

ADVANCED REVIEW

An overview of palm oil biomass for power generation sector decarbonization in Malaysia: Progress, challenges, and prospects

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Abstract

With the ever-increasing danger of climate change, power plants are shifting from polluting fossil fuels to sustainable bioenergy fuels. As Malaysia continues to pledge to decrease glasshouse gas (GHG) emissions, quick and dramatic action should resolve the reliance on fossil fuel power plants. Furthermore, the coal-fired power station is Malaysia's biggest supplier of energy and the final power plant to be decommissioned. In Malaysia, a significant portion of palm oil biomass has the potential to replace coal in the generation of renewable energy power. However, the deployment of palm oil biomass as a renewable energy source has not been fully achieved. Furthermore, the surplus of unutilized biomass from the palm oil milling process has emerged as the key talking point leading to environmental concerns. As estimated, this palm oil biomass can generate approximately 5000 MW of electricity under 40% of operation efficiency. This significant power potential has the ability to replace Malaysia's yearly reliance on coal. Nonetheless, the limitations of technological stability, budgetary constraints, and other government policy concerns have prevented the potentials from being fulfilled. This necessitates an integrated framework that synergizes the decarbonization drive in order to realize the primary advantages of energy renewability and carbon neutrality. Among the suggested actions to decarbonize the power generating sector is an integrated scheme of palm oil production, biogas plant for electricity and steam

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generation, and biofuel pellet manufacture. This review provides an in-depth overview of palm oil biomass for Malaysian power production decarbonization.

This article is categorized under:

Sustainable Energy > Bioenergy

Climate and Environment > Net Zero Planning and Decarbonization

Sustainable Development > Emerging Economies

KEYWORDS

bioenergy, palm oil biomass, power generation, synergetic decarbonization

1 | INTRODUCTION

As part of key measures to combat climate change, the global transition strategy toward green and sustainable fuel supplies receives significant attention on a regular basis. Malaysia, as a developing nation, has made an aggressive promise to decrease glasshouse gas (GHG) carbon emissions, including a 40% reduction by 2020 and a 45% reduction by 2030 (Susskind et al., 2020). Malaysia has intensified its action by seeking to be a carbon-neutral country by 2050, and the government will no longer be permitted to develop new coal-fired power plants, despite the fact that coal presently accounts for 40% of national energy output (Bernama, 2021). As reported by Griffin et al. (2014), the energy generated by the coal-fired power plant contributed 36% of the country's total GHG emissions based on average global direct GHG emissions factors for coal and natural gas. On the other hand, data given by World in Data Oxford University (Ritchie & Roser, 2020) shows that Malaysia has generated 272.61 million tons of annual carbon dioxide (CO₂) emissions from burning fossil fuels for energy and cement production. In addition, Malaysia has been ranked among the 11 most carbon dioxide emitters in Asia in 2017. Malaysia is presently focusing on the development and usage of renewable energy resources in order to reduce the contribution of coal-fired power plant carbon emissions from the energy power sector. As a result, the biomass power plant's use of renewable energy resources is progressing to fill the future empty spaces left by the coal power plant.

Spath and Mann (2004) looked at power generation for two fossil-based technologies: coal-fired power generation and natural gas combined-cycle (NGCC), as well as two biomass technologies: a biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop, a direct-fired biomass power plant using biomass residue, and a biomass residue/coal co-fired system. They reported that the production of electricity by biomass energy crop feedstocks has substantially reduced the GWP and the fossil energy consumption per kilowatt hour (kWh) of electricity generated. Interestingly the direct-fired biomass power plant with CO₂ sequestration and extra capacity from an NGCC system (depicted in Figure 1a) resulted in the highest net GWP balance (−1368 g CO₂-eq/kWh) compared with the coal-fired power reference case (depicted in Figure 1b). They concluded that producing electricity using biomass feedstocks would significantly lower the GWP and fossil energy consumption per kWh of electricity produced compared with fossil fuel-derived power. Even with CO₂ sequestration, the quantity of GHG emissions per kWh of energy generated is higher for fossil-fueled systems than biomass-powered systems. The comparison of GWP and energy balance for fossil and biomass systems from this study is summarized in Table 1.

Malaysia's principal agricultural crop is palm oil, accounting for 29% of world palm oil output (Wahab, 2018). Malaysia, the world's second-largest palm oil producer, has a plentiful supply of palm oil biomass resources. More than 100 million tons of palm oil fresh fruit bunches (FFB) were processed annually from Malaysia's 446 palm oil mills (POM; Zamri et al., 2019). As a key product of palm oil FFB, the POM operation primarily extracts crude palm oil (CPO) and palm kernel oil (PKO). Only 10% of the FFB was recovered, whereas the remaining 90% of processed FFB comprised diverse biomass components in solid and liquid forms (Loh, 2017). However, due to inefficient and irresponsible milling equipment and activities, these massive volumes of biomass have been recognized as contributors to GHG carbon footprint (Hosseini & Abdul Wahid, 2015). A significant amount of biomass, notably the empty fruit bunch and palm oil mill effluents (POME), are still left unharvested in the mills. Due to the open decomposition of empty fruit bunch (EFB) that generates non-CO₂ greenhouse gases into the atmosphere, as reported by Saritpongteeraka et al. (2022). Furthermore, it was said that palm oil production is related to a significant quantity of biomass, and the key difficulty is the high cost of disposal owing to the enormous

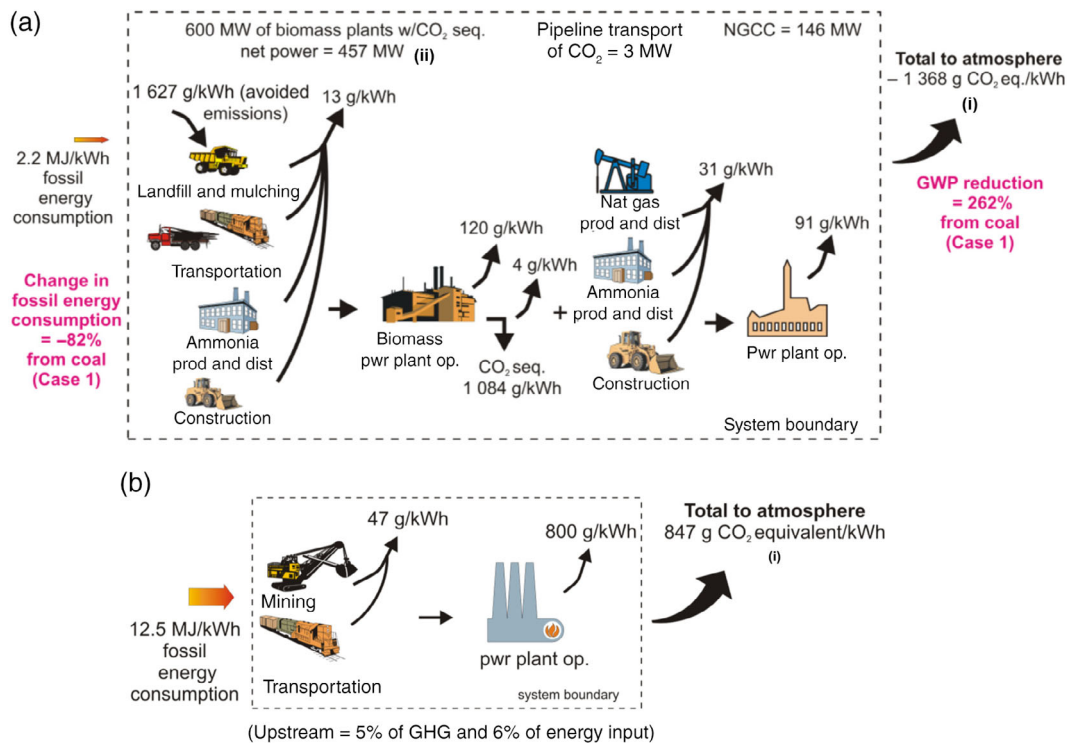


FIGURE 1 Comparison of GWP and energy balance for fossil fuels and biomass power systems (Spath & Mann, 2004). Here (i) GHGs (CO₂, CH₄, and N₂O) expressed in grams of CO₂-eq/kWh of electricity generated, (ii) several small biomass plants are required to produce 600 MW economically. (a) Biomass residue direct-fired system with CO₂ sequestration at constant capacity. (b) Coal-fired system reference case (Case 1 in Table 1)

TABLE 1 Summary of GWP and energy balance for fossil and biomass power systems

System	Case	Change from reference coal system(case 1)	
		Change in GWP ^a	Change in fossil energy consumption
Coal-fired	1	0	0
	1a ^b	-71%	16%
NGCC	2	-41%	-33%
	2a ^b	-71%	-22%
Biomass/coal co-firing	3	-19%	-12%
	3a ^b	-95%	4%
Biomass direct-fired	4	-148%	-99%
	4a ^b	-262%	-82%
Biomass IGCC	5	-94%	-98%
	5a ^b	-179%	-87%

^aGHG emissions expressed in terms of CO₂ equivalence.

^bThe w/CO₂ sequestration, and extra capacity from an NGCC system.

volume of EFB that does not have an appealing market value (Abdullah et al., 2013). As a result, the purpose of this article is to give a detailed discussion on using the palm oil biomass potential for usage as renewable energy (RE) source for power production in Malaysia in order to decarbonize the coal power sector synergetically. To give a unique perspective, the current and former environmental, technological, and economic policies established to expand palm oil bioenergy were examined and summarized for future expansion and improvement. The schematic flow diagram of the biomass value proposition is presented in Figure 2.

