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Research article

Analysis of current state, gaps, and opportunities for technologies in the Malaysian oil palm estates and palm oil mills towards net-zero emissions

Jaya Prasanth Rajakal [a,b], Foo Yuen Ng [c], Anna Zulkifli [c], Bing Shen How [a], Jaka Sunarso [a], Denny K.S. Ng [b], Viknesh Andiappan [a,*]

[a] *Biomass Waste-to-Wealth Special Interest Group, Research Centre for Sustainable Technologies, Faculty of Engineering, Computing and Science, Swinburne University of Technology, Kuching, 93350, Malaysia*
[b] *School of Engineering and Technology, Sunway University, Petaling Jaya, 47500, Malaysia*
[c] *Malaysian Palm Oil Council, Level 25, PJX HM Shah Tower, 16A, Persiaran Barat, PJS 52, 46200, Petaling Jaya, Selangor, Malaysia*

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ABSTRACT

Malaysia is the second largest producer and exporter of palm oil. Though several works have explored achieving emissions reduction in the palm oil sector, there existing gaps in analysing pathways for achieving net-zero emissions. Moreover, there are limited studies that evaluate the potential of palm oil biomass utilisation pathways based on emissions reduction capabilities, the cost of emissions reduction, and the technology readiness for implementation. Therefore, this study analysed decarbonisation pathways for the upstream and midstream segments of the palm oil sector in Malaysia, encompassing oil palm plantations and palm oil mills. Various sources of greenhouse gas emissions in oil palm plantations and palm oil mills were identified and estimates of emissions were determined as theoretical emissions. The current emissions were established based on the current best practice in the plantation and mill. Several biomass conversion technologies for the recovery of palm-based by-products and conversion into value-added products to decarbonise the palm oil sector and evaluated strategies to attain net-zero status are considered. In this work, the analysis considered both the existing technologies that are adopted by plantations and mills as well as the emerging technologies that have scope for implementation. With the proposed approach, the current emissions level for crude palm oil (CPO) production in Malaysia is estimated as 1121.49 kg CO_2-eq/t CPO. In current industry practice, empty fruit bunch (EFB) is underutilised as mills are typically located at rural areas with lack of suitable transportation. Besides, the lack of accessibility to the grid also limits the potential of converting EFB into electricity as supply for national grid. This work examined various pathways for EFB utilisation under different scenarios evaluating their contribution potential towards net-zero target in an energy self-sustained CPO production. As shown in the results, converting EFB to briquettes and pellets are able to achieve the net-zero objective. Furthermore, EFB-biochar and EFB-syngas pathways also exhibit the potential to accomplish the net-zero target. Note that this work also

Abbreviations: FFB, Fresh fruit bunch; CPO, Crude palm oil; EFB, Empty fruit bunch; PKS, Palm kernel shell; PMF, Palm mesocarp fiber; POME, Palm oil mill effluent; OPF, Oil palm frond; MSPO, Malaysian sustainable palm oil; RSPO, Roundtable of sustainable palm oil; ISCC, International sustainability and carbon certification; CHP, Combined heat and power; OER, Oil extraction ratio; TRL, Technology readiness level.

* Corresponding author
E-mail addresses: bshow@swinburne.edu.my (B.S. How), vmurugappan@swinburne.edu.my (V. Andiappan).

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assessed the technologies' readiness levels, identified challenges in implementation, and proposed several recommendations.

1. Introduction

Oil palm is one of the important oil crops globally that contributes about 35 % of the world's edible oil production in 2022. In the same year, Malaysia stood out as the second largest palm oil producer and exporter, contributing roughly 25 % to the global palm oil production and accounting for over 30 % of worldwide palm oil exports. Malaysia has an extensive oil palm cultivation that currently spans more than 5.67 million hectares, equivalent to approximately 17 % of nation's total land area [1]. This cultivation yields a substantial output, with 87.90 million tons of fresh fruit bunches (FFBs) producing 18.45 million tons of crude palm oil (CPO) in 2022 [2]. Concurrently, the export of palm oil products (crude and processed palm oil) for the same period stands at 15.71 million tons, with a total value of RM 86,472 million, i.e. USD 18,662.35 million [3].

In general, palm oil supply chain can be divided into three main segments: the upstream and midstream segment involving plantations and palm oil mills respectively, and the downstream segment (Fig. 1). Plantations serve as the fundamental component of the palm oil supply chain, producing the fresh fruit bunches (FFB). Based on the revised Malaysia Sustainable Palm Oil (MSPO) certification in 2023, the plantations can be categorised based on the type of ownership as independent smallholders (plantation area smaller than 40 ha), organised smallholders (plantations ranging from 40 to 1000 ha), and plantation companies (plantations with more than couple of thousands of hectares) [4]. In Malaysia, the independent smallholders account for 14.40 % of the total oil palm planted area, organised smallholders cover 11.80 %, and plantation companies contribute 73.80 % [1]. Moreover, 55.2 % of the total planted area is situated in East Malaysia (i.e. Sabah and Sarawak located on the Borneo Island), with the remaining 44.8 % located in West Malaysia (also known as Peninsular Malaysia) [1]. Table 1 presents the oil palm planted area with their respective FFB yield in 2022 for each of the states in Malaysia.

