

OIL PALM ECONOMIC PERFORMANCE IN MALAYSIA AND R&D PROGRESS IN 2021

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ABSTRACT

The palm oil industry fared better in 2021 compared to 2020, despite lower crude palm oil (CPO) production due to labour shortage and a restricted supply of CPO during the COVID-19 pandemic. As the industry recovers, research and development (R&D) activities remain dedicated towards ensuring the industry is sustainable and competitive. In the upstream sector, efforts continue to be focused in increasing the CPO yield per hectare through precision agriculture, advanced genomic technologies and improved breeding programmes, control of pest and diseases, as well as farm mechanisation. In the midstream sector, there were some improvements in mill productivity, that reduce the environmental impact of the milling operations. Intensification of R&D related to palm-based biomass has the potential to contribute to higher income for the industry. In the downstream sector, food safety and the nutrition-rich value of palm oil offer the best quality for this versatile and productive oil crop, to the world. Additionally, non-food products such as biofuels, biopolymers and bio-lubricants are also gaining research traction due to global movement towards a circular economy and sustainability.

Keywords: bioenergy, biomass, food safety and nutrition, oleochemicals, sustainability.

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INTRODUCTION

Oil palm is the most productive vegetable oil crop in the world, with a potential yield of 4 to 5 t of CPO ha⁻¹ yr⁻¹ (Hashim *et al.*, 2010). Being the most efficient oil crop, palm oil production from major producing countries constituted about 31.6% (76.39 million tonnes) of global total oil and fats production (241.36 million tonnes) for 2021 (Oil World, 2021). This massive oil production comes from a meagre 6% of global agricultural land devoted to oil crops (Our World in Data, 2021), which further strengthens palm oil's sustainability in terms of land usage.

On the domestic front, Malaysia produced about 18 million tonnes of CPO in 2021, which accounted for about 8.5% of the global oils and fats

production. The export of palm oil and oil palm products generated RM108.52 billion in revenue for Malaysia in 2021 (MPOB, 2022a). It is noteworthy that palm oil is one of the major contributors to the nation's export revenue, aside from electrical and electronic products as well as petroleum products (MATRADE, 2022). Furthermore, the Malaysian palm oil industry provides more than half a million employees and supports the livelihood of an estimated one million people (MPIC, 2018). Thus, the palm oil industry is vital for the economy and well-being of the country.

The year 2021 was indeed challenging for the palm oil industry, as the country was recovering from the economic downturn caused by the COVID-19 pandemic. However, the emergence of new COVID-19 variants has somewhat decelerated the progress of national economic recovery, as priority was placed on the nationwide vaccination programme. The situation was further exacerbated by the closure of international borders and the departure of foreign labour resulting in an acute

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shortage of workers in oil palm plantations. This led to an acute harvesting problem of oil palm fruits, which triggered its restricted supply in the market. Consequently, the prices of CPO have reached historical highs that subsequently contributed to higher export revenue for the industry. Nonetheless, the labour shortage offsets the gain in export revenue as the Malaysian palm oil industry lost billions of ringgits due to unharvested ripe fresh fruit bunches.

Ideally, the high price of CPO should be driven by strong demand for palm oil and oil palm products, together with high CPO production and high sales volume. Such a situation can only be realised via continuous R&D efforts across the palm oil supply chain covering upstream, midstream and downstream sectors, in tandem with the implementation of appropriate policies that make palm oil sustainable, safe and competitive. As such, R&D goals must be geared towards improving oil palm yield per hectare through precision agriculture, adoption of advanced biotechnology and breeding approaches to produce high yielding planting materials. These planting materials are tailored to be resistant to pests and diseases, resilient to climate change and facilitate farm mechanisation operations to overcome productivity issues caused by harvester shortages. Moreover, about 94.4% of the oil palm planted area has been Malaysian Sustainable Palm Oil (MSPO) certified, since the inception of the certification scheme in 2017. The MSPO certification complements the existing international certifications and ensures Malaysia meets the stringent market demands for sustainable palm oil.

The food safety and nutritional aspects of palm oil remain important and relevant to ensure its highest standard and quality for global food consumption. Additionally, R&D efforts enhance the circular economy of the industry through the utilisation of oil palm biomass and by-products as feedstock for various industrial applications. On top of that, enhancing the utilisation of palm oil mill effluent (POME) for biogas power generation is also desirable to boost the sustainability and environmental friendliness of the palm oil industry.

Moving forward, new palm oil usage in the food and non-food sectors is crucial to expand the market share and create new market segments in the global oils and fats economy, to maintain a healthy profit margin for the industry. Some examples of new and innovative applications are those associated with palm phytonutrients, cocoa butter alternative, bio-jet fuel, bio-polyol and polyurethane, bio-lubricants and personal care products.

This article provides valuable insights on the performance of the Malaysian palm oil industry in

2021 and reviews significant research advancements and innovative solutions across the whole supply chain of the palm oil industry. It also attempts to deliberate on strategies and future directions that the industry could embark on, to further enhance its competitiveness towards achieving a sustainable palm oil industry.

PERFORMANCE OF MALAYSIAN PALM OIL INDUSTRY

The year 2021 was deemed challenging as the COVID-19 pandemic continues to be threatening and hampering economic recovery efforts. Although 2021 was set for economic revival, the emergence of new variants of COVID-19 had somewhat decelerated the efforts. The economic activities were operated under great uncertainty and heavy pressure. In Malaysia, apart from rolling-out the vaccination programme, stringent border controls as well as strictly localised lockdowns were the critical strategies to contain the spread of the virus. These strategies, however, also affected the plantation sectors which rely heavily on foreign workers. The closures of international borders and the prolonged suspension of foreign worker intake affected oil palm harvesting activities and consequently have taken a toll on palm oil production. The significant decline in production has resulted in a much-reduced stockpile, hence limiting the capacity of Malaysia to export and ultimately pushing the price of the CPO to an all-time high, peaking several times in 2021.

Planted Area

The containment measures implemented to curb the spread of the COVID-19 pandemic had affected palm oil production in Malaysia. The series of local lockdowns had also slowed down replanting activities in oil palm plantations. In 2021, the total oil palm planted area had reduced by 2.2% to 5.74 million hectares from 5.87 million hectares recorded in 2020. At the regional level, planted area in Peninsular Malaysia and Sabah had declined by 4.7% and 1.3% against that of the previous year to 2.61 million hectares and 1.52 million hectares, respectively. Meanwhile in Sarawak, the oil palm planted area had increased by 1.4% to 1.61 million hectares (*Table 1*).

A similar trend was observed for the oil palm matured area. In totality, the oil palm matured area accounted for 5.14 million hectares or 89.7% of the total oil palm planted area, which was 1.7% lower than that of the previous year. The total matured area in Peninsular Malaysia was 2.36 million hectares, followed by Sarawak at 1.45 million hectares and Sabah at 1.33 million hectares. In terms

of ownership, 73.2% of the planted area was owned by private and government/state agency estates, 15.1% by the independent smallholders and 11.7% by the organised smallholders (*Figure 1*).

Status of Mills and Plants

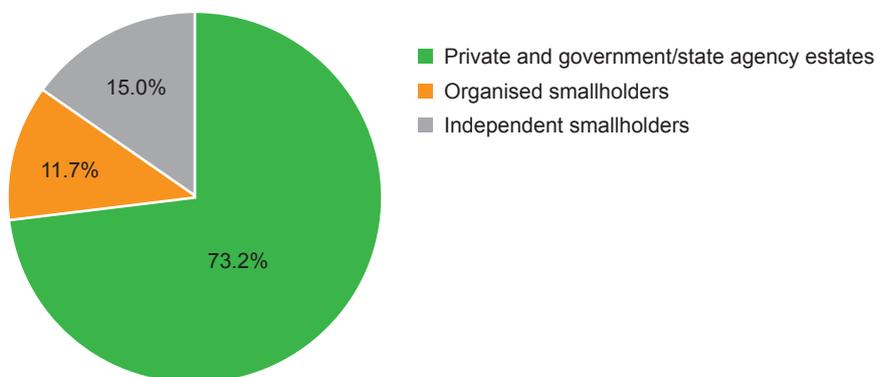
A total of 451 palm oil mills in Malaysia was in operation in 2021, with a combined annual processing capacity of 115.87 million tonnes of fresh fruit bunch (FFB), of which 52.50% of palm oil mills are located in Peninsular Malaysia with a total processing capacity of 57.50 million tonnes. The year 2021 had witnessed a decline in milling capacity utilisation rate by 5.70% to 77.56%, when compared to 82.26% recorded in the previous year, due to the lower FFB processed by palm oil mills (MPOB, 2022a). In the refining sector, a total of 49 palm oil refineries are in operation, with a total processing capacity of 25.76 million tonnes of CPO and crude palm kernel oil (CPKO). There are currently 33 refineries located in Peninsular Malaysia, with a total processing capacity of 14.28 million tonnes. The refining capacity utilisation rate for 2021 had reduced by 13.90% to 56.85% from 66.02% in the previous year, mainly due to the combination of lower CPO and CPKO processed, lower CPO production and higher CPO export (MPOB, 2022a).

Meanwhile, 43 palm kernel crushers were in operation with a total processing capacity of 7.42 million tonnes of palm kernel. There are 26 palm kernel crushers (60.5%) located in Peninsular Malaysia, with a total processing capacity of 4.59 million tonnes. The palm kernel crushing capacity utilisation rate had declined by 2.70% to 62.74% from 64.48% in 2020 due to a reduction in processed palm kernel and a lower supply of palm kernel, which arose from lower FFB production (MPOB, 2022a). A total of 19 oleochemical plants are in operation, with processing capacities of 2.67 million tonnes. These oleochemical plants processed a total of 2.25 million tonnes of palm oil products, which had declined by 9.7% when compared to 2020. The capacity utilisation rate of the oleochemical sector had also declined from 94.6% in 2020 to 84.1% in 2021, due to the lower volume of palm oil and palm kernel oil (PKO) processed (MPOB, 2022b). For biodiesel, there are currently 18 biodiesel plants in operation, with production capacities of 2.33 million tonnes. In terms of output, the total production of biodiesel was estimated at 0.92 million tonnes, an increase of 1.1% from 0.91 million tonnes in 2020 (Oil World, 2022). These oleochemical and biodiesel plants are mainly located in Selangor and Johor with eight and seven oleochemical plants, respectively, and six biodiesel plants in Selangor and Johor, respectively.

TABLE 1. MALAYSIAN OIL PALM AREA AS IN DECEMBER (ha)

	Planted area			Matured area		
	2021	2020	Difference (%)	2021	2020	Difference (%)
Peninsular Malaysia	2 607 847	2 737 723	(4.7)	2 363 870	2 455 535	(3.7)
Sabah	1 523 624	1 543 054	(1.3)	1 331 981	1 344 608	(0.9)
Sarawak	1 606 261	1 584 520	1.4	1 448 329	1 431 600	1.2
Malaysia	5 737 731	5 865 297	(2.2)	5 144 180	5 231 743	(1.7)

Source: MPOB (2022a).



Source: MPOB (2022a).

Figure 1. Oil palm planted area by category in 2021.

CPO Production

The average FFB yield for Malaysian oil palm estates in 2021 had declined to 15.47 t ha⁻¹, which was 7.5% lower compared to that of the previous year. The highest decline was recorded in Peninsular Malaysia, followed by Sarawak and Sabah, with a year-on-year percentage declines of 8.60%, 7.00% and 6.40% each (Table 2). Despite the decline in FFB yield, the oil extraction rate (OER) for CPO had increased slightly by 0.50% and increased year-on-year to 20.01% from 19.92% in 2020. However, the slight increase in the OER was still unable to offset the decline in the average FFB yield of Malaysian estates, hence had brought CPO production much lower than that in 2020.

CPO production had dropped by 5.4% year-on-year to 18.12 million tonnes, the lowest level since the occurrence of the *El-Nino* event in 2016. This decline was mainly attributable to the disruption in labour supply in oil palm plantations, arising from the freeze on foreign workers due to COVID-19 containment measures. The number of foreign workers that were employed in the oil palm plantation sector had reduced consecutively in 2020 and 2021 by 2.3% and 8.7%, respectively (MPOB, 2019; MPOB, 2020; MPOB, 2021). Zooming

into the regional performance, the CPO production in Peninsular Malaysia, Sabah and Sarawak were at 9.85 million tonnes, 4.36 million tonnes and 3.91 million tonnes, respectively (Table 3).

Palm Oil Exports and Imports

To support the increasing demand for the domestic processing sector, Malaysia imported 1.50 million tonnes of palm oil and other palm-based products (POPP) in 2021, 16.7% higher than that in 2020 (Table 4). The import of palm oil accounted for 78.3% of the total POPP imports with a volume of 1.18 million tonnes. This was 24.3% higher than that recorded in 2020. Almost all palm oil imports in Malaysia were sourced from Indonesia, wherein the amount was 1.14 t or 96.6% of total palm oil imports.

Regarding exports, the lower production of CPO in 2021 had limited the capacity of Malaysia to supply palm oil to the global market. The total export of POPP was estimated at 25.44 million tonnes, 4.4% lower than the previous year. The decline in the exports of POPP was mainly attributed to the drop in exports of palm oil, PKO and palm kernel cake by 8.5%, 0.7% and 11.1%, respectively (Table 5).

TABLE 2. AVERAGE FFB YIELD FOR MALAYSIAN OIL PALM ESTATES (t ha⁻¹)

	2021	2020	Difference	
			Volume	%
Peninsular Malaysia	16.24	17.76	-1.52	-8.6
Sabah	15.77	16.84	-1.07	-6.4
Sarawak	13.94	14.99	-1.05	-7.0
Malaysia	15.47	16.73	-1.26	-7.5

Source: MPOB (2022a).

TABLE 3. MALAYSIAN CRUDE PALM OIL (CPO) PRODUCTION (t)

	2021	2020	Difference	
			Volume	%
Peninsular Malaysia	9 847 022	10 438 899	(591 877)	(5.7)
Sabah	4 362 698	4 647 375	(284 677)	(6.1)
Sarawak	3 907 820	4 054 339	(146 519)	(3.6)
Malaysia	18 117 540	19 140 613	(1 023 073)	(5.3)

Source: MPOB (2022a).

TABLE 4. MALAYSIAN IMPORTS OF PALM OIL AND OIL PALM PRODUCTS (t)

	2021	2020	Difference	
			Volume	%
Palm oil	1 177 251	946 917	230 335	24.3
Palm kernel oil	273 691	281 514	(7 823)	(2.8)
Palm kernel	52 889	59 854	(6 965)	(11.6)
Total	1 503 831	1 288 285	(215 546)	16.7

Source: MPOB (2022a).

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

	Volume (t)			Value (RM million)		
	2021	2020	Difference (%)	2021	2020	Difference (%)
Palm oil	14 835 115	16 214 373	-8.5	64 615	45 647	41.6
Palm kernel oil	1 131 771	1 140 204	-0.7	6 668	4 152	60.6
Palm kernel cake	2 248 391	2 529 444	-11.1	1 394	1 295	7.7
Palm-based oleochemicals	4 760 115	4 423 971	7.6	26 803	16 501	62.4
Other palm-based products	2 466 031	2 302 922	7.1	9 035	5 738	57.5
Total	25 441 423	26 610 914	-4.4	108 516	73 332	48.0

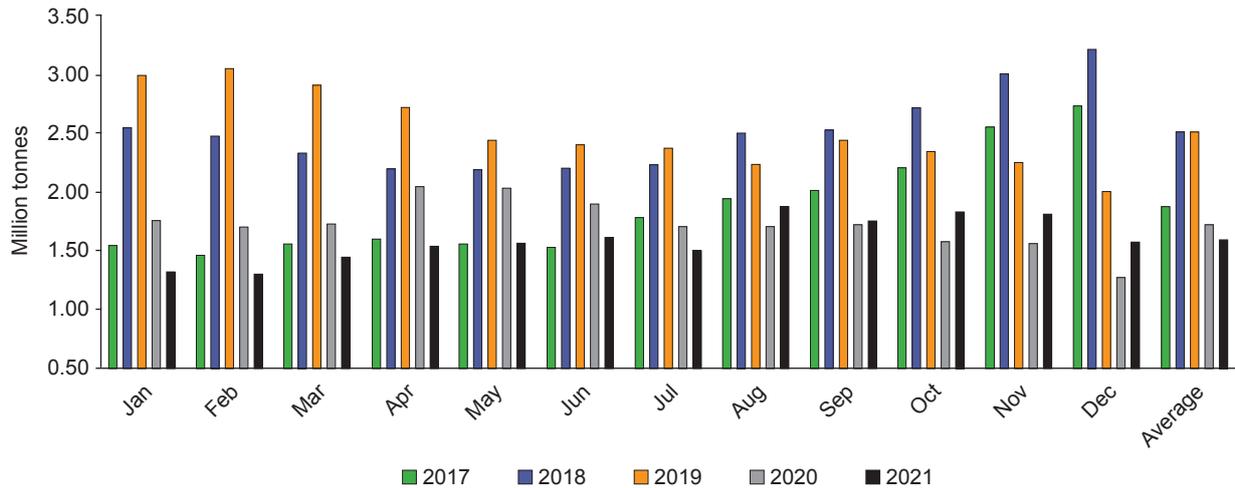


Figure 2. Palm oil monthly closing stocks and the average stocks level for each year.

Palm oil accounted for 64.1% of the total exports of POPP. The decline in palm oil exports was due to the weaker demand from major importing countries such as China and the European Union (EU). Exports of palm oil to China have decreased by 31.4% year-on-year to 1.87 million tonnes. The shift in the sourcing countries for palm oil from Malaysia to Indonesia explained the significant decline in the exports of Malaysian palm oil to China. In addition, the higher soybean imports from the USA have also influenced the intake of Malaysian palm oil by China. Exports of Malaysian palm oil to the EU have decreased by 15.4% year-on-year to 1.64 million tonnes because it was replaced by higher imports of soybean from Brazil. Unlike China and the EU, palm oil exports to India have surged by 31.3% year-on-year to 3.60 million tonnes. This significant increase was due to low palm oil uptake from Indonesia in view of the higher CPO export tax imposed by Indonesia. The sharp increase in palm oil export to India has commanded India to be the largest palm oil export market for Malaysia.

Despite the low export volume, the total export revenue of POPP recorded by the Department of Statistics Malaysia had surged by 48.0% to RM108.52 billion due to higher export prices of palm oil and other oil palm products (MPOB, 2022). Export revenue of palm oil and PKO had surged

by 41.6% and 60.6% to RM64.62 billion and RM6.67 billion, respectively. A significant growth in export revenue was also recorded for other products such as palm kernel cake, palm-based oleochemicals and other palm-based products, with the year-on-year growth of 7.7%, 62.4% and 57.5%, respectively.

Closing Stock

The reduction in CPO production in 2021 had greatly affected the Malaysian palm oil industry. It not only had limited palm oil export capacity but also put significant pressure on the national stocks level. The monthly closing of palm oil stock hit below 1.50 million tonnes more than twice in 2021, which has never happened in the previous five years. This had brought the monthly average closing stocks of palm oil to 1.60 million tonnes, the lowest level since 2017 (Figure 2). The tight supply of palm oil stocks had pushed CPO price to a record high, breaking the RM5000 t⁻¹ level.