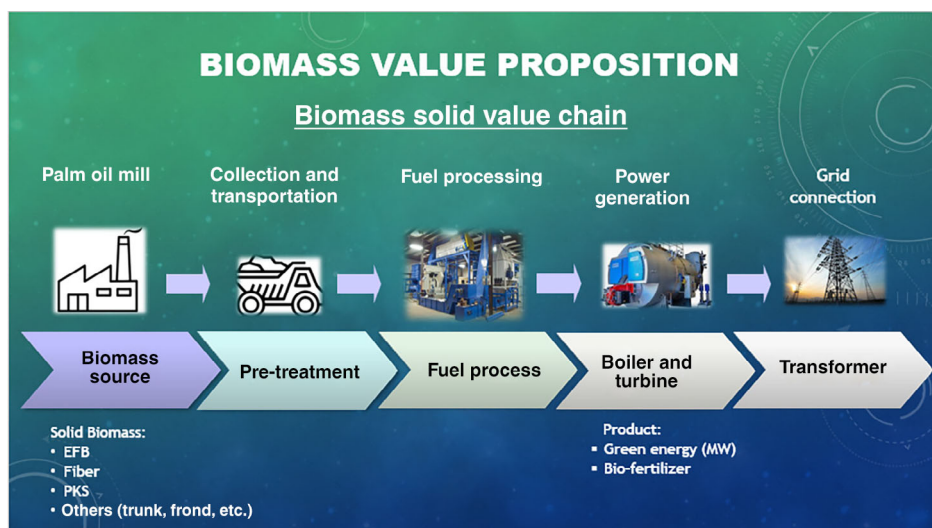


FIGURE 2 Schematic flow diagram of the biomass value proposition

TABLE 2 Malaysia palm oil sector operational capacity 2020 (tons/year) (MPOB, 2020)

Sector	Peninsular Malaysia		Sabah		Sarawak		Malaysia	
	Number	Operational capacity	Number	Operational capacity	Number	Operational capacity	Number	Operational capacity
FFB Mills	242	58,155,680	132	34,650,070	83	24,006,000	457	116,811,750
PK Crushers	26	4,397,500	12	2,072,200	4	697,200	42	7,166,900
Refineries	35	14,840,200	9	7,238,000	6	3,275,000	50	25,353,200
Oleochemicals	20	2,629,941	—	—	—	—	20	2,629,941

2 | ENVIRONMENTAL ISSUES OF MALAYSIA PALM OIL MILLING INDUSTRY

Malaysia's POM business has significantly increased over the previous 30 years, with dramatic increases in FFB processing capacity from 42.8 million to 112.5 million tons through 446 mills (Nambiappan et al., 2016). This large processed FFB capacity increment is mainly contributed by the number of POM that increased along with the expansion of the planted area from 2 million ha to 5.9 million ha (MPOB, 2019b). In Malaysia, 446 POM were operated at scattered locations in Peninsular Malaysia, Sabah, and Sarawak. According to MPOB report 2019 (MPOB, 2019a), the number of POM in Peninsular Malaysia recorded the highest FFB operation capacities via 241 operated mills, which are primarily located at Johor, Pahang, and Perak. Meanwhile, Sabah and Sarawak significantly contribute to the remaining operated mills, as shown in Table 2 and Figure 3. The overview of Malaysia's palm oil plantation that is majorly contributed by five top states that combine peninsular state (Perak, Pahang, and Johor) and East Malaysia (Sabah and Sarawak) is depicted in this figure.

Predominately, the number of processed FFB capacities depends on the mills' operation size and the process continuity. As reported by Akhbari et al. (2020), the size of POM is grouped into small and large-scale operations based on the designed capacity. Below 20 tons/ha, it is categorized as small scale. Besides, the amount of processed FFB is different between the integrated mills that continuously been processed from the harvested FFB compared with the mills located far from the plantation area. According to Foong et al. (2019), all harvested FFB are required to be processed immediately to prevent the rapid deterioration of CPO quality. Thus, each mill has a different FFB processed capacity due to the operating system that relies on the location, labor workforce, technology, and materials available. In this sense, most Malaysian POMs are located within the estate area to preserve the CPO quality and minimize the FFB transportation cost. These mills are far from the access of electrical grid and left with inefficient energy supply for the

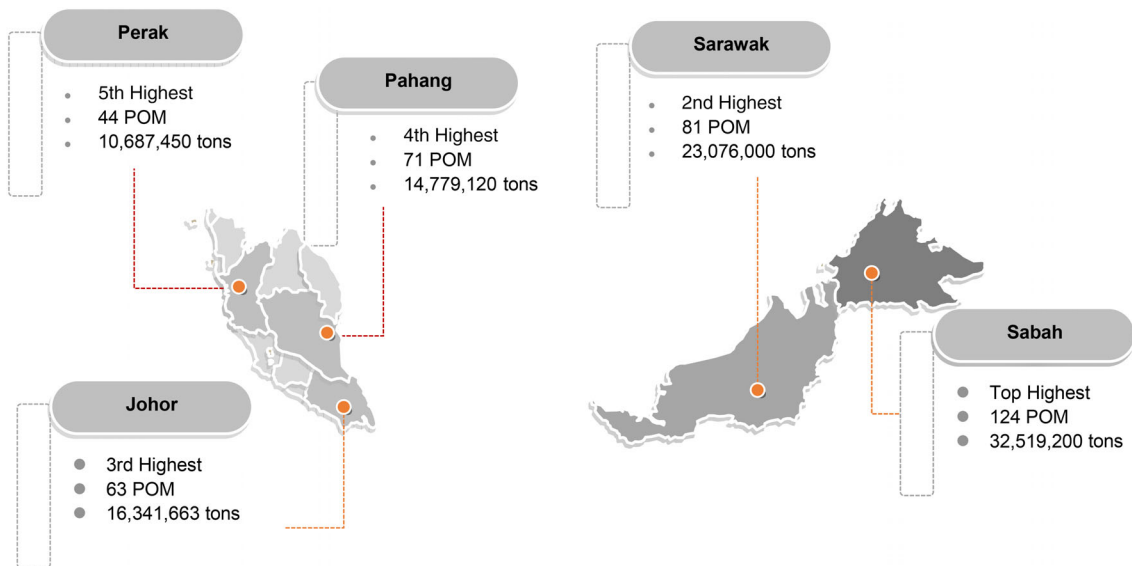


FIGURE 3 The top state of Malaysia palm oil milling industry for FFB processing

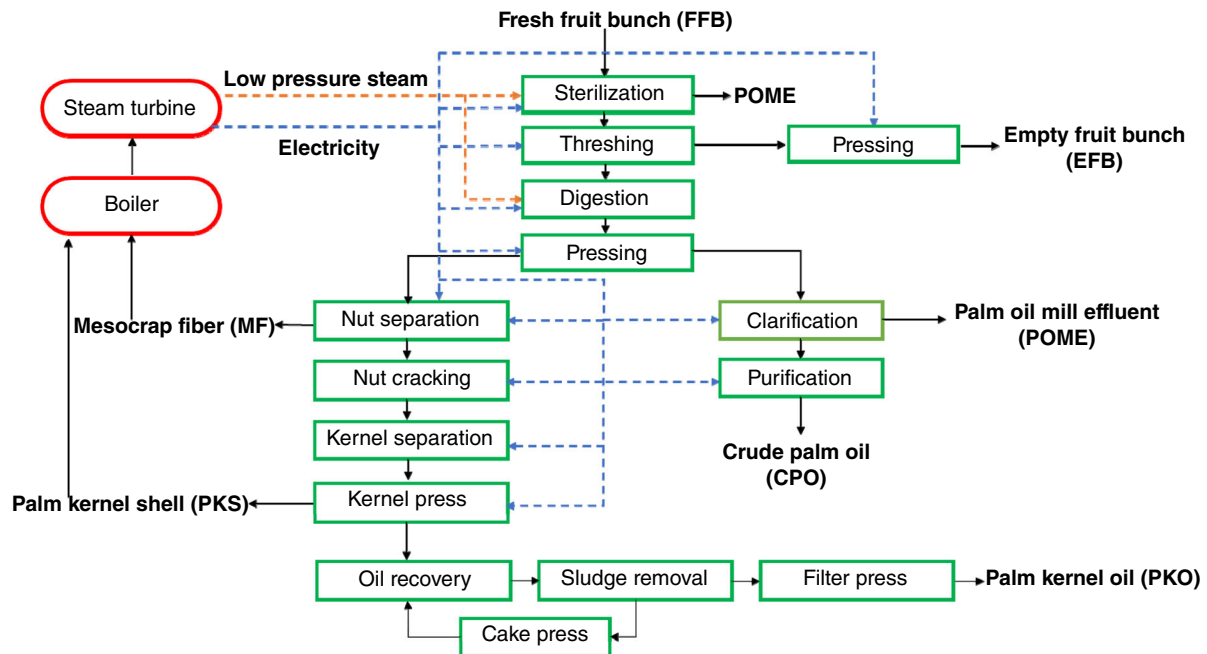


FIGURE 4 Palm oil mill process flow diagram for CPO and PKO extraction

CPO and PKO extraction process. Figure 4 shows the typical flow of FFB processing for CPO and PKO extraction using the alternative energy resource.

