REVIEW ARTICLE

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OIL PALM ECONOMIC PERFORMANCE IN MALAYSIA AND R&D PROGRESS IN 2020

GHULAM KADIR AHMAD PARVEEZ*; AZMIL HAIZAM AHMAD TARMIZI*; SHAMALA SUNDRAM*; SOH KHEANG LOH*; MEILINA ONG-ABDULLAH*; KOSHEELA DEVI POO PALAM*; KAMALRUDIN MOHAMED SALLEH*; SHEILYZA MOHD ISHAK* and ZAINAB IDRIS*

ABSTRACT

The year 2020 faced unprecedented challenge for most of the global economic growth due to the outbreak of Coronavirus disease (COVID-19). Despite a downward trend performance of the Malaysian oil palm industry, particularly for the first half of 2020, the impact is less severe due to the encouraging palm oil export revenue through the National Economic Recovery Plan (PENJANA) which nurtures a notable increase in crude palm oil (CPO) price. In honouring the Malaysian pledge on forest conservation, land expansion for the oil palm cultivation remains stagnant over the years. The effort is now shifting towards enhancing the oil palm yield performance through new planting materials and good agricultural practices, coupled with systematic pest and disease management. Sustainability continues to be the key agenda of the oil palm industry, in moving forward to sustain the industry ecosystem. The industry is now open for innovative palm oil processes to comply with the dynamic and stringent food safety and quality standards and trade regulations. Owing to the distinction in food and feed applicability together with health prospects, translating the information into consumer-friendly language is becoming crucial for effective communication. Valorisation via the concept of 'waste to wealth' has compelled series of innovations in capitalising oil palm co-products for greener bioenergy and oleochemicals, and source of phytonutrients to generate higher earnings without having to heavily rely on palm oil trade as commodity. Mandatory enactment of the Malaysian Sustainable Palm Oil (MSPO) certification scheme has portrayed a success story of showing the utmost commitment towards sustainability. With persistent dedication, the oil palm industry is envisaged to be self-sustaining, amidst the never-ending challenges surrounding economy, well-being and environment.

Keywords: bioenergy, COVID-19, food safety and health, MSPO, oleochemicals, palm oil, sustainability, valorisation.

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INTRODUCTION

Palm oil sector is one of the crucial revenue earners for Malaysia's economy after the electrical and electronic, petroleum and chemicals industries (MATRADE, 2021). The challenges in confronting the COVID-19 pandemic did not jeopardise its ranking as the fourth world's largest producers of oils and fats in 2020 accounting at 8.1% of the global total production (Oil World, 2020). Indeed, Malaysia is more prominent as the major exporter of palm oil, as reflected by 18.3% of the global oils and fats (17.37 million tonnes) while contributing to 34.3% of the total palm oil trade. The prevalence of COVID-19 pandemic, however, has shown less impact to most of the national oil palm industry performance indices particularly after the relaxation of movement restrictions, resumption of economic sectors in most countries and exemption of CPO export duty under the National Economic Recovery Plan or PENJANA. It is also worth to note that the aforesaid pandemic led to unexpectedly positive

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* Malaysian Palm Oil Board,
6 Persiaran Institusi, Bandar Baru Bangi,
43000 Kajang, Selangor, Malaysia.
E-mail: parveez@mpob.gov.my

effects on the national oil palm industry evidenced tremendous increase of 29.2% from the previous year (RM2079.00 t^{-1}), and this further reflected by the improvement of total export revenue by 8.4%.

Over the past few years, palm oil research is geared towards the sustainable development goals across the oil palm supply chain. Despite all the efforts made, palm oil cultivation is recently reported to adversely impacting the environment associated to deforestation, biodiversity and carbon footprint (Meijaard *et al*., 2020). Furthermore, the issues on nutrition and health relating to palm oil are imposed to suppress its applicability and potential use in food applications. Food safety concerns with regard to 3-monochloropropane-1,2-diol esters (3-MCPDE) and glycidyl esters (GE) have reached their pinnacles when the European Commission (EC) implemented the maximum limits of these contaminants in edible oils and fats on 1 January 2021 for 3-MCPDE (Commission Regulation (EU) 2020/1322, 2020) in addition to 19 March 2018 for GE (Commission Regulation (EU) 2018/290, 2018). Notwithstanding this, the world's reliance to palm oil is undeniable witnessing its significant global export in 2020 surpassing, 50% in comparison to other leading vegetable oils (Oil World, 2020). In order to remain sustainable and competitive globally, it is imperative to combat the aggravating environmental issues and move forward so that palm oil meets the quality and safety standards, hence gaining international recognition. Such effort can be seen from the commitment of the Malaysian Government to fully implement sustainable palm oil cultivation and processing practices across the whole value and supply chains through the Malaysian Sustainable Palm Oil (MSPO) certification scheme effectively from 1 January 2020. This initiative would enlighten the image of the national's palm oil in the arena of sustainability and to cater the demand of certified palm oil from the global markets. In order to safeguard the palm oil trade and authenticate the viability of palm oil industry, more proactive research and development (R&D) is needed to address outstanding issues particularly those requiring immediate action.

This article reviews the oil palm industry performance for the year 2020 as well as the key findings from some of the published scholars locally and internationally in the respective year. The discussion will emphasise on the current research advancement and innovation across the oil palm supply chain covering the upstream, midstream and downstream sectors so that the oil palm industry remains competitive and resilient. Finally, this review will highlight the strategies and directions to strive for the betterment of the oil palm industry performance in the coming years.

PERFORMANCE OF THE MALAYSIAN OIL PALM INDUSTRY

The year 2020 has been very tough as the COVID-19 pandemic disrupted the global political, social, economic and financial structures (Verma *et al*., 2021). In the light of the Malaysian palm oil industry, the pandemic has led the industry to experience a slowdown in the production, export demand and prices particularly at the beginning of the year. Approaching second half of the year, many countries have re-opened their economic sectors through the relaxation of movement restrictions and the Malaysian government has exempted the export duty of crude palm oil (CPO), crude palm kernel oil (CPKO) and refined, bleached and deodourised (RBD) palm kernel oil (PKO) from 1 July 2020 until 31 December 2020 under the PENJANA. This positive environment has led to the recovery of export demand of palm oil and other oil palm products despite the tight supply of CPO. In the end, the palm oil stock level in the country has subsequently reduced, hence improving its price. Overall, the year 2020 had witnessed the declining of Malaysian oil palm planted area, CPO production as well as palm oil exports, imports and stocks decline but an unexpected improvement in the CPO price and export revenue of palm oil products in comparison to the previous year.

Planted Area

Oil palm planted area in 2020 had reached 5.87 million hectares, which denoted a marginal drop of 0.6% (5.90 million hectares) recorded in the previous year. This is mainly attributed by the reduction of the planted area in the Peninsular Malaysia by 1.1% or 13 280 ha (*Table 1*). The restriction of the oil palm expansion and the delay in the oil palm replanting are primarily associated with the imposition of movement control order (MCO) that contributes to the downturn in planted area. Sarawak remains the largest oil palm planted state owing 1.58 million hectares or 27.0% of the total Malaysian oil palm planted area, and subsequently Sabah and Pahang with 1.54 million hectares and 0.78 million hectares, respectively.

The oil palm matured area reported for 2020 is 5.23 million hectares which accounts for 89.2% of the total oil palm planted area (*Table 2*). Sarawak has a total of 1.43 million hectares of matured oil palm trees constituted by 90.3% of total oil palm planted area in the respective state. With regard to ownership, oil palm plantation consists of approximately 4.24 million hectares which accounts for 72.2% of the total planted area (*Table 3*). On the other hand, organised and independent smallholders only hold 11.5% and 16.3% of the total share of the oil palm planted area, respectively. In comparison from the previous year, the total planted areas from both organised and independent smallholders have dropped for which the latter encountered 0.4% loss due to the shrinkage in the planted area.

Status of Mills and Plants

A total of 457 oil palm mills in Malaysia are in operation in 2020 with a total processing capacity of 116.81 million tonnes of fresh fruit bunches (FFB) per year of which 53.0% of the oil palm mills were located in the Peninsular Malaysia (58.16 million tonnes) (*Table 4*). The current year also witnessed a 4.40% depreciation in the milling capacity by 83.30% when compared to 87.16% in 2019 as a result of lower FFB production.

In the refining sector, a total of 50 palm oil refineries were in operation in 2020 with a total processing capacity of 25.35 million tonnes of CPO and CPKO. About 35 refineries are located in the Peninsular Malaysia with a total processing capacity of 14.84 million tonnes. The refining capacity showed a reduction of 8.50% from 72.12% to 66.02% in comparison to the previous year due to lower CPO production but higher CPO exportation.

There are a total of 42 Malaysian palm kernel crushers in operation in 2020 with a total processing capacity of 7.17 million tonnes. About 61.90% or 26 palm kernel crushers are located in the Peninsular Malaysia with a total processing capacity of 4.40 million tonnes. The palm kernel crushing capacity declined by 1.50% from 65.47% in 2019 to 64.48% because of inferior palm kernel supply arising from lower FFB production.

In 2020, a total of 20 Malaysian oleochemical plants and 19 biodiesel plants are in operation with processing capacities at 2.63 million tonnes and 2.23 million tonnes, respectively. The oleochemical and biodiesel plants are mainly located in Selangor and Johor with eight and seven oleochemical plants respectively, and six biodiesel plants are located in Selangor and Johor, respectively.

TABLE 1. MALAYSIAN OIL PALM PLANTED AREA AS AT DECEMBER (million hectares)

	Planted area		
	2020	2019	Difference (%)
Peninsular Malaysia	2.74	2.77	(1.1)
Sabah	1.54	1.54	(0.1)
Sarawak	1.58	1.59	(0.1)
Malaysia	5.87	5.90	(0.6)

Source: Department of Statistics Malaysia (2021).

TABLE 2. MALAYSIAN OIL PALM MATURED AREA AS AT DECEMBER (million hectares)

	Matured area		
	2020	2019	Difference (%)
Peninsular Malaysia	2.46	2.44	0.5
Sabah	1.34	1.35	(0.7)
Sarawak	1.43	1.42	0.9
Malaysia	5.23	5.22	0.3

Source: MPOB (2021).

TABLE 3. DISTRIBUTION OF OIL PALM PLANTED AREA BY OWNERSHIP IN MALAYSIA AS AT DECEMBER (million hectares)

Ownership	2020		2019	
	ha	%	ha	%
Plantation	4.24	72.2	4.23	71.7
Organised smallholders	0.67	11.5	0.68	11.6
Independent smallholders	0.96	16.3	0.99	16.7

Source: MPOB (2021).

TABLE 4. NUMBER OF OIL PALM MILLS, REFINERIES, PALM KERNEL CRUSHERS, OLEOCHEMICAL PLANTS AND BIODIESEL PLANTS AND THEIR CAPACITIES IN MALAYSIA IN 2020

Facility	No.	Processing capacity (million tonnes per year)
Oil palm mill		
Peninsular Malaysia	242	58.16
Sabah	132	34.65
Sarawak	83	24.01
Malaysia	457	116.81
Palm oil refinery		
Peninsular Malaysia	35	14.84
Sabah	9	7.24
Sarawak	6	3.28
Malaysia	50	25.35
Palm kernel crusher		
Peninsular Malaysia	26	4.40
Sabah	12	2.07
Sarawak	4	0.70
Malaysia	42	7.17
Oleochemical plant		
Selangor	8	0.80
Johor	7	0.68
Others	5	1.16
Malaysia	20	2.63
Biodiesel plant		
Johor	6	0.85
Selangor	6	0.67
Sabah	3	0.40
Others	4	0.32
Malaysia	19	2.23

Source: MPOB (2021).

CPO Production

Malaysian CPO production in the first quarter of 2020 was significantly lower by 22.1% when compared to the corresponding period of 2019. It is also reported that decreasing CPO production is contributed by lower FFB supply, and partly attributed by the dry season in early 2019, low fertiliser application during low CPO price in 2019 and flood in most areas in Malaysia due to northeast monsoon season (CPOPC, 2020; Leng, 2020). The highest CPO production was recorded in June 2020 (1.89 million tonnes) while the lowest production was observed in January (1.17 million tonnes). Overall, the CPO production in the current year portrayed a drop from 19.86 million tonnes in 2019 to 19.14 million tonnes where Sabah witnessed a notable reduction by 7.7% (*Table 5*).