Price

The supply-push factor drives the prices of all major oil palm products to be traded higher in 2021 compared to 2020 (Table 6). The local CPO price grew by 64.1% year-on-year to RM4407.00 t⁻¹

against RM2685.50 t⁻¹ in 2020. The highest monthly price was recorded in November 2021 at RM5341.00 t⁻¹. Apart from the lower-than-expected decline in production, higher prices of soybean oil in the world market have also supported the increase in the CPO price. The movement in palm oil prices is influenced by the fluctuations in soybean oil prices as both oils are competing for a share in the global vegetable oils market. In addition, the firmer Brent crude oil prices during that year had made palm biodiesel more attractive, hence helping to support the rise in CPO price.

Along with the increase in CPO price, export prices of major processed palm oil products namely refined, bleached and deodorised (RBD) palm oil, RBD palm olein and RBD palm stearin had also surged by 70.0%, 67.5% and 64.2% to RM4748.50 t⁻¹, RM4764.50 t⁻¹ and RM4598.00 t⁻¹, respectively while palm fatty acid distillate (PFAD) price rose by 66.3% to RM4233.00 t⁻¹. In the lauric market, the price of palm kernel had increased by 81.0% to RM2773.00 t⁻¹ from RM1532.00 t⁻¹ in 2020. This was mainly due to the higher domestic price of CPKO, which was improved by 74.8% to RM5674.50 t⁻¹ compared to RM3247.00 t⁻¹ in 2020. The higher CPKO prices were in tandem with the increase in lauric oil prices namely, PKO and coconut oil. PKO prices in the global market increased by USD691.00 or 83.7% year-on-year to USD1517.00 t⁻¹ and the coconut oil price increased by USD603.00 or 59.5% year-on-year to USD1617.00 t⁻¹. Conforming to the CPO and palm kernel prices hike, FFB price at the mill gate had surged by 70.2% to RM955.00 t⁻¹ against RM561.00 t⁻¹ in 2020.

R&D FOCUS AREAS IN 2021

Precision Agriculture using Digital Technologies in Oil Palm Plantation

Since the first commercial oil palm estate was established in 1917, the palm oil industry in Malaysia has grown by leaps and bounds over the

years to meet the ever-increasing global demand for food and non-food products (RSPO, 2015). The palm oil industry has generated many opportunities and societal benefits for the rural communities and has become an important contributor to the economies of Malaysia and Indonesia.

As oil palm cultivation needs continuous improvement to meet increasing demand, calls for a sustainable supply system have intensified globally. To achieve a balance between economic growth and environmental sustainability, intervention policies should address the concerns of deforestation through the conversion of degraded secondary forests and replacing other non-economically viable agricultural crops with oil palm (Mohd-Azlan *et al.*, 2021). The potential values of forest fragments and wildlife-friendly practices in oil palm landscapes and their roles in conservation in Malaysia need to be carefully evaluated. Agroforestry options such as mixed-species tree planting and natural regeneration in oil palm plantations may help alleviate the negative effects of forest biodiversity loss and to safeguard ecosystem functions (Donfack *et al.*, 2021).

Many studies have been carried out to monitor changes in ecology and biodiversity throughout the oil palm development processes so that the effects of land conversion can be minimised and managed. In 2021, most biodiversity studies were done on tropical peatlands, specifically in Sarawak. Amit *et al.* (2021) concluded that bird species diversity, abundance and their feeding guild can be improved by letting ground layer vegetation grow naturally and maintaining the water quality of the drainage system in the early stage of oil palm development to attract birds which prefer this habitat. Ayob *et al.* (2021) recovered 227 bacterial isolates belonging to four major phyla (22 genera) from culture-dependent and -independent approaches in oil palms planted on tropical peatland.

Using the denaturing gradient gel electrophoresis method, Wong *et al.* (2021) reported that the soil fungal composition and diversity in oil palm plantations were significantly different

TABLE 6. MALAYSIAN PRICES OF OIL PALM PRODUCTS (RM t⁻¹)

	2021	2020	Difference	
			RM	%
CPO (local delivered)	4 407.00	2 685.50	1 721.50	64.1
RBD palm oil (FOB)	4 748.50	2 794.00	1 954.50	70.0
RBD palm olein (FOB)	4 764.50	2 844.00	1 920.50	67.5
RBD palm stearin (FOB)	4 598.00	2 801.00	1 797.00	64.2
PFAD (FOB)	4 233.00	2 546.00		66.3
Palm kernel (ex-mill)	2 773.00	1 532.00	1 241.00	81.0
CPKO (local delivered)	5 674.50	3 247.00	2 427.50	74.8
FFB (mill gate)	955.00	561.00	394.00	70.2

Note: FOB - Free on board.

Source: MPOB (2022a).

compared to undisturbed secondary forest and disturbed secondary forest at Sungai Asap, Sarawak. Uke *et al.* (2021) found an increase in the abundance of microorganisms involved in lignocellulose decomposition, due to unregulated disposal of oil palm trunk fibre into plantation areas. From 62 canopy ant species belonging to six subfamilies found in Central Borneo, Indonesia, Rizali *et al.* (2021) inferred that the occurrence of natural habitats helps shape similar ant community in oil palm plantations, possibly via inhibiting the abundance of invasive species.

Land use change from oil palm expansion has accelerated in the last few decades, inducing significant ecological, hydrological and atmospheric effects. In 2021, many studies provided information on the impacts of palm oil trade and its expansion on socio-economic and ecosystem (Ayompe *et al.*, 2021; Jaroenkietkajorn *et al.*, 2021; Krishna *et al.*, 2021), as well as a map of oil palm cultivated areas in Malaysia and Indonesia (Tapia *et al.*, 2021). The outcome of these studies could lead to the development of strategies to provide a sustainable oil palm plantations ecosystem and to meet Sustainable Development Goals such as ensuring healthy living and promoting well-being as well as responsible consumption and production.

Research addressing agronomic and environmental issues in oil palm plantations aimed at increasing crop yield and minimising environmental impacts were also reported. Norizan *et al.* (2021) estimated oil palm water demand by using the FAO-CROPWAT model to manage irrigation plans prior to the project implementation because such site-specific implementation is risky and costly. Two studies focused on the effects of water deficit on the physiological state of young oil palm (Filho *et al.*, 2021) and seedlings of two different genotypes of *Elaeis guineensis* and four interspecific (*E. oleifera* × *E. guineensis*) hybrids (Tezara *et al.*, 2021) were also conducted. Rudolf *et al.* (2021) concluded that empty fruit bunch (EFB) mulching increases the sustainability of oil palm smallholders, provided the supply constraints can be resolved.

In India, Behera *et al.* (2021) have established an efficient soil nutrient (K, Ca, Mg) management system through soil and leaf nutrients stoichiometry. Looking into soil health and sustainable production, Mahmud *et al.* (2021) have described the potential use of EFB biomass as biofertiliser and the roles of growth-promoting microbes for plant growth and development. Several studies have been reported on carbon dioxide emissions and the value of carbon stocks from different oil palm ecosystems, *i.e.*, the replanting phase (Kusumawati *et al.*, 2021), peat soils in Sarawak (Mos *et al.*, 2021) and in Sumatra (Rahman *et al.*, 2021). Proper interpretation

of data published is important for site specific management.

Similar to 2020, there were noticeably many research publications addressing issues on pests and diseases in oil palm cultivation. Siddiqui *et al.* (2021) have critically reviewed the progress made in Basal Stem Rot (BSR) development and management in oil palm and suggested that all control methods should be re-evaluated and improved to prevent, treat and ultimately control the threatening effects of BSR. The yield losses due to BSR disease was estimated using Bayesian Model Averaging, which indicated that the most important predictor was the planting preparation technique, followed by disease progression, disease severity, number of infected neighbouring palms, and two interaction effects (Kamu *et al.*, 2021). Fahrizal *et al.* (2021) explored the potential of *Syncephalastrum racemosum* and *Rhizopus arrhizus* isolated from oil palm trunks to produce chitosans known to inhibit the growth of *Ganoderma boninense*, the main causing factor of BSR. Studies were also conducted to investigate the effect of commonly used herbicides in oil palm plantations, as a predisposing factor to BSR disease development (Hussin *et al.*, 2021).

Besides *Ganoderma*, the bunch moth is also a recurrent problem in the oil palm plantations. Ming *et al.* (2021) have established the Economic Injury Level (EIL), the percentage of fertile oil palm fruitlets and oil to bunch index at different infestation severity of the bunch moth, *Tirathaba mundella* Walker on oil palm (Figure 3). Sulaiman *et al.* (2021a) have reported the utilisation of light-trapping with fluorescent bulbs, which resulted in a significantly higher capture of *Tirathaba mundella*. It was also argued that the bunch moth could have developed resistance over time, due to the frequent exposure to *Bacillus thuringiensis*-based insecticide in the field, as well as irregular applications of insecticide to contain the situation (Khai *et al.*, 2021). Apart from that, the noxious weed growing in oil palm plantations, *Eleusine indica* (goose grass), was also reported to have developed resistance to glyphosate (Purba *et al.*, 2021). Meanwhile, the population density of *Elaeidobius kamerunicus* was found to be affected by different soil types, *i.e.*, mineral and peat soils, and the availability of oil palm male inflorescences (Mohamad *et al.*, 2021).

In the last decade, artificial intelligence, predictive analytics, the Internet of Things and other technologies, have emerged as essential tools for modern agriculture. These technologies help to strengthen precision agriculture to overcome challenges in the industry, especially for decision making, based on field spatial and temporal variability. Due to the high cost involved in adopting these technologies, it is therefore important to arrive at the right item, in the right place and at the right time.

Accurate mapping of oil palm is important for understanding its past and future impact on the environment. Rodriguez *et al.* (2021) estimated oil palm areas via a new, active deep learning method using images from Sentinel-2 satellite. He reported that there are more than 1.2 billion oil palms planted in Indonesia, covering more than 15.0 million hectares, while in Malaysia, it is only more than 0.5 billion oil palms, covering more than 5.0 million hectares. Oil palm mapping was also used to illustrate the geographical pattern of oil palm development in different parts of a country to calculate the associated reduction in other types of land uses. In Guatemala, Hervas (2021) concluded that oil palm cultivation has compromised local food systems in many of the poor rural regions where households rely mostly on locally produced and/or self-provisioned food.

Reliable and accurate predictions in oil palm production can provide the basis for making decisions with regard to budgeting, storage, distribution, and marketing. Digitisation of data collection processes in the fields will reduce dependency on labour and hence reduce the production cost. Sensors, cameras, drones, and other devices help to gather real-time data, with devices that are on the ground continuously. Mohammad *et al.* (2021) managed to spatially visualise the

nitrogen (N) status of immature oil palm area with an autopilot tractor-mounted active light sensor, while Zheng *et al.* (2021a) observed oil palm growth using Unmanned Aerial Vehicle captured images.

Proper interpretation of yield maps for site-specific management can help to increase crop yield. For example, Martinez *et al.* (2021) evaluated yield variability using terrain algorithms on a digital elevation model, while Hilal *et al.* (2021) developed Artificial Neural Network and Non-linear Autoregressive Exogenous Neural Network models to predict FFB yields in Peninsular Malaysia. Suharjo *et al.* (2021) created a mobile application to classify the ripeness levels of FFB using a lightweight Convolutional Neural Network and Ahmad *et al.* (2021a) identified the spectral signature of the bagworm species of *Metisa plana* Walker initiated by using Visible/Near Infrared spectroscopy. Adoption of all geospatial technologies in oil palm plantations is critical to assist in the decision-making process and hence, leading to effective management.

While advancing through technological innovations, the more immediate solution currently implementable is mechanisation. Several studies are currently focusing on health issues of harvesters in oil palm plantations. In handling a harvesting tool for FFB, some level of musculoskeletal disorders could be detrimental to workers, in particular the



Source: Ming *et al.* (2021).

Figure 3. (a) Ripe oil palm fruit bunch with moderate oil palm bunch moth infestation. (b) Post-anthesis oil palm male inflorescence with moderate oil palm bunch moth infestation. (c) Ripe oil palm fruit bunch with a severe bunch moth infestation. (d) Post-anthesis oil palm male inflorescence with severe bunch moth infestation. (e) Oil palm fruit bunches with severe new infestation covered by reddish faeces. (f) Oil palm fruit bunches with severe old infestation covered by brownish-black faeces.

shoulders and trunk area, due to posture distortion and responses to muscle activity. During loading of FFB using spike, a force of 16.36 N would impart the left triceps of a worker (Mohamaddan *et al.*, 2021). Adjustments in the design of the tool, tasks undertaken and working shifts may help in addressing this issue. On the other hand, an upper limb-assisted exoskeleton prototype has been found able to reduce up to 30.0%-50.0% of selected muscle activities of an oil palm harvester while handling a harvesting pole (Harith *et al.*, 2021). Though encouraging, the design needs to be further optimised for better technology acceptance. In addition, a global positioning system-assisted mathematical model (Lim *et al.*, 2021a) has been utilised to optimise harvesting routes of farmers and transporters by reducing up to 26.3% travelled distances, hence leading to savings of time and resources devoted to different harvestable plantation sites.

Integrative Science Driving Future Sustainability

Lately, the palm oil industry has been demonised rampantly. Food and hygiene products are brazenly carrying labels such as 'Proudly Palm Oil Free' (Divinechocolate, 2022) and "Always Palm Free" (Siliskisoaps, 2022) respectively, despite Indonesia and Malaysia, the major producing countries, striving for recognition as certified sustainable palm oil producers. This action simply negates the grandeur efforts by the palm oil industry to ensure sustainable practices are deeply entrenched, regardless of whether the produce is sourced from big plantations or smallholdings. The key contentious issue surrounding the palm oil industry is its impact on the environment, in particular, deforestation and loss of biodiversity (Vijay *et al.*, 2016). Substitutes of palm oil, such as other vegetable oils, cannot replicate palm oil's versatility and productivity per land area while a synthetic replacement is still a work in progress (Parsons *et al.*, 2020). As such, research on oil palm continues to move forward with sustainability, conservation of biodiversity, and food security as the common themes.

Advanced biotechnologies offer remarkable potential in crop improvement for oil palm. In most cases, these tools are adapted from model systems that are further optimised for use in oil palm. Yeap *et al.* (2021) recently reported their success in establishing an efficient Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)/CRISPR-associated Protein 9 (Cas9) mutagenesis system for the oil palm. The key optimising step was in determining the most effective cleavage and delivery methods to ensure efficient gene editing. While the CRISPR/Cas9 system undergoes further improvements for use in oil palm, utilisation of

model species continues to be an essential tool for research advancement. The CRISPR/Cas9 method was employed to knock-out the OsFAD2-1 gene in rice as a model system. The intention is to subsequently repeat this highly effective approach in knocking out the fatty acid desaturase genes in oil palm, to produce higher oleic acid in palm oil (Bahariah *et al.*, 2021).

Another potential component, carotenoids, at higher concentrations, can substantially enhance the quality of palm oil. Wan Nur Syuhada *et al.* (2021) had molecularly characterised the *phytoene synthase (psy)* gene, responsible for the synthesis of carotenoid in oil palm. Another oil quality characteristic studied is vitamin E, of which Shahrul *et al.* (2021) observed a Single Nucleotide Polymorphism (SNP) conversion from TAAT to form the CAAT-box which could be the promoter activity enhancing factor leading to an increased total tocotrienol content. Apart from manipulating genes to improve the quality of the oil, research focus has also been on developing more robust and resilient oil palm planting materials that are tolerant to abiotic stress such as drought.

As oil palm is highly reliant on water availability, prolonged drought stress could result in severe yield loss (Rodrigues Neto *et al.*, 2021). It is known that metabolites are the direct representation of plant phenotypes, therefore, their signatures would provide biological and chemical fingerprints of the reactivity of oil palms toward external stimuli (Shulaev *et al.*, 2008). The high capacity in compound detection and identification as well as the availability of methods to link pathways have made metabolomics an ideal tool for such comparative study (Vargas *et al.*, 2016). Using a web-based tool known as the MetaboAnalyst 4.0, coupled with robust analysis algorithms, Rodrigues Neto *et al.* (2021) was able to identify five key metabolic pathways affected by drought stress: starch and sucrose metabolism; glyoxylate and dicarboxylate metabolism; alanine, aspartate and glutamate metabolism; arginine and proline metabolism; and glycine, serine and threonine metabolism. Ishak *et al.* (2021) provided a comprehensive comparative survey of statistical tools that can be utilised. Ultimately, the knowledge of the affected pathways could be developed into biotechnological applications in the development of climate resilient genotypes, especially when integrated with other omics approaches.

Zhou and Yarra (2022) opted for a more targeted approach in which *bZIP* transcription factors were identified from the oil palm using a genome-wide approach. This class of transcription factors is known to be important in regulating various developmental and biological processes aside from being involved in stress responses in plants. Through detailed characterisation of the *bZIP*

transcription factors obtained from public oil palm genome databases, the authors identified several tissue-specific *EgbZIPs* as well as 11 *EgbZIPs* to be highly expressed under abiotic stresses such as cold, salinity and drought. By applying the same concept, the group expanded their research into the role of the auxin response factor (ARF) gene family (Jin *et al.*, 2022). Similarly, in this case, they were able to confirm 19 *EgARF* is prominently involved when oil palm is subjected to abiotic stresses.

Research into developing both biotic and abiotic resilient planting materials has become more prominent in recent times, mainly driven by the threat of climate change. However, this strategy needs to be carried out in tandem with the enhancement of yields. A review by Babu *et al.* (2021) aptly touched on the importance of leveraging a combination of factors, from the extensive use of genetic resources to the employment of various breeding methods coupled with the use of advanced omics and bioinformatics tools. This holistic approach ensures that all bases are covered in addressing oil palm crop improvement. The oil palm germplasm is an invaluable asset which is currently maintained *ex-situ* as a living collection in the field (Rajanaidu *et al.*, 2017). This manner of conserving the genebank is necessary as the genetic materials are used for the evaluation of new and improved traits to select future breeding programmes.

However, this presents several challenges; the requirement of a large land mass, high maintenance cost, as well as their probable exposure to pests and diseases (Gan *et al.*, 2021). In tackling these issues, Gan *et al.* (2021) introduced the use of molecular markers to determine the genetic diversity of the Nigerian-based germplasm paired with a robust statistical analysis method to assemble them into a reduced core set of palms with minimum redundancies while preserving its diversity. This approach is deemed most sustainable in the long term, in handling germplasms and MPOB is following suit in this endeavour (Myint *et al.*, 2021).

Seyum *et al.* (2021) reiterated the importance of incorporating high-density molecular markers onto large mapping populations as well as exploring the latest genome mapping software *e.g.*, Lep-MAP3 as a means to accelerate oil palm breeding while enhancing its economic products. In line with this, Zolkafli *et al.* (2021) reported the use of 4451 SNP and more than 600 Simple Sequence Repeat (SSR) markers which led to the revelation of several common quantitative trait loci (QTLs) associated with yield components for two advanced breeding populations, namely the P2 (Deli *dura* x Yangambi *pisifera*) and KULIM DxP (Deli *dura* x AVROS *pisifera*). Further dissection of these regions provided clues on candidate genes impacting yield which can further be developed

into potential markers for oil palm genomic selection. Apart from focusing on the commercial hybrid populations, Tupaz-Vera *et al.* (2021), focused their efforts on improving the selection of the parental line, *dura*. Through progeny testing and meticulous phenotyping, they successfully selected elite dwarfed *dura* parents with high yields for their commercial cultivar development.

Nonetheless, the limited genetic diversity of existing *Elaeis guineensis* cultivars due to extensive breeding remains a contentious issue (Adon *et al.*, 2021). In broadening the genetic base, wild populations of both *E. guineensis* and *E. oleifera* are leveraged. Genotyped wild *E. oleifera* as reported by Ithnin *et al.* (2021) presents an opportunity for SNPs linked to key agronomic traits such as yield and fatty acid composition to be utilised in future breeding programmes via marker-assisted selection and genetic modification.