FFB is sterilized, separated, digested, and pressed in a typical milling system, yielding intermediate processing products of press liquid and fiber nuts (Akhbari et al., 2020). These products are then purified and separated in preparation for CPO and PKO manufacturing. The FFB is cooked and heated utilizing the steam boiler's energy by burning solid biomass's secondary byproducts in this procedure. Furthermore, the steam generated is utilized to power the palm oil mill's electrical cogeneration system. Although the steam boiler might replace the grid's electrical power source, poor combustion and solid biomass breakdown added to GHG emissions. According to Saswattecha et al. (2015), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) were among the GHG equivalents emitted, all of which contributed to air pollution. The CH₄ gases are also produced by the liquid biomass, which is released as a POME during the milling process.

TABLE 3 Malaysia palm oil milling environmental sustainability issues

Main points	Issues	Standard limit and regulations	Challenges	References
GHG emission	The high concentration gases and particulate emissions from transportation, POME, biomass decomposition, and combustion are the process sources of the GHG emissions in POM.	Air emission limit of particulate matter 150 $\mu\text{g}/\text{m}^3$ (EQA 2014)	Challenging for the old milling industry to be equipped with the current advanced technology in fulfilling the requirement due to high capital investment for the technology installation.	DOE (2019)
Wastewater	POME produced a high concentration of contaminants: biological oxygen demand (BOD), chemical oxygen demand (COD), and suspended solids 100 times higher than domestic sewage. Pointed as the second-largest methane gas producer after municipal solid waste landfill.	Parameters limit of environmental quality (EQA 1982) BOD (20 mg/L) pH (5–9) TSS (100 mg/L) Total nitrogen (150 mg/L)	The millers cannot sustain the treatment operation consistency due to a lack of expertise personnel, technical experience, and high maintenance costs.	Meng (2012); Nahrul et al. (2017); Soleimaninanadegani and Manshad (2014)
Waste management	The excessive of naturally degraded palm oil biomass could contribute to the various environmental implications that may result in air pollution and contamination in soil and groundwater resources.	Environmental quality act 1974 (Act 127) and the Environmental quality (scheduled waste 2005)	The landfill disposal will require more land usage and is not able to efficiently utilize the potential of the generated waste due to the lack of demand for biomass valorization.	Faizi et al. (2017); Hamzah et al. (2019); Singh et al. (2011)
Inefficient energy	Inefficient operation boiler system and resulted toward the released concentrated particulate matter that polluted the atmosphere.	Air emission limit of particulate matter 150 $\mu\text{g}/\text{m}^3$ (EQA 1997)	Applying the higher performance of combustion through combined heat and power systems requires an increased capital investment that is difficult for small milling operations.	UNDP (2014)

As illustrated in Table 3, the primary discussion points of POM environmental issues have been GHG emissions, wastewater contamination, and inefficient energy and waste management. In the present circumstances, the functioning of the ancient mills is having difficulty meeting the severe criteria imposed by authorities. The particle matter standard for air pollution had been amended to $150 \mu\text{g}/\text{m}^3$ and went into effect in April 2019. However, Malaysia's Department of Environment (DOE) has reported that only 52 POM has met with the regulation at that time. High investment capital to upgrade the old operational system is among the millers' main challenges in meeting the requirements. Moreover, the generated biomass was not considered worth in economic value to be fully utilized by the palm oil millers. The disposal cost using inefficient practice was much low rather than valorizing the mill operational power demand's biomass potential. As highlighted by Abd Rahman et al. (2017), in addressing the biomass disposal matter, the high moisture EFB was reused in other applications such as soil conditioner or biofertilizer rather than converting into fuel feedstock that requiring an additional process of drying and pressing which certainly will escalate the operating cost. Consequently, this inefficient disposal of palm oil biomass gave implications toward air pollution and the contaminations in soil and groundwater resources (Singh et al., 2011).

Aside from waste management concerns, the release of highly polluted raw POME into a body of water may impair the aquatic life's habitat owing to oxygen depletion (Soleimaninanadegani & Manshad, 2014). To prevent contamination to the water body, DOE has established a severe BOD discharge limit (20 mg/L) of Standard A for POME-treated effluent (Meng, 2012). In practice, the treatment system's irregularity is due to a lack of skilled staff, experience, and a high operating cost for technology installation and maintenance (Kushairi et al., 2017). The RE project previously launched under the National Key Economic Area (NKEA) and the Clean Development Mechanism (CDM) program for POM concluded with low effect outcomes (Chuen & Yusoff, 2012). The developed RE facilities in POM are not consistently operated, and the number of anaerobic digestion (AD) plants is reduced as the funding for the program ends (Zamri et al., 2019). Besides, Omar et al. (2018) reported that the existing method of conventional steam sterilization is inefficient for FFB breakdown and inactivation. It also necessitates a huge quantity of water, which requires increased energy consumption and the production of a significant amount of POME.

However, the use of greater performance and a combined heat and power system to replace the present inefficient boiler system necessitates a large capital expenditure, which is challenging for small milling plant operations. The closed-loop system could not achieve net-zero GHG emissions in the current operating system. The biomass fuel utilization in the boiler system is as inefficient as the biomass feedstock. On the other hand, POME is not effectively exploited for the mill to continually sustain the operational system. As a result, a complete solution that offers a holistic strategy for POM to remove GHG, decrease wastewater discharge, and enhance palm oil production efficiency is greatly wanted. In this respect, a major economic model to thoroughly enhance the POM operation at high efficiency should be established to assure the milling industry's complementary role in ensuring the environment's long-term sustainability.

3 | MALAYSIA PALM OIL MILLING BIOMASS GHG EMISSION AND REDUCTION POTENTIAL

The palm oil industries have been claimed to be a significant contributor to global warming through GHG emissions from the land-use change of palm oil expansion and the milling residual biomass. Lee et al. (2018) reported that palm oil was included among the agriculture activities that contributed to the second-highest GHG emissions by the economic sector. In palm oil milling operation, the GHG mainly contributes from the solid and liquid biomass released from inefficient boiler combustion, biomass degradation, and POME throughout the milling process. Based on the study conducted by Roundtable of sustainable palm oil (RSPO, 2009), POME is the largest source of CO_2 emission in POM,

TABLE 4 The amount of Malaysia GHG emission from POME, EFB, and MF (Shamsuddin, 2012)

Biomass	GHG emissions produced (kg CO_2 -eq/t)	Annual amount of CPO produced (million ton/year)	Annual amount of GHG emissions produced from the biomass (million tons CO_2 /year)
POME	1467	19.9	29.1
EFB	1130	19.9	22.5
MF	715	19.9	14.2
		Total	65.2

which is in the order of 625–1467 kg CO₂-eq per ton CPO (based on a yield range of 3.2–4 tons CPO/ha). Furthermore, the EFB and mesocarp fiber (MF) are significant sources of unutilized biomass that contributed to the CO₂ emissions. Saswattecha et al. (2015) calculated that the unutilized EFB dumped by the non-certified RSPO POM is the main source of CH₄ emissions that largely contribute to the global warming impact and contributes about 1130 kg CO₂-eq for each ton of CPO produced. Despite the inefficient practice of MF in boilers for steam production and electricity generation, it also contributes to environmental pollution. Therefore, by taking the reported data as a reference, the amount of Malaysia GHG emission from POME, EFB, and MF can be calculated as shown in Table 4. The amount of CO₂ emission is calculated based on Malaysia's CPO production in 2019.

As calculated, the total of Malaysia POM GHG emissions from the unutilized biomass of POME, EFB, and MF is approximately produced 65.18 million tons/year. This amount of gas emission is required to be eliminated from being polluting the environment. Besides, the elimination of CO₂ is an enormous contribution toward achieving Malaysia's goal of sustainability. Therefore, the usage of RE resources (carbon-neutral energy sources) from palm oil biomass to displace as much as possible the use of fossil fuels, which is one of the most significant contributors to GHG reduction. As Shamsuddin (2012) estimated, the palm oil biomass has the potential of 3470 MW of power under 30% efficiency. However, based on the updated data in Table 5, the power generation from palm oil biomass could be maximized to 4947 MW under 40% process efficiency of co-firing with coal power plant system that almost equivalent to the current power generation of 4100 MW at TNB Jana Manjung Power Plant (Bernama, 2019).

In addition, the utilization of biomass fuel for power generation also contributes to further carbon emission reduction from coal power generation. As shown in Equations (1) and (2), the calculation of carbon emission from the power plant is produced 25.92 million tons CO₂-eq. Therefore, the total GHG emissions reduction by utilizing palm oil biomass for power generation is further increased to 91.1 million tons (Shamsuddin, 2012).

$$\begin{aligned} &= \text{Power generation} \times \text{operation hour} \times \text{mix fuel factor} \\ \text{Power of mix fuel} &= 4947 \text{ MW} \times 8000 \text{ h} \times 0.9 \\ &= 36 \times 10^6 \text{ MWh} \end{aligned} \quad (1)$$

$$\begin{aligned} &\text{Total carbon emission produced from power generation} \\ &= \text{Amount of CO}_2 \text{ generated from each KWh of power generated} \times \text{Total power generated} \\ &= (720 \text{ g CO}_2 / \text{KWh}) \times 36 \times 10^6 \text{ MWh} \\ &= 25.9 \text{ million tons CO}_2 / \text{year} \end{aligned} \quad (2)$$

Interestingly, this estimated total GHG emission reduction could contribute to Malaysia's GHG emission per capita reduction from 8.2 tons CO₂-eq to 5.7 tons CO₂-eq per capita. Moreover, the surplus decarbonization of the GHG emission is incredibly significant for Malaysia to fulfilling the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement 2016 commitment to reducing the emissions of 13.1 million tons CO₂-eq for the year 2030. Nevertheless, the concept of POM GHG reduction requires a comprehensive policy setting in aligning the direction and goals toward continuous implementation of POM sustainability practice. In this regard, the assessment of current RE policy and strategies could be focused on defining an applicable approach for palm oil biomass as a potential RE resource and contributing to GHG reduction. The replacement of fossil fuel by palm oil biomass could be the best potential to improve environmental sustainability.