The FFB yield for 2020 went down by 2.7% (16.73 t ha^{-1}) in comparison to 17.19 t ha^{-1} in 2019 due to lower yield performance in the first quarter of 2020 (*Table 6*). Comparable to that of the CPO production, all regions experienced FFB yield decline, especially in Sabah and Sarawak, which recorded a notable decline of 4.6% and 3.7% to 16.84 t ha^{-1} and 14.99 t ha^{-1}, respectively. Similarly, the oil extraction rate (OER) dropped by 1.4% from 20.21% (2019) to 19.92% in 2020 reflecting the inferior quality of FFB supplied to the palm oil mills (*Table 7*). On a monthly year-on-year comparison, OER performance for 2020 was found lower throughout the year in correspondence to the previous year; June 2020 recorded the lowest OER at 19.47% while the highest OER was achieved in October 2020 at the rate of 20.36%. Sarawak suffered severe OER reduction by 2.0% (19.62%) whereas OER loss in Sabah was published at 1.1% (20.74%).

TABLE 5. MALAYSIAN CRUDE PALM OIL (CPO) PRODUCTION (million tonnes)

	2020	2019	Difference	
			Volume	%
Peninsular Malaysia	10.44	10.58	(0.14)	(1.4)
Sabah	4.65	5.04	(0.39)	(7.7)
Sarawak	4.05	4.24	(0.18)	(4.3)
Malaysia	19.14	19.86	(0.72)	(3.6)

Source: MPOB (2021).

TABLE 6. MALAYSIAN FRESH FRUIT BUNCHES (FFB) PRODUCTIVITY (t ha^{-1})

	2020	2019	Difference	
			Volume	%
Peninsular Malaysia	17.76	17.95	(0.19)	(1.1)
Sabah	16.84	17.66	(0.82)	(4.6)
Sarawak	14.99	15.56	(0.57)	(3.7)
Malaysia	16.73	17.19	(0.46)	(2.7)

Source: MPOB (2021).

TABLE 7. MALAYSIAN OIL EXTRACTION RATE (OER) (%)

	2020	2019	Difference	
			Volume	%
Peninsular Malaysia	19.68	19.93	(0.25)	(1.3)
Sabah	20.74	20.97	(0.23)	(1.1)
Sarawak	19.62	20.03	(0.41)	(2.0)
Malaysia	19.92	20.21	(0.29)	(1.4)

Source: MPOB (2021).

Exports

According to the Department of Statistics Malaysia, the total exports of oil palm products in 2020 stood at 26.59 million tonnes, down by 8.5% against 29.04 million tonnes reported in 2019 because of weakening in palm oil, palm-based oleochemicals and biodiesel exportation (*Table 8*). Exports of palm oil for 2020 was 16.22 million tonnes, which was reflected by a significant decrease of 7.0% from 17.43 million tonnes in 2019, primarily caused by lower CPO production. On the other hand, exports of PKO in 2020 had surged by 13.3% to 1.14 million tonnes from 1.01 million tonnes in 2019 due to the higher demand from the European Union (EU), China and USA. Meanwhile, exports of palm-based oleochemicals and biodiesel had also dropped substantially by 19.4% and 53.7% to 4.41 million tonnes and 0.33 million tonnes, respectively, due to lower demand from the EU and China.

In spite of low exports performance, the total export revenue for palm products had increased by 8.4% to RM73.25 billion from RM67.55 billion in 2019 due to higher export prices of palm oil and other oil palm products in 2020. Export revenue of palm oil and PKO surged by 16.7% and 25.6% to RM45.66 billion and RM4.15 billion in 2020, respectively. In the case of palm-based oleochemicals and biodiesel, the higher prices in 2020 eased the export revenue loss to 9.4% and 40.1%, respectively.

Imports

The importation of Malaysian oil palm products stood at 1.29 million tonnes in 2020, down by 1.7% from 1.31 million tonnes in 2019. Palm oil represents 73.6% of total Malaysian imports of oil palm products for 2020, followed by PKO (21.7%) and palm kernel (4.6%) (*Table 9*). Imports of palm oil declined by 3.1% to 0.95 million tonnes from 0.98 million tonnes in 2019 which was associated with lesser demand from domestic palm oil refining and processing sector by 13.9% to 17.51 million tonnes as against 20.34 million tonnes in 2019.

Closing Stocks

Palm oil closing stocks in December 2020 was lower by 37.0% to 1.27 million tonnes *vis-à-vis* 2.01 million tonnes recorded in December 2019, mainly due to lower palm oil production (*Table 10*). All the three regions in Malaysia experienced a substantial reduction in the palm oil stocks with major drop recorded in Sarawak and Sabah by 52.1% and 45.9% to 0.17 million tonnes and 0.35 million tonnes, respectively.

Price

All major oil palm products were highly traded in 2020 as opposed to 2019 (*Table 11*). Local CPO price peaked by 29.2% or RM606.50 t^{-1} to RM2685.50 t^{-1} when compared to RM2079.00 t^{-1} in 2019. The highest traded CPO price for 2020 was reported in December amounting at RM3620.50 t^{-1} while the lowest was recorded in May at RM2074.00 t^{-1}. The higher CPO price in 2020 was in line with the higher prices of other major vegetable oils in the global market due to the supply disruptions in key edible oils as well as lower palm oil supply, which in turn indicates lower palm oil stocks in 2020 (CPOPC, 2020).

Following the increase in CPO price, export prices of major processed palm oil products namely RBD palm oil, RBD palm olein and RBD palm stearin in 2020 had showed an increment by 28.6% (RM2887.00 t^{-1}), 27.2% (RM2844.00 t^{-1}) and 29.1% (RM2801.00 t^{-1}), respectively while the price of palm fatty acid distillate (PFAD) rose by 40.9% (RM2546.00 t^{-1}).

In the lauric-based market, the price of palm kernel increased by 26.2% (RM1532.00 t^{-1}) compared to RM1214.00 t^{-1} in 2019 mainly due to the higher domestic CPKO price. Moreover, the CPKO price in 2020 improved by 23.6% (RM3247.00 t^{-1}) in comparison to RM2626.50 t^{-1} as reported in the previous year. The higher CPKO price in 2020 was in agreement with higher PKO price in the global market by USD158.00 or 23.7% (USD826.00 t^{-1}) which coincided with higher price in coconut oil by USD276.00 or 37.4% (USD1014.00 t^{-1}).

Conforming to the substantial increase in CPO and palm kernel prices, FFB price at 1% OER in 2019 had increased by 34.7% to RM28.51 as opposed to RM21.17 in 2019. With reference to the national OER, FFB price in 2020 was equivalent to RM561.00 t^{-1}, which was higher by 32.9% when compared to RM422.00 t^{-1} reported in 2019.

TABLE 8. MALAYSIAN EXPORTS OF PALM OIL AND OIL PALM PRODUCTS

	Volume (million tonnes)			Value (RM million)		
	2020	2019	Difference (%)	2020	2019	Difference (%)
Palm oil	16.22	17.43	(7.0)	45 656	39 128	16.7
Palm kernel oil	1.14	1.01	13.3	4 151	3 306	25.6
Palm-based oleochemicals	4.41	5.46	(19.4)	16 415	18 121	(9.4)
Biodiesel	0.33	0.72	(53.7)	1 194	1 994	(40.1)
Other palm-based products	1.96	1.84	6.8	4 542	3 951	15.0
Palm kernel cake	2.53	2.58	(2.1)	1 295	1 045	23.9
Total	26.59	29.04	(8.5)	73 253	67 546	8.4

Source: Department of Statistics Malaysia (2021).

TABLE 9. MALAYSIAN IMPORTS OF OIL PALM PRODUCTS (million tonnes)

	2020	2019	Difference	
			Volume	%
Palm oil	0.95	0.98	-0.03	(3.1)
Palm kernel oil	0.28	0.26	0.02	7.9
Palm kernel	0.06	0.07	-0.01	(18.0)
Total	1.29	1.31	-0.02	(1.7)

Source: MPOB (2021).

TABLE 10. MALAYSIAN PALM OIL CLOSING STOCKS AS AT DECEMBER (million tonnes)

	2020	2019	Difference	
			Volume	%
Peninsular Malaysia	0.74	1.00	(0.26)	(25.9)
Sabah	0.35	0.65	(0.30)	(45.9)
Sarawak	0.17	0.36	(0.19)	(52.1)
Malaysia	1.27	2.01	(0.74)	(37.0)

Source: MPOB (2021).

TABLE 11. MALAYSIAN PRICES OF OIL PALM PRODUCTS (RM t^{-1})

	2020	2019	Difference	
			RM t^{-1}	%
CPO	2 685.50	2 079.00	606.50	29.2
RBD palm oil	2 887.00	2 245.50	641.50	28.6
RBD palm olein	2 844.00	2 236.50	607.50	27.2
RBD palm stearin	2 801.00	2 169.00	632.00	29.1
PFAD	2 546.00	1 807.00	739.00	40.9
Palm kernel	1 532.00	1 214.00	318.00	26.2
CPKO	3 247.00	2 626.50	620.50	23.6
FFB at 1% OER	28.51	21.17	7.34	34.7

Note: CPO - crude palm oil; RBD - refined, bleached and deodourised; PFAD - palm fatty acid distillate; CPKO - crude palm kernel oil; FFB - fresh fruit bunches; OER - oil extraction rate.

Source: MPOB (2021).

R&D FOCUS AREAS IN 2020

Biotechnology and Green Approaches in Upstream

The demand of palm oil has been in continuous growing trend over the years. To meet this demand, large conversion of tropical peatlands in the last decade with more than 3.1 million hectares area have been cultivated with oil palm (Miettinen *et al*., 2016). While tropical peatland in the South East Asia (SEA) cover more than half of the global peatlands area, it is Malaysia and Indonesia which occupy the largest areas (Page *et al*., 2011). The significant peatland conversion has sparked an on-going debate internationally, predominantly due to the loss of biodiversity, ecosystem carbon emissions, reduced carbon sink source and loss of flood regulators (Kiew *et al*., 2020; Lupascu *et al*., 2020; Meijaard *et al*., 2020). Most of the articles in 2020 narrated the negative impacts of tropical and peatland conversion for agricultural purposes. Several articles reported a significant loss in bacterial, macrofungi and spider community diversity (Kusai and Ayob, 2020; Potapov *et al*., 2020; Shuhada *et al*., 2020) while Cooper *et al*. (2020) highlighted the importance to include the different stages of peatlands conversion in estimating global warming potential (GWP). The net impact of forest conversion to oil palm was found nearly doubling GWP over a period of 30 years.

Besides the general negative accounts of peatlands conversion by scientific findings, the role of media coverage in providing misleading claims on the peatlands sustainability; an article, *denialist narrative* as analysed by Liu *et al*. (2020) had heavily criticised the role of media in supporting unproven claims on peatland cultivation, influenced by political and socio-economic nuances respective to the country. On the contrary, a big data analytics study had found the same media specifically discusses the role of social media that drives negative public perception on palm oil through on-going online discussions and campaigns despite the continuous efforts by the oil palm industry to lift the negative perception (Teng *et al*., 2020). Ultimately, we foresee the amalgamation of these reports with the conscious move by Malaysian government prohibiting future oil palm planting on peatlands in 2019, reflecting its commitment to establish oil palm as a sustainable crop. The oil palm industry strives hard and continues to innovate and address the negative social impacts implied on palm oil trade with some of the perceptions illustrated in the 57 case studies reported by Ayompe *et al*. (2021).