Using molecular tools, Sarimana *et al.* (2021) not only studied the genetic diversity of the hybrid (DxP) oil palm populations but extended the use of the molecular information in the form of DNA fingerprints of the individual palms to track their parental origins. This becomes important in the case of fraudulent seed trade (Cheyins and Rafflegeau, 2005). The assimilation of genome technology into the oil palm seed supply has been an ongoing process since the discovery of the *SHELL* gene assay (Figure 4) (Singh *et al.*, 2013) but became more critical when Ooi *et al.* (2016) established a non-*tenera* contamination rate of 10.9% in the supply chain. The issue at hand is not new as it has been highlighted by Parveez *et al.* (2020). One of the key reasons for the slow acceptance by the industry is the imminent increase in the cost of the planting materials. In view of this, Singh *et al.* (2021b) explored the potential of statistical seed testing in addition to the established method of leaf sampling at nurseries encompassing all the possible *SHELL* variants in commercial populations associated with the fruit form phenotype (Ooi *et al.*, 2016).

This bunch-by-bunch destructive sampling strategy enables the culling of contaminated bunches before they get into the supply chain. A quality control tool powered by genome technology is in line with the industry's aspiration towards a more extensive adoption of technology as well as underscores the sustainable efforts invested by the palm oil industry. In a follow up article by Singh *et al.* (2021a), the *SHELL* gene testing innovation has been instrumental in exposing the 10.9% non-*tenera* contamination amongst seedlings (Ooi *et al.*, 2016), a level which is twice the permissible rate of the Malaysian Standards MS157:2017 at 5.0%. The economic analysis further demonstrated an annual monetary gain of approximately RM2.6 billion yr⁻¹ could potentially be realised if 100.0% *tenera* were planted (Figure 4).

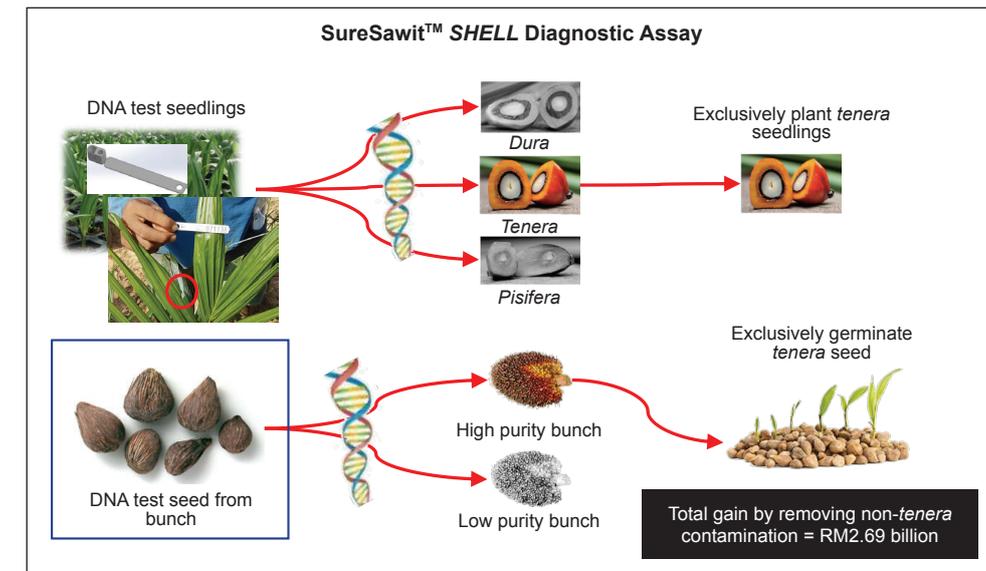


Figure 4. Authentication of tenera planting materials via SureSawit™ SHELL DNA testing of seedlings and seeds.

In knowledge building, the primary input or building block of a system is the data. Oil palm research as with other crops has benefited from the advent of technologies as well as the publicly available deluge of information to progress research. Method development and protocol optimisation may be mundane but are crucial for research to advance to the more exciting phase of discovery. Azimi *et al.* (2021) demonstrated the tediousness of organellar related research, especially in dealing with the mitochondria. Similarly, Nagappan *et al.* (2021) experimented with several protocols to finally confirm the Boehm method to be the best suited for *Ganoderma zonatum* DNA extraction. Following suit, Apriyanto and Tambunan (2021) reported and publicly deposited the first draft genome of the oil palm pollinating weevil, *Elaeidobius kamerunicus*, a valuable resource to study the weevil in-depth. It is envisioned that this would pave the way for more weevil related research in the near future.

Kok *et al.* (2021) in proteomics, Sarpan *et al.* (2021) in epigenetics and Nadzirah *et al.* (2022) in transcriptomics, have through their research facilitated the enrichment of valuable data into the oil palm knowledge database. Trending now is the emphasis on applying robust data analytics to interpret research data (Sarker, 2021). Ooi *et al.* (2021) identified a total of 171 genes deemed able to potentially discriminate highly embryogenic ortets, with an upregulation observed amongst genes related to flowering time. Despite these findings, the authors opined that for practical use of these leaf expression biomarkers as a predictive tool, the integration of machine learning techniques is needed to further improve the sensitivity of the model.

Sustainable Development for Smallholders

The MSPO certification scheme serves as one of the platforms to address the concerns over issues related to environmental, social and economic impacts of the palm oil industry in Malaysia. Incomplete information and technical errors during the application for MSPO certification, illiteracy rate and level of education of the smallholder, accessibility of the holding, and the lack of competent attending officers, are factors that have influenced the certification process during the MSPO pre-audit activities (Yap *et al.*, 2021c). The existing standards should be revised to expedite the MSPO certification process for independent smallholders (ISH) in Malaysia, and to support our commitment towards sustainability of the palm oil industry. The implementation of Good Agriculture Practice (GAP) is also considered as the baseline for the MSPO certification. Mansor *et al.* (2021) revealed that 58% of the ISH partially complied with GAP requirements. Whereas, only 26% of ISH fulfilled the requirements, and thus, were eligible for the GAP certification. Two factors that significantly influenced the GAP compliance among the ISH were the respondents' education level and the age of oil palm plantation. The results of this study indicated that fertiliser application and record-keeping adopted by the ISH had significantly affected their compliance level in MPOB GAP Certification.

For the recognition of MSPO in the international market, the MSPO standard was approved as a tool for sourcing code by the Tokyo 2020 Olympics and Paralympic Games Organising Committee in June 2018. The first shipment of MSPO certified palm

oil to Japan had taken place in September 2019. Furthermore, a memorandum of understanding was signed in 2019 between Malaysia Palm Oil Certification Council and China Green Food Development Centre to create acceptance of MSPO certified palm oil in China. Moreover, a collaboration between Malaysia with Solvent Extractors' Association of India resulted in the adoption of MSPO principle into Indian Palm Oil Sustainability Framework. Finally, the signing of a Letter of Intent in November 2019 had given the opportunity for Malaysia to work with The Netherlands on the National Initiative on Sustainable and Climate Smart Oil Palm Smallholder programme which support the implementation of MSPO certification scheme among independent smallholders in Malaysia (Rahimi, 2021).

An extension officer plays a key role in the dissemination of oil palm technologies to the ISH. The study done by Nur *et al.* (2021) revealed that ISH has a positive perception and attitude towards extension services, contributing to a high acceptance level of extension service activities by extension groups among ISH. Despite the positive results reported, improvements especially relating to the lowest mean score of perception and attitude towards the Q&A and discussion sessions as well as extension officers responses are much needed. It is also suggested that extension officers be encouraged to use a variety of new teaching methods to ensure active interactions between smallholders and extension officers. Furthermore, extension officers must improve their skills and knowledge in extension services by participating in various courses and programmes. The Sustainable Oil Palm Growers Cooperative (KPSM) in Malaysia is responsible to boost the income of ISH whilst creating job opportunities. However, it seemed that members' participation could be affected more by the good governance factor as demonstrated by the cooperative, rather than the role of the extension officer (Ainul *et al.*, 2021b).

Labour shortage has also impacted yields among the ISH, albeit at a smaller scale as compared to the plantations. According to Nazirah *et al.* (2021), the majority of oil palm ISH were not entirely reliant on foreign workers to carry out activities in their smallholdings. The study provide an insight which showed that ISH hired 21.8% of foreign workers for harvesting, 19.8% for weed control, and 16.8% for fertiliser application. These findings provided justification for the government to support and formulate relevant policies to meet the basic needs of the ISH. A survey by Ainul *et al.* (2021a) revealed six significant factors affecting FFB yields of the ISH in Sabah; the level of education, monthly household income, farm management status, weeding, pests and nutrient deficiencies and agricultural input costs. These findings are

important as they can be used as guidelines by the relevant parties to implement strategies to improve the FFB yield of ISH.

The main purpose of livestock or crop integration with oil palm is to diversify the source of ISH income through optimum utilisation of land and natural resources available in the oil palm planted areas. Sohimi *et al.* (2021) revealed that a total of 67.7% of respondents who participated in the Crop Integration Scheme implemented by MPOB from 2016 to 2017, chose to integrate banana with oil palm, followed by pineapple and papaya. They prefer to sell the produce, instead of for their consumption. Overall, the income derived from this scheme was estimated at RM200 to RM600 ha⁻¹ month⁻¹, depending on the types of crops. In another study, Shafirul *et al.* (2021) revealed that respondents who participated in the livestock integration scheme could end up earning additional income or *vice versa*. Respondents who failed to manage their livestock were faced with problems of high mortality rate and high operational costs. However, with good management practice, costs incurred in integration could be reduced and coupled with the sale of their livestock at market price, a positive net income can be achieved. Therefore, there is a need for renewed efforts in driving livestock or crop integration as the concept is clearly beneficial to smallholders.

Biomass and Bioenergy Innovations

The palm oil industry generates plentiful biomass resources and by-products for value addition towards the creation of a circular economy. Particularly, in the palm oil milling process, by-products such as palm oil fuel ash (POFA), palm oil clinker (POC) and residual oil of palm oil mill effluent (ROPOME) have been actively exploited as seen with their increasing research activities spanning from fundamental, applied to simulation work. Efforts have also been made to improve oil and biomass production in palm oil mills by minimising water consumption during oil palm sterilisation via integrating the boiler and the steriliser into a combined unit. This is achieved by omitting piping and continuous heating. An optimal sterilisation condition of 2.5 bars and 60 min provides good fruit-bunch separation with acceptable oil quality, and four times lesser water consumption than the conventional method (Wae-hayee *et al.*, 2022). Instead of sterilising whole palm fruits, it is possible now to process only the detached palm fruitlets via microwave heat (Hadi *et al.*, 2021), but its practical implementation needs to be substantiated with an efficient mechanism for fruitlets separation from the bunches. Further processing of palm kernel cake from a crusher via solid-state fermentation could increase the crude protein content to serve as

a more nutritive mono-gastric feed material (Mohd Firdaus *et al.*, 2020). Besides, the non-compliant finding of odour emission limit of $12\ 000\ \text{OUm}^{-3}$, as proposed for assessment at source and *in-situ* palm oil mill sites, calls for an urgent counter proposal to fully comply and mitigate the sensory annoyance complaints by the public (Chung *et al.*, 2021).

The incorporation of POFA, in 10 wt.% as cement replacer, and POC, 50 wt.% as sand replacer has a potential to form a structured foamed concrete with the required strength (Abraham *et al.*, 2021). POC can also be made into nanoparticles to enhance the compressive strength of concrete (Hamada *et al.*, 2021). Its presence as sand replacer together with fly ash and furnace slag as a binder are promising in making cement and geopolymer mortars (Darvish *et al.*, 2021). The resultant cement exhibits up to 20% lighter weight with higher strengths. POFA is also a potential clay replacer (at optimum 10 wt.%) in brick manufacturing (Tjaronge and Caronge, 2021). These innovations help resolve POFA and POC disposal issues, conserving resources and maximising their utilisation, to yield more environmental-friendly innovative construction materials. In addition, for the first time, POFA is also used as a cheap carbon precursor for the production of economical graphene nanosheets via a single-step chemical reaction. The highly porous graphene material is 70 times higher in its surface area (*i.e.*, from $22\ \text{m}^2\ \text{g}^{-1}$ to $1506.60\ \text{m}^2\ \text{g}^{-1}$) (Ayub *et al.*, 2021). On the other hand, 0.3 wt.% of EFB can serve as a stabiliser, for reinforced stone matrix asphalt concrete production (Yaro *et al.*, 2021). Active exploitation of these by-products can contribute to the sustainable production of construction materials.

Palm-based biochar as adsorbent continues as a recent interest topic. By converting oil palm frond through process-dependent parameters, the resultant biochar, in particularly activated biochar, has a high capability for SO_2 adsorption from flue gasses of power plants and factories (Iberahim *et al.*, 2022). The used biochar can be regenerated thermally. Palm kernel shell (PKS)-based activated carbon (0.85 mm in size) can remove 98% of phenolic pollutants (Sahu *et al.*, 2021). Oil palm trunk is another feedstock of interest to the scientific communities. Powdered oil palm trunk can bind with rubberwood veneer via a one-step liquefaction process at 180°C hot pressing for 5 min to form bio-adhesives, with or without citric acid as a chelating agent (Choowang and Luengchavanon, 2021). Bio-succinic acid continues to be researched via whole slurry saccharification at a mild oxalic acid concentration by Bukhari *et al.* (2021) for yield improvement. Inorganic salt-pretreated EFB gives a high titer and yield of succinic acid via simultaneous saccharification and fermentation (Anwar *et al.*, 2021).

In gearing toward addressing fossil fuel depletion and rising fuel cost, the current focus is to seek alternative biofuels with outstanding stability and combustion behaviour. The immediate 'low-hanging fruit' approach is through blending palm oil/PKO with methanol or ethanol in the presence of co-solvent such as tetrahydrofuran (THF) to yield a single-phase liquid termed micro-emulsion fuel (Jin *et al.*, 2021). By practically adjusting the proportion of each fuel ingredient, the resultant blended fuel would achieve optimal performance for the desired fuel properties. A combined blend of palm methyl esters (palm biodiesel) with cottonseed oil methyl esters and petroleum diesel fuel at a 20/80 ratio (*i.e.*, B20) can act as compatible diesel fuel for use without engine modification (Jamshaid *et al.*, 2022). Besides, it is possible to increase the combustion efficiency of palm biodiesel by just adding a single water droplet (Masharuddin *et al.*, 2021). The emulsified fuel experiences four stages of micro-explosion due to larger water particles and higher hydrophilic-lipophilic balance, thus, performing excellently with a reduced particulate matter (soot) and NO_x emissions. It has also been proven that the mandated B7 (7 wt.% palm biodiesel in 93 wt.% petroleum diesel) and higher blends up to 20 wt.% can be comfortably used at Malaysia's highlands as their cold flow properties are lower than the lowest temperature recorded for the past 10 years in these places (Jalil *et al.*, 2021).

To improve process sustainability, industrial oil residues such as the ROPOME have increasingly been sought as a biodiesel feedstock. As the oil is similar to palm oil for conventional alkali-catalysed transesterification, its maximum oil recovery for biodiesel conversion must be accomplished. Four different types of solvents: n-hexane, methanol, ethanol, and toluene have been attempted (Zulqarnain *et al.*, 2021), yielding 90% of ROPOME at 1:1 (v/v) n-hexane-to-POME ratio, 500 rpm, pH 10 and 25 min mixing time. Its conversion into methyl esters reached 93%. Its combustion efficiency, *i.e.*, 10 wt.% (B10) blend can be greatly enhanced via enrichment of hydroxy gas in low-displacement engines (Duarte-Forero *et al.*, 2021). Similarly, sludge palm oil from the milling process has also been made into biodiesel via an enzymatic process, employing a genetically modified *Aspergillus oryzae* lipase (0.2 wt.%) and 5:1 methanol-to-oil molar ratio at 45°C (Loh *et al.*, 2021). The process has managed to produce crude biodiesel with 94 wt.% ester content, and the crude glycerol produced has higher purity compared to those from other established technologies. Ng *et al.* (2021) further applied this approach for rural electrification by supplying the enzymatically produced biodiesel to the surrounding households and mill operators. The approach shows high feasibility: 29% return on investment and <4 years payback period. Palm

oil soap stock is another biowaste which can firstly be acidified to yield 91 wt.% free fatty acids, then esterified using an immobilised lipase (alginate-polyvinyl alcohol) to produce biodiesel (Muanruksa *et al.*, 2021). The biocatalyst employed can be recycled up to 16 times.

Besides, the anaerobic digestion of POME for biogas production remains opportunistic as a form of renewable energy. Biogas capturing remains relevant in addressing greenhouse gas emissions associated with POME degradation. As of December 2020, a cumulative total of 130 biogas plants were on stream in Malaysia (Parveez *et al.*, 2021). This has increased to 135 plants in 2021 (unpublished data). One of the systems to treat POME is by integrating anaerobic (granular-sludge blanket) and aerobic (biofilm and activated sludge) processes, which can remove 99.7% of chemical oxygen demand (COD) (Show *et al.*, 2021). This approach generates revenue for combined heat and power as well as reduces greenhouse gas emissions. Moving forward, enhancement via co-fermentation has been made. Anaerobic co-digestion of POME with EFB for maximising biowaste value offers promising outcomes thus, far (Liew *et al.*, 2021). EFB must be pre-treated first prior to microbial degradation. Production of biogas through this approach at an optimal co-digestion ratio of EFB: POME, 0.6:1 is double that of mono-digestion under mesophilic conditions. Another integrated pilot-scale anaerobic-aerobic bioreactor loaded with an organic loading rate, *i.e.*, COD of 30.0 g L⁻¹ day⁻¹, has successfully produced POME with biological oxygen demand (BOD) of <20 ppm consistently over 165 days (Yap *et al.* 2021a), besides enabling co-digestion with *Moringa oleifera* to enhance methane yield 1.5-fold (Yap *et al.*, 2021b). The protein-rich *M. oleifera* seed extract acts as a natural coagulant for enhanced microbial activity (Yap *et al.*, 2021b). The *M. oleifera* seed extract can also be made into magnetic nanoparticles via microwave and ultrasonic irradiation, which shows >75% removal of COD from POME (Noor *et al.*, 2021a). Another substrate, decanter cake, can double the methane yield when co-digested with POME (Lim *et al.*, 2021b). Nevertheless, Chan *et al.* (2021b) concluded that EFB exhibits a much-balanced C:N ratio for microbial rejuvenation, thus, offering better overall biogas enhancement when used as a co-substrate compared to decanter cake.