TABLE 5 Biomass power generation capacity (MW) for 8000 h operation (Shamsuddin, 2012)

Biomass type	Efficiency: 30%	Efficiency: 35%	Efficiency: 40%
MF	1500	1746	1996
PKS	1034	1206	1379
EFB	1182	1377	1572
Total	3716 MW	4329 MW	4947 MW

Note: Efficiency: 30%–35%—dedicated biomass generation plant. Efficiency: 40%—co-firing with coal in utility size coal power plants.

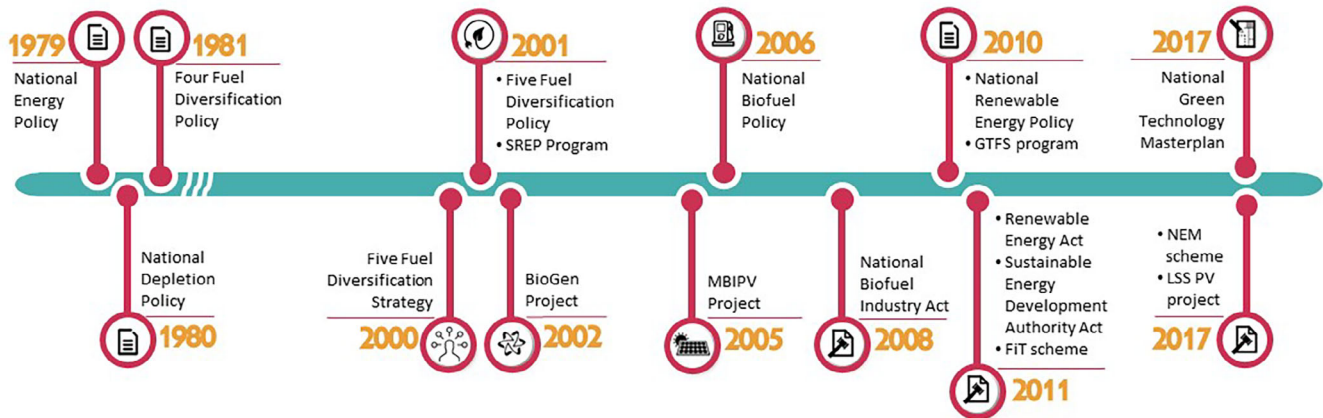


FIGURE 5 Progress timeline of Malaysia's energy policies and renewable energy initiatives (1979–2017)

4 | MALAYSIA BIOMASS ENERGY ROADMAP, POLICY, AND STRATEGIES

Malaysia's energy landscape is evolving toward a more diverse mix with increasing renewable energy. As shown in Figure 5, Malaysia's first National Energy Policy, enacted in 1979, paved the way for a future energy supply that was efficient, secure, and environmentally sustainable (Khairul et al., 2014). Simultaneously, the “National Depletion Policy” was implemented to conserve the country's fuel supplies by restricting the use of crude oil and gas.

Because oil remained the dominant source of energy supply, the “Four-Fuel Diversification Policy 1981” was developed to prioritize other resources in the energy mix, including gas, hydropower, and coal. This has resulted in an increase in coal usage, mainly in electricity generation and industry. In the year 2000, coal power production in Peninsular Malaysia started to rise, explaining the progressive increase in coal supply into the energy supply mix rapidly (Malaysia Energy Commission, 2017). In the same year, the Eighth Malaysia Plan developed the Five Fuel Diversification Strategy, in which biomass, biogas, municipal waste, solar, and mini-hydro were identified as possible RE resources in electricity generation (Chua et al., 2011; IBP, 2015). Consequently, under the Five-Fuel Diversification Policy, RE was included as the fifth fuel in the energy mix in 2001 as a crucial move to promote sustainable energy sector development and stimulate RE's growth in Malaysia.

To promote RE as the fifth fuel, the government launched the Small Renewable Energy Power (SREP) program in 2001. Under this initiative, small RE power-producing units could sell the produced energy to the grid. However, this initiative was not well-received since it only achieved 3% of its aim of installing 500 MW of RE by 2005. The poor return rate was one of the causes for the failure since it did not entice new investors to engage in SREP (Hashim & Ho, 2011). Besides that, the time-consuming approval process, low capacity cap, and lack of support from the electric supply's stakeholders are why the program is far from its goal (Sovacool & Drupady, 2011). The RE facilities' profit was barely enough to cover the overall maintenance of the operation cost, which has led the RE companies to find other sources of income.

The palm oil industry's “Biomass-based Power Generation and Cogeneration (BioGen)” initiative was formed in 2010 to stimulate the use of biomass and biogas waste from palm oil mills to replace a portion of the fossil fuels used in power generation (Aldover & Hun-Yang, 2010). In addition, the “National Biofuel Policy” was developed to support the “Five-Fuel Diversification Policy,” with the view that stable palm oil prices would have a knock-on impact on mobilizing local resources and boosting biofuel exports (Masjuki et al., 2013). Unfortunately, owing to the low global oil prices and the comparatively high price of palm oil at the same time, this endeavor was also unsuccessful. Aside from that, technical issues with biofuel, such as its unsuitability for engines and tendency to cause clogs, have damaged public interest (Bujang et al., 2016). After 2 years, the “Biofuel Industry Act” of Malaysia was enacted to further ease biofuel consumption by reducing administrative impediments. Despite this, the expansion of RE was still sluggish at the time.

The government developed the National Renewable Energy Policy in 2010, which incorporates parts of energy, industrial, and environmental regulations to create a convergent policy (Hashim & Ho, 2011). The “Green Technology Financing Scheme (GTFS)” was created to increase the use of green technology. The Renewable Energy Act was then passed in 2011. The legislation created a specific tariff structure known as the feed-in tariff (FIT) to regulate the

implementation. The implementation of FiT has substantially accelerated the production of RE and mitigated the shortcomings of SREP (Muhammad-Sukki et al., 2014). It reduced the investment risk by ensuring that the RE developers would have grid connection and a long-term power supply contract with the power utility business. A significantly higher profit margin under the new FiT tariffs under the Renewable Energy Act 2011 and the Sustainable Energy Development Authority Act 2011 has also piqued the attention of stakeholders (Wong et al., 2015). The “Sustainable Energy Development Authority (SEDA)” has played a significant role in helping the RE project developers in gaining financial aid under GTFS, besides for developers and the state government (Ludin et al., 2013). The acceptable RE sources under this plan include biogas, biomass, small hydro, solar photovoltaic, and geothermal, which was introduced in 2015. The length of the FiT system varies depending to the kind of renewable resource and technology used. The length for biomass and biogas resources is 16 years, whereas modest hydropower and solar photovoltaic technologies need 21 years. As of December 2016, a total of 11,264 cumulative Feed-in Approval (FiA) with an installed capacity of 1386.4 MW have been allowed for the quota through the year 2019 (excluding for solar photovoltaic [PV], which was permitted until the year 2016). From the total of approved installed capacity, solar PV has contributed the most (31%), followed by biomass (27%), small hydro (25%), biogas (14%), and finally, geothermal (3%; Ludin et al., 2013).

Figure 6 shows the annual power generation review by commissioned RE plants of 5 years of FiT implementation, from 2012 to 2016. Since its inception in 2011, FiT has successfully increased the portion of RE contribution as it steadily increases, until they make up about 1.3% and 0.4% of the fuel mix, respectively, in 2016, which are almost 90% of the total RE contribution in the year 2016. Predominately, solar PV owns the highest share (50%) in the RE generation mix with the highest power generation, 306,751 MWh. The FiT rate for solar PV has already closed for registration in 2016 and was replaced by net energy metering (NEM) with the total target capacity of 500 MW, which is capped at 100 MW annually until 2020. On the other hand, biomass power generation did not improve after the year 2013. Its share of biomass in the RE generation mix declined dramatically from 73% in 2012 to 28% in 2016.