The potential threat and impact of climate change on the environment and livelihood of people is acknowledged especially in the agricultural sector and the economy. A 30 years' time series data on oil palm production found a significant negative relationship between annual average temperatures and oil palm production (Sarkar *et al*., 2020). A maximum of 41% of oil palm production decrease was recorded for a 4°C temperature rise and a similar impact was also recorded by the sea level rise. The authors suggest several mitigation strategies to methodically reduce the negative impacts but requires revamping the current water and agriculture policies while providing adequate trainings to planters with viable financial aid. The multibillion-dollar industry requires greater attentions to investigate impacts of palm oil production compared to alternatives for the trade-offs to be assessed at a global scale (Meijaard *et al*., 2020).

Research in the past decade recognises the well-being of the below ground, soil as one of the most pertinent backbone of the agriculture sector. Looking back a few decades ago, the mainstream research in oil palm industry has always been predominantly focusing on the above ground which is the yield while unconsciously neglecting below ground. The scenario is further aggravated by activities such as agronomic practices, fertiliser and chemical applications, and land use changes that took place in agriculture which negatively impact the general soil health in the long run (Sundram *et al*., 2019). With sustainable development sought after in each sector of the supply chain, research is emphasised more in sustainable approaches of fertiliser management in the field. This conventional assessment for nutrient deficiency requires *in situ* leaf sampling which then goes through laborious and lengthy protocols. This additional activity increases the production cost of the already overly dependent industry with foreign labour. Therefore, any reduction in labour and cost of production is highly welcomed by the industry. Yadegari *et al*. (2020) investigated the use of satellite imagery in determining nitrogen deficiency in field. The technique used vegetative indices (VI) via SPOT-7 satellite images and compared the predicted satellite data and actual leaf analysis with an accuracy of 77%. The approach allows appropriate dosage of nutrients to be applied to the palm, to avoid excessive application that will lead to environmental and ecological disruption. Whilst the application of agrochemicals is an integral component in the well-being of palm, it is still not recognised as a sustainable practice and affects the soil health in the long run. Leveraging on the prospect of sustainable approaches, the mixing of 75% cow manure together with 25% nitrogen, phosphorus and potassium (NPK) compounds fertiliser was found to give the best vegetative growth among the five dosages examined on pre and main nursery seedlings (Adileksana *et al*., 2020). These are some of the optimisations that can be incorporated into best management practices (BMP), which has the appropriate fertiliser application in achieving optimum production. Despite the fact that BMP in oil palm is well established, failing to adopt the practices will result in yield declines as seen in the two studies reported in Ghana and Cameroon (Kome *et al*., 2020; Rhebergen *et al*., 2020). The studies identified production issues such as labour constraints, and funding limitations apart from recognising characteristics such as variation in soil properties which contribute to compromised yield. Both studies identified the intrinsic details that led to the decline and recommended mitigation approaches in addressing the yield decline. Besides the need for the industry to establish sustainable farming, active agronomic research using advanced technological methods need to be performed, by focusing on yield improvements and incorporating green technologies for the sustainable well-being of the palm. One such research area which needs to be explored intensely in the oil palm cultivation is the identification of nutrient solubilising microbes (NSB) as a long-term programme, either to replace or to be used in combination with agrochemicals in the future.

The description of an undesirable presence of organisms in agriculture is commonly referred to as pest and diseases (P&D), particularly when grievous losses to agricultural sector is experienced, hence affecting the national economy. The oil palm industry is no exception in facing multifaceted challenges which include the severe yield decline incurred by the P&D infestation. In Malaysia for instance, P&D research is mainly driven by the significant economic losses suffered by the industry which then navigates investment to focus more on the biology, early detection and control of these P&D. Chemical application promises an almost immediate control of P&D outbreaks, but the approach is not sustainably commended due to its harmful effects on beneficial insects, microbial community and chemical residues. Therefore, green approaches using naturally occurring enemies are more preferred, which play a key role in integrated pest management (IPM). Natural predators such as *Sycanus dichotomus* STAL. and *Bacillus thuringiensis* are among the two naturally occurring enemies in the environment and can be formulated to control bagworm in oil palm fields. Ahmad *et al*. (2020b) found the adult stage of *S. dichotomus* as a potential predator of bagworm based on the voracity and predation rate. The study has completed its initial laboratory stage and will be expanded to assess the dynamics of the control in the field.

Moving on to a more established biocontrol agent (BCA) of bagworm, the bacterium, *B. thuringiensis'* (*Bt.*) performance as a BCA has been influenced by the fermentation protocols during its cultivation stage. Masri and Ariff (2020) reported that intermittent fed-batch cultivation recorded higher mortality rate at 80% after seven days of treatment. This is an interesting finding considering the fact that the method of *Bt.* cultivation influences its toxicity towards its target pest and establishes that the efficiency and performance of *Bt.* depend largely on the control and monitoring of every step of production and delivery of any *Bt.* are in fact crucial. A more innovative approach in pest control is explored by a group of researchers that investigated the transcriptome dataset from four different developmental stages of *Metisa plana* (Rahmat *et al*., 2020). The study found seven regulatory genes in chitin biosynthesis; an important biosynthesis pathway across each development stage of the pest. RNAi-mediated pest management by targeting certain pathways to cease the chitin biosynthesis in the leaf defoliator is proposed. More than a decade ago, red palm weevil (RPW) emerged as a potential threat to the local coconut industry. Initial records only reported the infestation in 58 localities which then quickly spread to 858 localities in Terengganu within a short span of four years (DOA, 2011). The pest was then reported to be able to transit in oil palm with no damage or reports of outbreak. Whilst being mindful on the potential threat on oil palm, immediate surveys and research investigations were initiated. Based on the two studies reported in 2020, the pest preferred bait from pineapple tissue to oil palm or coconut tissues while the artificial infectivity of the pest in oil palm seedlings indicated compromised physiological readings (Haris-Hussain *et al*., 2020; Harith Fadzilah *et al*., 2020). More studies should be conducted to investigate and suggest measures to prevent, mitigate and to understand the potential threat imposed by the pest as part of the biosecurity plan of oil palm.

It is very interesting to note that the year 2020 had witnessed the overwhelming increase in studies conducted on one of the deadliest oil palm diseases in SEA countries namely basal stem rot (BSR) caused by a white rot fungi *Ganoderma boninense*. More than 60 articles covering various research areas of the pathogen were published and can be categorised as follows: (1) early detection methodologies; (2) chemical-based controls; (3) BCA articles; (4) plant-pathogen interactions at cellular and molecule; (5) genetic diversity of the pathogen; (6) economic impact of disease, and finally (7) soil characteristics on disease development. The oil palm industry is already witnessing the impact of the disease prevalence increase over the years with all evidence leading to the significant reduction in productivity. Evidently, the highest number of publications recorded in 2020 was also coincidentally on the control and early detection of the disease. To begin with, Olaniyi and Szulczyk (2020) published an interesting forecast of the economic damage caused by BSR disease. The article discussed on the potential economic damage based on four infection rates and treatment costing models. Despite the fact that BSR is a slow-spreading disease, the model stimulation predicts significant economic losses by 2040. Nevertheless, the predictive models did not include the effect of prevention and surveillance as part of the disease mitigation measures which in turn reinforces the need to increase research activities in preventing and controlling the disease. Additionally, climate change was also noted to affect BSR incidences in oil palm cultivation by 2050 (Paterson, 2019).

Timely prevention with effective mitigation measures are important components of both integrated disease management (IDM) and integrated pest management (IPM) which also requires a reliable early detection of the P&D. Among the early detection tools, multispectral and hyperspectral remote sensing imaging have been explored quite extensively in the past decade with most reports reporting its efficiency on field palms (Izzuddin, *et al*., 2020). A similar approach was then designed to detect early infection of the disease but at the seedlings stage via the spectral reflectance with an accuracy of 100% for disease classification (Noor Azmi *et al*., 2020). This gave rise to the potential use of the multispectral technology to be utilised in quick screening of disease onset, especially in the selection of progeny tolerance, assessment of biological and chemical control agents with an added advantage of reduced experimental time. Nevertheless, this technique requires further exploration and validation before it can be recommended. Apart from the aerial detection tools, application of ground-based Light Detection and Ranging (LIDAR) also known as Terrestrial Laser Scanning (TLS) have been gaining popularity based on its high precision in detection and innovative plant phenotyping (Husin *et al*., 2020a, 2020b, 2020c). The studies examined the use of the technology in the application, classification and characteristics of BSR disease in mature palms. The classification study for instance, gave a 100% accuracy in predicting actual disease severity using TLS. This is an emerging technology potential to be exploited further for disease detection, pest outbreak and other physiological assessments such as nutrient deficiency in palms. Aside from the contactless aerial and ground census tools, the use of deoxyribonucleic acid (DNA)-nanoparticle is another emerging technology with a huge potential for early detection devices (Rani *et al*., 2020).

Ultimately, effective control measures are the backbone of any IDM programmes and can be categorised into three universal approaches: (1) biological, (2) chemical, and (3) cultural practices. In recent years, we have witnessed developments in greener technologies with most research attempting to control or prevent diseases in oil palm. It is an undeniable fact that greener technologies compliment Sustainable Development Goals (SDG) due to their added environmental benefits. However, the preliminary investigation of these technologies that focuses too much on the early stage, neglected the more crucial stage; delivery and persistence of the BCA in the environment for a continued control (O'Brien, 2017). Once again in 2020, we see a surplus of publications identifying potential microbes, their modes of actions and disease suppression either in the laboratory or in the nursery stages (Ahmad *et al*., 2020a; Anggita *et al*., 2020; Goh *et al*., 2020a; Naeimi *et al*., 2020; Parvin *et al*., 2020; Pramudito *et al*., 2020). There were no article focusing into the efficacy of an established product in the field. There has been an interesting development on the use of fungicide for BSR control through nanoformulation. A series of studies was conducted on encapsulated hexaconazole fungicide, using chitosan nanoparticles for their delivery as a sustainable alternative to the conventional fungicide application (Maluin *et al*., 2020a; 2020b). The formulation emerges to be a successful application in controlling the BSR with 74.5% suppression compared to that of untreated seedlings.

Aside from addressing the potential control measures and early detection tools, deciphering the role of soil in predisposing the palms to BSR disease was also addressed. A study by Anothai and Chairin (2020) has put forward some interesting postulations on the role of soil physico-chemical properties; pH, fungal enzymes and plant defence enzymes in predisposing the palms to the disease. It was established that there is a correlation between soil organic matter (OM), organic carbon (OC) and pH influencing the fluctuation of enzymes in the soil. These enzymes include the cell wall degrading enzymes (CWDE) such as chitinase, β-1,3-glucanase, peroxidase (POX) and degradation enzymes (*e.g.* laccase, lignin peroxidase and manganese peroxide) with the former enzymes dominant in the natural suppression of phytopathogens while the latter are influential in accelerating degradation. In a similar approach, the profiling of soil microbial community in two contrasting BSR disease affected areas were compared through a high-throughput sequencing (Goh *et al*., 2020b). Interestingly, the soil community in the less affected BSR area had a higher abundance of rare metabolically diverse and versatile bacterial taxa as compared to the presence of predominantly disease-inducible bacterial taxa in the higher disease incidences area. The two studies identified the role of physico-chemical properties such as pH and carbon content in driving the distinct differences in the soil microbial community. It is therefore recommended that more investigations should be conducted for the industry to move forward to a sustainable green management of the disease, with innovative technologies embedded along the way. Nevertheless, the increased number of publications in the varied research fields resonates with the industries' commitment to decipher, understand and formulate sustainable control for the disease in the future.

Mitigating the Changing Environment through Technology

The year 2020 started with some devastating news of fires raging the forests from Australia to West America, Amazon to Siberia (Cove, 2020; Pike, 2020) and reports of crop destruction by swarms of desert locust decimating crops in India and Pakistan (Agarwal and Jain, 2020; Khan, 2020). One common denominator that seems to link these incidences is likely, climate change. It is believed that these, once considered as natural disasters, but more so now as human-induced calamities (Union of Concerned Scientists, 2021), were triggered by general global warming. With rising temperatures, extreme weather has become a norm. We are now witnessing prolonged heat waves, cold spells as well as severe drought and flooding. Even the invasion by crop pests such as the desert locust was attributed to climate change (Khan, 2020).