The other aspect which should be addressed when dealing with POME treatment is to remove the high organic strength BOD and COD before subjecting the final discharge into a waterway. Removal addresses pollutant load while nutrient recovery adds additional value to POME. Magnetic composite adsorbents show good performance in enhancing the POME treatment without having to go through polishing (Ratnasari *et al.*, 2022). A

Fe-magnetised and activated carbon from palm kernel shell, having <250 µm particle size and 611.85 m² g⁻¹ specific surface area, is able to polish and remove up to 99.7% and 85.0% of the initial colour and COD of raw POME, respectively (Tan *et al.*, 2021). Its reusability is great, with only <2.0% losses in removal efficiency after four reuse cycles. Furthermore, as POME is loaded with nutrients and beneficial microorganisms, research has also geared towards recovering and utilising it as a co-substrate for enhancing microbial degradation. Some of the examples exploited are as described in Ani *et al.* (2021) and Sayed *et al.* (2021), where POME has been shown to serve as a potential bio-stimulant in hydrocarbon degradation of contaminated soils, and for biodegradation of petroleum oil spills in shoreline, with an efficiency of 95.0% after 40 days. POME remains a relevant cultivation medium for microalgae growth targeting phytonutrients particularly, astaxanthin production, as well as pollutant bioremediation (Fernando *et al.*, 2021). Interestingly, the microalgae exploited, *Haematococcus pluvialis*, shows better adaptability in 7.5 wt.% POME concentration, compared to a lower, 5.0 wt.%, concentration for *Chlorella vulgaris* as a feedstock for biodiesel production three years ago (Idris *et al.*, 2018). Inorganic phosphorus can be recovered from POME while producing hydrogen via gasification in supercritical water (600°C, 25 MPa) (Mainil and Matsumura, 2021). Besides, a statistically optimised microbial electrolysis cell achieved a maximum production rate of 1.1747 m³ hydrogen per 1 m³ POME and can be performed daily (Kadier *et al.*, 2021).

The combustion behaviour of oil palm biomass determines the suitability of its conversion into solid biofuels making it an area worth investigating. A high potassium (K) content of the biomass usually causes slagging and fouling of power plants; thus, its removal is necessary before rendering the biomass for practical use to generate electricity. In doing so, Nasrin *et al.* (2021) have demonstrated that a combined sieving and water spraying method can produce low-ash (1.58 wt.%) pellets from EFB that originally contained 4.07 wt% ash, along with ~50.00% K removal. In another study, the content of K in EFB could be reduced via hydrothermal treatment prior to anaerobic digestion (biogas) and combustion in a boiler (electricity) (Saritpongteeraka *et al.*, 2021). Although >90.00% removal of K and higher methane production are achievable for a longer reaction time, only the former is able to recover ~70.00% residual oil. Judging from the energy and mass balances, the former shows a better advantage for incorporation into the existing milling practices.

Deoxygenation is paramount for producing advanced biofuel. An acid-base catalyst, such as acid-activated spent zeolite-based catalyst

recovered from an industrial cracking process (Istadi *et al.*, 2021), and zeolite beta (Nur Azreena *et al.*, 2021) employed during palm oil and oleic acid hydrocracking process, respectively, produced low-oxygenated hydrocarbon fuel (green diesel) with a composition similar to that of petroleum fuel. This type of high-quality biofuel can be directly used, with excellent corrosion resistance, stability and heating value. On the other hand, high-quality biohydrogenated diesel can be processed from palm oil with the help of Rh/HZSM-5 catalyst in a reduced hydrogen environment, for <1 min residence time (Kaewchada *et al.*, 2021). The high amount of hydrogen released during conventional hydro-treating of palm oil can be recovered (46%); the feasibility of hydrotreating can be improved (23% internal rate of return, 2.8 years payback period) (Phichitsurathaworn *et al.*, 2021).

Biojet fuel is worth researching due to fast-growing sustainable aviation fuel demand. Catalytic conversion using Ni/desilicated mesoporous zeolite-based catalyst yields biojet fuel from palm oil (Panarmasar *et al.*, 2021). The bioconversion and selectivity of jet-fuel products rely on the type of catalyst, reaction temperature and pressure. CPKO is another feedstock subjected to deoxygenation, employing Pt/Pd supported on activated carbon (Makcharoen *et al.*, 2021). A moderate yield of 58% of biojet fuel is attainable, of which 28% are linear alkane (C8-C16). Additional adjacent catalytic cracking and aromatisation process by HZSM-5 can lower its freezing point by 30°C.

Environmental Sustainability of Oil Palm Value Chain

In assessing environmental sustainability, life cycle assessment (LCA) serves as a promising tool, as seen with burgeoning R&D activities in this area, be it for a technology, product or system. A pilot-scale up-flow anaerobic sludge blanket fixed-film reactor for biohydrogen production from POME was subjected to on LCA (Akhbari *et al.*, 2021). The resultant global warming impact by electricity usage can be further reduced to 54.9 kg CO₂ eq kg⁻¹ H₂ if a cleaner electricity source can be identified and the burden in POME treatment avoided. In another study, Julio *et al.* (2021) showed that biodiesel and biojet fuel produced in an integrated palm oil biorefinery could avoid 24.65 kg CO₂ eq t⁻¹ and 3281.36 kg CO₂ eq t⁻¹, respectively, compared to their fossil counterparts.

While it is beneficial to focus on LCA for large-scale palm oil processing, it is equally critical to conduct a gate-to-gate LCA of Nigerian mills with varying technological levels: large-, semi-mechanised, and smallholder-owned scales (Anyaocha and Zhang, 2021). Interesting findings include the existence of different hot spots in

greenhouse gas emissions. While smaller-size and semi-mechanised mills emit 47% and 73% more CO₂ and N₂O, respectively than large-scale mills due to open burning of biomass residues and high diesel consumption, the latter emits 71% more methane due to inefficient EFB and POME management.

In a pioneering social-LCA study of CPO production, five palm oil companies located in Peninsular Malaysia show above average performance in fulfilling the eight subcategories of worker's indicators and basic requirements using the Subcategory Assessment Method, except for working hour (Haryati *et al.*, 2022). Long working hours are the social hot spots identified for further improvement, and the proposed mitigation is to train workers for the desired skills and also to incorporate advanced technology such as mechanisation. To better demonstrate environmental sustainability, all biomass residues generated from palm oil mills should be treated as by-products, which can be recycled and reutilised either as fuel, mulching materials or fertilisers (Subramaniam *et al.*, 2021).

As palm oil production has been scrutinised for causing high risk of indirect land-use change, reforming land policy is essential to enable oil palm planters to share their productive lands with those landless/displaced farmers (Azhar *et al.*, 2021). Such strategy has been shown via Monte Carlo simulations to mitigate land clearance and encourage intercropping and livestock integration.

Food Safety and Quality Research and Measures

Food safety and quality related issues remain important factors affecting consumers' food buying decisions worldwide. Increasing awareness and accessibility to a safe and healthy food supply are essential for the palm oil industry to deal with expectations from demanding consumers since palm oil is the most heavily traded edible oil. The situation has become direr for the industry and more highly relevant due to an ever-increasing demand to meet food safety regulations and quality standards. The most resilient issue at hand is how to address the inadvertent occurrence of 3-monochloropropane-1,2-diol esters (3-MCPDEs) and glycidyl esters (GEs) contaminants during the refining process of palm oil. Serious efforts are in place by the industry to eliminate these contaminants, in particular with the adoption of the Code of Practice (COP) in refined oils and food products made with refined oils, as adopted in CXC 79-2019 by the CODEX Alimentarius Commission (FAO, 2019).

Several mitigation strategies for 3-MCPDEs and GEs in palm oil have been reported by Tivanello *et al.* (2021). Reduction of these compounds in food products by reducing agents (0.05%, w/w) during

toasting (Belkova *et al.*, 2021) and food preparation processes (Huang *et al.*, 2021) are possible. Abd Razak *et al.* (2021) found that palm olein performed better compared to other oils such as soybean and canola oils, with a significant reduction of 3-MCPDE and GE content, while acrylamide concentration was dependent on the oil type and lipid oxidation profile. In a comprehensive review by Ahmad Tarmizi and Kuntom (2021), an in-depth deliberation on various parameters in relation to frying conditions and properties affecting the occurrence of these contaminants in vegetable oils was discussed. The varying observations further warrant explorations on the effects of different types of frying procedures, including food load and frying cycles.

The importance of detecting these compounds in vegetable oils and foods led to an increased number of studies on improvements in detection methods, including rapid detection methods (Martin *et al.*, 2021), and simultaneous determination of esterified 2-/3-MCPD and glycidol in foods by GC-MS/MS (Zheng *et al.*, 2021b). A new approach using a molecularly imprinted label-free sensor platform for impedimetric detection of 3-MCPD was also proposed (Yaman *et al.*, 2021). Shaari *et al.* (2021) on the other hand reported a detection and extraction method for bound 3- and 2-MCPD and glycidol using accelerated solvent extraction and GC/MS. Besides, Sulaiman *et al.* (2021b) developed and validated a method for measuring residual 2,4-dichlorophenoxyacetic acid (2,4-D) herbicide in CPO using LC/MS/MS. The developed method is simple, economic, reliable and serves as an important tool for the regulatory monitoring of 2,4-D in palm oil. The successful combination of any available methods could be applied to the determination of the above-named contaminants in selected food products.

Studies in relation to other contaminants, apart from 3-MCPDE and GE, are also of importance in the efforts to address food safety issues of palm oil. Ahmad *et al.* (2021c) investigated the effect of different vegetable oils and frying cycles on the formation of acrylamide during intermittent frying of beef nuggets. Four different vegetable oil types (palm olein, red palm olein, sunflower oil and soybean oil) were compared in an 80-cycle frying experiment. It was found that the oil type but not the frying cycles affected acrylamide concentration in beef nuggets. The fate of acrylamide in the presence of Vitamin A and E homologues was also investigated by Kuek *et al.* (2021). An equimolar Asparagine-Glucose model system was used to evaluate the influence of Vitamin A and E homologues on acrylamide formation. The study reported that different Vitamin A and E concentrations could determine their functionality either as anti-oxidants or pro-oxidants. Further studies to look at the

combined effects of the homologues on acrylamide formation are warranted.

The quality of commercial palm-based cooking oil in two types of packaging materials, the plastic pouch/packet and polyethylene terephthalate (PET) bottle, was compared in a study by Hassim *et al.* (2021a) to address the concern and misconception regarding the subsidised plastic pouch/packet oil which is cheaper than the oil sold in PET bottles. The study concluded that all parameters tested in the oils from both packagings were within the cooking oil specifications or guidelines set by both the Malaysian Standard (MS) 682:2004, MS 816:2007 and Palm Oil Refiners' Association (PORAM). This helps to clear the concern and misconception regarding the poorer quality of subsidised oil *vis-à-vis* those sold in PET bottles.

Food and Feed Research

As the most versatile oil for food manufacturing, there have been continuous efforts undertaken to valorise palm oil, PKO and their fractions in edible food uses. Palm oil, being semi-solid in nature, confers the desired characteristics and remains the exceptional choice for the cooking and baking industry, in providing the right fats such as margarines, shortenings and vanaspati. PKO on the other hand is the preferred fat for confectionary use due to its high lauric acid content and sharp melting properties. Likewise, the many fractions of palm oil and PKO have been continuously dissected and explored for innovations in the food as well as feed industry.

Hassim *et al.* (2021b) reported the use of blended palm fractions such as palm mid fraction (PMF) iodine value (IV) 45, PKO and palm stearin (POs) IV 33 and IV 14 as cocoa butter alternatives for chocolate bar production. The authors after testing eight different optimised blend ratios between solid fat content and varying temperatures reported a successful identification of the most suitable alternative fat for cocoa butter for the chocolate bars which would benefit the confectionery industry. In another study, Chaijan and Panpipat (2021) used pre-neutralised crude palm oil (NCPO) as a natural colourant and bioactive ingredient in tilapia fish sausages. It was found that 50 g/100 g substitution of NCPO for commercial refined palm oil could serve as a substitute for healthier tilapia sausage production.

A study by Kanagaratnam *et al.* (2021) documented the quality characteristics of retail refrigerated and non-refrigerated margarines and fat spreads, which are commonly used by Malaysians. Such information will be useful to consumers, especially when vast variations were observed in the characteristics and functionalities of these different fats in relation to their storage

and handling temperatures. It was noted that the refrigerated margarine and fat spreads were predominantly imported while all non-refrigerated ones were locally produced. Palm oil-based fats are the right choice as a replacer for partially hydrogenated fats in margarine / fat spreads as they can deliver the desired functionality with a reduced *trans* fatty acid content. The authors, in addition, reported a lower slip melting point, denoting a lower saturated fat content in refrigerated fats, compared to the non-refrigerated counterpart.

Innovations in food uses of palm oil will continue to be explored due to its unique properties and versatility. At this juncture, it is crucial to deliberate on the use of palm oil and its products in the feed industry. Saminathan *et al.* (2021) discussed the potential utilisation of treated oil palm frond (OPF) to improve feedstuff for ruminants. While the OPF could be an important source of feedstuff for ruminants, it confers several limitations, such as low metabolisable energy and high lignocellulosic content. Various pre-treatment approaches and the respective challenges warrant further enhancement of OPF nutritive values, in terms of biological and economic aspects.

For improvement in ruminant feed formulation, Ibrahim *et al.* (2021) reviewed the effects of vegetable oil supplementation on rumen fermentation and microbial population in ruminants. The authors discussed in detail the physiology of nutrient digestion in ruminants in relation to improvements in rumen fermentation and the distribution of microbes following supplementation with vegetable oils. Interestingly, it was found that the oil type caused no different effects towards fermentation in the rumen. However, oils which contain higher unsaturated fatty acids tend to show increased inhibition of the bacterial population in the rumen.

Palm Oil Nutrition Research

Palm oil nutritional research remains one of the key focus areas, especially because palm oil is mainly used in the food industry. Consumers are becoming more health conscious and are demanding the availability of reliable scientific evidence when selecting their choice of healthy foods. As such, extensive studies have been published to further strengthen the nutritional properties of palm oil and its loaded phytonutrients.

In 2021, several publications reviewed the effects of oil consumption on various disease conditions. One such study was on the role of dietary fats in inducing obesity-related postmenopausal breast cancer and the insights from mouse models (Tan and Teng, 2021). The authors highlighted the importance of choosing a suitable and reliable animal model, particularly postmenopausal breast

cancer mouse models based on the biochemical mechanism related to the said condition. The effects confer on other parameters such as adipocytes, inflammatory mediators and related signalling molecules which are involved in the process. In addition, it was stressed that the types of dietary fats also play an important role in the development of postmenopausal breast cancer. Among the studies reviewed, there was no indication of a specific model which is best suited for conclusive effects on postmenopausal breast cancer. However, the authors suggest the establishment of new xenograft models which may serve as a more reliable model for future studies.

Moreover, Yap *et al.* (2021d) discussed the association of various dietary fats on the profile of gut microbiota and the possible effects of the palm oil diet. The review described the variation observed in the gut microbial population with the consumption of different dietary fats. As an example, there was less bacterial diversity when the saturated fatty acids rich diet was consumed. The bacterial diversity only increased with the monounsaturated fatty acids diet, and with the polyunsaturated fatty acids diet, a wider variation in bacterial diversity was observed. More studies are required to establish the microbial distribution in relation to palm oil consumption as the oil has a unique and balanced composition.

Several studies investigating the various fractions of palm oil were focused upon in 2021. Nagapan *et al.* (2021) explored the role of interesterified (IE) fats on lipid sub-fractions and hepatic gene expression involved in lipoprotein regulation, using F1B male Golden Syrian hamster (*Mesocricetus auratus*) model. Over a period of 12 weeks, the animals were fed high-fat diets *ad libitum*, containing 0.1% dietary cholesterol and 30.0% energy from dietary fat. The fats were either native or interesterified, namely, palm olein (PO), chemically interesterified palm olein (CIEPO), sal fat (from *S. robusta*) blend (SFB), and chemically interesterified sal fat blend (CIESFB). Plasma lipid profiles including low density lipoprotein (LDL) and high-density lipoprotein (HDL) sub-fractions, and hepatic gene expression levels were analysed. PO- and CIEPO-fed hamsters had 38.0% and 27.0% higher plasma HDL levels compared to SFB and CIESFB, respectively.

In addition, the authors also reported a greater proportion of the larger HDL particles in the PO diet fed animals, compared to those which received SFB and CIESFB diets. Whereas, animals fed with SFB and CIESFB had a greater proportion of larger LDL particles, compared to both palmitic counterparts. All diets have upregulated genes involved in liver fat accumulation. Palmitic-rich diets presented significant upregulation for the APO A1 gene ($p < 0.05$). LDL metabolism related

genes such as LDLR, PCSK9, APO B, CYP7A1, PCSK9 were downregulated in all diets. In conclusion, native and IE saturated high-fat diets have induced liver steatosis in hamsters. The effects on plasma level HDL cholesterol and large HDL sub-fractions, however, were only seen in palmitic rich fats. Instead, the LDLR mediated cholesterol clearance was downregulated, with suppression of LDLR gene with similar effects on plasma LDL in all diets.

Voon *et al.* (2021a) reported on two studies on a specific fraction of palm oil *i.e.*, PMF, which is rich in 1, 3-dipalmitoyl-2-oleoglycerol (POP) triacylglycerol (TAG), produced by re-fractioning palm olein or palm stearin. The first study examined the role of PMF, equivalent to cocoa butter, as an alternative for healthier fat. The findings from the study indicated similar effects from the fats tested on postprandial lipoprotein metabolism, glycemia and insulinemic response. The second study by Voon *et al.* (2021b) reported on the effects of PMF on adult satiety, an indicator for reduced hunger and subsequently reduced food intake. The results showed that the PMF diets and high oleic sunflower diet have increased glucose dependant insulinotropic polypeptide (GIP) that may induce satiety response in human adults.

Over the years, the scientific evidence around fats and oils has mounted on the detrimental effects of *trans* fatty acids, especially on the increased risk of coronary heart disease (CHD) and mortality from CHD among others. A global exercise was initiated by the World Health Organization to eliminate industrially produced *trans* fatty acids by partial hydrogenation. A majority of the countries has started implementing various strategies to either prohibit the use of partially hydrogenated oils and/or limiting the levels of *trans* fatty acids. Palm oil has been the preferred choice to mitigate *trans* fatty acid occurrence in various food applications, because it does not require hydrogenation which is the major cause of the formation of *trans* fatty acids (Parveez *et al.*, 2020). Nevertheless, there is also very limited data on the levels of *trans* fatty acids in cooking oils in Malaysia. Hishamuddin *et al.* (2022) studied the distribution levels of *trans* fatty acids in refined palm-based oils and other commercial vegetable oils in Malaysia. The findings showed that the palm-based cooking oils in Malaysia were superior to other oils, in that the levels of *trans* fatty acids were low, thereby meeting the regulatory levels of *trans* fatty acids of 1 g/100 mL.

On the palm phytonutrient research front, several studies were published on the mechanisms of action by tocotrienols in inhibiting breast cancer cell growth both *in vitro* and *in vivo*. Loganathan *et al.* (2021) reported that tocotrienols have exhibited anti-proliferative effects on human breast cancer cells by promoting programmed cell death or

apoptosis possibly through the inactivation and down-regulation of two significant markers: poly-(ADP)-ribose polymerase-1 (PARP-1) and cyclooxygenase-2 (COX-2). In a breast cancer mice model, gamma-tocotrienol supplementation suppresses the growth of breast cancer tumour, as well as metastasis (Subramaniam *et al.*, 2021a). The regulation of the immune system in the breast cancer mice model describes the mechanism of action imposed by gamma-tocotrienol (Subramaniam *et al.*, 2021b).