Malaysia's annual capacity for processing FFBs is 87.90 tons, with 49.50 % located in East Malaysia and the remaining 50.50 % in West Malaysia [5]. As reported by MPOB [6], there are a total of 447 operating palm oil mills, each with processing capacities ranging from 20 t/h to 120 t/h. The state-wise CPO production in 2022 can also be found in Table 1. The downstream segment consists of palm oil refineries, palm kernel crusher, and palm-based oleochemical industries. In 2022, there are total of 49 palm oil refineries with a combined annual capacity to process 25.35 million tons of CPO into refined palm oil, a major product of interest [6]. On the other hand, the palm kernel crushing facilities, crushed palm kernels into crude palm kernel oil, with a total processing capacity of 7.35 million tons distributed across 41 crushing plants [6]. Additionally, there are 21 palm-based oleochemical industries with a total annual capacity to process 2.69 million tons of CPO [6].

The 12th Malaysia plan, released by the Economic Planning Unit of the Ministry of Economy, Government of Malaysia has set forth an ambitious target of attaining carbon neutrality by 2050. To accomplish the net-zero target, sector specific, long-term, low carbon development strategies are needed. Palm oil sector stands out as the largest plantation industry in Malaysia, contributing 3 % to the nation's GDP in 2022 [7]. Furthermore, the agriculture sector accounts for 3 % of the total GHG emissions in Malaysia [8]. Given the contribution of the palm oil sector to Malaysia's economy, decarbonisation of its operations will contribute to the nation's net-zero target by 2050.

The aim of this study is to analyse the various existing and emerging decarbonisation pathways for palm oil sector in Malaysia. This

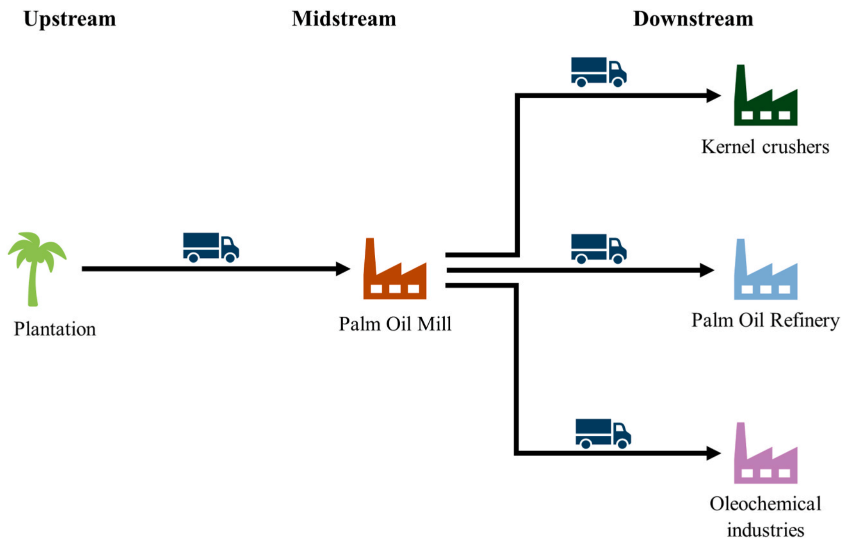

Fig. 1. Palm oil sector overview.

analysis specifically focuses on the upstream and midstream segment, i.e. oil palm plantations and palm oil mills (Fig. 2) to investigate the emissions associated with CPO production, which ultimately serves as a primary raw material for other downstream processes. This study also analyses the emissions and evaluate the gaps and opportunities towards achieving net-zero emissions at Malaysia's oil palm estates and palm oil mills. Finally, valuable insights and recommendations to support the transition towards achieving net-zero emissions in Malaysia's oil palm estates and palm oil mills are suggested.

Moreover, it is worth noting that the land use change emissions and carbon sink capacity of oil palm plantations are beyond the scope of this work as it depends on specific location and the type of soil. Nevertheless, Malaysia's Biennial Update Report to UNFCCC has recognised the contribution of oil palm plantations as a carbon sink under Agriculture, Forestry, and Other Land Use category [8]. The report highlights that oil palm plantations as a key carbon sink next to forests in Malaysia. Therefore, the additional decarbonisation efforts discussed in this study further empowers Malaysian palm oil sector in achieving the net-zero target.