Crop threatening extreme weathers have influenced some of the research direction undertaken in agriculture (Lesk *et al*., 2016; Zandalinas *et al*., 2020). Similarly, for the oil palm, there has been a concerted effort to address the impact of abiotic stresses on yields of this oil-bearing crop. To further dissect the biology involved in environment adaptation, accessibility to genome information is crucial. The publicly available oil palm reference genome (Singh *et al*., 2013b) expedited the application of molecular breeding approaches for crop improvement, which has to date been further improved. The updated physical genome coverage of 79% from the earlier 43%, has successfully placed 1968 unassigned scaffolds onto the genome which extended the 16 pseudochromosomes thus, enhancing its overall quality (Ong *et al*., 2020). Leveraging the available oil palm genome databases as well as next generation sequencing technologies, Zhou *et al.* (2020) and Wang *et al.* (2020) identified candidate genes, potential pathways as well as transcription factors likely to be involved in drought tolerance in the oil palm. Aside from drought, *EgMYB* transcription factors (Zhou *et al*., 2020) were also found to be differentially expressed when exposed to other stresses such as cold and salinity.

Oil palm generally adapts well to high water table, but prolonged waterlogging has negative effect on its root system due to oxygen deprivation which could lead to lower yields. Nuanlaong *et al.* (2020) carried out differential gene expression studies of oil palm roots under waterlogging conditions using a less commonly used sequencing platform, the ion torrent as opposed to Illumina. This study established the Deli x Ghana variety to be tolerant to waterlogging with genes such as (Glutathione S-Transferase (*GST*), Serine/threonine-Protein Kinase (*SAPK10*) and NAC transcription factor 29 (*NAC29*) acting as potential markers.

Developing planting materials that are adaptive to the environment aligns well with the industry's aspirations. However, improved yields as well as quality of the palm oil produced remain the key criteria that directly tackles both consumer-driven sustainability and food security demands. That being said, a series of publications had addressed yield traits (Babu *et al*., 2020; Teh *et al*., 2020; Bhagya *et al*., 2020) and oil quality based on fatty acids composition (Ting *et al*., 2020a; Constant *et al*., 2020) and successfully identified quantitative trait loci as well as candidate genes, using approaches such as Genome Wide Association Study (GWAS) and Genotyping-by-Sequencing (GBS). Herrero *et al.* (2020) explored the Single Primer Enrichment Technology (SPET) as an alternative to GBS and microarrays in constructing a high-density linkage map which apparently is a more cost-effective alternative.

As the oil palm industry continues to embrace technology in its research pursuit, genome editing has begun to gain traction due to its precision and less invasive nature supported by available whole genome information (Yarra *et al*., 2020). This revolutionary technology also known as the CRISPR/Cas9 system is pioneered by Jennifer Doudna and Emmanuelle Charpentier, which won the 2020 Nobel Prize in Chemistry, touted as a game-changer for crop agriculture (Carpenter, 2019) and more so if coupled with speed breeding (Haroon *et al*., 2019). Recently, with the introduction of prime editing, this has opened up more avenues for editing the plant genome (Lin *et al*., 2020).

As the saying goes, 'Necessity is the Mother of Invention', and this holds true for Daza *et al*. (2020). Despite the fact that cultivating OxG interspecific hybrids requires assisted pollination due to its poor bunch formation, it is still a promising genotype to grow for its productivity, oil quality and partial resistance to some diseases. OxG hybrids tend to produce both types of fruits, with and without seeds. Hence, it was an attractive idea to stimulate the production of seedless or parthenocarpic fruits without assisted pollination, via the application of plant hormones. Daza *et al.* (2020) showed that with auxins, in particularly NAA and 2,4-D, it is feasible to produce good bunch of parthenocarpic fruits without having to rely on pollination. With its striking characteristics and the need to diversify the current *guineensis*-based planting materials, more efforts are being channelled to further unravel the *oleifera* and its hybrids for future applications (Ting *et al*., 2020b; Zulkifli *et al*., 2020).

Research in tissue culture-derived oil palm is picking up pace with renewed confidence in utilising clonal oil palms as a choice for commercial planting (Nur Nadia *et al*., 2020; Ang *et al*., 2020). Through studies carried out by Aroonluk *et al.* (2020) and Sarpan *et al.* (2020), a better understanding of the mechanisms, both from the aspects of genetics and epigenetics could shed light on further improving the process. Nyouma *et al*. (2020) suggested that the genomic selection (GS) approach could be extended to improve selection of ortets prior to cloning as its predictive power is by far more accurate than phenotypic selection for most traits of interest.

Whilst it is argued that genomics, in particularly the Human Genome Project has yet to deliver any major clinical breakthroughs (November, 2018), and with agricultural genomics being well behind that of human genomics, it was envisaged that the latter would probably realise the benefits earlier, generally because it is easier and less controversial to put the technology into practice. One of the earliest demonstrations of the commercial use of genomics in oil palm is in addressing the non-*tenera* contamination in the industry (Ooi *et al*., 2016). The discovery of *SHELL* gene (Singh *et al*., 2013a) which subsequently led to the unearthing of more novel mutant alleles (Ooi *et al*., 2016; Singh *et al*., 2020) was the basis of the diagnostic assay. Despite the potential of the technology in improving overall yields, its broad adoption within the industry has been lukewarm. Although we are empowered to drive discovery as well as pursue new applications, we foresee the adoption of any future technologies requires a clear strategic advocacy plan without which the impact of the research will not make a difference to the industry (ASHG, 2020).

Sustainable Development for Smallholders

The implementation of Good Agriculture Practice (GAP) is considered as the baseline for the MSPO certification. Soil and water conservation (SWC) practices are of importance for the production of oil palm whilst preserving the quality of natural resources and environment protection. To date, there is no scientific study conducted to reflect the degree of awareness and adoption of SWC amongst independent smallholders (ISH). Realising this limitation, the study done by Johari *et al.* (2020) had revealed that adoption of SWC by the members of Saratok Sustainable Oil Palm Growers Cooperation by quantitative and qualitative analyses and through *in-situ* assessment and face-to-face interviews were albeit high degree of awareness amongst ISH, and thus, recommends government assistance in promoting MSPO through the smallholders' cooperative.

Weed management at the oil palm plantation is also another aspect of GAP requirement. These unwanted plants intensely compete for nutrients, water, light and space with the oil palm. Ismail *et al.* (2020b) revealed that no oil palm seedlings are contaminated by *Bipolaris sorokiniana*. Other host plants such as strawberry, okra, sweet corn, chives, bananas, eggplants, chillies, sweet potatoes, spinach and Napier lawn exhibited a moderate *B. sorokiniana* manifestation between 10% and 20%. It was also suggested that an appropriate biological control agent is required to control *Eleusine indica* and *B. sorokiniana* at the oil palm plantation. According to Ibrahim *et al.* (2020a), a total of 3450.70 ha owned by the ISH is contaminated with BSR covering planting area in three states in Peninsula Malaysia namely Johor (1032.97 ha), Sabah (930.85 ha) and Perak (718.49 ha).

The requirement of optimum fertiliser application is crucial in capitalising the palm oil productivity. Research work by Tan *et al.* (2020) revealed that majority of ISH have a general understanding of good practice to fertilising oil palm. However, the rate of fertiliser applied by the ISH is relatively lower than the recommended dosage. Most of the ISH not only have inadequate information on oil palm nutrient deficiency but also failed to perform soil analysis prior to planting. There is a need to reinforce the extension service in providing awareness to the ISH on proper fertiliser application. More studies are needed to understand the impact of ISH decision on the application of fertiliser. A survey was done by Zaki *et al.* (2020a) which aimed to understand the behaviour of purchasing fertiliser amongst ISH in Sabah in term of price, distributor and fertiliser purchase intention. Almost two-third or 61.2% of ISH has applied fertiliser based on their own experience and expertise while the remaining ISH obtained technical advice from MPOB. It was also noted that about 40.0% of ISH have hired workers to fertilise their oil palm. Except for price, brand and dealer portrayed good relationship with fertiliser purchase. Factors such as types and dosage of fertiliser, number of harvesting rounds, weed control and farm management were all found to be affecting the oil palm yield.

In 2016, the Malaysian Government has allocated about RM37.60 million and RM1.03 billion through Oil Palm Seedling Assistance Scheme (SBABB) and Tenth Malaysian Plan, respectively, with the aim to facilitate ISH for replanting in order to improve productivity through proper adherence to GAP. Sheilyza and Abd Manaf (2020) correlated the influence of knowledge, attitude and skill on GAP of the SBABB recipients towards the oil palm production, which clearly showed that most of the ISH aged between 48 and 59 years old have a moderate knowledge and skill operating at their farms. Majority of the respondents was reported to only harvest FFB between 10 and less than 20 t ha^{-1} yr^{-1}, which are notably lower than the national average production (20 t ha^{-1} yr^{-1}). Factors such as farm size, knowledge on farm management, farm operating skills, perception towards SBABB and perception towards MPOB as the implementer agency were positively correlated with the productivity. This observation is in agreement with the study done by Sheilyza *et al.* (2020) where another scheme known as the Oil Palm Replanting Scheme (TSSPK) and New Planting Scheme (TBSPK) were introduced to gauge its effectiveness towards oil palm replanting and hence improve the productivity and income of the ISH. The FFB harvested was found to be lower than 4.6 t ha^{-1} yr^{-1} for the first two years of replanting, but the ISH still enjoyed an uptrend price reflected by their income. The researchers also proposed that future schemes shall incorporate agricultural input distribution and clustering of the ISH into cooperatives for the betterment of input distribution and deliverability of extension services.

Clustering the ISH was found to be the best way to overcome issues on extension services. The Sustainable Oil Palm Growers Cooperative (KPSM) is responsible to boost the income of ISH whilst creating job opportunities in the Malaysian oil palm sectors. Based on the study by Zaki *et al.* (2020b), almost 70% of KPSM's Board Members possess experience in managing the business and had accomplished their cooperative-related training. Albeit most of them understood their positions in terms of communication with other Board Members, as well as internal control system policy and cooperative regulations, the researchers observed their lack of experience in financial literacy, and hence, suggested the Board Members to be equipped with appropriate knowledge to contribute new ideas in churning profit to the cooperative.

Biomass and Bioenergy Innovations

The research in palm oil midstream sector concentrates on utilisation and management of biomass in reducing environmental impacts. Two main by-products generated from the palm oil milling process are the solid oil palm biomass and liquid wastewater or palm oil mill effluent (POME). These abundantly generated lignocellulosic materials have been the main feedstock for the value-added conversion into bioenergy, biochemicals and bioproducts (*Figure 1*). Due to the inherited recalcitrance characteristics, pre-treatment is required before the biomass can be efficiently exploited. Promising pre-treatment method of recent interest is supercritical carbon dioxide (SC-CO_2) has resulted in high diffusivity, which subsequently enhances the structural disruption, promotes sugar's solubilisation and eventually led to better enzymatic digestibility of the pre-treated biomass (Sohni *et al.*, 2020). Another method involving hydrothermal pre-treatment between 100°C and 200°C showed the ability to depolymerise oil palm biomass in producing lignin-based aromatic chemicals as precursors for protocatechuic acid (polyphenols antioxidant) synthesis (Ramachandran *et al.*, 2020). The pre-treated biomass was proven to be more effective. The hydroperoxide (H_2O_2)-assisted hydrothermal pre-treated empty fruit bunches (EFB) showed better degradation performance to enhance batch anaerobic digestion at mesophilic condition with 43% increase in methane yield and 30% lesser greenhouse gas (GHG) emissions when compared to the control (Lee *et al.*, 2020).