The government recognizes the necessity of enhancing governance in the future energy economy and energy planning framework in the most recent Green Technology Masterplan (GTMP) for 2017–2030 (Ministry of Energy Green Technology and Water [KeTTHA], 2017). The RE mix is set to increase up to 20% of the total installed capacity by 2020, 23% by the year 2025, and 30% by 2030. They look at the present situation, which includes new power plant projects with a total installed capacity of 4735 MW. By 2020, the national installed capacity was expected to reach 39,983 MW. According to the projected power fuel mix in terms of installed capacity, the total installed capacity of RE would be 3347 MW by 2020. This translates to an 8.4% share of renewable energy in the power supply mix by 2020, falling short of the GTMP objective of 11.6%. However, with the revised RE definition of large hydro, the GTMP aim becomes highly achievable, with a projected 23.6% contribution of RE in the fuel mix (Ministry of Energy Green Technology and Water [KeTTHA], 2017). While solar energy seems to be attracting the attention and support of the government and business

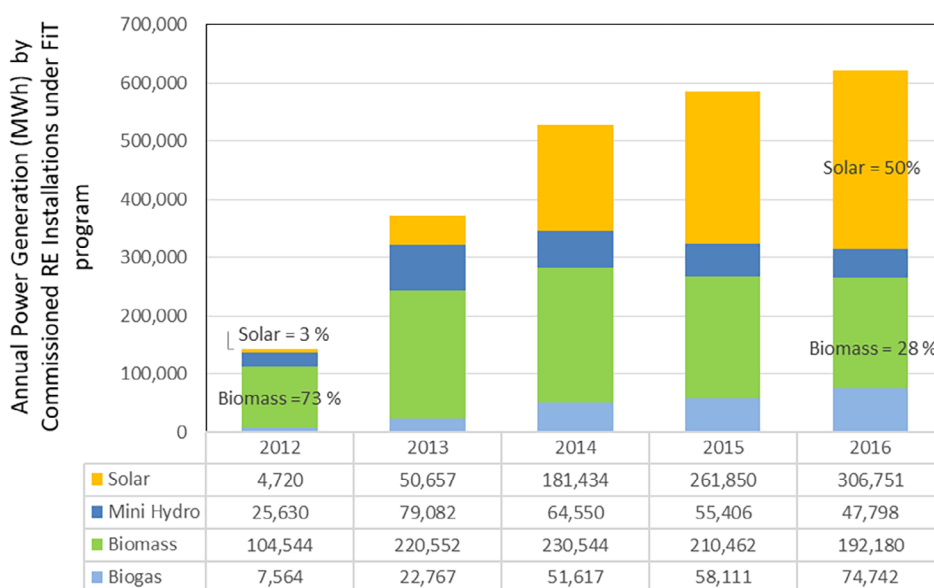


FIGURE 6 Annual power generation (GWh) from commissioned RE installations under the FiT program (Salleh et al., 2020)

sectors, other renewable energy resources are still battling to acquire finance for future project development. As a result, the future RE projects will favor solar, resulting in an imbalance in the RE power generating mix. The current energy policy should be more supportive of bioenergy conversion to avoid becoming too dependent on a single RE source. Furthermore, stronger legal measures should be placed on firms or organizations that harm the environment on a constant basis. Without substantial enforcement to reduce the use of fossil fuels in power plants, bioenergy resources will be sidelined indefinitely, and GHG emissions will grow. The biggest technical and financial constraints might be overcome by increasing the security of biomass supply and utilizing existing fossil fuel facilities that are flexible for all POM participants to regularly execute the green and clean system. Furthermore, the future planning generated economic model that is feasible for all POM is critical in keeping the whole commitment to biomass power generation.

5 | BIOMASS UTILIZATION TECHNOLOGIES

Biomass is a type of solar energy resource that is stored in the form of chemical energy inside the plant through the photosynthesis process, which people have traditionally used. The major components of lignocellulosic biomass are cellulose, hemicellulose, and lignin (Hoang et al., 2021). There are several strategies for using biomass, physical conversion technologies, thermochemical conversion technologies, and biochemical conversion technologies are the three main strategies. Physical conversion technologies modify and process biomass to produce high-value products while maximizing the usage of lignocellulosic resources. Physical conversion technologies are used to make sheets, structural materials, and lignocellulosic composites. Chemical conversion technologies were used in the pulp and paper sector. Bagasse, wheat straw, corncob, cotton stalk, and shive may all be used to make artificial biomass sheets. These sheets, especially nontimber lignocellulosic biomass artificial sheets, may aid in the conservation of forest resources and environmental preservation (Chen & Wang, 2016). On the other hand, artificial boards and building wall materials are very primitive applications of lignocellulosic materials.

Thermochemical conversion is the most feasible technique to convert biomass which includes combustion, carbonization, pyrolysis, gasification, hydrothermal liquefaction, and hydrolysis to sugars. The degree of oxidation, temperature, heating rate, and residence time are the major operational parameters influencing thermochemical conversion. Combustion is the rapid interaction of fuel and oxygen that produces thermal energy and flue gas, which is mostly composed of carbon dioxide and water (Demirbas, 2004). The combustion of biomass generates heat and power at moderate to high temperatures (800°C–1600°C). This technique has a lengthy history. Carbonization is the process of heating complex carbonaceous material like lignocellulosic biomass to break down into elemental carbon and chemical molecules that contain carbon (Brown, 2011). Gasification is the process of converting lignocellulosic biomass at high temperatures and in an oxygen-depleted environment into syngas, a flammable gas combination of carbon monoxide, hydrogen, methane, nitrogen, carbon dioxide, and trace amounts of hydrocarbons (Sikarwar et al., 2016). Pyrolysis is

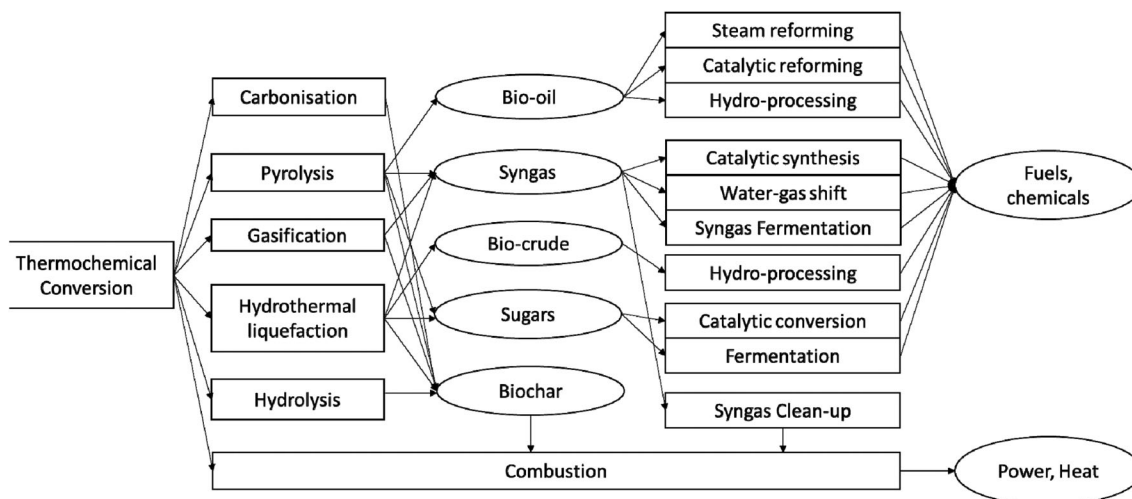


FIGURE 7 Thermochemical options for the production of fuels, chemicals, power, and heat

the anaerobic decomposition of biomass at temperatures between 300°C and 800°C (Hoang et al., 2021). The pyrolytic products include syngas, tar, and char, with ash as an unwanted residue. Hydrothermal liquefaction refers to the thermal treatment of wet biomass at high temperatures and pressures to generate carbohydrate, liquid hydrocarbons, or gaseous products. Hydrolysis is the process of thermally depolymerizing biomass into monosaccharides and then catalytically synthesizing fuel molecules from these carbohydrate building blocks (Brown, 2011). The thermochemical conversion of biomass to fuels, chemical power, and heat can be shown in Figure 7.

The biochemical conversion process uses enzymes and microorganisms to transform plant polymers into fuels, chemicals, or power, contrasting the thermochemical method that uses heat and catalysts. Biomass biochemical conversion methods are mild, pure, clean, and efficient when compared with other conversion processes. Before being transformed into final market goods, lignocellulosic biomass resources are first separated into cellulose, hemicellulose, and lignin. Carbohydrate polymer fractions, such as starch, cellulose, and hemicelluloses, are physicochemically or biochemically degraded to fermentable sugars once they have been separated. These fermentable sugars are subsequently used to make biofuels and other compounds. Figure 8 depicts the pathways of biochemical conversion of biomass. Biomass power production is a method that utilizes steam generated by biomass fuel combustion to drive a turbine. Table 6 shows the available biomass power generation technology and the characteristic of those technologies.

The conversion of palm oil biomass into electricity generation might result in the production of a variety of solid, liquid, and gas biofuels. These energy biofuels are created by combining thermochemical, biochemical, and physical conversion mechanisms (Tan et al., 2015). Each of the processes has a distinct condition that is dependent on palm oil biomass feedstock. Currently, the system used can handle power generating capacity ranging from 1 to 50 MW by employing various kinds of palm oil biomass feedstock. As reported by Malek et al. (2017), small-scale plants (<5 MW) have been mainly used compared with medium scale (10 to 50 MW) plants where the availability was still few and used at demonstration level. Fixed bed gasification technology with internal combustion has been mostly employed for biomass thermochemical process power generation. However, alternative forms of conversion technologies can create electricity from palm oil feedstock. Furthermore, each technique has its own pretreatment procedure and combustion furnace. Figure 8 shows the updates of the characteristic of the technology for palm oil biomass feedstock.