2. Literature overview

This section provides an overview of recent research pertaining to the emissions in the Malaysian palm oil sector and the technologies available for reducing these emissions. The various sources of emissions from the upstream and midstream segments are as follows:

- Fertilisers and agrochemicals application in the plantation,
- Fossil fuel use (diesel and petrol) for plantation operations,
- Degradation of palm oil mill effluent (POME),
- Energy consumption for milling operation, and
- Degradation of palm-based biomass.

The main source of emissions in plantation operations is from fossil fuel use to power machinery and fertiliser application in the plantations. Meanwhile, the main source of midstream emissions is the degradation of POME in the palm oil mills. Such emissions fall under the Scope 1 category while emissions related to energy consumption for milling operation, fertiliser production and etc. are categorised as Scope 2 emissions. A brief description on Scope 1 and Scope 2 classification is discussed in Section 3.

Few studies in the literature have attempted to estimate the greenhouse gas (GHG) emissions for CPO production in Malaysia. For instance, Subramaniam et al. [9] analysed the GHG emissions from 12 palm oil mills in Malaysia with capacities ranging from 40 to 90 t/h. The average GHG emissions observed is 987.18 kg CO_2-eq/t CPO. However, the emissions accounted only for POME degradation and process energy emissions at the mills. Later, Hosseieni and Wahid [10] analysed the emissions from 20 palm oil mills with process capacities ranging from 40 to 100 t/h located in the Malaysian states of Johor, Melaka, and Selangor. The emissions from energy consumption for milling operation, transportation, and POME degradation were considered. The average emissions was determined as 1102.36 kg CO_2-eq/t CPO. It is worth noting that both works did not account for emissions related to plantations and palm-based biomass degradation at mill. This gap was addressed by Subramaniam et al. [9], whose analysis showed the total GHG emissions when none of palm-based biomass is recovered can be as high as 3584.05 kg CO_2-eq/t CPO.

Additionally, it is worth noting that all of the above-mentioned works have reported that POME degradation is the largest source of GHG emissions within the entire CPO supply chain. More recently, Hong [11] reviewed the POME degradation emissions reported by various literatures, which range from 637 to 1137 kg CO_2-eq/t CPO. These variations were attributed to the different production rates of POME per unit of FFBs processed, the concentration and dilution of POME during milling, and the chemical oxygen demand (COD) of the effluent.

Apart from research studies, different stakeholders in the palm oil sector have made significant efforts to estimate emissions in CPO

Table 1
State-wise production data in 2022 – upstream and midstream segment [1,2].

States	Planted area (ha)	FFB yield (t)	CPO production (t)
Johor	676,853	11,946,455	2,969,525
Kedah	86,487	1,307,683	237,382
Kelantan	161,852	1,804,649	336,061
Negeri Sembilan	178,560	3,128,371	675,767
Pahang	749,813	12,274,438	3,013,107
Perak	352,098	6,471,561	1,866,423
Selangor	106,008	1,787,965	498,904
Terengganu	170,825	2,096,022	407,500
Meleka	52,347	948,527	156,661
Perlis	886	–	
Pulau Pinang	8579	97,371	
Sabah	1,508,060	23,209,043	4,286,665
Sarawak	1,622,374	22,924,144	4,005,425
Malaysia	**5,674,742**	**87,901,753**	**18,453,420**

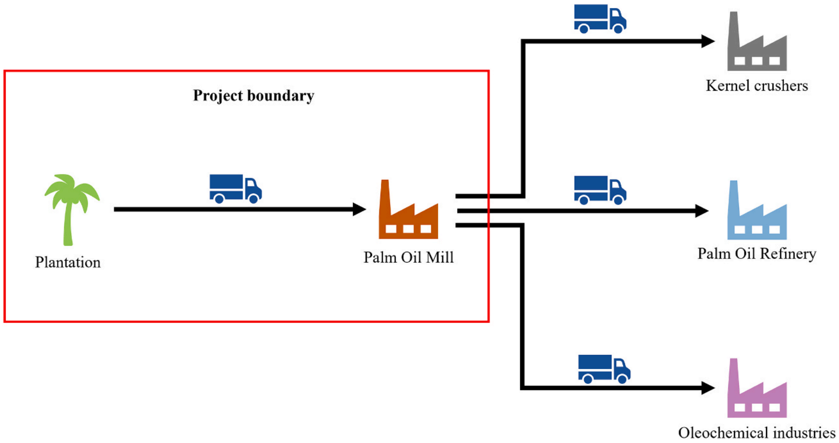

Fig. 2. Scope of work – Project boundary.