Furthermore, torrefaction (Sukiran *et al.*, 2020a) and microwave-assisted wet torrefaction pre-treatment (Sangjan *et al.*, 2020) of oil palm biomass demonstrate a promising route for improving energy content of solid biofuel and bio-oil yield via hydrothermal liquefaction, respectively. As moisture retention in the oil palm biomass influences the mass and energy yields of the torrefied final solid product, the ultimate recovered energy content could vary tremendously. This observation has been validated through a development of a least squares power regression model based on quadratic equations (Sukiran *et al.*, 2020b) which showed strong correlation with the experimental values, and thus, can be practically applied to estimate the energy potential of torrefied products for possible fuel mix or displacement in biomass boilers. A kinetic modelling study of CO_2 gasification behaviour and reactivity profiles between 800°C and 900°C demonstrated an apparent activation energy of the torrefied oil palm biomass as affected by the physico-chemical compositions, in particular the inorganic mineral, carbon, moisture and volatile matter contents (Chew *et al.*, 2020).

Many bio-products have been innovated using pre-treated oil palm biomass. The cellulase-pre-treated EFB fibre is found as a good substrate for bioflocculant production using *Aspergillus niger* DWB (Mohd Luthfi *et al.*, 2020) via solid state fermentation. Previously, bioflocculant was produced from POME (Nurul-Adela *et al.*, 2016). A low oxalic acid (1% w/v) pre-treated oil palm trunk (OPT) biomass is favourable for succinic acid production albeit requiring longer reaction time. Oxalic acid exceeding 1% (w/v) seems to prohibit the fermentation of *A. succinogenes* 130Z, thus, should be avoided (Bukhari *et al.*, 2020). Indeed, palm oil has also been exploited as a renewable feedstock for bioprocessing. One example is production of bioplastic, *i.e.* medium chain length polyhydroxyalkanoates (PHA) which can further converted into biopolymers (Tanikkul *et al.*, 2020).

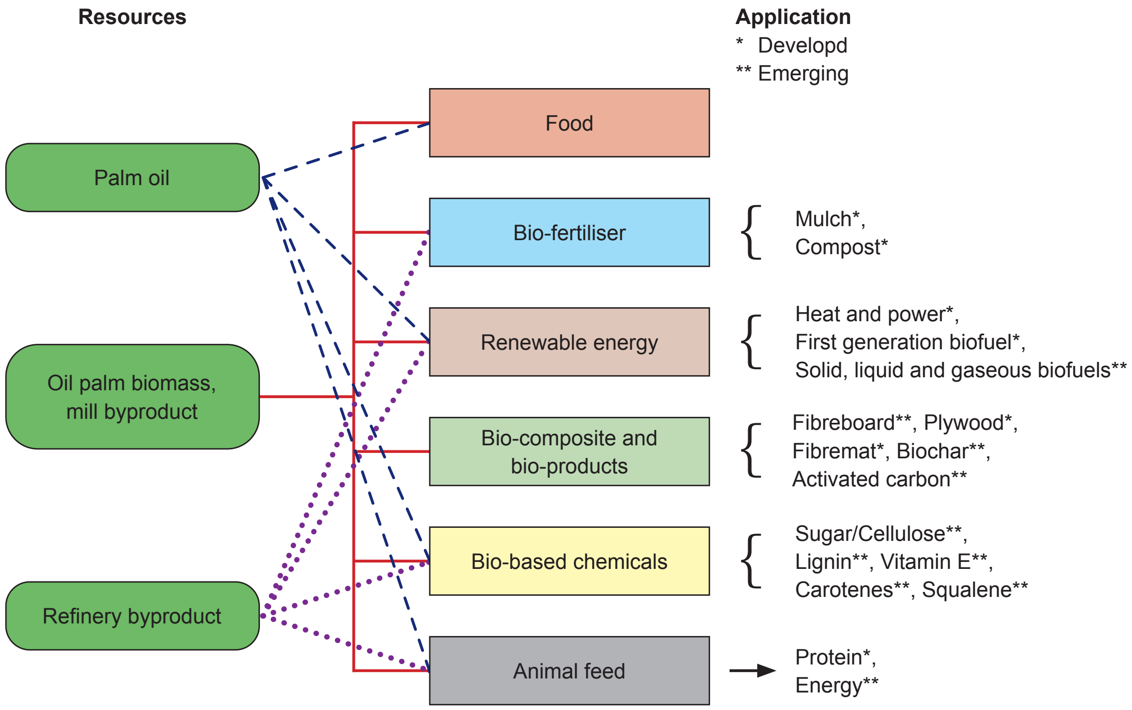


Figure 1. Resource optimisation and diversification strategy for food, feed, fuel chemicals and other bio-products.

Biochar research currently focuses on assessing carbon sequestration potential (CSP) as a soil amendment. The types of biomass feedstock and mode of production are important parameters in biomass-to-biochar valorisation. *Table 12* shows the Brunauer-Emmett-Teller (BET) surface area and CSP of some biochars derived from oil palm biomass. Oil palm frond biochar with a BET surface area between 180 and 190 $m^2 g^{-1}$ has an average CSP of 0.27 t of CO_2 for every tonnage of biomass (Karananidi *et al.*, 2020). Palm kernel shell (PKS) biochar shows higher BET surface area and better CO_2 adsorption (Kong *et al.*, 2019; Dominguez *et al.*, 2020; Promraksa and Rakmak, 2020). Furthermore, the CSP of this biochar increases over surface properties. Higher temperature promotes volatilisation during biochar production leading to more porous materials and active sites that could improve the CO_2 sequester. However, further enhancement of this carbonaceous material such as chemical treatment is required for carbon sequestration. Pyrolysis using microwave under vacuum resulted in a highly porous PKS biochar with a very moist and suitable substrate that can promote mycelium colonisation for mushroom growth (Mahari *et al.*, 2020). Green carbon-based nanomaterials namely carbon quantum dots have been produced from EFB-derived activated carbon through hydrothermal carbonisation-activation processes. The materials were of good optical properties, water stability and solubility which offer versatile applications as bio-imaging and sensor materials (Mahat and Shamsudin, 2020).

Metal oxide impregnation of oil palm biomass-based magnetic biochar can be used as a heterogeneous catalyst to improve biodiesel production and eases catalyst separation (Quah *et al.*, 2020). In addition, a green tea-based catalyst called magnesium oxide (MgO)-clinoptilolite nanocomposite could transform used frying oil into biodiesel in compliance with international specifications with the advantages of relatively high yield (approximately 9%) and high degree of catalyst recyclability (Basyouny *et al.*, 2020). In addition, the calcium oxide (CaO) catalyst derived from raw chicken eggshell is capable of reducing 95% of free fatty acids content in palm fatty acid distillate to be used as biodiesel feedstock (Idris *et al.*, 2020).

Cellulose nanofibre (CNF) extracted from oil palm biomass can be impregnated and sandwiched in the polyvinyl alcohol (PVA) film to produce PVA-CNF nanocomposite which encompasses of reinforced thermal stability, tensile strength and crystallinity (Okahisa *et al.*, 2020). The sodium hydroxide (NaOH)-treated oil palm fibres (OPF) have been added to cement paste containing 0.25% of superplasticiser to form less viscous cementitious matrix (Bonnet-Masimbert *et al.*, 2020). The reinforced cement is chemically and mechanically compatible, allowing cement hydration due to the enhanced fibre-and-cement interface properties. Nanosized lignin from oil palm biomass isolated through soda pulping process is a stable and non-toxic water-in-oil emulsifying agent (Sekeri *et al.*, 2020).

Of the many non-food applications, starch derived from the OPT has successfully been extracted and chemically modified to form a binder that reduces the usage of formaldehyde in wood composite production. However, the inclusion of small amount of conventional binder, *i.e.* urea-formaldehyde into the formulations is still required as it could further improve the moisture and fungal resistance of the products (Amini *et al.*, 2021). Moreover, OPT pre-treated with sodium chloride solution could potentially be used as fire-retardant particleboards with high thermal stability (Yusof *et al.*, 2020) when bonded with poly(vinyl) alcohol as well as additives such as citric acid and calcium carbonate. The OPT biocoal produced via pyrolysis emits nitrogen oxide (NOx) and sulphur dioxide (SO_2) emission of 296 and 190 ppm, respectively, when co-combusted with sub-bituminous coal as a solid biofuel between 600ºC to 900ºC. The emission

TABLE 12. CARBON SEQUESTRATION POTENTIAL (CSP) OF OIL PALM BIOMASS-BASED BIOCHAR

Biomass source	Brunauer-Emmett-Teller (BET) surface area, $m^2 g^{-1}$	CSP, t CO_2 t^{-1} biomass	Production mode	Reference
Oil palm fronds	180 - 190	0.27	Kon-Tiki flame curtain pyrolysis. 200°C-800°C, 100 min	Karananidi *et al.* (2020)
Palm kernel shell	389	0.46 mmol g^{-1} (CO_2 adsorption)	Fixed bed pyrolysis at 500°C, 60 min	Promraksa and Rakmak (2020)
Palm kernel shell	135	0.398	Gasification at >700°C. Biochar was impregnated with NH_4NO_3 and KH_2PO_4 as a slow-release fertiliser	Dominguez *et al.* (2020)
Palm kernel shell	200 - 329	0.49 - 0.63	Multi-mode allothermal pyrolysis, 400°C-600°C, 30-90 min	Kong *et al.* (2019)

Note: NH_4NO_3 - ammonium nitrate; KH_2PO_4 - potassium dihydrogen phosphate.

of these gases is well below the legislative limits enforced by the Environmental Quality (Clean Air) Regulation 2014 (Nudri *et al*., 2020).

One of the greatest challenges in POME treatment is the consistent performance of polishing plant in meeting the stringent biological oxygen demand (BOD) discharge standard set by the Department of Environment Malaysia (DOE). It depends largely on the hydraulic retention time (anaerobic stage), aeration system (aerobic stage) and availability of microbial cells in POME. Chin *et al*. (2020) concludes that the modified Stover-Kincannon model is most suitable to gauge the performance of anaerobic POME treatment through a covered lagoon with hydraulic mixing. The findings facilitate the selection of industrial-scale method and equipment sizing for wastewater treatment. The following are some of the adsorbents developed for POME treatment: (1) PKS activated carbon produced via a two-in-one carbonisation activation system and packed in a continuous system (Nahrul Hayawin *et al*., 2020); and (2) steam-pyrolysed and pulverised oil palm frond biochar (Lawal *et al*., 2020). The latter exhibits an increased new external surface area and less pore blockage, capable of adsorbing POME contaminants.

The capturing of biogas releasing from POME during anaerobic digestion should be pursued prior to discharging the treated final discharge into a watercourse (Loh *et al*., 2017). As of December 2019, a cumulative of 125 biogas plants were installed corresponding to 28% of biogas implementation in the country (Loh *et al*., 2020). The serial biogas capturing has shown the capability to mitigate an estimated GHG emission of about 5.52 million tonnes CO_2 eq. annually in comparison to without biogas capture (18 million tonnes CO_2 eq). In 2020, another five plants were established giving a total of 130 plants equipped with biogas capturing facilities across 457 palm oil mills in the country. Biogas has a huge untapped potential not only as a readily form of bioenergy but also could be upgraded into bio-compressed natural gas (bio-CNG). This approach could be made more economically viable if a biogas plant at the palm oil mill is integrated with a purifying plant to produce biomethane (>92% biomethane) or bio-CNG for industrial uses (Nasrin *et al*., 2020). On that note, POME is proven as an effective solvent to pre-treat EFB fibre for fermentable sugars production (Tang *et al*., 2020).

Environmental Sustainability of the Oil Palm Life Cycle

Findings from a life cycle impact assessment of refined palm oils with co-products allocated based on economic value (Yung *et al*., 2020) call for the improvement on bleaching earth usage and transportation of CPO during refining and fractionation processes. Separately, in production of palm oil, the main contributors to water footprint along the oil palm supply chain through the concept of cradle-to-gate are: (1) cultivation of oil palm FFB in plantations, (2) boiler and process water in mills, and (3) processing of palm kernel from kernel crushers. The water footprint assessment based on the water accounting and vulnerability evaluation (WAVE) method has been compared via mass, economic and energy allocation (Berger *et al*., 2014; 2018). Mills with the highest water footprint impact are urged to avoid dilution after the screw press of CPO (Subramaniam *et al*., 2020).