6 | CHALLENGES

Figure 9 summarizes the technical, financial, governance, and policy barriers of biomass energy projects. Technically, most of Malaysia's current biomass combustion systems continue to rely on inefficient low-pressure boilers, which is the fundamental reason why biomass power generation has not progressed (Umar et al., 2018). A big biomass power

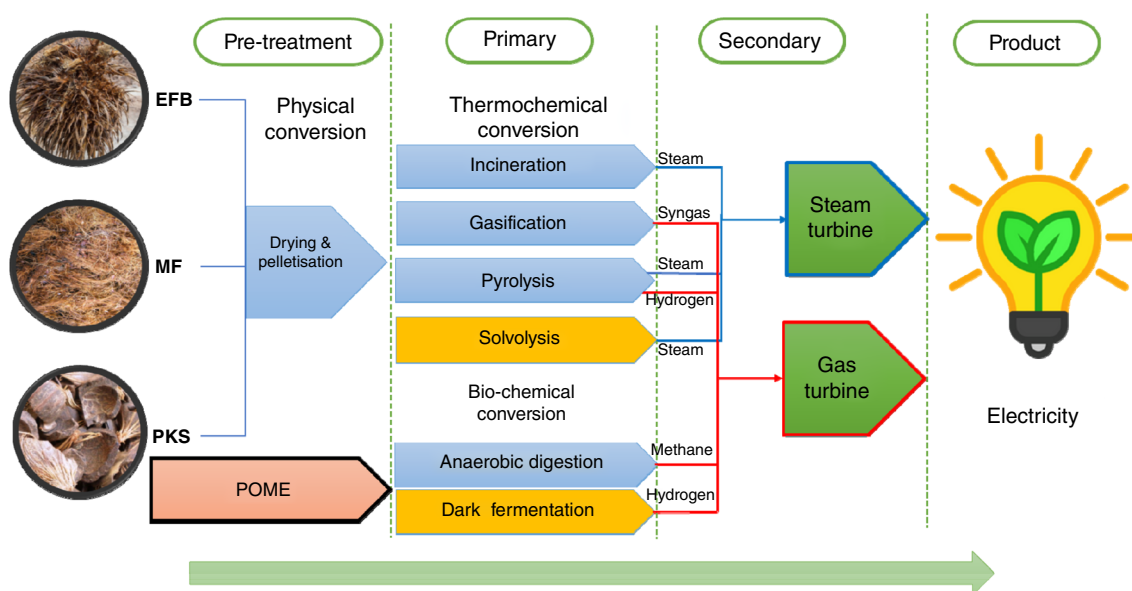


FIGURE 8 Palm oil biomass power generation technology

TABLE 6 Biomass technology for power generation

Technology	Installation type option	Operation conditions	Type of biomass	Advantages	Challenges	References
Combustion	Fixed bed	Power output: 0.15–150 MW Moisture content: 5–60 wt% Ash content: <50 wt% Particle size: <150 mm	All types biomass	1. Grate technology is cheaper 2. Require less energy than fluidized bed technology	Fuel ash from different fuels burnt together lead toward excessive fouling and bed sintering problems	Hupa (2012); Tillman et al. (2009)
	Fixed grate					
	Moving grate:					
	1. Traveling grate					
	2. Rotating grate					
	3. Vibrating grate					
	Bubbling					
	Fluidized	Power output: 5–120 MW Moisture content: 5–60 wt% Ash content: <10 wt% Particle size: <100 mm	Bark, wood chips, sludge, and bagasse	1. The bed stayed mostly in the furnace's bottom, floating above the principal air feed level, increasing particle distance. 2. An inert substance (ash, sand, silica, or dolomite) accounts for 90%–98% of the mass of a fluidized bed, enhancing heat transmission and resulting in a constant temperature.	1. Fluidized bed requires higher capital and maintenance costs than grate-fired systems. 2. A fluidized bed is sensitive to bed agglomeration,	Caillat and Vakkilainen (2013)
	Circulating	Power output: 15–250 MW Moisture content: 5–60 wt% Ash content: <10 wt% Particle size: <100 mm	Bark, wood chips, sludge, and bagasse	A circulating boiler provides for greater turbulence and better heat transfer, resulting in more uniform temperature distribution and higher burnout efficiency than a burble furnace.	The circulating process has a direct impact on operating costs since biomass is often fibrous and thus difficult to grind	Caillat and Vakkilainen (2013)
	Pulverized	Power output: 5–80 MW Moisture content: 20 wt% Ash content: <1 wt% Particle size: <5 mm	Wood pellets	Produced more uniform and definable heat absorption patterns	Because biomass contains alkali metals, particularly potassium and frequently chlorine, corrosive biomass burning in PF boilers may induce superheater corrosion.	Tillman et al. (2012)
	Burner					

(Continues)

TABLE 6 (Continued)

Technology	Installation type option	Operation conditions	Type of biomass	Advantages	Challenges	References
Gasification	Co-combustion	Power output: 100–1000 MW Moisture content: <20 wt% Ash content: <1 wt% Particle size: <2–4 mm	Wood, sawdust, and pellets	Widely used for large-scale power plants. Because of the high turbulence and tiny particles, combustion is quicker and more efficient, with a greater energy density.	This technology requires a uniform fuel quality and low fuel moisture content. The biomass that has a high content of volatiles requires special care of fuel feeding	Caillat and Vakkilainen (2013); Tillman et al. (2012)
	Fixed bed	Power output: 2–30 MW Reaction temperature: 1000°C Moisture content: <60 wt% Particle size: 5–100 mm	Wide-range fuel High ash (<25%) High moisture (<60%) Low-volatile fuel	Simple construction, a wide range of fuel-type	High (10–20 wt%) tar produced and not cracked	Basu (2013); Sikarwar et al. (2016)
	Downdraft	Power output: 1–2 MW Reaction temperature: 1200°C–1400°C Moisture content: <25 wt% Particle size: 20–100 mm	Pellet-type fuel Low ash (<6%) Low moisture (<25%) Fuel	1. Tars produced significantly cracked, leading to less tarry off-gas 2. Shorter igniting time	1. Throated construction restricts types of biomass 2. Low moisture content required (<25%)	Basu (2013); Sikarwar et al. (2016)
	Circulating	Thermal Input: 5–100 MW Reaction temperature: 800–1000°C Moisture content: <30% Particle size: <6 mm	Fuel with high volatiles e.g. wood and peat straw	Long gas residence time	Require long time to produce more uniform heat	Basu (2013); Sikarwar et al. (2016)
	Dual	Reaction temperature: >900°C Moisture content: ~40% Particle size: > 1 mm	Coal and biomass	Separation of combustion and gasification reactor 2. Nitrogen-free syngas produced 3. Relatively product gas free of tar	1. External heating may be necessary 2. Large heat consumption 3. Product gas dilution	Basu (2013); Sikarwar et al. (2016)
	Entrained flow	Reaction temperature: 1300°C–1500°C	Biomass		Requires three stages (pre-gasification,	Basu (2013)

TABLE 6 (Continued)

Technology	Installation type option	Operation conditions	Type of biomass	Advantages	Challenges	References
Plasma	Top fed	(combustion), 800°C (endothermic gasification) Reaction temperature: 13,000°C	All types of biomass	One of the successful entrained-flow biomass gasifiers Feasible to various quality of feedstock	combustion, and endothermic (gasification) High temperature affects the life of the reactor	Basu (2013); Sikarwar et al. (2016)
Pyrolysis	Pneumatic bed Fixed or moving	Reaction temperature: 300°C–600°C	All types of biomass	Simple in construction	1. Product may flow out of the pyrolyzer 2. May require an external heating source	Lewandowski et al. (2019)
	Fluidized (bubbling, circulating)	Reaction temperature: 450°C–600°C Particle size: 2–6 mm	Wood, corn, rice husk, sugarcane bagasse, wheat straw, sunflower hulls, and sorghum bagasse	1. Easy to scale up, control over residence time 2. High velocity combined with excellent mixing allows a circulating fluidized bed (CFB) to have large throughputs of biomass. 3. Char entrained from the reactor is easily separated and burnt in an external fluidized bed.	1. Large reactor size 2. High cost of construction 3. High operation cost	Basu (2013); Dhyani and Bhaskar (2018); Garcia-Nunez et al. (2017); Lewandowski et al. (2019)
Mechanical	Auger	Reaction temperature: 500°C–600°C	Wood, solid biomass, and tire	1. Compact and can be made portable, allowing on-site biomass conversion 2. Cost reduction due to on-site conversion	Lower heat transfer rate observed	Dhyani and Bhaskar (2018); Lewandowski et al. (2019)
	Rotary	Reaction temperature: 450°C–700°C	Empty fruit bunch, wood residues, and tire	1. No carrier gas is required to transport the vapors, reducing the cost of operation	Additional system to control rotation	Dhyani and Bhaskar (2018); Lewandowski et al. (2019)

(Continues)

TABLE 6 (Continued)

Technology	Installation type option	Operation conditions	Type of biomass	Advantages	Challenges	References
				<ol style="list-style-type: none"> Easily adjusted residence time Good mixing of wastes Uniform product 		
	Ablative	Reaction temperature: 500°C	Rubber tire, beech, poplar, straw, etc.	<ol style="list-style-type: none"> Accepts large feedstock sizes and allow an excellent mechanical abrasion of char High heat transfer and high liquid yield 	Problem of heat transfer from the hot surface of the reactor because of low heat transfer coefficient and indirect heating employed. May need larger chamber volume	Auersvald et al. (2020); Dhyani and Bhaskar (2018); Lewandowski et al. (2019)
Gravity	Pyrolyzers with gravitational batch transport	Reaction temperature: 510°C Particle size: 2–6 mm	Tyre	Simple and cheap way to continuously move substrates in pyrolyzers		
Anaerobic digestion	Mesophilic/thermophilic	Inoculum volatile solid: 75–80 g/L Gas engine efficiency: 35% EFB size: <0.5 cm POME COD: 50 mg/L COD loading daily: 25,000 kg/day Power output: 1–1.9 MW	POME and EFB	<ol style="list-style-type: none"> Liquid and solid processes in biogas production reduced the operation cost and enhanced the energy recovery Bio-methane gas produced from the solid-state AD process was 2–3 times higher than the liquid AD process Stable AD process able to supply a minimum load of 1 MW required by normal palm oil milling process 	<ol style="list-style-type: none"> Require additional post-treatment to enrich the quality of biogas that is required for a gas engine to produce electricity. Solid-state AD required a large inoculum amount for an operational start-up. Digestate generated is ineffective as an inoculum owing to its high concentration of undigested organic components with poor microbial activity. 	Firdaus et al. (2017); Suksong et al. (2020)