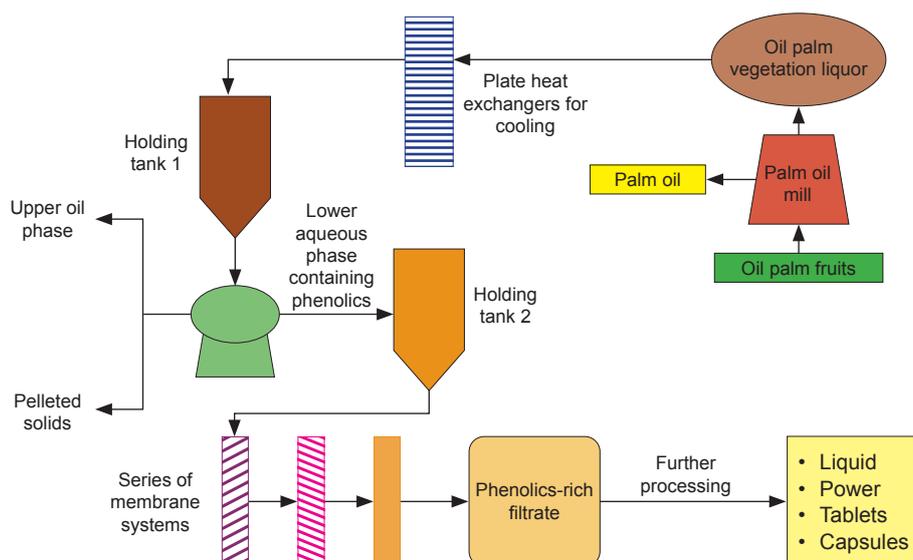
Research on water-soluble palm phytonutrients is another frontier in palm oil nutrition research. In 2021, Leow *et al.* (2021a) described the many facets of this unique compound, named water-soluble palm fruit extract (WSPFE), found in the aqueous extract of the palm fruit (Figure 5). The review described the complex compositions of the compound, and its biological properties as well as an in-depth discussion on its health and non-health applications. In another study, Leow *et al.* (2021b) investigated the possible neuroprotective effect of WSPFE as potential inhibitor of cholinesterase enzyme, which is crucial for the symptomatic treatment of Alzheimer's disease. The study found that WSPFE inhibited the cholinesterase and related enzymes, which warrants further exploration through *in vivo* models, as the way forward.

Oleochemical Innovation

The global growth of oleochemical market size is driven by the increasing consumption of renewable and sustainable bio-based chemicals in cosmetics, personal care, lubricants, polymers, pharmaceuticals, food, and other industries. The same 'green' market demand is also driving innovations in the development of products that utilise oleochemicals such as biolubricants, surfactants, bio-polyol, glycerol derivatives, agrochemicals and polymers.

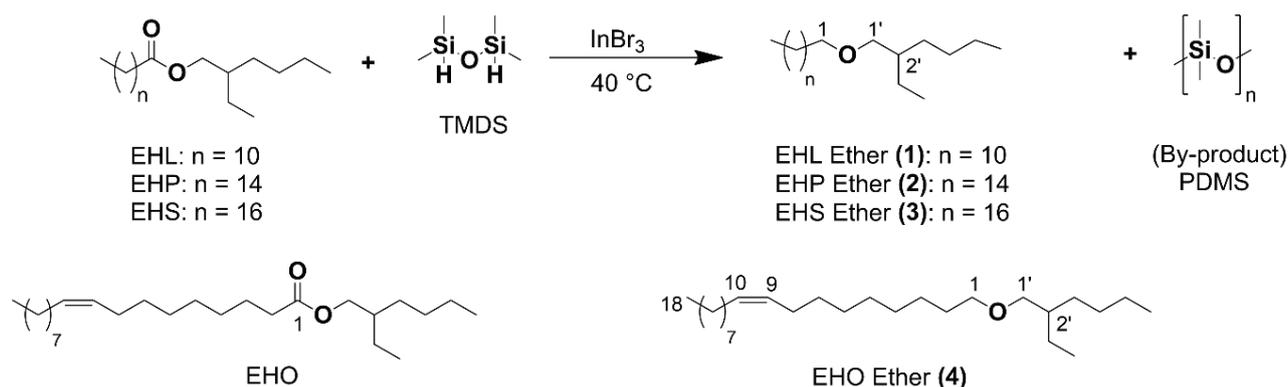
One of the focus areas of innovation is bio-lubricant, made from palm-based oleochemicals. In general, the use of bio-lubricants from renewable sources is gaining momentum due to rising concerns over the use of toxic and non-renewable mineral oil counterparts (Cecilia *et al.*, 2020). Besides being environmental-friendly, non-toxic and renewable, bio-lubricants have a higher flash point and very low volatile content, which make them safer to be used commercially.

However, several drawbacks such as poor oxidation stability and inferior cold flow properties, limit their usage in mainstream lubricant applications (Salih and Salimon, 2021). These drawbacks can be overcome through structural modification, as studied by Hoong *et al.* (2022), by producing estolide esters from palm-based oleic acid and lauric acid. Specifically, oleic acid is converted



Source: Leow *et al.* (2021a).

Figure 5. Water Soluble Palm Fruit Extract (WSPFE) production process.



Source: Tang *et al.* (2021).

Figure 6. Reduction of 2-ethylhexyl fatty esters to 2-ethylhexyl fatty ethers.

to estolide with hydroxyl groups through a reaction with hydrogen peroxide. Subsequently, hydroxyl groups of estolide are transformed into ester groups by end-capping them with organic acids of different chain lengths and structures. It was concluded that estolide esters, end-capped with lauric acid and 2-ethylhexanoic acid exhibited excellent cold flow properties with pour point as low as -36°C , and good oxidation stability with oxidation onset temperatures ranging from 193°C - 200°C .

Another study by Tang *et al.* (2021) revealed that a series of 2-ethylhexyl alkyl ethers can be prepared from palm-based fatty esters through a reduction step catalysed by indium bromide in mild reaction conditions as shown in Figure 6. The synthesised bio-lubricants exhibited low kinematic viscosity of 4-9 cSt at 40°C , suggesting they are suitable for use in lubrication applications for fuel economy

enhancement and energy efficiency. Additionally, the prepared bio-lubricants also showed good cold flow properties, with the lowest pour point of -27°C , they are most desirable for cold climates. The developed bio-lubricants can be employed across the supply chain of the palm oil industry, especially in palm oil mills, to substitute conventionally used mineral oil-based lubricants. These bio-lubricants not only incur low risk in the event of incidental contact with oil palm fruits or palm oil during harvesting and processing but are also more environmental-friendly, in case of any accidental release into the environment. Additionally, they could potentially be more cost-effective in the long run, compared to imported bio-lubricants.

Another focus area of innovation is the specialty chemicals, which can be derived from the common oleochemical glycerol. It contains three hydroxyl

groups for chemical modification to generate many high value-added bio-chemicals such as glycerol acetals that can be used as a fuel additive, surfactant and solvent. Instead of employing previously adopted homogeneous catalysts, Armylisas *et al.* (2021) employed bio-based aldehydes and the heterogeneous acid catalyst, Amberlyst-46, to prepare glycerol acetals under solvent-free conditions, to simplify subsequent product purification steps which finally eliminate the use of solvent. The product yield and catalytic selectivity were influenced by the molecular structure and carbon chain length of the bio-based aldehyde. High yield was achieved using aldehydes with short carbon chain length such as acetaldehyde, while aromatic and longer chain length aldehydes gave low yield. Furthermore, the heterogeneous catalyst was shown to exhibit good reactivity and stability even after 10 reaction cycles. The prepared glycerol acetals have good potential to be used as a bio-based solvents to replace hazardous and non-renewable petroleum-based solvents due to their low toxicity and environmentally benign properties.

In another development, Mariam *et al.* (2021) reported on the synthesis of solketal levulinate ester, which can potentially be used as a potential additive to improve the properties of biodiesel such as cold flow, combustion profile and cetane number. In this study, the synthesised additive is wholly bio-based, using starting materials *i.e.*, solketal derived from glycerol, and methyl levulinate derived from biomass. The solketal levulinate ester with 95% purity at 75% yield will be applicable for biodiesel fuel upgrading.

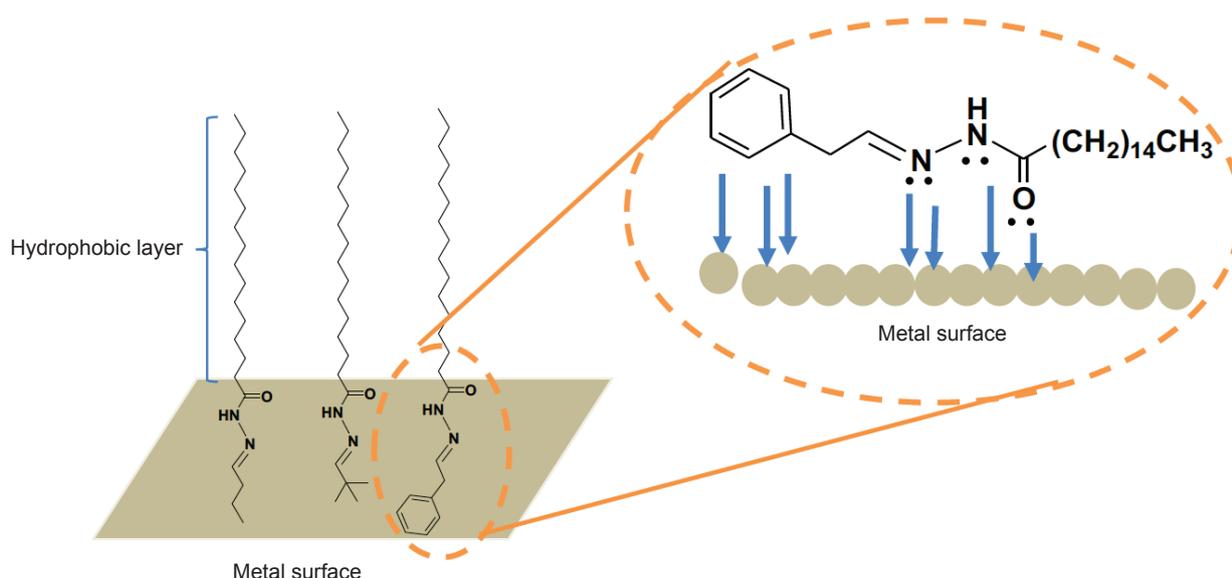
The demand for renewable and sustainable chemicals is also observed in the field of polymeric materials such as bio-based polyol and polyurethane. These polymers have experienced significant growth in market share due to increasing demand for 'green' construction materials and renewable polymers in the automotive industry (Grand View Research, 2021). In response to such market demand, Noor *et al.* (2021b) synthesised palm-based polyols using both homogeneous and heterogeneous catalysts. The study revealed that polyol with a higher degree of oligomerisation, higher viscosity and higher hydroxyl functionality was attainable with $\text{BF}_3 \cdot \text{Et}_2\text{O}$ as the homogeneous catalyst, and the opposite properties were observed using K10-montmorillonite as the heterogeneous catalyst. This study gears towards the synthesis of palm-based polyol with specific properties for targeted application. In palm-based polyol's purification, the presence of impurity is crucial, *e.g.*, sodium (Na) and K, as they might affect the reactivity of polyol with isocyanate for the preparation of polyurethanes. Therefore, the Na and K content in polyol are both limited to 10 mg kg^{-1} . In this regard, Ramli *et al.* (2021) developed a method to analyse Na and K content

in palm-based polyols via graphite furnace atomic absorption spectroscopy. The developed method has been validated for routine analysis of Na and K contents in palm-based polyols.

Tailor-made palm-based thermoplastic polyurethane is another area worth innovating for a wide range of applications including coating, adhesive, sealant and elastomer. Ismail *et al.* (2021) reported that the co-monomeric polyester polyol-based thermoplastic polyurethane produced from palm-based azelaic acid in combination with succinic and adipic acids showed lower mechanical hysteresis (tensile) and tensile strength than those from conventional monomeric polyester polyol. The lower hysteresis of the prepared polymer suggested lower heat build-up, which is one of the desired properties for use in dynamic applications such as rollers and wheels.

R&D innovations for oleochemical derivatives have been extended into the field of thermal energy storage. Poopalam *et al.* (2021) studied the synthesis of 12 symmetrical fatty diamides from saturated fatty acids and aliphatic linear diamines. The study suggested that hydrogen bonding among fatty diamides is the key factor that affects the phase change properties of fatty diamides, and hydrogen bonding strength is mainly influenced by the chain length of diamine and fatty acid, which determine the molecular structure of fatty diamide and their crystallisation structures. The prepared fatty diamides were evaluated as phase change material (PCM), which can absorb and release thermal energy during phase transitions, which enables it to function as thermal energy storage material. Analysis results showed that the prepared fatty diamides broaden the range of operational temperature, with a melting point which is 80°C higher than current vegetable oil-based PCMs. Furthermore, the fatty diamides also exhibited better latent heat (220 J g^{-1}), thermal stability (380°C), and heat conductivity in comparison with current bio-based organic PCMs. These results suggested that the fatty diamides can be used as thermal energy storage materials for conservation of solar energy, re-cycling waste heat from industrial processes, improvement of thermal efficiency of buildings, and electric vehicles.

Mohd *et al.* (2021a) studied the physicochemical and electrical insulating properties of palm-based products such as RBD palm olein (RBDPOo), fatty acids, fatty esters and glycerol as the electrical insulating medium in oil-filled transformers for electrical energy transmission. RBDPOo was found to exhibit a high flash point of 320°C and an appropriate kinematic viscosity of 40 cSt at 40°C , which conformed to the required ASTM D6871 standard specification. The study also revealed that the dielectric breakdown strength of RBDPOo can be improved from 31.1 kV to 76.8 kV , by reducing the moisture content of RBDPOo from



Source: Mohd *et al.* (2021b).

Figure 7. The proposed adsorption sites of hydrophobic-tailed palm-based imines inhibitors on carbon steel surface in an acidic solution through π -electrons and lone pair electrons of heteroatoms.

400 ppm to 100 ppm. The blending of RBDPOo with fatty esters or fatty acids not only improved the kinematic viscosity of the blend but also enabled the blend to achieve a better flash and fire point than conventional mineral oil. This study suggested that palm oil products namely RBDPOo, fatty esters and fatty acids have good potential to be used as insulating oils for oil-filled transformers with better environmental footprint and fire-proof features than mineral oil.

Renewable, sustainable and environmentally friendly bio-based corrosion inhibitor is another focus area of oleochemical innovation due to rising demand for low toxicity, 'green' and cost-effective corrosion inhibitors by several industries. As a response to the demand, Mohd *et al.* (2021b) conducted a study to synthesise imine compounds from palm-based fatty acids and evaluated the synthesised compounds as corrosion inhibitors for carbon steel in hydrochloric acid solution. The imine compounds were prepared from a reaction between palmitic acid, hydrazine and various aldehydes with linear alkyl, branched alkyl and phenyl moiety, respectively.

Analysis of results from the study showed that palm-based imines prepared from aldehyde with linear alkyl and phenyl groups reduced the extent of corrosion damage on the surface of carbon steel exposed to the hydrochloric acid solution. The proposed adsorption sites of hydrophobic-tailed palm-based imines inhibitors on carbon steel surface in an acidic solution are illustrated in Figure 7. The hydrophobic layer originating from fatty acid protects the metal surface from being

attacked by corrosive species. This study clearly indicated that palm-based imines have a high potential to be used as 'green' corrosion inhibitors for the protection of carbon steel.

Cosmetics and personal care products have been one of the main users of palm-based oleochemicals (Salimon *et al.*, 2012). Specifically, transparent soap is a beauty product sold in the upper-middle class market segment due to its luxurious appearance. Generally, plant extracts such as phenolics are included in the formulation of transparent soap to impart antioxidant properties that can prolong its shelf life. A study was carried out by Ahmad *et al.* (2021b), which incorporated oil palm leaf extracts containing phenolics into the palm-based transparent soap. The study showed that the addition of oil palm leaves extracts into transparent soap did not affect the foaming power and foam stability of the soap and improved the anti-oxidant properties of the soap, better than the commercial green tea extract transparent soap. Additionally, the prepared transparent soap with oil palm leaves extract exhibited natural yellow colour and showed stable hardness upon storage for 90 days. This study has shown that innovations could bring new zests in established technologies such as soap products and generate prospects for value creation.

Innovation in the oleochemical segment also extends into the engineering aspect of the oleochemical manufacturing technologies. Chan *et al.* (2021a) studied the synthesis of the oleochemical derivatives using microwave irradiation technology. A strategy to design a reactor and scaling-up the

synthesis of glycerol carbonate via microwave heating were assessed based on two parameters namely absorbed microwave energy density and absorbed microwave power density. Optimisation of both parameters enabled the determination of optimum microwave power requirement and heating duration for the synthesis of glycerol carbonate in a constant-power microwave heating mode. Findings from this study will enable further development of microwave heating technology such as continuous-flow microwave heating technology to produce oleochemical derivatives.

New analytical method development is also an important innovation to safeguard the quality of oleochemicals. Tay and Wai (2021) developed an analytical method to detect and quantify chlorpyrifos in food-grade palm-based fatty acids. Chlorpyrifos is a pesticide approved by the Malaysian Pesticide Board for use on oil palm trees to control related pests. There are worries that chlorpyrifos residues could be found in fatty acids after specific processing steps. Therefore, an analytical method was established to specifically detect and quantify chlorpyrifos in palm-based fatty acids by using a simple direct injection method, coupled with gas chromatography-mass spectrometry (GC-MS). The limits of detection and quantification of chlorpyrifos for this developed method were $0.5 \mu\text{g g}^{-1}$ and $5 \mu\text{g g}^{-1}$, respectively. It is noteworthy that the level of chlorpyrifos found in commercial fatty acids was below $0.5 \mu\text{g g}^{-1}$, the legally permitted level of pesticides in food commodities and animal feed in Malaysia. This result suggested that any chlorpyrifos residue found in commercial fatty acids will not be harmful to humans.

CONCLUSION

In general, the economic performance of the Malaysian palm oil industry in 2021 was very impressive, with many oil palm plantation companies reported healthy profits from their business operation. This was due to lower CPO production brought about by shortage of labour due to the COVID-19 pandemic, which restricted the supply of palm oil which in turn, favourably drove CPO prices to an all-time high. Despite the stellar economic achievement, continuous R&D efforts are being conducted in all sectors of the palm oil industry, to persistently enhance the well-being of the industry. In the upstream sector, precision agriculture technology, farm mechanisation, advanced breeding and genomics research as well as an effective pest and diseases controls contributed to the overall improvement of CPO yield while simultaneously enhancing the sustainability of oil palm plantation by minimising environmental impact. As for the midstream

sector, R&D efforts were focused on improving the productivity of palm oil mills and mitigating the environmental impact of milling operations, especially relating to POME. Furthermore, R&D emphasis on the utilisation of palm-based biomass is a vital approach to unlock the potential value from by-products of the industry while moving towards a circular economy. The downstream sector of the industry also plays an important role in supplying the world with food and non-food products, that are not only safe but also sustainable. Therefore, R&D efforts have been intensified to mitigate any food safety issues related to palm oil in addition to efforts that were made to enhance the nutritious value of palm oil in food products. Moreover, R&D activities in producing sustainable and value-added non-food products from palm oil such as bio-fuel, bio-polyol, bio-lubricants and personal care products were strengthened to offer global consumers greener products as well as to increase the consumption of palm oil. Nonetheless, continuous efforts are needed to strengthen the palm oil industry, in its journey towards circular economy and sustainability.