production. The Roundtable on Sustainable Palm Oil (RSPO), a global non-profit organisation developed a GHG emissions calculator known as Palm-GHG calculator. This tool was developed to enable plantation and mill owners to calculate their emissions. The adoption of the Palm-GHG calculator has streamlined the RSPO certification process for sustainable CPO production and has gained widespread use among plantation and mill owners in Malaysia. Similarly, the Malaysia Sustainable Palm Oil (MSPO) has also introduced its own MSPO GHG calculator, which is utilised to estimate emissions for GHG reporting by its certified plantations and palm oil mills. Additionally, some of the Malaysian plantations and palm oil mills adhere to the International Sustainability and Carbon Certification (ISCC) scheme to ensure compliance of their products with international standards. These standards guide the palm oil sector to enhance the sustainability of palm oil production. Note that these standards and certifications are focused on compliance activities rather than aiding stakeholders to develop emissions reduction strategies in the palm oil sector.

Based on the annual palm oil production, large amounts of biomass such as oil palm frond (OPF), empty fruit bunch (EFB), palm kernel shell (PKS), palm mesocarp fibre (PMF), and etc are generated. Based on the recently launched of National Biomass Action Plan 2023–2030, palm-based biomass has been identified as the key biomass (87 %) to convert into high value-added products and aimed to generate significant sustainable development benefits in terms of green wealth creation, socioeconomic development and meet Malaysia's net-zero emissions target [12].

Table 2 presents a review of some of the key contributions in the literature related to optimisation of various palm-based biomass utilisation pathways. Ng et al. [13] presented one of the earliest works in estimating the potential of palm-based biomass for power generation in Malaysia. Similarly, Loh [14] estimated the availability of different palm-based biomass in Malaysia and their respective energy generation potential based on their calorific value. However, Loh [14] did not delve on estimating the emissions reduction potential and energy conversion technologies that can be deployed for these biomass materials. Recently, Zamri et. [15] estimated the availability of EFB, PKS, PMF, and POME in Malaysia. The work determined the total energy generation potential of these available palm-based biomass as 4329 MW based on 35 % conversion efficiency from their calorific values. Furthermore, GHG emissions reduction based on the theoretical energy potential from palm-based biomass utilisation is estimated as 91.10 million tCO_2. However, Zamri et al. [15] did not explore the emissions reduction potential specific to each energy conversion pathway. Likewise, Idris et al.

Table 2
Key optimisation works on palm-based biomass utilisation pathways.

Literature	Contribution
Ng et al. [17]	Optimised a palm-based biomass based integrated biorefinery for 60 t/h palm oil mill.
Kasivisvanathan et al. [18]	Optimised the retrofitting of 50 t/h palm oil mill into an integrated biorefinery.
Foo et al. [19]	Optimised the allocation of EFB to different power plants in northern region of Sabah state in Malaysia.
Ng and Ng [20]	Optimised a palm oil processing complex by integrating the biomass generated from palm oil mill of 80 t/h capacity with CHP system, biorefinery, and palm oil refinery.
Theo et al. [21]	Optimised the palm-based biomass and POME utilisation pathways for a palm oil mill cluster in Malaysia.
Abdulrazik et al. [22]	Optimised the utilisation pathway of EFB generated in peninsular Malaysia into multiple green products.
Ling et al. [23]	Optimised an EFB based bioelectricity supply chain for Selangor state in Malaysia.
Yeo et al. [24]	Optimised a palm based integrated biorefinery for biomass generated from a 60 t/h palm oil mill.
Tan et al. [25]	Optimised a palm oil mill complex with integrated milling, POME treatment, and biogas utilisation for a 60 t/h mill.
Ong et al. [26]	Optimised a palm-based biochar supply chain for a palm oil mill cluster in Malaysia.
Foong et al. [27]	Optimised a palm based eco-industrial park by integrating a 60 t/h palm oil mill with CHP system, integrated biogas wastewater treatment plant, and palm-based biorefinery.
Foong et al. [27]	Optimised the POME treatment and utilisation *via* an integrated biogas and wastewater treatment plant for a 60 t/h palm oil mill in Malaysia.
Rajakal et al. [28]	Optimised the integration of palm-based biomass utilisation with other industries to form a circular economy.

[16] analysed the palm-based biomass availability in Malaysia and performed spatial optimisation of biomass utilisation based on different demand and carbon reduction target scenarios.

Although prior research studies have explored the use of palm-based biomass for power generation, there is a notable gap in achieving net-zero status in the palm oil sector. Previous studies have primarily focused on quantifying the potential of palm-based biomass power generation and the resulting emissions reduction. Nonetheless, none of the above-mentioned works have computed the existing gaps in achieving the net-zero target within the palm oil sector or evaluated the different palm-based biomass utilisation pathways in terms of their emissions reduction capabilities, the cost of emissions reduction, and the technology readiness for implementation. This work aims to analyse the current state of emissions and identify the gaps towards achieving net-zero at Malaysia's plantations and palm oil mills. Furthermore, the work evaluates the emissions reduction potential of each of the identified biomass utilisation technologies alongside with their cost. Moreover, an assessment on the technology readiness of these technologies for commercial implementation is conducted.