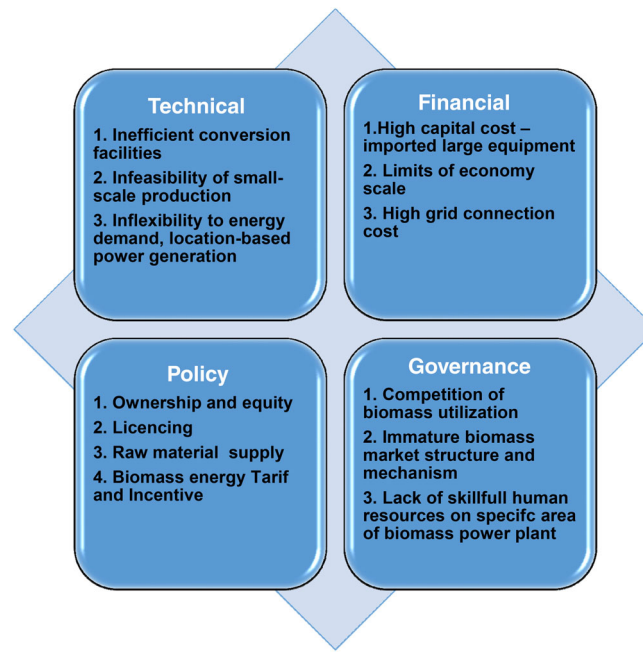


FIGURE 9 The barriers associated with biomass energy implementation

plant often takes longer than a small plant to be certified by stringent connectivity regulations in terms of grid connection. Additional system modifications and feasibility studies may be required in certain circumstances before the biomass power systems can be connected to the power grid, significantly delaying the already intricate process (Sovacool & Drupady, 2011). Local energy demand is often significantly lower in rural regions than the biomass power plant can provide. Because of the transmission distance, if the biomass plant sought to connect to the terminal local power transmission network, the cost of plugging in may be prohibitively high. As a result, the biomass plant has no alternative but to shut down its operation regularly to meet the local demand load. The immaturity of the biomass market structure and supply chain mechanism is another key issue. Even though biomass is plentiful in Malaysia, it is dispersed across the nation. As a result, the logistical cost of transporting biomass from the supply source to the power plant might be substantial.

In terms of biomass resource availability and mobilization, unlike oil, biomass resources do not belong to the Malaysian government. Private farms and independent smallholders control more than 77% of the palm oil, while governmental agencies possess just 6% (Nambiappan, 2018). Most of them are not interested in converting the waste to energy or other green products since it will not benefit their core businesses (Rahman & Shamsuddin, 2013). At least 30% of the millers have biomass processing facilities to convert their biomass into empty fruit bunch fibers, biofertilizers, and biogas (De Meyer et al., 2014). These high value-added downstream productions, including bio-oil, compete for the already limited accessible biomass resources for energy. Those private estates and millers have divergent interests and perspectives. Consequently, a biomass power plant is a significant challenge to secure feedstock supply at an affordable price over its operational lifetime of 18–30 years.

Besides, the local manufacturers still lack efficient high-pressure steam generators; thus, companies require importing most of the equipment for biomass-based power generation and combined heat and power (CHP). The current investment cost to build a CHP medium scale biomass plant (10–50 MW) ranges between 3550 and 6820 USD/kW, whereas the cost of a good-quality feedstock such as biomass pellets are higher than coal with the price of 12 USD/GJ (IRENA, 2019). Suppose the plant deploys a biomass-fired stoker boiler or circulating fluidized bed boiler. In that case, the payback period could be as long as 6.7 and 9.7 years, respectively, which makes the investment grossly infeasible from the general cost justification point of view (Malek et al., 2017). The stakeholders are also still struggling to build their RE technology capacity (Ludin et al., 2013) due to the lack of a centralized training institution which resulted in poor dissemination of information and knowledge (Sovacool & Drupady, 2011; Umar et al., 2018).

The cumulative CO₂ emission reduction resulting from the FiT implementation in Malaysia in the year 2016 is 1.3 million tons of CO₂/MWh (SEDA, 2016). Natural gas subsidies, low coal prices, and consistent supply of both fuels all substantially influence the growth of renewable energy. In Malaysia, the coal power output is unlikely to be decreased,

as the current coal power stations in Peninsular are scheduled to close in 2029. With a forecast growth in coal consumption of more than 30 million tons per year, coal supremacy in the power supply sector is strongly expected (Malaysia Energy Commission, 2016). On the other hand, biomass has yet to make a significant contribution to the power mix. This is particularly true given that biomass is still in its infancy and is severely hampered by woefully insufficient competence as well as unsystematic resource control and supply chain management. The POM cannot make a significant contribution to Malaysia's environmental and economic stability under the current system framework. In this regard, a comprehensive core strategy including policy, technology, and economics should be substantially constructed in order to provide a firm and comprehensive response to POM's current problems and challenges. The government should prioritize the execution of a comprehensive biomass energy strategy, which would use biomass resources to generate extra electricity that would be connected to the grid through a large-scale biomass power plant program.

7 | FUTURE OUTLOOK

Oil palm biomass is Malaysia's most abundant agricultural biomass that has yet to be completely utilized. With the progress of green technology, a certain amount of oil palm biomass has been converted into usable industrial feedstock such as "solid, liquid, and gaseous biofuels, bio-composites, bio-fertilizers, green chemicals, industrial sugars, and polymers" (Onoja et al., 2019). This accomplishment is based on the Malaysian government's strategy of promoting green technology, which acts as a source of motivation for industry participants and other stakeholders to transform biomass into value-added products.

7.1 | Large scale biomass power plant system

Figure 10a–c show the typical practice of biomass power generation in palm oil mills. Some larger palm oil mills sell palm kernel shells (PKS) and palm kernel cake (PKC) as additional revenue sources. Practically, the power and steam required for CPO production are met mainly by consuming palm MF as fuel in an on-site boiler. Besides, PKS could also utilize fuel for the boiler, but this practice was disallowable as the combustion produced soot and particulates emissions that exceeded current standard limits. On the other hand, POME is treated in-situ before discharge to nearby water bodies as required by current environmental regulations. Increasingly, POME is converted to biogas via anaerobic digestion as a treatment method. The biogas can then be used for electricity generation for export to the grid, as shown in Figure 10b. Some of these mills have explored the idea of upgrading to bio-compressed natural gas (Bio-CNG) and bottling the Bio-CNG for sale but found this option to be uneconomical due to the undeveloped nearby market.

Meanwhile, EFB may be marketed for various purposes, but its high moisture content and poor density put off prospective purchasers. Several palm oil factories have begun the process of pelletizing EFB into higher-quality fuel, as shown in Figure 10c. The pelletizing factory would need an extra source of power, which is typically supplied by the power grid. This method has also proved to be uneconomical for many palm oil factories located in rural locations distant from the grid. Furthermore, FFB production from plantation changes throughout the year and year on year, reducing the output of palm oil, biogas, power export, or biofuel pellets, making these current programs less economically appealing. In this regard, the integrated system of a large-scale power plant might be a viable future solution. Figure 11 depicts the planned integrated system of palm oil production, biogas plant for power and steam generation, and biofuel pellet manufacture.

The palm oil mill will continue to sell CPO as its principal income source under this suggested approach while ceasing on-site steam and energy generation. This will result in cost savings from the mill's maintenance and staffing of a boiler-turbine complex. All mill wastes will be sent to the biogas plant, lowering oil production costs even more by eliminating the requirement for environmental protection measures. In return for all oil milling byproducts, a biogas plant will supply the mill with heat and electricity. The biogas facility will also supply heat and electricity to a fuel processing plant, which will convert MF and EFB into biofuel. The trade of dried PKS and fertilizer will produce additional money. Subject to surplus capacity and regional demand, the biogas plant may export electricity to the local distribution network under the current FiT system.

Biofuel pellets from MF and EFB will be transferred to a centralized large-scale biomass power plant for transmission-level voltage production. The power plant will need fuel from numerous mills that are part of similar programs (Plant A to Plant D in Figure 11). Biofuel pellets might potentially be co-fired at existing coal power stations to decrease total fossil carbon emissions while making use of their greater conversion efficiency.