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REFERENCES

- Abd Razak, R A; Ahmad Tarmizi, A H; Kuntom, A; Sanny, M and Ismail, I S (2021). Intermittent frying effect on French fries in palm olein, sunflower, soybean and canola oils on quality indices, 3-monochloropropane-1, 2-diol esters (3-MCPDE), glycidyl esters (GE) and acrylamide contents. *Food Control*, 124: 107887.
- Abraham, H B; Alengaram, U J; Alnahhal, A M; Haddadian, A; Karthick, S and Deboucha, W (2021). Performance evaluation of cellular lightweight concrete using palm oil industrial waste as cement and fine aggregate replacement materials. *Mater. Today: Proc.*, 52: 902-910. DOI: 10.1016/j.matpr.2021.10.301.
- Adon, B; Konan, J N; Cochard, B; Flori, A; Diabaté, S; Bakoumé, C and Sokouri, D P (2021). Agronomical performances of Angolan natural oil palm accessions and interests for oil palm selection in Côte d'Ivoire. *J. Agric. Sci.*, 13(11): 64-73.
- Ahmad, M N; Shariff, A R M; Aris, I; Halin, I A and Moslim, R (2021a). Identification and determination of the spectral reflectance properties of live and

- dead bagworms, *Metisa plana* Walker (Lepidoptera: Psychidae) using VIS/NIR spectroscopy. *J. Oil Palm Res.*, 33(3): 425-435.
- Ahmad, N; Hasan, Z A A and Bilal, S H (2021b). Stability and performance of palm-based transparent soap with oil palm leaves extract. *J. Oil Palm Res.*, 33(4): 724-731. DOI: 10.21894/jopr.2021.0024.
- Ahmad, S N S; Ahmad Tarmizi, A H; Abd Razak, R A; Jinap, S; Norliza, S; Sulaiman, R and Sanny, M (2021c). Selection of vegetable oils and frying cycles influencing acrylamide formation in the intermittently fried beef nuggets. *Foods*, 10(2): 257.
- Ahmad Tarmizi, A H and Kuntom, A (2021). The occurrence of 3-monochloropropane-1, 2-diol esters and glycidyl esters in vegetable oils during frying. *Crit. Rev. Food Sci. Nutr.*, 62(12): 1-17. DOI: 10.1080/10408398.2020.1865264.
- Ainul, S S; Ali, Z A N; Kamalrudin, M S; Amran A; and Rahmahwati, R (2021a). Factors affecting fresh fruit bunch yields of independent smallholders in Sabah. *Oil Palm Industry Economic J.*, 21(2): 22-34. DOI: 10.21894/opiej.2021.06.
- Ainul, S S; Zaki, A; Abdul Rahman, A R; Nazirah, C J; Humaira, M T; Rahmahwati, R; Amran A; and Sohimi, M R (2021b). Factors influencing the performance of sustainable oil palm grower's cooperative in Sabah. *International Journal of Modern Trends in Social Sciences*, 4(16): 25-34. DOI: 10.35631/IJMTSS.416003.
- Akhbari, A; Onn, C C and Ibrahim, S (2021). Analysis of biohydrogen production from palm oil mill effluent using a pilot-scale up-flow anaerobic sludge blanket fixed-film reactor in life cycle perspective. *Int. J. Hydrog. Energy*, 46(68): 34059-34072.
- Amit, B; Tuen, A A and Kho, L K (2021). Bird species richness, abundance, and their feeding guild across oil palms development through mist-netting method in Betong, Sarawak. *J. Oil Palm Res.*, 33(4): 617-628.
- Ani, K A; Agu, C M and Menkiti, M C (2021). Preliminary investigation and neural network modeling of palm oil mill effluent as a potential bio-stimulating organic co-substrate in hydrocarbon degradation. *Environmental Challenges*, 5: 100216.
- Anwar, N A K K; Hassan, N; Idris, A; Ramli, S and Malek, R A (2021). Large scale production of succinic acid by fermentation of sequential inorganic salt pretreated oil palm empty fruit bunch. *Biomass Bioenergy*, 155(3): 106307.
- Anyaocha, K E and Zhang, L (2021). Renewable energy for environmental protection: Life cycle inventory of Nigeria's palm oil production. *Resour. Conserv. Recycl.*, 174: 105797.
- Apriyanto, A and Tambunan, V B (2021). Draft genome sequence, annotation, and SSR mining data of *Elaeidobius kamerunicus* Faust., an essential oil palm pollinating weevil. *Data Br.*, 34(7): 106745.
- Armylisas, A H N; Yeong, S K; Maznee, T I T N and Hoong, S S (2021). Effect of bio-based aldehyde structure on the conversion and selectivity towards glycerol acetal over Amberlyst-46 by using a solvent-free approach. *ChemistrySelect*, 6(7): 256-263. DOI: 10.1002/slct.202004215.
- Ayob, Z and Kusai N A (2021). A comparative study of bacterial communities determined by culture-dependent and-independent approaches in oil palm planted on tropical peatland. *J. Oil Palm Res.*, 33(4): 588-606.
- Ayompe, L M; Schaafsma, M and Egoh, B N (2021). Towards sustainable palm oil production: the positive and negative impacts on ecosystem services and human wellbeing. *J. Clean. Prod.*, 278(3): 123914.
- Ayub, M; Othman, M H D; Yusop, M Z M; Khan, I U and Zakria, H S (2021). Facile and economical, single-step single-chemical method for conversion of palm oil fuel ash waste into graphene nanosheets. *Appl. Mater. Today*, 25(80): 101193.
- Azhar, B; Nobilly, F; Lechner, A M; Tohiran, K A; Maxwell, T M R; Zulkifli, R; Kamel, M F and Oon, A (2021). Mitigating the risks of indirect land use change (ILUC) related deforestation from industrial palm oil expansion by sharing land access with displaced crop and cattle farmers. *Land Use Policy*, 107: 105498.
- Azimi, N; Ooi, S E and Ong-Abdullah, M (2021). Evaluation of mitochondrial DNA isolation methods for oil palm (*Elaeis guineensis*) leaf. *J. Oil Palm Res.*, 33(4): 607-616. DOI: 10.21894/jopr.2021.0009.
- Babu, K B; Mathur, R K; Anitha, P; Ravichandran, G and Bhagya, H P (2021). Phenomics, genomics of oil palm (*Elaeis guineensis* Jacq.): Way forward for making sustainable and high yielding quality oil palm. *Physiol. Mol. Biol. Plants*, 27(3): 587-604. DOI: 10.1007/s12298-021-00964-w.
- Bahariah, B; Masani, M Y A; Rasid, O A and Parveez, G K A (2021). Multiplex CRISPR/Cas9-mediated genome editing of the FAD2 gene in rice: a model genome editing system for oil palm. *J. Genet. Eng.*

- Biotechnol.*, 19(1): 86. DOI: 10.1186/s43141-021-00185-4.
- Behera, S K; Suresh, K; Shukla, A K; Kamireddy, M; Mathur, R K and Majumdar K (2021). Soil and leaf potassium, calcium, and magnesium in oil palm (*Elaeis guineensis* Jacq.) plantations grown on three different soils of India: Status, stoichiometry and relations. *Ind. Crops Prod.*, 168(3): 113589.
- Belkova, B; Chytilova, L; Kocourek, V; Slukova, M; Mastovska, K; Kyselka, J and Hajslova, J (2021). Influence of dough composition on the formation of processing contaminants in yeast-leavened wheat toasted bread. *Food Chem.*, 338(1): 127715.
- Bukhari, N A; Loh, S K; Luthfi, A A I; Abdul, P M; Nasrin, A B; Harun, S and Jahim, J M (2021). Whole slurry saccharification of mild oxalic acid-pretreated oil palm trunk biomass improves succinic acid production. *Ind. Crops Prod.*, 171: 113854.
- Cecilia, J A; Plata, D B; Saboya, R M A; Luna, F M T; Cavalcante, C L and Rodriguez-Castellon, E (2020). An overview of the biolubricant production process: Challenges and future perspectives. *Processes*, 8(3): 257. DOI: 10.3390/pr8030257.
- Chaijan, M and Panpipat, W (2021). Pre-neutralized crude palm oil as natural colorant and bioactive ingredient in fish sausage prepared from tilapia (*Oreochromis niloticus*). *LWT*, 135: 110289.
- Chan, C H; Manap, N I A; Din, N S M N M; Hazmi, A S A; Kow, K W and Ho, Y K (2021a). Strategy to scale up microwave synthesis with insight into the thermal and non-thermal effects from energy-based perspective. *Chem. Eng. Process.*, 168: 108594. DOI: 10.1016/j.cep.2021.108594.
- Chan, Y J; Lee, H W and Selvarajoo, A (2021b). Comparative study of the synergistic effect of decanter cake (DC) and empty fruit bunch (EFB) as the co-substrates in the anaerobic co-digestion (ACD) of palm oil mill effluent (POME). *Environmental Challenges*, 5: 100257.
- Cheyns, E and Rafflebeau, S (2005). Family agriculture and the sustainable development issue: Possible approaches from the African oil palm sector. The example of Ivory Coast and Cameroon. *OCL Oilseeds and Fats, Crops and Lipids*, 12(2): 111-120. DOI: 10.1051/ocl.2005.0111.
- Choowang, R and Luengchavanon, M (2021). Oil palm trunk powder blended with citric acid directly used as wood adhesive by one step liquefaction reaction. *Ind. Crops Prod.*, 170(2): 113809.
- Chung, A Y K; Zaman, N Q; Manaf, F Y A; Halim, R M and Majid, R A (2021). Palm oil mills odour emission survey based on different POME treatment system. *Jurnal Kejuruteraan*, 33(1): 113-131.
- Darvish, P; Alengaram, U J; Alnahhal, A M; Poh, Y S and Ibrahim, S (2021). Enunciation of size effect of sustainable palm oil clinker sand on the characteristics of cement and geopolymer mortars. *J. Build. Eng.*, 44(3165): 103335.
- Divinechocolate (2022). The divine difference. <https://www.divinechocolate.com>, accessed on 17 May 2022.
- Donfack, L S; Röhl, A; Ellsäßer, F; Ehbrecht, M; Irawan, B; Hölscher, D; Knohl, A; Kreft, H; Siahaan, E J; Sundawati, L; Stiegler, C and Zemp, C D (2021). Microclimate and land surface temperature in a biodiversity enriched oil palm plantation. *For. Ecol. Manag.*, 497: 119480.
- Duarte-Forero, J; Mendoza-Casseres, D and Valencia-Ochoa, G (2021). Energy, Exergy, and emissions (3E) assessment of a low-displacement engine powered by biodiesel blends of palm oil mill effluent (POME) and hydroxy gas. *Ther. Sci. Eng. Prog.*, 26(8): 101126.
- Fahrizal, M; Sarifuddin and Sabrina, T (2021). Potential of *Syncephalastrum racemosum* and *Rhizopus arrhizus* isolated from oil palm trunks produce chitosans that inhibit the growth of *Ganoderma boninense*. *J. Oil Palm Res.*, 33(2): 381-386.
- FAO (2019). CODEX Alimentarius, CXC 79-2019. Code of practice for the reduction of 3-monochloropropane-1,2- diol esters (3-MCPDEs) and glycidyl esters (GEs) in refined oils and food products made with refined oils. https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252Fstandards%252FCXC%252B79-2019%252FCXC_079e.pdf, accessed on 19 March 2022.
- Fernando, J S R; Premaratne, M; Dinalankara, D M S D; Perera, G L N J and Ariyadasa, T U (2021). Cultivation of microalgae in palm oil mill effluent (POME) for astaxanthin production and simultaneous phycoremediation. *J. Environ. Chem. Eng.*, 9(4): 105375.
- Filho, W R L L; Rodrigues, F H S; Ferreira, I V L; Correa, L O; Cunha, R L and Pinheiro, H

- A (2021). Physiological responses of young oil palm (*Elaeis guineensis* Jacq.) plants to repetitive water deficit events. *Ind. Crops Prod.*, 172: 114052.
- Fitzherbert, E B; Struebig, M J; Morel, A; Danielsen, F; Brühl, C A; Donald, P F and Phalan, B. (2008). How will oil palm expansion affect biodiversity?. *Trends Ecol. Evol.*, 23(10): 538-545.
- Gan, S T; Teo, C J; Manirasa, S; Wong, W C and Wong, C K (2021). Assessment of genetic diversity and population structure of oil palm (*Elaeis guineensis* Jacq.) field genebank: A step towards molecular-assisted germplasm conservation. *PLoS ONE*, 16(7): e0255418. DOI: 10.1371/journal.pone.0255418.
- Grand View Research (2021). Bio-based polyurethane market size, share and trends analysis report by product (rigid foam, coatings, adhesives and sealants, flexible foam), by end use (packaging, building and construction), and segment forecasts, 2021-2028. <https://www.grandviewresearch.com/industry-analysis/bio-based-polyurethane-industry>, accessed on 27 December 2021.
- Hadi, N A; Han, N M; Majid, R A and Mat, C R C (2021). The effect of microwave treatment and delayed harvesting on oil palm fruitlets (*Elaeis guineensis*) oil quality. *J. Oil Palm Res.*, 33(4): 678-688. DOI: 10.21894/jopr.2021.0015.
- Hamada, H M; Alattar, A A; Yahaya, F M; Muthusamy, K and Tayeh, B A (2021). Mechanical properties of semi-lightweight concrete containing nano-palm oil clinker powder. *Phys. Chem. Earth (2022), Parts A/B/C*, 121: 102977.
- Harith, H H; Mohd, M F and Sowat, S N (2021). A preliminary investigation on upper limb exoskeleton assistance for simulated agricultural tasks. *Appl. Ergon.*, 95: 103455.
- Haryati, Z; Subramaniam, V; Noor, Z Z; Loh, S K and Aziz, A A (2022). Social life cycle assessment of crude palm oil production in Malaysia. *Sustain. Prod. Consum.*, 29: 90-99.
- Hashim, Z; Muhamad, H; Chan, K W; Choo, Y M and Wahid, M B (2010). Life cycle assessment for oil palm fresh fruit bunch production from continued land use for oil palm planted on mineral soil (Part 2). *J. Oil Palm Res.*, 22: 887-894.
- Hassim, N A M; Ismail, N H; Kanagaratnam, S; Isa, W R A and Dian, N L H M (2021a). Quality of commercial palm-based cooking oil packed in plastic pouch and polyethylene terephthalate (PET) bottle. *J. Oil Palm Res.*, 33(3): 493-513.
- Hassim, N A M; Kanagaratnam, S and Dian, N L H M (2021b). Blended palm fractions as confectionery fats: A preliminary study. *J. Oil Palm Res.*, 33(2): 360-380.
- Hervas, A (2021). Mapping oil palm-related land use change in Guatemala, 2003-2019: Implications for food security. *Land Use Policy*, 109: 105657.
- Hilal, Y Y; Yahya, A; Ismail, W I W and Asha'ari, Z H (2021). Neural networks method in predicting oil palm FFB yields for the Peninsular States of Malaysia. *J. Oil Palm Res.*, 33(3): 400-412.
- Hishamuddin, E; Abd Razak, R A; Yeoh, C B and Ahmad Tarmizi, A H (2022). Assessment of trans fatty acid levels in refined palm-based oils and commercial vegetable oils in the Malaysian market. *J. Oil Palm Res.*, 34(1): 129-138. DOI: 10.21894/jopr.2021.0029.
- Hoong, S S; Arniza, M Z; Mariam, N M D N S; Armylisas, A H N, Tang, S W; Ismail, T N M T and Yeong, S K (2022). Synthesis and physicochemical properties of new estolide esters as potential biolubricant base oil. *J. Oil Palm Res.*, 34(1): 152-166. DOI: 10.21894/jopr.2021.0032.
- Huang, Z; Xie, D; Cao, Z; Guo, Z; Chen, L; Jiang, L; Sui, X and Wang, Z (2021). The effects of chloride and the antioxidant capacity of fried foods on 3-chloro-1, 2-propanediol esters and glycidyl esters during long-term deep-frying. *LWT*, 145: 111511.
- Hussin, S H; Seman, I A; Rusli, M H; Mohamed, M S and Sapak, Z (2021). Herbicide effects on *Ganoderma boninense* infection in oil palm seedlings. *J. Oil Palm Res.*, 33(1): 56-63.
- Iberahim, N; Sethupathi, S; Bashir, M J K; Kanthasamy, R and Ahmad, T (2022). Evaluation of oil palm fiber biochar and activated biochar for sulphur dioxide adsorption. *Sci. Total Environ.*, 805(2020): 150421.
- Ibrahim, N A; Alimon, A R; Yaakub, H; Samsudin, A A; Candyrine, S C L; Wan Mohamed, W N; Md Noh, A; Fuat, M A and Saminathan, M (2021). Effects of vegetable oil supplementation on rumen fermentation and microbial population in ruminant: A review. *Trop. Anim. Health Prod.*, 53(4): 1-11.
- Idris, N A; Loh, S K; Lau, H L N; Yau, T C; Mustafa, E M; Vello, V and Moi, P S (2018). Palm oil mill effluent as algae cultivation medium for biodiesel production. *J. Oil Palm Res.*, 30(1): 141-149.