3. Methodology

Fig. 3 presents the general methodology used in this study and is outlined as follows:

- **Material and energy flow mapping**: Investigating the inputs and outputs of material and energy in the plantation and palm oil mill to identify potential areas for emissions reduction.
- **GHG emissions estimation**: Developing a GHG calculator for estimating GHG emissions from both direct sources (Scope 1) and indirect sources (Scope 2) within the defined system boundary. According to the GHG protocol standards, Scope 1 emissions are direct GHG emissions that occur from the operation of the facility (e.g. emissions associated with fuel combustion in boilers, furnaces, vehicles). Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling. Although Scope 2 emissions physically do not occur at the facility, they are accounted for because they are a result of the facility's utility consumption. The total GHG emissions, E from plantation and mill can be determined as shown in the following equation:

$$E = \sum_{i}^{I} F_i^{PL} X_i^{PL} + \sum_{o}^{O} F_o^{PL} X_o^{PL} + \sum_{i}^{I} F_i^{POM} X_i^{POM} + \sum_{o}^{O} F_o^{POM} X_o^{POM}$$

where, F_i^{PL}, F_o^{PL}, F_i^{POM}, and F_o^{POM} are the total annual material and energy inputs and outputs from the considered plantations and palm

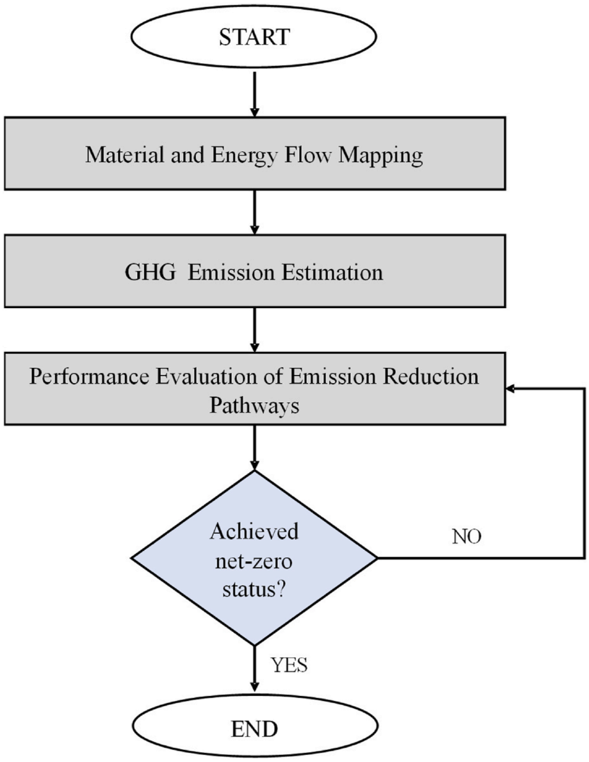

Fig. 3. General methodology.

oil mills while X_i^{PL}, X_o^{PL}, X_i^{POM}, and X_o^{POM} are the emissions factors of these material and energy inputs and outputs.

- **Performance evaluation of emissions reduction technologies**
  - o *Review on emissions reduction technologies*: Examining various emissions reduction technologies applicable to oil palm plantations and palm oil mills and evaluating their readiness levels for implementation.
  - o *Assessment of emissions reduction capability*: Evaluating the potential of the identified technologies to reduce emissions in the oil palm estates and palm oil mills.
  - o *Cost analysis of emissions reduction technologies*: Assessing the costs associated with implementing the emissions reduction technologies to understand their economic feasibility. Note that this work focuses on analysing the cost directly connected to each technology. Meanwhile, a detailed economic analysis considering interest rates, manpower costs, exchange rates, and etc. does not fall under the scope of this study as these are influenced by specific case studies.

By conducting these analyses, the study aims to provide valuable insights and recommendations to support the transition towards achieving net-zero emissions in Malaysia's oil palm plantations and palm oil mills.

This study took into the following considerations in performing the analysis:

- The theoretical emissions are estimated based on the FFB yield and oil extraction rate published by MPOB [2].
- The emissions of all GHG gases (i.e., CO_2, CH_4) are expressed in terms of CO_2 equivalent.
- Malaysia has restricted its land cover under oil palm plantation to be 6.5 million hectarage, thereby limiting any new land use change for plantation development. Moreover, the revised MSPO 2.0 certification has set a no deforestation cut-off date as December 31, 2019. In fact, this certification forbids planting or expanding into forested or areas with high biodiversity. As of now, 93 % of the industry is MSPO certified [4]. Therefore, the newly certified plantations under MSPO 2.0 will not come from either conversion of natural forest or peatlands. Considering this, land use change emissions are not accounted in this analysis. Likewise, the carbon sink potential of oil palm plantation is not included in this analysis.

