloride (DSDMAC) due to biodegradability concerns. However, higher incorporation of these active compounds increases the risk of residual DMS. Given its toxicological concerns and classification as a potential human carcinogen, detecting DMS in fabric softeners, even at trace levels, is crucial. The simple direct injection method followed by gas chromatography-mass spectrometry (GC-MS) with selected ion monitoring analysis was validated according to International Council for Harmonisation (ICH) guidelines and demonstrated good selectivity, sensitivity, repeatability, inter-day precision, and accuracy. This analytical monitoring can serve as an effective quality control tool for quantifying unreacted DMS that may be present in fabric softeners.

Environmental sustainability and safety are the key factors to the development and application of palm-based oleochemicals. The lifespan of the developed bio-based products must adhere to the stringent ecological and health standards. To address this concern, studies have also focused on evaluating the potential risks posed by environmental contaminants to human and aquatic organism health, providing critical data to guide sustainable production practices and ensure consumer safety. The effects of plasticisers and additives in plastics on oysters were evaluated to assess their impact on marine ecosystems and the safety of seafood harvested from contaminated waters (Ishak et al., 2025). The widespread use of plasticisers, prevalent chemical contaminants that leach from plastics into aquatic ecosystems, poses potential risks to human and aquatic organism health. Both phthalate and non-phthalate-based plasticisers, including epoxidised methyl oleate (EMO), derived from palm-based sources, were evaluated, and the palm-based plasticiser was found to be less toxic than conventional petroleum-based phthalate plasticisers, making them a safer and more environmentally friendly alternative.

## CONCLUSION

In summary, the Malaysian oil palm sector in 2025 showed signs of recovery and adaptation, although many of these gains remain conditional and uneven. The most strategically important R&D priorities are those that can improve yield recovery after replanting, reduce labour dependence, strengthen sustainability verification, and increase downstream value capture. Future progress will depend not only on scientific advances but also on effective technology deployment, smallholder inclusion, and market acceptance. The oil palm industry remains a vital pillar of socioeconomic

development, contributing positively to the growth of the Malaysian economy. Although the global commodity market continues to be affected by volatility arising from ongoing geopolitical tensions, fiscal uncertainties, and policy challenges, the oil palm industry has demonstrated resilience, as reflected in its strong performance in 2025. Continued demand from key markets, including domestic consumption, together with favourable prices, has supported the industry's competitiveness. The oil palm industry continues to progress, driven by the transition towards a low-carbon and circular economy. Robust R&D progress and achievement are being further strengthened and accelerated by the technological advancements, ensuring that the industry remains sustainable, resilient, and competitive within the global vegetable oils industry.

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