- Ishak, N A; Tahir, N I; Mohd Sa'id, S N; Gopal, K; Othman, A and Ramli, U S (2021). Comparative analysis of statistical tools for oil palm phytochemical research. *Heliyon*, 7(2): e06048.
- Ismail, T N M T; Ibrahim, N A; Palam, K D P; Sendijarevic, A; Sendijarevic, I; Schiffman, C M; Hoong, S S; Noor, M A M; Yeong, S K; Malek, E A; Zainuddin, E and Sendijarevic, V (2021). Improved dynamic properties of thermoplastic polyurethanes made from co-monomeric polyester polyol soft segments based on azelaic acid. *J. Appl. Polym. Sci.*, 138(33): 50815. DOI: 10.1002/app.50815.
- Istadi, I; Riyanto, T; Khofiyanda, E; Buchori, L; Anggoro, D D; Sumantri, I; Putro, B H S and Firnanda, A S (2021). Low-oxygenated biofuels production from palm oil through hydrocracking process using the enhanced spent RFCC catalysts. *Bioresource Technology Reports*, 14: 100677.
- Ithnin, M; Vu, W T; Shin, M G; Suryawanshi, V; Sherbina, K; Zolkafli, S H; Norhalida, M S; Mohd Din, A; Abdullah, N; Mustafa, S; Marjuni, M; Rajanaidu, N; Kushairi, A; Marjoram, P; Nuzhdin, S V; Chang, P L and Singh, R (2021). Genomic diversity and genome-wide association analysis related to yield and fatty acid composition of wild American oil palm. *Plant Sci.*, 304(2): 110731.
- Jalil, N; Lau, H L N and Jalal, R I A (2021). The cold flow properties of palm biodiesel for diesel blends mandate in Malaysia's highlands. *J. Oil Palm Res.*, 34(1): 116-128. DOI: 10.21894/jopr.2021.0027.
- Jamshaid, M; Masjuki, H H; Kalam, M A; Zulkifli N W M; Arslan, A and Qureshi, A A (2022). Experimental investigation of performance, emissions and tribological characteristics of B20 blend from cottonseed and palm oil biodiesels. *Energy*, 239: 121894.
- Jaroenkietkajorn, U and Gheewala, S H (2021). Understanding the impacts on land use through GHG-water-land-biodiversity nexus: The case of oil palm plantations in Thailand. *Sci. Total Environ.*, 800(6): 149425.
- Jin, C; Liu, X; Sun, T; Ampah, J D; Geng, Z; Ikram, M; Ji, J; Wang, G and Liu, H (2021). Preparation of ethanol and palm oil/palm kernel oil alternative biofuels based on property improvement and particle size analysis. *Fuel*, 305: 121569.
- Jin, L; Yarra, R; Zhou, L and Cao, H (2022). The auxin response factor (ARF) gene family in oil palm (*Elaeis guineensis* Jacq.): Genome-wide identification and their expression profiling under abiotic stresses. *Protoplasma*, 259(1): 47-60. DOI: 10.1007/s00709-021-01639-9.
- Julio, A A V; Batlle, E A O; Trindade, A B; Nebra, S A; Reyes, A M M and Palacio, J C E (2021). Energy, exergy, exergoeconomic, and environmental assessment of different technologies in the production of bio-jet fuel by palm oil biorefineries. *Energy Convers. Manag.*, 243(7): 114393.
- Kadier, A; Wang, J; Chandrasekhar K; Abdeshahian, P; Amirul Islam, M; Ghanbari, F; Bajpai, M; Katoch, S S; Bhagawati, P B; Li, H; Kalil, M S; Hamid, A A; Hasan, H A and Ma, P C (2021). Performance optimization of microbial electrolysis cell (MEC) for palm oil mill effluent (POME) wastewater treatment and sustainable Bio-H₂ production using response surface methodology (RSM). *Int. J. Hydrog. Energy*. DOI: 10.1016/j.ijhydene.2021.09.259.
- Kaewchada, A; Akkarawatkhoosith, N; Bunpim, D; Bangjang, T; Ngamcharussrivichai, C and Jaree, A (2021). Production of bio-hydrogenated diesel from palm oil using Rh/HZSM-5 in a continuous mini fixed-bed reactor. *Chem. Eng. Process.*, 168(338): 108586.
- Kamu, A; Phin, C K; Seman, I A; Gabda, D and Mun, H C (2021). Estimating the yield loss of oil palm due to *Ganoderma* basal stem rot disease by using Bayesian Model Averaging. *J. Oil Palm Res.*, 33(1): 46-55.
- Kanagaratnam, S; Teng, K T; Ismail, N H; Hassim, N A M; Isa, W R A and Dian, N L H M (2021). Characteristics of retail refrigerated and non-refrigerated margarines/fat spreads sold in Malaysia. *J. Oil Palm Res.*, 33(4): 689-702. DOI: 10.21894/jopr.2021.0006.
- Khai, C T Z; Hung, P K J; Ming, S C; Lian, H K and Hong, L W (2021). Expression of cadherin gene in *Bacillus thuringiensis* Cry1A toxin resistant and susceptible strains of *Tirathaba mundella*. *J. Oil Palm Res.*, 33(2): 248-256.
- Kok, S Y; Namasivayam, P; Ee, G C L and Ong-Abdullah, M (2021). Comparative proteomic analysis of oil palm (*Elaeis guineensis* Jacq.) during early fruit development. *J. Proteomics*, 232: 104052. DOI: 10.1016/j.jprot.2020.104052.
- Krishna, V V and Kubitza, C (2021). Impact of oil palm expansion on the provision of private and community goods in rural Indonesia. *Ecol. Econ.*, 179: 106829.

- Kuek, S L; Ahmad Tarmizi, A H; Abd Razak, R A; Jinap, S and Sanny, M (2021). Vitamin A and E homologues impacting the fate of acrylamide in Equimolar Asparagine-glucose Model system. *Antioxidants*, 10(7): 993.
- Kusumawati, S A; Yahya, S; Hariyadi; Mulatsih, S and Istina, I N (2021). The dynamic of carbon dioxide (CO₂) emission and land coverage on intercropping system on oil palm replanting area. *J. Oil Palm Res.*, 33(2): 267-277.
- Leow, S S; Fairus, S and Sambanthamurthi, R (2021a). Water-soluble palm fruit extract: composition, biological properties, and molecular mechanisms for health and non-health applications. *Crit. Rev. Food Sci. Nutr.* DOI: 10.1080/10408398.2021.1939648.
- Leow, S S; Fairus, S and Sambanthamurthi, R (2021b). Inhibition of cholinesterases by water-soluble palm fruit extract. *J. Oil Palm Res.*, 34(1): 139-151. DOI: 10.21894/jopr.2021.0028.
- Liew, Z K; Chan, Y J; Ho, Z T; Yip, Y H; Teng, M C; Ameer Abbas, A I T; Chong, S; Show, P L and Chew, C L (2021). Biogas production enhancement by co-digestion of empty fruit bunch (EFB) with palm oil mill effluent (POME): Performance and kinetic evaluation. *Renew. Energ.*, 179: 766-777.
- Lim, C H; Cheah, Z H; Lee, X H; How, B S; Ng, W P Q; Ngan, S L; Lim, S and Lam, H L (2021a). Harvesting and evacuation route optimisation model for fresh fruit bunch in the oil palm plantation site. *J. Clean. Prod.*, 307: 127238.
- Lim, Y F; Chan, Y J; Hue, F S; Ng, S C and Hashma, H (2021b). Anaerobic co-digestion of palm oil mill effluent (POME) with decanter cake (DC): Effect of mixing ratio and kinetic study. *Bioresource Technology Reports*, 15: 100736.
- Loganathan, R; Selvaduray, K R; Nesaretnam, K and Radhakrishnan, A K (2021). Palm tocotrienols cause cleavage of poly-(adp)-ribose polymerase enzyme and down-regulation of cyclooxygenase-2 protein level in human breast cancer cells. *J. Oil Palm Res.*, 33(1): 119-128.
- Loh, J M; Amelia; Gourich, W; Chew, C L; Song, C P and Chan, E S (2021). Improved biodiesel production from sludge palm oil catalyzed by a low-cost liquid lipase under low-input process conditions. *Renew. Energ.*, 177: 348-358.
- Mahmud, M S and Chong, K P (2021). Formulation of biofertilizers from oil palm empty fruit bunches and plant growth-promoting microbes: A comprehensive and novel approach towards plant health. *J. King Saud Univ. Sci.*, 33(8): 101647.
- Mainil, R I and Matsumura, Y (2021). Effect of heating rate on gasification and phosphorus recovery for palm oil mill effluent in supercritical water. *J. Supercrit. Fluids*, 173: 105217.
- Makcharoen, M; Kaewchada, A; Akkarawatkhoosith, N and Jaree, A (2021). Biojet fuel production via deoxygenation of crude palm kernel oil using Pt/C as catalyst in a continuous fixed bed reactor. *Energy Convers. Manag.*, 12: 100125.
- Mansor, H N; Nazirah, C J; Johari, M A; Parthiban, K and Tan, S P (2021). Acceptance of good agricultural practices (GAP) among independent oil palm smallholders in Malaysia. *International Journal of Modern Trends in Social Sciences*, 4(16): 1-12. DOI: 10.35631/IJMTSS.416001.
- Mariam, N M D N S; Hoong, S S; Arniza, M Z; Adnan, S; Ismail, T N M T; Yeong, S K and Yusop, M R (2021). Optimisation of reaction parameters for the synthesis of solketal levulinate as potential biodiesel additive. *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0052.
- Martin, A A; Fodjo, E K; Marc, G B I; Albert, T and Kong, C (2021). Simple and rapid detection of free 3-monochloropropane-1, 2-diol based on cysteine modified silver nanoparticles. *Food Chem.*, 338: 127787.
- Martinez, A; Camberato, J J; Owens, P and Ashtekar, J (2021). Using terrain algorithms on a digital elevation model to evaluate yield variability in oil palm. *J. Oil Palm Res.*, 33(1): 84-92.
- Masharuddin, S M S; Karim, Z A A; Said, M A M; Amran, N H and Ismael, M A (2021). The evolution of a single droplet water-in-palm oil derived biodiesel emulsion leading to micro-explosion. *Alex. Eng. J.*, 61(1): 541-547.
- MATRADE (2022). Top 10 major export products 2021. <https://www.matrade.gov.my/en/malaysian-exporters/services-for-exporters/trade-market-information/trade-statistics/28-malaysian-exporters/trade-statistics/5255-top-10-major-export-products-2021>, accessed on 13 February 2022.
- Ming, S C; Hung, P K J; Ming, K Y; Aziz, Z F A and Huat, O K (2021). Economic injury level of oil palm bunch moth, *Tirathaba mundella* walker for pest management recommendations in oil palm production. *J. Oil Palm Res.*, 33(1): 37-45.

- Mohamaddan, S; Rahman, M A; Andrew Munot, M; Tanjong, S J; Deros, B M; Md Dawal, S Z and Case, K (2021). Investigation of oil palm harvesting tools design and technique on work-related musculoskeletal disorders of the upper body. *Int. J. Ind. Ergon.*, 86: 103226.
- Mohamad, S A; Sharif, M N Y; Ahmad, S N; Masri, M M M; Hung, K J and Kamarudin, N (2021). Population density of *Elaeidobius kamerunicus* FAUST in different spikelet position at anthesising male inflorescence of *Elaeis guineensis* Jacq. in Sabah and Sarawak, Malaysia. *J. Oil Palm Res.*, 33(1): 21-36.
- Mohammad, R; Pebrian, D E; Azmi, M A and Husin, E M (2021). Mapping the nitrogen status on immature oil palm area in Malaysian oil palm plantation with autopilot tractor-mounted active light sensor. *J. Oil Palm Res.*, 33(4): 629-642.
- Mohd-Azlan, J and Lok, L (2021). Is there a sustainable future for wildlife in oil palm plantations in Malaysia? *J. Oil Palm Res.*, 33(4): 732-738.
- Mohd Firdaus, O; Rohaya, M H; Miskandar, M S and Astimar, A A (2021). Nutrient enhancement of palm kernel cake via solid state fermentation by locally isolated *Rhizopus oryzae* ME01. *J. Oil Palm Res.*, 34(1): 92-103. DOI: 10.21894/jopr.2021.0022.
- Mohd, N K; Lim, W H; Armylisas, A H N and Yeong, S K (2021a). Potential application of palm oil products as electrical insulating medium in oil-immersed transformer. *Environ. Prog. Sustain. Energy*, 40(6): e13728. DOI: 10.1002/ep.13728.
- Mohd, N K; Yeong, S K; Ibrahim, N A; Nor, S M M; Yunus, W M Z W; Ghazali, M J and Lim, W H (2021b). Corrosion inhibition, adsorption and thermodynamic properties of hydrophobic-tailed imines on carbon steel in hydrochloric acid solution: A comparative study. *J. Adhes. Sci. Technol.*, 35: 2558-2579. DOI: 10.1080/01694243.2021.1892426.
- Mos, H; Harun, M H; Khoon, K H; Jantan, N M; Razak, A A; Shahabuddin, N A; Othman, H; Kamarudin, N; Parveez, G K A; Din, A K; Selliah, P; Salam, N D and Yusup, Y (2021). Soil carbon dioxide (CO₂) efflux rate and oil palm yield from different peat types in Sarawak, Malaysia. *J. Oil Palm Res.*, 33(2): 257-266.
- MPIC (2018). *The employment survey in oil palm plantations, Malaysia 2018*. Ministry of Plantation Industries and Commodities, Putrajaya.
- MPOB (2022a). *Malaysian Oil Palm Statistics 2021*. 41st edition. MPOB, Bangi.
- MPOB (2022b). *Review of the Malaysian Oil Palm Industry 2021*. MPOB, Bangi.
- MPOB (2021). *Report on Labour Situation in the Malaysian Oil Palm Plantation Sector*. Internal MPOB Quarterly Reports. Unpublished.
- MPOB (2020). *Report on Labour Situation in the Malaysian Oil Palm Plantation Sector*. Internal MPOB Quarterly Reports. Unpublished.
- MPOB (2019). *Report on Labour Situation in the Malaysian Oil Palm Plantation Sector*. Internal MPOB Quarterly Reports. Unpublished.
- Muanruksa, P; Wongsirichot, P; Winterburn, J and Kaewkannetra, P (2021). Valorization of palm oil soap stock waste toward for biodiesel production: Process optimization under zero waste concept. *Biomass Bioenergy*, 154: 106231.
- Myint, K A; Zulkifli, Y; Rafii, M Y; Oladosu, Y; Abd Samad, M Y; Ramlee, S I; Mustafa, S; Arolu, F; Abdullah, N; Marjuni, M and Mohd Din (2021). A genetic diversity assessment of MPOB-Senegal oil palm germplasm using microsatellite markers. *BioMed Res. Int.* DOI: 10.1155/2021/6620645.
- Nadzirah, A; Chan, P L; Chan, K L; Ong, P W; Morris, P E; Ong-Abdullah, M; Subhi, S M and Low, E T L (2022). Determination of reliable reference genes for reverse transcription quantitative real-time PCR from oil palm transcriptomes. *J. Oil Palm Res.* DOI: 10.21894/jopr.2022.0002.
- Nagapan, G; Goh, Y M; Dian, N L H M; Idris, C A C; Selvaduray, K R and Balasundram, N (2021). Effects of interesterified fats on lipoprotein sub fractions and hepatic gene expressions in a hamster model. *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0046.
- Nagappan, J; Kadri, F; Chin, C F; Cooper, R M; May, S T; Abu Seman, I and Low, E T L (2021). A rapid and efficient DNA extraction protocol for *Ganoderma zonatum*, a basal and upper stem rot pathogen of oil palm in Malaysia. *J. Oil Palm Res.*, 33(1): 12-20. DOI: 10.21894/jopr.2020.0058.
- Nasrin, A B; Loh, S K; Sukiran, M A; Bukhari, N A; Aziz, A A; Lim, J; Lim, S and Chin, E (2021). Production and characterization of low-ash empty fruit bunches pellets as a solid biofuel. *BioEnergy Res.*, 15: 517-529. DOI: 10.1007/s12155-021-10316-x.
- Nazirah, C J; Humaira, M T; Zaki, A; Sohimi, M R and Ainul, S S (2021). Workforces among oil palm independent smallholders (OPISH). *J. Oil Palm and Palm Oil Research*, 2(2): 91-105.

- Ng, W Z; Obon, A A; Lee, C L; Ong, Y H; Gourich, W; Maran, K; Tang, D B Y; Song, C P and Chan, E S (2021). Techno-economic analysis of enzymatic biodiesel co-produced in palm oil mills from sludge palm oil for improving renewable energy access in rural areas. *Energy*, 243: 122745. DOI: 10.1016/j.energy.2021.122745.
- Noor, M H M; Lee, W J; Azli, M F Z M; Ngadi, N; Mohamed, M; Inuwa, I M and Opotu, L A (2021a). Microwave- vs. ultrasonic-synthesis of magnetic *Moringa oleifera* coagulant for the reduction of chemical oxygen demand in palm oil wastewater. *Environ. Technol. Innov.*, 24: 102069.
- Noor, N M; Ismail, T N M T; Noor, M A M; Palam, K D P; Sattar, M N; Hanzah, N A; Adnan, S and Yeong, S K (2021b). Physicochemical properties of palm olein-based polyols prepared using homogeneous and heterogeneous catalysts. *J. Oil Palm Res.*, 34(1): 167-176. DOI: 10.21894/jopr.2021.0034.
- Norizan, M S; Wayayok, A; Karim, Y A; Abdullah, A F and Mahadi, M R (2021). Quantitative approach for irrigation requirement of oil palm: Case study in Chuping, Northern Malaysia. *J. Oil Palm Res.*, 33(2): 278-288.
- Nur Azreena, I; Lau, H L N; Asikin-Mijan, N; Hassan, M A; Izham, S M; Kennedy, E; Stockenhuber, M; Mastuli, M S; Alharthi, F A; Alghamdi, A A and Taufiq-Yap, Y H (2021). A promoter effect on hydrodeoxygenation reactions of oleic acid by zeolite beta catalysts. *J. Anal. Appl. Pyrolysis*, 155: 105044.
- Nur, H B; Parthiban, K; Khairuman, H; Johari, M A; Nursuhana, D and Mohd, K A I (2021). Acceptance level of independent oil palm smallholders in Malaysia towards extension services. *International Journal of Modern Trends in Social Sciences*, 4(18): 17-33. DOI: 10.35631/IJMTSS.418003.
- Oil World (2021). *Oil World Monthly*. No. 50, Vol. 64. 17 December 2021. ISTA Mielke GmbH, Germany.
- Oil World (2022). *Oil World Weekly Statistics Update*. 1 April 2022. ISTA Mielke GmbH, Germany.
- Ooi, L C L; Low, E T L; Ong-Abdullah, M; Rajanaidu, N; Ting, N C; Nagappan, J; Abd Manaf, M A; Chan, K L; Halim, M A; Azizi, N; Omar, W; Murad, A J; Lakey, N; Ordway, J M; Favello, A; Budiman, M A; Van Brunt, A; Beil, M; Leininger, M T; Jiang, N; Smith, S W; Brown, C R; Kuek, A C S; Bahrain, S; Hoynes-O'Connor, A; Nguyen, A Y; Chaudhari, H G; Shah, S A; Choo, Y M; Sambanthamurthi, R and Singh, R (2016). Non-*tenera* contamination and the economic impact of SHELL genetic testing in the Malaysian independent oil palm industry. *Front. Plant Sci.*, 7: 771. DOI: 10.3389/fpls.2016.00771.
- Ooi, S E; Feshah, I; Azimi, N; Sarpan, N; Nabeel, A; Lim, C C; Choo, C N; Wong, W C; Wong, F H; Wong, C K and Ong-Abdullah, M (2021). Leaf transcriptomic signatures for somatic embryogenesis potential of *Elaeis guineensis*. *Plant Cell Rep.*, 40(7): 1141-1154. DOI: 10.1007/s00299-021-02698-1.
- Our World in Data (2021). Forests and deforestation. <https://ourworldindata.org/forests-and-deforestation>, accessed on 12 February 2022.
- Panarmasar, N; Hinchiranan, N and Kuchonthara, P (2021). Catalytic hydrotreating of palm oil for bio-jet fuel production over Ni supported on mesoporous zeolite. *Mater. Today: Proc.*, 57: 1082-1087. DOI: 10.1016/j.matpr.2021.09.385.
- Parsons, S; Raikova, S and Chuck, C J (2020). The viability and desirability of replacing palm oil. *Nat. Sustain.*, 3(6): 412-418. DOI: 10.1038/s41893-020-0487-8.
- Parveez, G K A; Ahmad Tarmizi, A H; Sundram, S; Loh, S K; Ong-Abdullah, M; Poo Palam, K D; Salleh, K M; Ishak, S M and Idris, Z (2021). Oil palm economic performance in Malaysia and R&D progress in 2020. *J. Oil Palm Res.*, 33(2): 181-214.
- Parveez, G K A; Hishamuddin, E; Loh, S K; Ong-Abdullah, M; Salleh, K M; Bidin, M N I Z; Sundram, S; Hasan, Z A A and Idris, Z (2020). Oil palm economic performance in Malaysia and R&D progress in 2019. *J. Oil Palm Res.*, 32(2): 159-190.
- Phichitsurathaworn, N; Simasatitkul, L; Amornraksa, S; Anantpinijwatna, A; Charoensuppanimit, P and Assabumrungrat, S (2021). Techno-economic analysis of co-production of bio-hydrogenated diesel from palm oil and methanol. *Energy Convers. Manag.*, 244: 114464.
- Poopalam, K D; Raghunanan, L; Bouzidi, L; Yeong, S K and Narine, S S (2021). Aliphatic fatty diamide as renewable phase change materials for thermal energy storage. *J. Energy Storage*, 42: 102934. DOI: 10.1016/j.est.2021.102934.
- Purba, E and Sipayung, R (2021). Confirmation and control of glyphosate-resistant biotype of goosegrass (*Eleusine indica* L.) in Sumatran oil palm. *J. Saudi Soc. Agric. Sci.* DOI: 10.1016/j.jssas.2021.10.010.
- Rahimi, M S (2021). *Management of Sustainable Palm Oil: Policies and Environmental Considerations*. 1st edition. UKM, Bangi. p. 41-54.