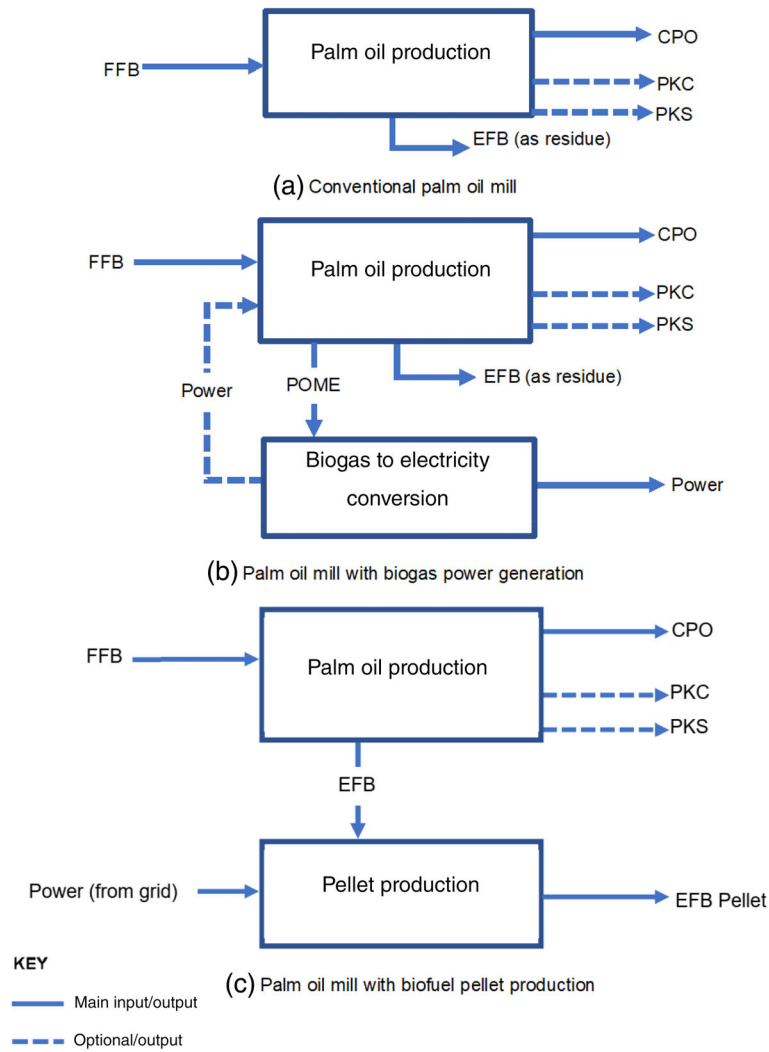


FIGURE 10 The existing palm oil mill operation and the proposed schemes

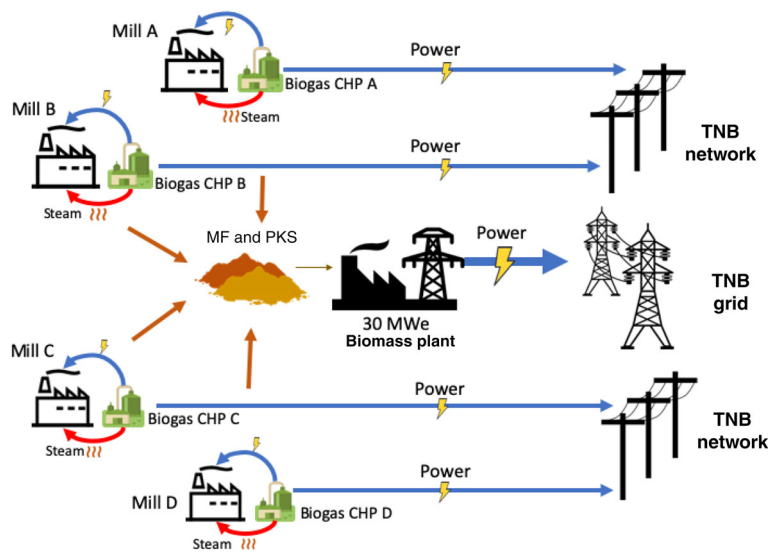


FIGURE 11 The proposed integrated large-scale palm oil biomass power plant

7.2 | Palm oil biomass energy policy

Currently, bioenergy companies are in a dilemma because investors are uninterested in the technical feasibility of the palm oil biomass power generating technology being deployed and its commercial viability. In this regard, a well-thought-out long-term palm oil biomass to energy strategy must be devised to secure biomass supplies and guarantee bioenergy production projects get the necessary financial assistance to compete in the highly competitive energy market. Public and private investors are critical market participants in launching this new RE initiative. However, their investment patterns and responsibilities in determining the path of biomass power plant technology development and introduction remain unknown. In practice, the incentive system might be altered to provide a greater level of compensation to the targeted group of biomass power industry participants. Simultaneously, special attention must be paid to the pricing system to ensure that the amended rate does not raise electricity prices. A special excise duty on independent power producers (IPPs) that produce power from fossil fuels might potentially be imposed to incentivize RE production and minimize GHG emissions from the energy sector in order to enhance financing.

Creating a well-coordinated strategy to build a strategic palm oil biomass market requires a synergy among government agencies, key agricultural players, and commercial sectors. An integrated supply chain management is crucial to ensure a sustainable biomass feedstock supply, competitive biomass price, and effective use of biomass for high-value downstream activities (Akhtari et al., 2018; De Laporte et al., 2016; De Meyer et al., 2014; Mafakheri & Nasiri, 2014; Paulo et al., 2015). To guarantee sustainable palm oil biomass supply and to standardize quality and pricing, a nationwide collecting center for palm oil biomass should be built. The government should also impose stricter environmental codes and regulations on coal power plants and grant them an ecological mandate to replace the aging plant by promoting biomass co-firing system installation in Malaysia. Besides that, the government should also provide incentives to support decentralized, off-grid renewable energy power generation in rural areas rich with renewable resources. In addition, the palm oil biomass co-firing in a coal power plant could be explored to ensure economic growth and reduce environmental pollution systematically. In this regard, the ending life of coal power plants could be continuing by upgrading the system into co-firing power plant systems. This is the best approach to regulate the policy in the early stage to evaluate the feasibility and attract investors to get involved in the large-scale power generation plant.

7.3 | Palm oil biomass power plant economic aspect

The large-scale palm oil biomass power plan requires a comprehensive economic plan to ensure long-term operation sustainability. In fulfilling the aim, the palm oil biomass market should be organized by establishing centralized trading, logistics, technology expertise, and human capital to empower regional economic growth. The superstructure of the biomass financial plan should involve a holistic and circulating aspect that enables the market's continuous growth. In this initial stage, the centralized biomass power plant facilities should be developed at the significant geographical location of the biomass accessibility, distances, and transportation network. This centralized trading system enables the supply chain's demand to feed, which promotes the sustainable economic growth of palm oil biomass power plants.

On the other hand, the technical expertise for palm oil biomass power generation must be established by recruiting more local experts. Predominately, palm oil biomass technology has a high maintenance cost and a prolonged period for investment return. In this sense, local technology development improves the return of investment and encourages more investment in the industry. Moreover, the development of local technology ownership will minimize the operation cost and create a new economic opportunity for Malaysia. The empowerment of local human capital in palm oil biomass power industries will also stimulate local economic growth, education, and other services. Besides, this will enhance human capital empowerment and capacity building through skills, talent development, research, and innovation. This local human capital development will ensure the firm foundation of economic growth and strengthen the global market network's success.

8 | CONCLUSIONS

This review has underlined the need for and provided fresh insights into the long-term deployment of renewable energy production. The integration of palm oil biomass to decarbonize power production is a critical step in Malaysia's quest for energy sustainability and carbon neutrality. Based on the current scenario, the renewable energy initiative could

achieve the unconditional carbon reduction commitment by eliminating the fired-coal power plant and utilizing the non-environmentally process of palm oil industry power potential (~5000 MW) from biomass and POME into a renewable power producer. However, there are several problems in implementing the idea of greening enterprises by increasing electricity capacity, which must be enhanced. Moreover, continual feedstock security and market stability are provided by the price rates of renewable energy resources into the national grid. At present, this is dominated by solar power and is not equitably shared with other resources, notably biomass. Furthermore, the biomass renewable energy transition needs a major financial model in order to replace the power demand of the palm oil sector, especially small-holder palm oil mills. Despite this, it has been a long-standing challenge for small business owners to comply with any laws imposed by the government due to financial constraints. At the same time, the worldwide market for biomass value is much more appealing than the domestic market, where palm oil millers are readily diverted, necessitating government policy involvement. Furthermore, the technical preparedness for replacing the present system is still immature, relying heavily on outside expertise. In order to secure the national impetus, a pilot-scale model of the integrated plan should be constructed. As a result, in order to embrace the global bioenergy future, an integrated biomass energy strategy blueprint with a comprehensive plan that includes social, economic, environmental, and technological elements toward a sustainable future of renewable energy development of biomass bioenergy development should be established immediately.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mohd F. M. A. Zamri: Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); writing – original draft (lead); writing – review and editing (supporting). **Jassinnee Milano:** Writing – review and editing (equal). **Abd H. Shamsuddin:** Funding acquisition (lead); methodology (equal); project administration (lead); supervision (lead). **Mohd E. M. Roslan:** Investigation (equal); methodology (equal); resources (equal). **Siti F. Salleh:** Data curation (equal); formal analysis (equal). **Adlansyah A. Rahman:** Data curation (equal); investigation (equal); methodology (equal). **Raihana Bahru:** Visualization (equal); writing – review and editing (equal). **T. M. Indra Mahlia:** Project administration (lead); supervision (lead); writing – review and editing (lead). **Islam M. R. Fattah:** Data curation (lead); resources (lead); writing – review and editing (lead).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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