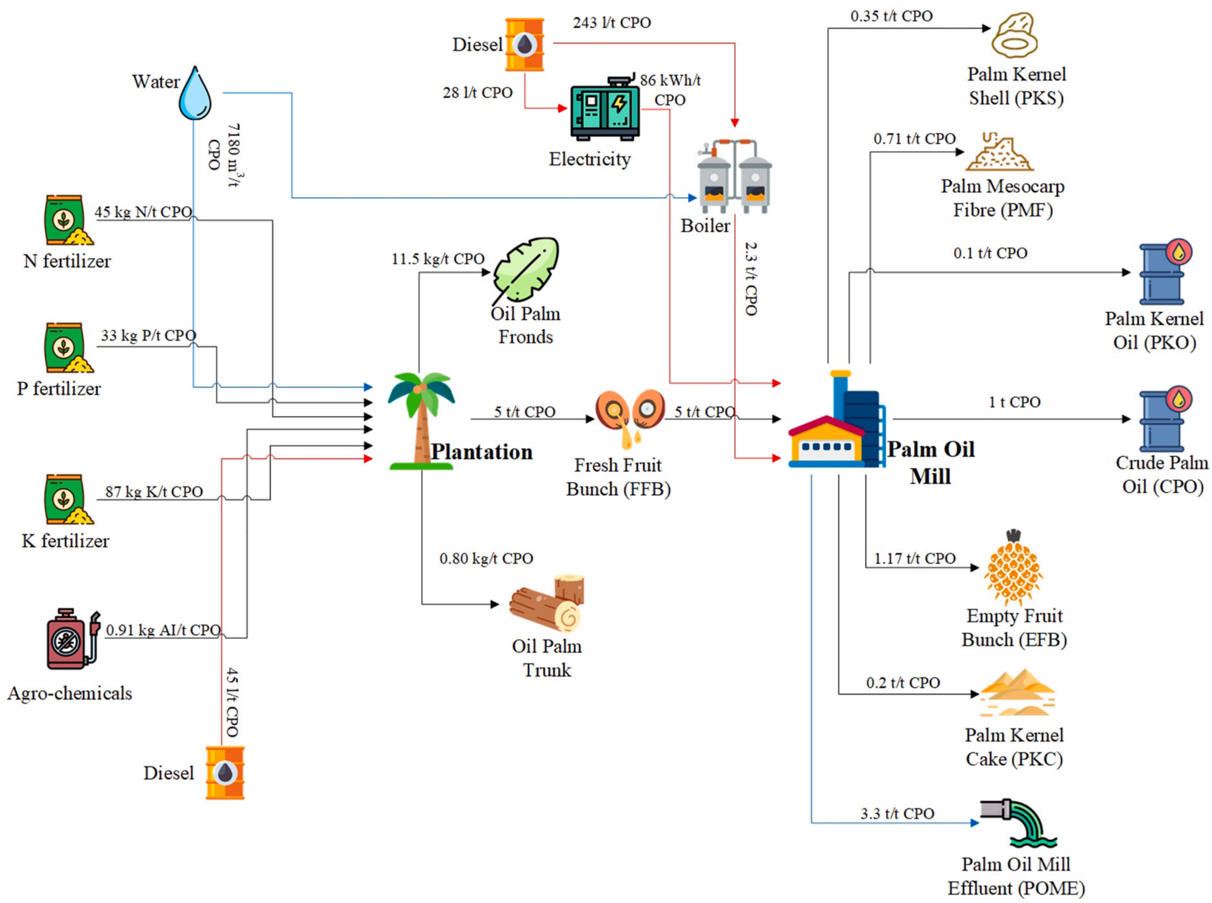

Fig. 4. Material and energy flow for 1 ton CPO production.

- Steady-state operation is assumed, where the uncertainties in terms of energy consumption, conversion factors, cost factors, and emissions rates of each technology are not considered in this work.
- The yield of by-products (palm-based biomass and POME) is assumed to remain consistent across all plantations and mills.
- The quality of the materials such as calorific value, moisture content, and chemical composition is assumed to remain consistent across all plantations and mills.

On the other hand, specific assumptions used in each scenario are described in Sections 4–6.