- Rahman, N; Giller, K E; de Neergaard A; Magid, J, de Ven, G V and Bruun, T B (2021). The effects of management practices on soil organic carbon stocks of oil palm plantations in Sumatra, Indonesia. *J. Environ. Manag.*, 278: 111446.
- Rajanaidu, N; Kushairi, A and Mohd Din, A (2017). *Monograph Oil Palm Genetic Resources*. MPOB, Bangi. 289 pp.
- Ramli, N A S; Noor, M A M and Ismail, T N M T (2021). Determination of sodium and potassium contents in palm-based polyols using graphite furnace atomic absorption spectrometer. *Chem. Pap.*, 75: 2561-2574. DOI: 10.1007/s11696-020-01493-8.
- Ratnasari, A; Syafiuddin, A; Boopathy, R; Malik, S; Mehmood, M A; Amalia, R; Prastyo, D D and Zaidi, N S (2022). Advances in pretreatment technology for handling the palm oil mill effluent: Challenges and prospects. *Bioresour. Technol.*, 344(B): 126239.
- Rizali, A; Karindah, S; Nugroho, C T and Rahardjo, B T (2021). Similarity of ant communities increases with isolation from natural habitat and abundance of invasive ants in oil palm plantations of Central Borneo. *Glob. Ecol. Conserv.*, 28: e01690.
- Rodrigues Neto, J C; Vieira, L R; de Aquino Ribeiro, J A; de Sousa, C A F; Souza Júnior, M T and Abdelnur, P V (2021). Metabolic effect of drought stress on the leaves of young oil palm (*Elaeis guineensis*) plants using UHPLC-MS and multivariate analysis. *Sci. Rep.*, 11: 18271. DOI: 10.1038/s41598-021-97835-x.
- Rodriguez, A C; D'Aronco, S; Schindler, K and Wegner, J D (2021). Mapping oil palm density at country scale: An active learning approach. *Remote Sensing of Environment*, 261: 112479.
- RSPO (2015). *A Shared Vision 100% Sustainable Palm Oil in Europe: A Snapshot of National Initiatives*. RSPO, Kuala Lumpur, Malaysia. 16 pp.
- Rudolf, K; Hennings, N; Dippold, M A; Edison, E and Wollni, M (2021). Improving economic and environmental outcomes in oil palm smallholdings: The relationship between mulching, soil properties and yields. *Agric. Syst.*, 193: 103242.
- Sahu, J N; Karri, R R and Jayakumar, N S (2021). Improvement in phenol adsorption capacity on eco-friendly biosorbent derived from waste palm-oil shells using optimized parametric modelling of isotherms and kinetics by differential evolution. *Ind. Crops Prod.*, 164: 113333.
- Salih, N and Salimon, J (2021). A review of eco-friendly green biolubricants from renewable and sustainable plant oil sources. *Biointerface Res. Appl. Chem.*, 11(5): 13303-13327. DOI: 10.33263/BRIAC115.1330313327.
- Salimon, J; Salih, N and Yousif, E (2012). Industrial development and applications of plant oils and their biobased oleochemicals. *Arab. J. Chem.*, 5(2): 135-145.
- Saminathan, M; Wan Mohamed, W N; Md Noh, A; Ibrahim, N A; Fuat, M A; Kumari Ramiah, S; Lim T C E and Dian, N L H M (2021). Treated oil palm frond and its utilisation as an improved feedstuff for ruminants: An overview. *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0041.
- Sarimana, U; Herrero, J; Pratiwi Erika, P; Indarto, N; Fahmi Wendra, F; Baitha Santika, B; Ritter, E; Sembiring, Z and Dwi Asmono, D (2021). Analysis of genetic diversity and discrimination of oil palm DxP populations based on the origins of *pisifera* elite parents. *Breed. Sci.*, 71(2): 134-143. DOI: 10.1270/jsbbs.20043.
- Saritpongteeraka, K; Natisupacheevin, K; Tan, C; Rehman, S; Charnnok, B; Vaur, L P; Leu, S-Y and Chaiprapat, S (2021). Comparative assessment between hydrothermal treatment and anaerobic digestion as fuel pretreatment for industrial conversion of oil palm empty fruit bunch to methane and electricity - A preparation study to full scale. *Fuel*, 310(C): 122479. DOI: 10.1016/j.fuel.2021.122479.
- Sarker, I H (2021). Data science and analytics: An overview from data-driven smart computing, decision-making and applications perspective. *SN Comp. Sci.*, 2(5): 377. DOI: 10.1007/s42979-021-00765-8.
- Sarpan, N; Tatarinova, T V; Low, E-T L; Ong-Abdullah, M; Sapian, I S and Ooi, S E (2021). Histone modification marks improve identification of oil palm transcription start sites. *J. Oil Palm Res.*, 34(1): 35-45. DOI: 10.21894/jopr.2021.0021.
- Sayed, K; Baloo, L; Kutty, S R B M and Makba, F (2021). Potential biodegradation of Tapis light crude petroleum oil, using palm oil mill effluent final discharge as biostimulant for isolated halotolerant *Bacillus* strains. *Mar. Pollut. Bull.*, 172: 112863.
- Seyum, E G; Bille, N H; Abteu, W G; Ntsomboh-Ntsefong, G and Bell, J M (2021). Genome mapping to enhance efficient marker-assisted selection and breeding of the oil palm (*Elaeis guineensis* Jacq.). *Adv. Biosci. Biotechnol.*, 12: 407-425.

- Shaari, N A; Ahmad Tarmizi, A H and Md Sikin, A (2021). In-house validation of accelerated solvent extraction-gas chromatography-mass spectrometry for the determination of bound 3-and 2-monochloropropanediols (MCPD) and glycidol in food products. *Food Addit. Contam. Part A, Chem. Anal. Control Expo. Risk Assess.* 38(2): 223-236.
- Shafirul, A W; Kamil, A T; Ayatollah, K A R and Humaira, M T (2021). The adaptability of smallholders toward livestock integration with oil palm and income generated. *Jurnal Penyelidikan Sains Sosial*, 4(12): 67-78.
- Shahrul, M N K; Abdullah, S N A; Mas Muniroh, M N; Moradpour, M; Noor Azmi, S and Ong-Abdullah, M (2021). Single nucleotide polymorphisms in oil palm homogenisate geranyl-geranyl transferase promoter for species differentiation and tocotrienol improvement. *Meta Gene.*, 27: 100818. DOI: 10.1016/j.mgene.2020.100818.
- Show, K Y; Lo, E K V; Wong, W S; Lee, J Y; Yan, Y and Lee, D J (2021). Integrated anaerobic/oxic/oxic treatment for high strength palm oil mill effluent. *Bioresour. Technol.*, 338: 125509.
- Shulaev, V; Cortes, D; Miller, G and Mittler, R (2008). Metabolomics for plant stress response. *Physiol. Plant.*, 13(2): 199-208.
- Siddiqui, Y; Surendran, A; Paterson, R R M; Ali, A and Ahmad, K (2021). Current strategies and perspectives in detection and control of basal stem rot of oil palm. *Saudi J. Biol. Sci.*, 28(5): 2840-2849.
- Siliskisoaps (2022). Siliski soaps. <https://www.siliskisoaps.com>, accessed on 17 May 2022.
- Singh, R; Low, E T L; Ooi, L C L; Ong-Abdullah, M; Ting, N C; Nagappan, J; Rajanaidu, N; Mohd Din, A; Rosli, R; Abdul Manaf, M A; Chan, K L; Halim, M A; Azizi, N; Lakey, N; Smith, S W; Budiman, M A; Hogan, M; Bacher, B; Van Brunt, A; Wang, C; Ordway, J M; Sambanthamurthi, R and Martienssen, R A (2013). The oil palm *SHELL* gene controls oil yield and encodes a homologue of SEEDSTICK. *Nature*, 500(7462): 340-344.
- Singh, R; Lee, K T; Ooi, L C L; Low, E T L; Ong-Abdullah, M; Sambanthamurthi, R and Azman, I (2021a). An overview of the development of the oil palm industry and impact of the shell gene innovation as a quality control tool to improve productivity. *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0001.
- Singh, R; Ooi, L C L; Ting, N C; Low, E T L; Ong-Abdullah, M; Rajanaidu, N; Marjuni, M; Mustafa, S; Abdul Manaf, M A; Garner, P; Reed, J; Wischmeyer, C; Beil, M; Bacher, B; Lakey, N D; Ordway, J M and Sambanthamurthi, R (2021b). A genetic platform for predicting and reducing non-*tenera* contamination in oil palm (*Elaeis guineensis*) seed supply. *Tree Genet. Genomes*, 17: 45. DOI: 10.1007/s11295-021-01527-6.
- Sohimi, M R; Humaira, M T; Zaki, A; Mohd, H A H and Ainul, S S (2021). Implementation of crop integration with oil palm under government assistance scheme by oil palm independent smallholders (OPISH) in Malaysia. *Jurnal Penyelidikan Sains Sosial*, 4(12): 22-30.
- Subramaniam, S; Anandha Rao, J S; Ramdas, P; Ng, M H; Kannan Kutty, M; Selvaduray, K R and Radhakrishnan, A K (2021a). Palm gamma-tocotrienol supplementation suppress tumour growth and metastasis in a syngeneic mouse model of breast cancer. *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0048.
- Subramaniam, S; Anandha Rao, J S; Ramdas, P; Ng, M H; Kannan Kutty, M; Selvaduray, K R and Radhakrishnan, A K (2021b). Reduced infiltration of regulatory T cells in tumours from mice fed daily with gamma-tocotrienol supplementation. *Clin. Exp. Immunol.*, 206(2): 161-172.
- Subramaniam, V; Loh, S K and Aziz, A A (2021). GHG analysis of the production of crude palm oil considering the conversion of agricultural wastes to by-products. *Sustain. Prod. Consum.*, 28: 1552-1564.
- Suharjito, Elwirehardja, G N and Prayoga, J S (2021). Oil palm fresh fruit bunch ripeness classification on mobile devices using deep learning approaches. *Comput. Electron. Agric.*, 188: 106359.
- Sulaiman, M R; Mohamad, S A; Masri, M M M; Ahmad, S N and Kamarudin, N (2021a). Preliminary study on efficiency of different time and light source in light traps for capturing population of adult oil palm bunch moth, *Tirathaba mundella* (Lepidoptera: Pyralidae). *J. Oil Palm Res.*, 33(3): 413-424.
- Sulaiman, N; Yeoh, C B; Khairuddin, N S K and Ahmad Bustamam, F K (2021b). Development and validation of an LCMS/MS method for determination of residual 2,4-dichlorophenoxyacetic acid herbicide in palm oil. *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0042.
- Tang, S W; Chan, C H; Mohd, N K; Lim, W H; Hoong, S S; Ismail, T N M T and Yeong, S K (2021). Synthesis and physicochemical properties of low viscosity 2-ethylhexyl alkyl ethers made from palm-based esters as potential biolubricant. *Eur. J. Lipid Sci. Technol.*, 124: 2100072. DOI: 10.1002/ejlt.202100072.

- Tan, P Y and Teng, K T (2021). Role of dietary fat on obesity-related postmenopausal breast cancer: Insights from mouse models and methodological considerations. *Breast Cancer*, 28(3): 556-571.
- Tan, Y Y; Bello, M M and Raman, A A A (2021). Towards cleaner production in palm oil industry: Advanced treatment of biologically-treated POME using palm kernel shell-based adsorbent. *Cleaner Eng. Technol.*, 2: 100079.
- Tapia, J F D; Doliente, S S and Samsatli, S (2021). How much land is available for sustainable palm oil. *Land Use Policy*, 102: 105187.
- Tay, B Y P and Wai, W H (2021). A gas chromatography-mass spectrometry method for the detection of chlorpyrifos contamination in palm-based fatty acids. *J. Am. Oil Chem. Soc.*, 98(8): 881-887.
- Tezara, W; Domínguez, T S T; Loyaga, D W; Ortiz, R N; Chila, V H R and Ortega, M J B (2021). Photosynthetic activity of oil palm (*Elaeis guineensis*) and interspecific hybrid genotypes (*Elaeis oleifera* × *Elaeis guineensis*), and response of hybrids to water deficit. *Sci. Hortic.*, 287: 110263.
- Tivanello, R G; Capristo, M F; Leme, F M; Ferrari, R A; Sampaio, K A; Arisseto, A P and Vicente, E (2021). Mitigation studies based on the contribution of chlorides and acids to the formation of 3-MCPD, 2-MCPD, and glycidyl esters in palm oil. *ACS Food Sci. Technol.*, 1(7): 1190-1197.
- Tjaronge, M W and Caronge, M A (2021). Physico-mechanical and thermal performances of eco-friendly fired clay bricks incorporating palm oil fuel ash. *Materialia*, 17: 101130.
- Tupaz-Vera, A; Ayala-Diaz, I; Barrera, C F and Romero, H M (2021). Selection of elite *dura*-type parents to produce dwarf progenies of *Elaeis guineensis* using genetic parameters. *Agronomy*, 11(12): 2581. DOI: 10.3390/agronomy11122581.
- Uke, A; Nagaoka, E N; Chuah, J A; Zain, N A A; Amir, H G; Sudesh, K; Abidin, N Z H A Z; Hashim, Z and Kosugi, A (2021). Effect of decomposing oil palm trunk fibers on plant growth and soil microbial community composition. *J. Environ. Manag.*, 295: 113050.
- Vargas, L H G; Neto, J C R; de Aquino Ribeiro, J A; Ricci-Silva, M E; Souza, M T Jr; Rodrigues, C M; de Oliveira, A E and Abdelnur, P V (2016). Metabolomics analysis of oil palm (*Elaeis guineensis*) leaf: Evaluation of sample preparation steps using UHPLC-MS/MS. *Metabolomics*, 12: 153. DOI 10.1007/s11306-016-1100-z.
- Vijay, V; Pimm, S L; Jenkins, C N and Smith, S J (2016). The impacts of oil palm on recent deforestation and biodiversity loss. *PLoS ONE*, 11(7): e0159668. DOI: 10.1371/journal.pone.0159668.
- Voon, P T; Toh, S W H; Ng, T K W; Lee, V K M; Yong, X S; Ng, Y T and Nesaretnam, K (2021a). Is palm mid fraction a healthier choice as a cocoa butter equivalent? *J. Oil Palm Res.*, 33(3): 532-541.
- Voon, P T; Toh, S W H; Ng, T K W; Lee, V K M; Yong, X S; Yap, S Y and Nesaretnam, K (2021b). Does palm mid fraction affect adult satiety? *J. Oil Palm Res.*, 33(4): 713-723.
- Wae-hayee, M; Pakdeechot, S; Hanifarianty, S and Sukswan, W (2022). Minimizing water consumption in oil palm sterilization using direct steaming: Effects of sterilization pressure and time. *J. Food Eng.*, 315: 110804.
- Wan Nur Syuhada, W N; Rasid, O A and Parveez, G K A (2021). Molecular cloning of *Elaeis guineensis* phytoene synthase (*Egpsy*) and its expression in mesocarp tissues. *J. Oil Palm Res.*, 33(3): 447-457. DOI: 10.21894/jopr.2020.0113.
- Wong, Sharron; Muharam, F M; Rashed, O and Ahmad, K (2021). Soil fungal composition and diversity in oil palm plantation at Sungai Asap, Sarawak, Malaysia. *J. Oil Palm Res.*, 33(2): 215-226.
- Yaman, Y T; Bolat, G; Saygin, T B and Abaci, S (2021). Molecularly imprinted label-free sensor platform for impedimetric detection of 3-monochloropropane-1, 2- diol. *Sens. Actuators B Chem.*, 328: 128986.
- Yap, C C; Chan, Y J; Loh, S K; Supramaniam, C V; Soh, A C; Chong, M F and Lim, L K (2021a). Pilot-scale investigation of the integrated anaerobic-aerobic bioreactor (IAAB) treating palm oil mill effluent (POME): Startup and performance evaluation. *Ind. Eng. Chem. Res.*, 60(10): 3839-3859.
- Yap, C C; Loh, S K; Chan, Y J; Supramaniam, C V; Chong, M F; Soh, A C; Lim, L K and Loo, L S (2021b). Synergistic effect of anaerobic co-digestion of palm oil mill effluent (POME) with *Moringa oleifera* extract. *Biomass Bioenergy*, 144: 105885.
- Yap, P; Amiratul, A A A R; Mohamad, H A; Mohd, R I and Hafifi, H Z (2021c). Factors influencing certification process of Malaysian Sustainable Palm Oil (MSPO) during the preparation phase for

- independent smallholders in Malaysia. *Oil Palm Industry Economic J.*, 21(1): 13-20.
- Yap, S Y; Voon, P T; Cheah, Y K; Lee, V K M and Selvaduray, K R (2021d). Association of dietary fats with gut microbiota profile: How does palm oil fit in? *J. Oil Palm Res.* DOI: 10.21894/jopr.2021.0004.
- Yaro, N S A; Napiah, M B; Sutanto, M H; Usman, A and Saeed, S M (2021). Performance evaluation of waste palm oil fiber reinforced stone matrix asphalt mixtures using traditional and sequential mixing processes. *Case Stud. Constr. Mater.*, 15: e00783. DOI: 10.1016/j.cscm.2021.e00783.
- Yeap, W C; Norkhairunnisa, C M K; Norfadzilah, J; Muhammad, R M; Appleton, D R and Harikrishna, K (2021). An efficient clustered regularly interspaced short palindromic repeat (CRISPR)/CRISPR-associated protein 9 mutagenesis system for oil palm (*Elaeis guineensis*). *Front. Plant Sci.*, 12: 773656. DOI: 10.3389/fpls.2021.773656.
- Zheng, J; Fu, H; Li, W; Wu, W; Yu, L; Yuan, S; Tao, W Y W; Pang, T K and Kanniah, K D (2021a). Growing status observation for oil palm trees using Unmanned Aerial Vehicle (UAV) images. *ISPRS J. Photogramm. Remote Sensing*, 173: 95-121.
- Zheng, X; Fu, W; Zheng, K; Gao, B; Lin, L; Liu, W; Lin, Z and Fang, Q (2021b). A novel method for the simultaneous determination of esterified 2-/3-MCPD and glycidol in foods by GC-MS/MS. *Food Control*, 123: 107766.
- Zhou, L and Yarra, R (2022). Genome-wide identification and expression analysis of bZIP transcription factors in oil palm (*Elaeis guineensis* Jacq.) under abiotic stress. *Protoplasma*, 259(2): 469-483. DOI: 10.1007/s00709-021-01666-6.
- Zolkafli, S H; Ting, N C; Nik Mohd Sanusi, N S; Ithnin, M; Mayes, S; Massawe, F; Sambanthamurthi, R; Ismail, I; Zainol Abidin, M I; Roowi, S H; Lee, Y P; Hanafi, N F F and Singh, R (2021). Comparison of quantitative trait loci (QTLs) associated with yield components in two commercial *Dura* × *Pisifera* breeding crosses. *Euphytica*, 217: 104. DOI: 10.1007/s10681-021-02825-9.
- Zulqarnain Yusoff, M H M; Ayoub, M; Nazir, M H; Sher, F; Zahid, I and Ameen, M (2021). Solvent extraction and performance analysis of residual palm oil for biodiesel production: Experimental and simulation study. *J. Environ. Chem. Eng.*, 9(4): 105519.