In evaluating the suitability of oil palm as bioenergy crop, Heidari *et al*. (2020) have looked into the hydrological impacts and water-biomass trade-offs associated with oil palm cultivation in Tabasco, Mexico using a calibrated Soil Water Assessment Tool (SWAT) model (Arnold *et al*., 2012). The hydrologic-agronomic relation for palm biodiesel feedstock production has been modelled through different land use management scenarios. In a separate study, oil palm residues have been investigated via a weighted decision matrix to measure its bioenergy potential and technical feasibility by taking into account the sustainability criteria (Ordoñez-Frías *et al*., 2020). Nevertheless, a more structured holistic research should be initiated through an integrated analysis of all the potential impacts to ecosystem and socioeconomic aspects in identifying the crop most suitably used for bioenergy production. In addition, an investigation on spatio-temporal analysis of oil palm biomass value chain or biomass-to-bioenergy in Indonesia has been conducted using an optimisation model called 'BeWhere Indonesia' which shows huge bioenergy potential for palm oil-based biorefinery configuration in two islands of Kalimantan and Sumatra until 2030 (Harahap *et al*., 2020). The findings suggest that policy revision is required to attract investment in harnessing the untapped full potential of palm oil coupled with oil palm biomass. In particular, bioenergy exploiting multiple biomass feedstock shows great applicability at rural areas to overcome electricity shortage (Mahidin *et al*., 2020).

In a detailed consequential and attributional life cycle assessment study, Schmidt and De Rosa (2020) show that certified palm oil through Roundtable on Sustainable Palm Oil (RSPO) scheme is more reputable with lesser GHG emissions than the non-certified. Certified palm oil features higher oil yield, lesser land use and peat cultivation, and higher biogas capturing rate at palm oil mill.

Challenges in Food Safety and Quality

Food safety and quality are often ascribed as the assurance of food produced for human consumption. The acceptance of food particularly for trading purposes much relies on the compliance with the latest food safety legislations and quality standards. Pertinent issues related to 3-MCPDE and GE in processed edible oils continues to dwell amongst edible oil processors and food regulators for more than a decade as evidenced from an increase in research works related to toxicity impacts, mechanistic pathways, analytical methods and mitigation strategies (Gao *et al*., 2020). The time has come for the EC to mandate the regulation of 3-MCPDE and GE thresholds in edible oils and fats with an effective date of 1 January 2021 (Commission Regulation (EU) 2020/1322, 2020). The imposition is certainly a challenge to the global palm oil producers, not only to comply with the EU importation prerequisite, but also countries that are adopting the similar requirement. As palm oil witnesses relatively higher 3-MCPDE and GE contents, remedial mitigation action is highly needed to ensure its acceptance globally.

There are many publications which detailed the mitigation strategies in minimising the formation of 3-MCPDE and GE in refined palm oil (Arris *et al*., 2020). A recent study by Sim *et al*. (2020) demonstrated a remarkable reduction of more than 80% of 3-MCPDE and 65% of GE after optimising the refining conditions using micro- and macro-scale deodorisers with the capacity between 0.1 kg and 3.0 kg. It is worth noting that the majority of research works performed at laboratory scale often encounter obstacles when converting the optimum process conditions to a commercial plant setup.

On that note, Ramli *et al*. (2020a) have initiated series of commercial trials at the mill and refinery to attest the efficiency of washing CPO at the former premise and subsequently lowering the formation of 3-MCPDE and GE in processed palm oil at the latter premise. Washing 900 t of CPO lessened the total chloride content by 85% which yielded the final total chloride content of 0.9 ppm. Reduced chloride content in washed CPO further lowered 3-MCPDE content in the refined oil (1.4 ppm) when subjected to processing at a 500 t capacity physical refining plant. A reduction of 86% in GE content was prevailed when the refined oil underwent post-refining trials at lower deodourisation temperature in the absence of degumming stage and reduced dosage of acid activated clay.

Gao *et al*. (2020) highlighted the importance of integrating three mitigation approaches involving reactant control, inhibition of promoter, catalyst or intermediate, and minimising contamination occurrence during refining that should be undertaken to resolve the presence of 3-MCPDE and GE in both cooking oils and oil-based food products. Bognár *et al*. (2020) showed that different chlorinated salts influence the fate of 3-MCPDE in edible oil when subjected to frying. Frying of potato chips depicted by the increase in oil temperature and frying interval have significantly enhanced the development of 3-MCPDE but displayed a declining trend in GE content over frying time (Wong *et al*., 2020). The inclusion of external antioxidants such as butylated hydroxyanisole (BHA) and tocopherol in baked cakes have shown the ability to retard 3-MCPDE and GE formation while rosemary extract was demonstrated to be the most effective in minimising the presence of these compounds (Goh *et al*., 2020).

The use of pesticides at the oil palm plantations could lead to the presence of pesticide residues in the FFB after harvesting. Cypermethrin, indaziflam, metsulphuron-methyl, glyphosate and glyphosinate are amongst the 29 pesticides registered under Regulation 41 of Schedule Sixteenth of the Malaysian Department of Agriculture (DOA) that are allowed for use at oil palm plantations. Maznah *et al*. (2020) have established a method to detect the residue of metsulphuron-methyl, and observed that accumulation of metsulphuron-methyl gives a minimal impact to the soil, thanks to its rapid degradation with the half-life of up to eight days. The potential use of gas-chromatography mass-spectrometry (GC-MS) to detect the presence of trace cypermethrin has been established by Sulaiman *et al*. (2020) with satisfactory performance and acceptable recoveries and precisions. The application of indaziflam at the oil palm plantations can potentially lead to the migration of its residues through its root system and possibly accumulates in the raw agricultural commodities (RAC). This has led Halim *et al*. (2020) to develop a detection method of indaziflam residue and its three metabolites namely diaminotriazanie, triazine indanone and carboxylic acid based on the application of a liquid-chromatography tandem mass-spectrometry (LC-MS/MS). The application of similar instrument was also beneficial to simultaneously detect glyphosite and gluphosinate residues including their metabolites (Shinde *et al*., 2020).

Palm oil is often regarded as one of the ideal vegetable oils for culinary and frying sectors because of its nature to resist excessive heat under intensive operation. Recently, Hu *et al*. (2020) conducted a comparative intermittent frying trials using palm stearin and oil blend containing a mixture of high oleic sunflower oil and canola oil, and depicted that the combined level of primary and secondary oxidation in palm stearin was two folds lower than that of blended oil. According to Su *et al*. (2020), the oil types and frying cycles could also influence the fate of acrylamide in fried products. The consumption of naturally stable oil for frying is not only found to be cost-effective but also overcomes public concern towards oils produced from genetically modified crops (Qi *et al*., 2020). Thermal resistance of red palm olein for different cooking techniques showed an apparent vitamin E and carotenes retention when heating under conventional oven and frying conditions (Loganathan *et al*., 2020a). A separate study by Loganathan *et al*. (2020b) demonstrated an excellent thermal stability of vitamin E and carotenes exceeding 87% in baked cupcakes made of red palm olein whilst preserving similar sensory characteristics as those containing conventionally refined palm olein.

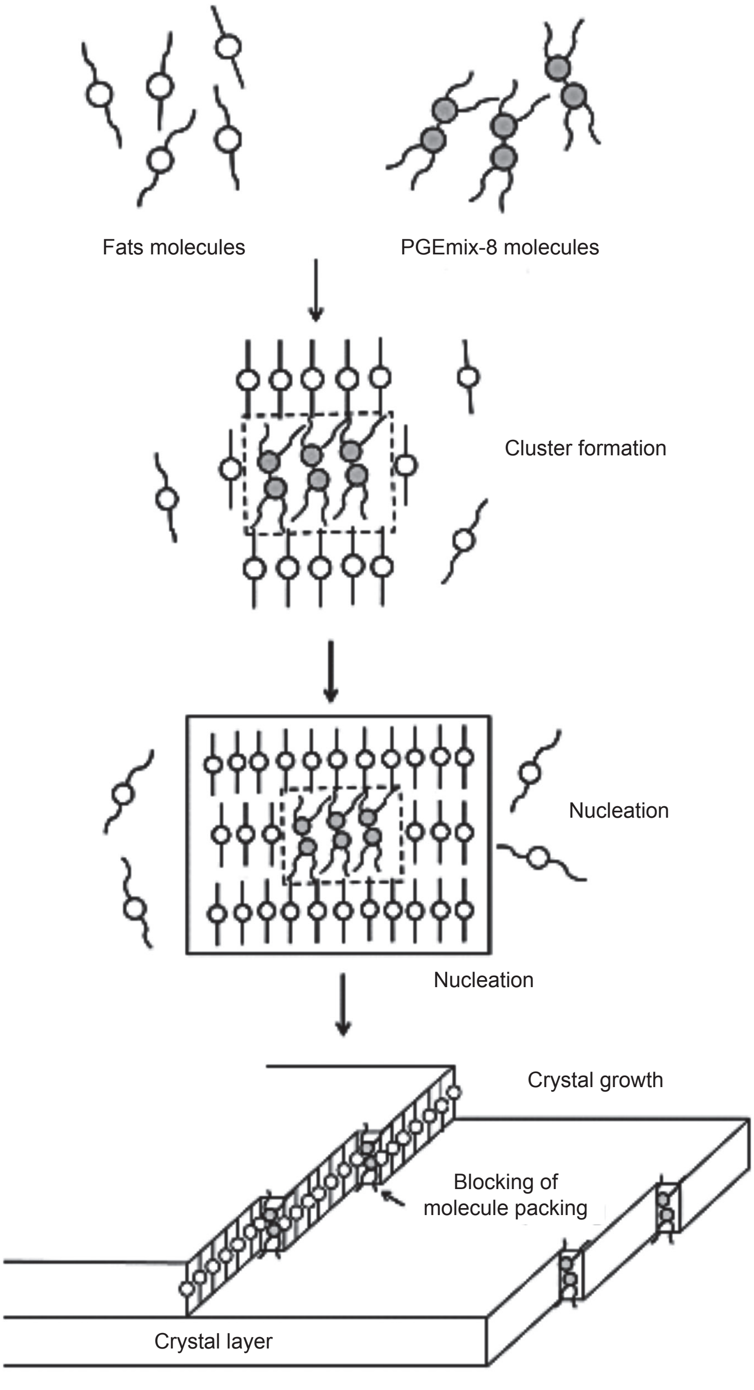
Superiority of vegetable oils is somehow appreciable when they are properly handled during storage and food processing. An investigation on the shelf-life stability of red palm olein by Loganathan *et al*. (2020c) displayed minimal oil degradation associated to hydrolysis and oxidation while retaining vitamin E and carotenes contents even after four months of storage at relatively lower temperature in the absence of light and sealed bottles. A survey conducted at the selected fast-food restaurants in the East Coast of Peninsula Malaysia by Ismail *et al*. (2020c) monitored the quality of fresh, in-use and discarded oils for discrete frying of different food products. From all four fast-food brands evaluated, most of used frying oils collected from two premises had exceeded the threshold limit of total polar compounds (27%) while almost one-fifth of the used oils exhibited extremely high level of total polar compounds ranging from 35% and 48%. This experience clearly indicates that the insufficient oil management and handling could shorten frying oil usability.

Valorisation in Food and Feed Innovation

Recognition on the unique intrinsic characteristics and functionality of palm oil creates a vast opportunity to innovate myriad of food products. Valorisation of specialty fats derived from multiple fractionation processes could fetch premium price and marketability for niche food segments (Bruce, 2020). Characterisation of soft palm mid fraction (PMF) by Kanagaratnam *et al*. (2020) aims to distinguish it from soft palm stearin considering their overlapped iodine value and thus, fatty acids composition. Research efforts on oleogel development has been active in the recent years to enhance the thermal resistance, texture attributes, and structural binding capacity of lipids (Park and Maleky, 2020). Recent fundamental research work by Saw *et al*. (2020a) had found a marginal increase in olein yield of between 3% and 6% when different dosages of polyglycerol esters (PGE) of 0.1%-0.7% were added into palm oil before fractionation. This indicates the role of PGE to retard the growth of palm oil crystals following a possible mechanism as illustrated in *Figure 2*. In another study, Saw *et al*. (2020b) have screened several organogelators that can be potentially used to build oleogel network with palm superolein. Alteration of palm oil crystallisation can also be affected by the imposition of shear and dispersion of particle phase (West and Rousseau, 2020).