4. Analysis of theoretical emissions

The major input resources to plantations include fertilisers, agrochemicals, water, and energy (e.g. diesel) as shown in Fig. 4. The fertilisers provide the essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) for the growth and maturity of oil palms. The most common N, P, K, and Mg fertilisers used in Malaysian oil palm plantations are urea, rock phosphate, muriate of potash (MOP), and kieserite. Additionally, agrochemicals such as pesticides, herbicides are used for pest and weed management. For example, glyphosate is the commonly used herbicide for weed control in Malaysian oil palm plantations. Water is another vital resource, which is predominantly rainfed in Malaysia. Apart from this, diesel is used for plantation operations and transport of the harvested products. The FFB is the primary harvest at the plantations. In addition, other notable outputs from plantations include oil palm fronds and palm trunks. The oil palm fronds are regularly cut down as a part of plantation management practices to facilitate FFB harvesting. Conversely, oil palm trunks are felled during the replanting process of the plantation.

Referring to Fig. 4, the harvested FFB from the plantation is fed as input resource to the palm oil mill. Besides, the milling process requires steam and power as input. This requirement is met by palm-based biomass fired combined heat and power (CHP) plant located in a significant number of the mills. In the current practice, diesel is normally used as a backup fuel source to produce steam and power. The primary output from the mill is CPO. Additionally, substantial amount of palm-based biomass such as PMF, PKS, empty fruit bunch (EFB), and palm kernel cake are generated. Apart from this, the effluent stream discharged at the mill is referred as POME. The typical material and energy input and output at plantations and palm oil mills are presented in Appendix. Fig. 4 shows the material and energy flow for 1 ton of CPO production.

The emissions sources are identified from analysing the material and energy flow within the system. The emissions from plantations and palm oil mills can be categorised as follows:

- Application of fertilisers and agrochemicals
- Fuel consumption for plantation operation
- Biomass degradation of unused PMF and EFB
- POME degradation
- Fossil fuel use to generate steam and power for mill operation

Table 3 outlines the emissions factors associated with these aforementioned sources.

Based on the information collected from literature, a GHG calculator has been developed in this work to estimate the theoretical emissions in plantations and palm oil mills. Note that the estimated GHG emissions values are denoted in kilograms of CO_2 equivalent (kg CO_2). The calculator employs a baseline scenario of material and energy flow to establish theoretical emissions from both sites as presented in Fig. 5. In this theoretical baseline emissions calculation, palm-based biomass and wastes are not recovered. The theoretical emissions are determined as 3579.37 kg CO_2/t CPO. Fig. 6 shows the breakdown of theoretical emissions form different sources.

To establish the theoretical emissions, the Malaysian mean FFB yield of 15.49 t/h and an oil extraction ratio (OER) of 0.1970 for the

Table 3
Emissions factors.

Source	Emissions factor		References
Fertiliser			
Nitrogen	3.14	kg CO_2/kg N	Almeida Frazão et al. [29]
Phosphate	0.61	kg CO_2/kg P	Almeida Frazão et al. [29]
Potassium	0.44	kg CO_2/kg K	Almeida Frazão et al. [29]
Magnesium	0.38	kg CO_2/kg Mg	West et al. [30]
Weed & Pest chemicals			
Glyphosate	15.95	kg CO_2/kg AI	Almeida Frazão et al. [29]
Energy			
Diesel	2.7	kg CO_2/l	IPCC [31]
Petrol	2.3	kg CO_2/l	IPCC [31]
Electricity (Malaysian grid)	0.622	kg CO_2/kWh	WBA [32]
Biomass degradation			
PMF	49.08	kg CO_2/t PMF	Saswattecha et al. [33]
PKS	0	kg CO_2/t PKS	–
EFB	948.78	kg CO_2/t EFB	IPCC [34]
POME	384	kg CO_2/t POME	Sodri et al. [35]