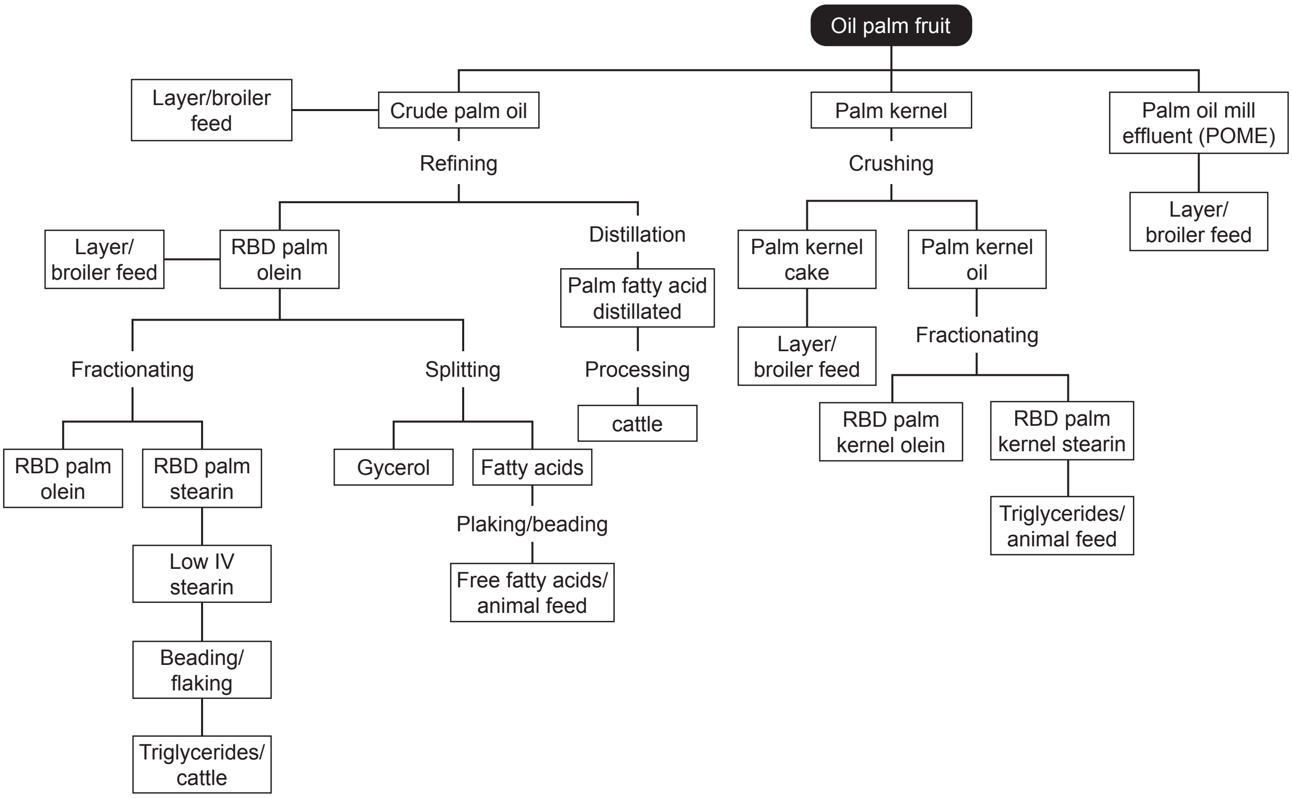
The increase in demand for healthy food of meat-free products had motivated Chen *et al*. (2020) to revolutionise meat homologues from soya protein fortified with palm-fat. It was reported that a lower cholesterol content of 12.1 mg kg^{-1} was observed in comparison to the conventional meat balls which ranged from 148.3 mg kg^{-1} and 287.1 mg kg^{-1}, and furthermore, enhanced product texture and sensory characteristics. Similarly, Mohd Hassim *et al*. (2020) looked into the marketability of palm-based milk drink or lassi as an alternative to traditional milk-based fermented drink, and improved the product feasibility based on the quality characteristics and sensory acceptance. Exploration of the potential use of palm mid fraction and palm stearin blend in producing frozen Chinese pancake by Xie *et al*. (2020) yielded comparable texture but outperformed four bestselling lard-based pancakes, with respect to thermal stability and appearance. Notwithstanding that, palm oil which is the essence of food innovation, has somehow been bombarded by irresponsible allegations associated to health, deforestation and human rights, which in turn, advocates inversely to reduce reliance on palm oil (Parsons *et al*., 2020; Ramli *et al*., 2020b). In a study by Nicholson and Marangoni (2020), the ability of enzymatic glycerolysis for structuring liquid oils could offer alternative to saturated oils in formulating solid fat-based products. Of course, any attempts to construct liquid oil structure in favour to direct use of palm oil would incur unnecessary cost pertaining to additional processes related to enzymatic treatment. Likewise, substituting palm oil with high oleic oils would command higher premium attributed by the limited source and supply (Bruce, 2020).

Animal feed represents a significant portion of the total production cost in the livestock and aquaculture industry. The Malaysia's importation of raw ingredients for animal feed was reported to surpass 70% annually encompassing 2000 t of corn meal and 1000 t of soyabean meal (Nur Atiqah *et al*., 2020). Utilisation of palm oil derivatives and oil palm by-products as shown in *Figure 3* indicates an initiative to substitute some of the rations in feed formulations to ensure consistency in supply and cost-effective without the need to highly rely on imported ingredients. Exploration on the application of palm-based calcium soap in feed ration for broiler chickens portrayed similar growth performance and carcass characteristics with the diet without calcium soap (Villanueva-Lopez *et al*., 2020). Comparable observation on growth performance and carcass traits was also witnessed by Nur Atiqah *et al*. (2020) when formulating goat feed pallets with oil palm by-products such as OPF, palm kernel cake (PKC), EFB and PFAD. Palomar *et al*., 2020 performed a comparative study on laying hens' dietary preferences toward feed diet formulations each with palm oil, PFAD and soyabean, and discovered that the hens have better preference towards diet containing palm oil and PFAD. Incorporation of encapsulated palm oil in the feed ingredient for piglets has been reported to enhance tract digestibility, lowers the incidence diarrhoea and increases high-density lipoprotein cholesterol (HDL-C) in the blood serum (Ren *et al*., 2020). The prospect of CPO and its by-products on the performance of laying hens and egg quality has been reviewed by Saminathan *et al*. (2020) and found that the inclusion of CPO in the feed ration stimulates the growth performance and metabolisable energy consumption. In the light of aquaculture segment, Wan Nooraida *et al*. (2020) appraised comparable sensory properties of tilapia (*Oreochromis niloticus*) fillets fed with diets containing emulsified PFAD and CPO, respectively, with those fed with commercial diet.



Source: Saw *et al*. (2020).

Figure 2. The proposed mechanism of interaction between polyglycerol esters (PGE) and oil molecules.



Note: RBD - refined, bleached and deodourised; IV - iodine value.

Source: Saminathan *et al*. (2020).

Figure 3. Potential use of palm oil and its co-products for poultry feed applications.

Nutrition and Health

The past two decades have marked a dramatic growth of research interest in the studies related to palm oil nutrition and health. A review on animal intervention studies by Syarifah-Noratiqah *et al*. (2020) deliberated on the role of palm oil to induce total cholesterol (TC) and low-density lipoprotein cholesterol (LDL-C) profiles and further suggests the potential of palm oil as lipid-lowering agents. Another review with special reference to palm olein has reported a promising effect of blood lipid profiles in healthy adults and notably comparable with oils comprising of high monounsaturated fatty acids (Yilmaz and Ağagündüz, 2020). A research work on hypocholesterolaemic and anti-atherogenic effects of palm-based oils namely NoveLin I (oil with balanced ratio of saturated-, monounsaturated and polyunsaturated fatty acids) and NoveLin II (oil with moderate levels of monounsaturated fatty acids and lower in saturated- and poly-unsaturated fatty acids) in rabbit model by Che Idris *et al*. (2020) observed that both oils significantly lessen TC and LDL-C when compared to rabbit fed with diet containing coconut oil.

Human intervention study on three confectionery products made of PMF, shea stearin (SS) and high oleic sunflower oil (HOSFO) showed that dietary fats rich in palmitic acid (PMF) and oleic acid (HOSFO) at sn-1,3 positions of triacylglycerol backbones exhibited similar postprandial lipid and glucose responses in comparison to SS with higher stearic acid (Voon *et al*., 2020). It is a known fact that the intake of used oils through food poses the tendency of health incidences. Recently published findings revealed the effect of consuming overheated oils which lead to higher occurrence of non-alcoholic fatty liver disease based on the intervention studies using human hepatic carcinoma cell line (HepG2) (Chatuphonprasert *et al*., 2020) and C57 mice (Li *et al*., 2020). In a study comparing the effect of heated canola and palm olein on gut microflora in rats, Ruan *et al*. (2020) found that the latter oil significantly stimulates the proliferation of beneficial probiotics namely *Lactobacillus* and *Roseburia*.

Palm puree derived from oil palm mesocarp is abundant with phytonutrients such as vitamin E (in the form of tocopherols and tocotrienol homologues), carotenoids, phenolics, squalene, polyphenols and flavonoids, and thus, requires confirmative measure for human consumption. Based on this understanding, Zainal *et al*. (2020) performed a systematic acute and sub-chronic toxicity assessment and discovered that palm puree did not exhibit any signs of substantial toxicity or mortality. Driven by the growing evidence on the prospect of oil palm phenolic (OPP), many studies have been undertaken to gauge its bioactivity on health benefits. A review by Ibrahim *et al*. (2020b) explicated the current evidence of several mechanisms associated to cholesterol biosynthesis pathway, anti-inflammation and antioxidant capacity of OPP in providing cardioprotective effects to human. The OPP was also reported to improve bowel health in rats coincides with the increase in some essential bacteria that could aid the barrier turnover (Conlon *et al*., 2020). A study by Leow *et al*. (2020) has successfully identified and characterised the reference genes from quantitative reverse transcription polymerase chain reaction (RT-qPCR) gene expression from Nile rats supplemented with OPP, which could further support future hepatic gene expression research particularly related to metabolic syndrome and type-2 diabetes melitus.

Palm oil is one of the natural sources of tocotrienols which generally accounts for at least two-third of the total vitamin E content. Tocotrienols are established as natural bioactive compounds with the ability to reduce cancer risk (Aggarwal *et al*., 2019). The latest findings by Loganathan *et al*. (2020d) portrayed the functionality of palm tocotrienols to exert anti-proliferative and pro-apoptotic effects based on the manifestation of poly-(adenosine diphosphate)-ribose polymerase (PARP-1) cleavage and cyclooxygenase-2 (COX-2) inactivation of human breast cancer cells. A systematic review on the safety and neuroprotective efficacy of palm oil and tocotrienols-rich fractions (TRF) by Ismail *et al*. (2020a) inferred that the role of palm TRF or alpha-tocotrienol (α-T3) stimulates the cognitive performance of healthy animal and cognitive functions. A study by Fairus *et al*. (2020) discovered similarity in the overall antioxidant synergistic effect between TRF and alpha-tocopherol (α-T).

Oleochemical Innovations

Consumers' preferences for sustainable and bio-based products are the key factors fuelling the market with such products. Besides, favourable government policies regarding financial incentives and tax benefits for bio-based chemical producers are also positively impacting the industry. Bio-based products are exclusively or partly derived from biological origin materials, and various methods are developed to detect bio-based content of these products. Bio-based content is defined as the weight ratio of the bio-based carbon to the total organic carbon in product. According to American Society for Testing and Materials (ASTM) D6866 Standard Test Method, the bio-based content should be calculated based on the percentage of modern carbon. The ASTM D6866 standard regulates three measuring methods using ^{14}C concentration such as a liquid scintillation counter (LSC), accelerator mass spectrometry (AMS) or isotope ratio mass spectrometry. Mohd Azmil *et al*. (2020) studied bio-based content of several vegetable oils along with polyols derived from the vegetable oils, mainly palm oil, using Sample Oxidiser and LSC. The optimised method was validated with respect to trueness (recovery and memory tests), linearity (quench curves) and precision. The recovery tests using ^{14}C standard verified the performance of sample oxidiser and LSC. All of the vegetable oils have 100% of ^{14}C, which signifies an entirely modern carbon (biomass) source. Polyols derived from castor oil, palm oil and fatty acid methyl esters (FAME) had lower bio-based content (71% to 96%) than their respective oils. This is due to the addition of reactants derived from the fossil carbon source during the ring-opening reaction of the epoxidised oils to obtain the polyols. Thus, the method based on LSC analysis of ^{14}C cocktails can be used as a tool to determine the bio-based content of palm-based polyols. It was proven to provide reliable results and is comparable to the more expensive AMS technique.

In another development, research on bio-based thermoplastic polyurethane (TPU) is continuously being carried out using dicarboxylic acids and diols from vegetable oils, fatty acids, FAME and PFAD produced via sustainable processes. Besides, the bio-content in TPU materials increases with incorporating bio-based polyols as an alternative to petrochemical polyols, which gives immense benefits. However, to find the suitability of bio-based polyester polyols for different applications, the effect of the structure-properties relationship between the diols and diacids to synthesise polyester polyols is essential (Zhou *et al.*, 2019). Tuan Noor Maznee *et al*. (2020) developed polyester polyols with 2000 g mol^{-1} molecular weight from 1,4-butane-diol and linear dicarboxylic acid (DCA) having different carbon numbers (odd and even numbers). TPU prepared with DCA, which consists of even carbon numbers, possessed higher hardness, tensile strength, hysteresis, and tensile set than DCA with odd carbons due to stronger hydrogen bonds. The findings from this study were valid to select suitable polyester polyols in designing TPU for specific products.

Vegetable oil-based lubricants are environmental friendly and have been widely studied as an alternative for mainstream petroleum-based lubricants. It is anticipated that the driving force of competitiveness among the commercially produced lubricants is the synthesis of biolubricant from cheaper feedstocks via a simple synthesis route. Herein, Hoong *et al*. (2020) successfully studied the synthesis of biodegradable lubricant using the following cheap feedstocks: oleic acid, acetic acid, and hydrogen peroxide via a simple one-pot process. The synthesised biolubricant, which consists of acetylated polyhydroxy estolide (AcPE) and polyhydroxy estolide (PE), was further modified for enhancing its functionality. The prepared AcPE and PE with ester and amide functionality, respectively, holds comparable physico-chemical properties to the commercial samples with respect to pour point, oxidation stability, viscosity index, and anti-wear. The outcomes of this study clearly showed that the inferior properties of plant oil-based lubricants such as poor oxidation stability and high pour point could be improved with chemically modified palm oil molecules. Besides their excellent lubricant properties as lubricant base oil for environmentally acceptable biolubricant, they are also inherently biodegradable.

In addition to the advancement in a new class of biolubricant, the development of useful tribological models to understand better the fundamentals of friction and wear, and fast characterisation of lubricants properties without overly relying on tribology test machines is necessary (Vakis *et al.*, 2018). Therefore, Chan *et al.* (2020) developed the first-ever friction-wear model for four-ball extreme pressure (EP) lubrication test (ASTM D2783) using 12 oil samples comprising of minerals, esters, and other formulated lubricants. It was rationalised using a single equation model based on non-equilibrium thermodynamics principles. The model estimated the EP performance of an unknown lubricant based on the model parameter, the dissipative coefficient that describes the proportionality between the friction and the wear phenomena based on the thermodynamic analysis. It is practical and easy to use since it involves only one parameter, the dissipative coefficient. In conclusion, this study provides useful tools and fundamentals for more advance studies related to the dissipative coefficient of various formulation or lubricant components to be investigated strenuously without over depending on the tribology test machine.

Utilisation of corrosion inhibitors is still one of the most practical techniques to combat corrosion. Moreover, replacement of toxic inorganic inhibitors with green, non-toxic and safe chemicals is always sought for. The effectiveness of corrosion inhibition largely depends on the presence of heteroatoms such as sulphur, nitrogen and oxygen and/or in the form of double or triple bonds between the aforesaid atoms (multiple bonds). Therefore, Schiff-base with long-chain alkyl that can be produced from nitrogen-based compounds from derivatives of various vegetable oils, including palm oil, can be an interesting alternative. Imine functional group in Schiff-base molecules can act as active centres for adsorption on the metal surfaces. Noor Khairin *et al.* (2020), successfully synthesised a new Schiff-base compound known as N-cinnamalidene palmitohydridize (CHP) via one-pot reaction between palmityl hydrazide and trans-cinnamaldehyde. The inhibition efficiencies of CPH noticeably increased with increasing inhibitor concentration and temperature. Importantly, CPH acts as a suitable inhibitor on mild steel.

The technology to produce biosurfactants and bio-based surfactants using palm-based oleochemicals is continuously developed to meet the demanding requirements of major end-use industries. Sugar esters are classified as non-ionic bio-based surfactants with excellent emulsifying, conditioning, and stabilising properties, making it suitable for use in pharmaceutical, cosmetic, food and detergent industries. Typically, sugar esters are produced via chemical routes that are poorly sustainable, which requires metal, acid or base catalyst, high temperature, toxic organic solvents and reduced pressure conditions. In the present years, the application of enzymes has emerged as an interesting alternative for synthesis (Pyo *et al.*, 2019). The enzymatic synthesis route is desirable as it is green, safe, and environmental-friendly. Arniza *et al.* (2020) studied possible route to produce bio-based surfactants without using toxic and expensive solvents commonly employed for the derivatisation of sugars or pre-derivatisation of the substrate's molecules. The performance of commercial immobilised lipase from Thermomyces lanuginosus (Lipozyme® TL IM) as a catalyst was evaluated to produce palm-based sorbitol monoesters via esterification reaction in a non-toxic organic solvent. Seven types of sorbitol monoesters with acylation at C_1 and C_6 of sorbitol, were successfully synthesised from fatty acids found in palm and PKO. Approximately 76% of sorbitol conversion was achieved under optimal reaction conditions. The conversion was found higher for medium-chain fatty acids ($\leq C_{12}$) when compared to longer chain fatty acids. The lipase catalyst can be used for at least four batch reaction cycles before it undergoes inactivation. The synthesised sorbitol monoesters, the bio-based non-ionic surfactants, could be potentially used in foods, personal care products, and pharmaceuticals.

Biosurfactants are derived from living cells compared to chemically synthesised surfactants and possess similar surface-active properties allowing their applications as cleaning, emulsifying, foaming, and dispersing agents. Biosurfactants from various microbial species have been produced on a range of carbon substrates. Most reported studies on biosurfactants are on glycolipids biosurfactants such as sophorolipid (SL) and rhamnolipids, but SL is the most studied biosurfactant. Abdul Rashid *et al*. (2020) utilised *Starmerlla bombicola* (*S. bombicola*) for the preparation of SL from palm oil. The SL component structure was elucidated using matrix-assisted laser desorption ionisation-time of flight mass spectrometry (MALDI-TOF MS) under positive and negative ion modes with 3-hydroxypicolinic acid (HPA) as the matrix. The use of HPA as the matrix for the structure elucidation of SL using MALDI-TOF-MS was never reported before. The 3-HPA has been established to be the superior matrix for the elucidation of SL structures using MALDI-TOF-MS. Furthermore, rapid analysis technique of 2 min run times identified the SL congeners produced, all of which contain 17-hydroxy *cis-9*-octadecenoic acid homologue. The determination of the distribution of SL congeners is essential as it regulates their self-assembly structures and, therefore, their application as glycolipid biosurfactants in environmental remediation, cosmetics, and personal care applications. Overall, favourable support from government regulatory bodies regarding the bio-based process and utilisation of bio-based raw materials act as a significant support system for the industry.

A study to investigate the potential of heterogeneous catalysts CaO, zinc oxide (ZnO) and MgO was conducted on transesterification reactions between methyl palmitate and triethanolamine to produce fatty esteramine an intermediate used in the production of esterquats (Haliza *et al.,* 2020). Among the metal oxides investigated, the CaO catalyst with low dosage (0.1%) showed the best catalytic activity towards the transesterification process as it gave the highest conversion (94.5%) of methyl palmitate and yielded fatty esteramine (46% diesteramine) compositions analogous to the conventional homogeneous catalyst within a relatively shorter reaction time. Therefore, the production of esterquats from esteramine becomes efficient and economically viable using the heterogeneous catalyst herein, CaO catalyst that can be recycled three times. Overall, the development of green process is positioned as an alternative to the conventional homogeneous approach for esterquats production.

Methyl ester sulphonates (MES) are known as an alternative green surfactant for the detergent market. The application of MES largely depends on the quality, which includes the composition, active content, purity and physical appearance. Growing emphasis are also given on eco-friendly manufacturing processes and raw material procurements. Moreover, the purification method of MES is of great interest to further expand the application of MES with high active content. Zulina *et al*. (2020) studied the factors influencing the purification of MES derived from palm methyl ester with different chain lengths (C_{12}, C_{14}, C_{16} and $C_{16–18}$). Purification of MES powder was conducted via crystallisation process with ethanol as the solvent. Interestingly, the process successfully attained more than 97% active content and 96% crystallinity index without changing MES structure. The crystallised MES C_{16} and $C_{16–18}$ attained excellent flow characteristics. Crystallisation also allows MES C_{12} and C_{14} conversion into solid powder, which was previously available, in the form of paste. The morphology, structural and its crystallinity analyses showed that the crystals MES had good solubility properties. The crystallised MES containing C_{12}, C_{14}, C_{16} and $C_{16–18}$ with high active content have β-polymorphic form, triclinic lateral structure, which are the most stable arrangement. The brittleness of MES crystals increased from a β′ to a β sub-cell. Crystal with high brittleness has the potential to ease the production of powder, which leads to a reduction in the cost of production and improves efficiency. Notably, the crystallisation of MES enable high active MES derivatives to be derived from palm methyl ester with different chain lengths.

CONCLUSION

The oil palm industry in 2020 was blessed with an upsurge of export revenue that counterbalance the depreciation of overall oil palm performance over the challenging landscape of COVID-19 pandemic. With the emphasis of achieving sustainable development goals, the latest research advancements are primarily driven towards oil palm cultivation, environmental management, food and health, renewable energy, green technologies and society. All of the misconceptions pertaining to palm oil have been taken positively for dynamic participation in research activities in addressing the international concerns. In fact, unwavering commitment by the Malaysian palm oil industry in combatting issues and critics related to sustainable development is reflected through various policies and regulations administered within the industry. The enhancement of oil palm productivity can be attained through precision agriculture for early pest and disease detection using non-invasive tools, aside from translating the knowledge of genomics research into cost-effective technology and application to end-users. In the perspective of the midstream sector, it is vital to improve milling efficiency via disruptive technology, process integration and digitalisation for higher extraction rate without compromising the safety and quality aspects of produced CPO. Moreover, the underutilised by-product streams at the palm oil mills can be potentially harnessed by ensuring the technologies and products attained are following the environmental regulations. As the world's population continue to grow for the next decades, sustainable palm oil has its pivotal role to play to intensify the value-creation of the downstream sector for both food and non-food applications to cater the demand from global industries. Apart from nutrition and health, the palm oil industry has doubled their efforts to mitigate the concerns associated to food safety and quality via innovative technology and good manufacturing practices. On that note, it is now the time for the industry to gravitate towards strengthening the consolidation between upstream, midstream and downstream for the retainment of palm oil existing market, aside from capturing more trade opportunities at the international arena. Focus should be also directed in embracing the fourth industrial revolution in leveraging the oil palm productivity and blockchain technology to reflect the industry's commitment for sustainable and transparent supply chain.

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