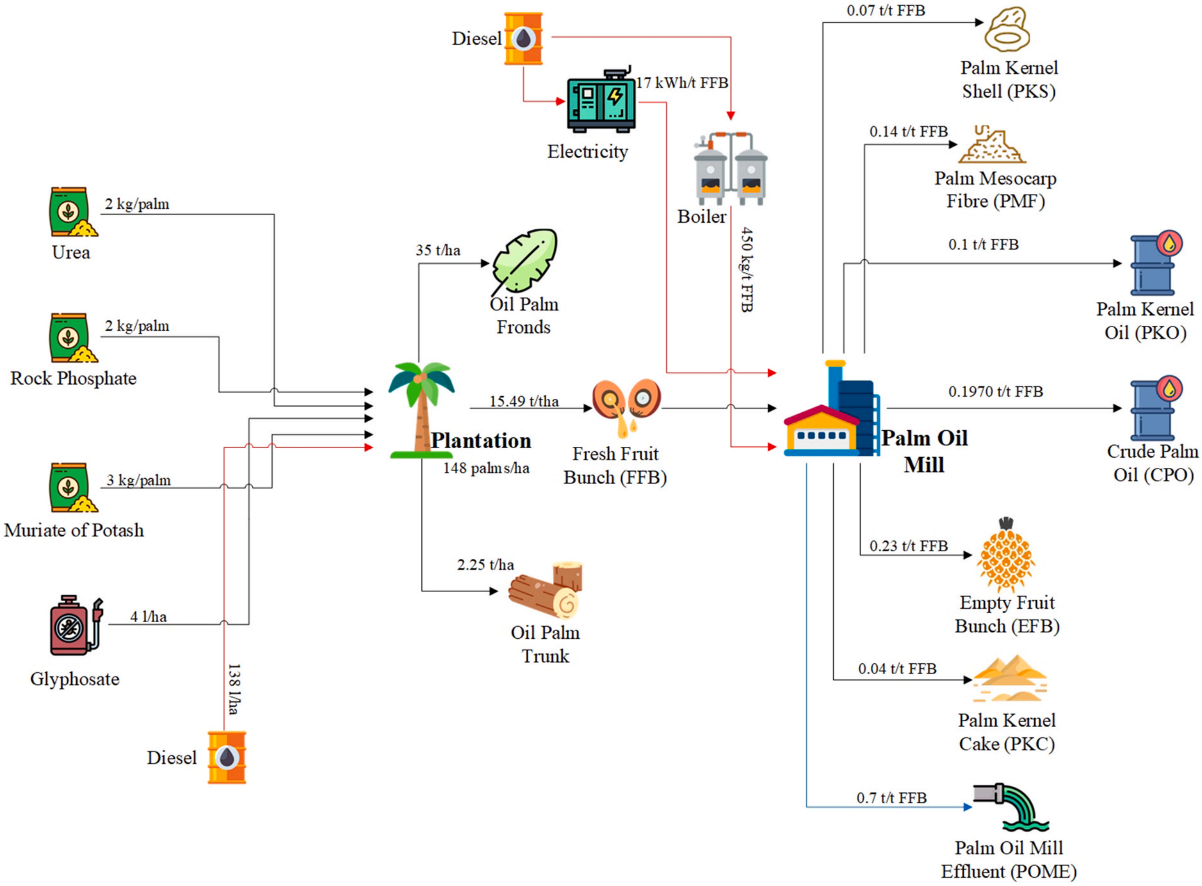

Fig. 5. Material and energy flow considerations for baseline scenario.

year 2022 were utilised [2]. It is noting that the FFB yield and OER exhibit variations among the different states within Malaysia. As a result, Table 4 presents state-specific theoretical emissions, which exhibit a variation of up to ±5 % from the national value. The distribution of each state's contribution to the total emissions is visually represented in Fig. 7. Sabah and Sarawak emerge as responsible for 23 % and 22 %, respectively, of the overall emissions. In West Malaysia, the major emitters are Pahang, Perak and Johor, which are responsible for 16 % of the total emissions each.

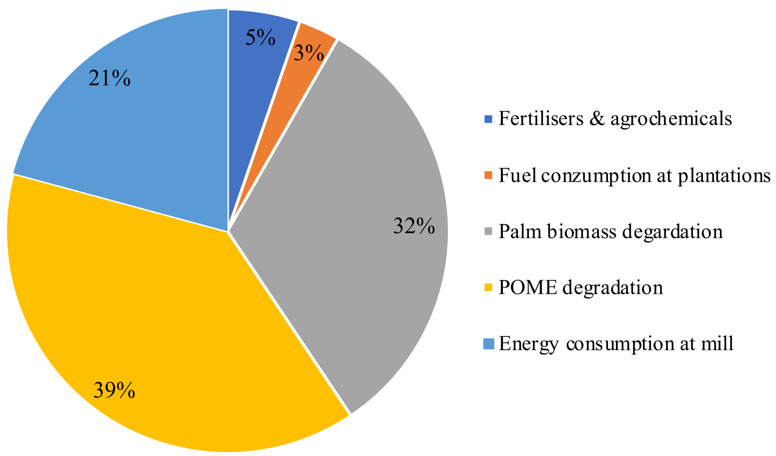

Fig. 6. Contribution of emissions sources.

Table 4
State-wise theoretical emissions.

States	Theoretical Emissions (kg CO_2/t CPO)	CPO production (t CPO/y)	Annual Emissions (M tCO_2/y)
Johor	3571.58	2,969,525	10.61
Kedah	3590.10	237,382	0.85
Kelantan	3536.95	336,061	1.19
Negeri Sembilan	3571.31	675,767	2.41
Pahang	3598.09	3,013,107	10.84
Perak	3593.79	1,866,423	6.71
Selangor	3720.11	498,904	1.86
Terengganu	3663.56	407,500	1.49
Other States	3494.37	156,661	0.55
Sabah	3499.04	4,286,665	15.00
Sarawak	3670.19	4,005,425	14.70
Malaysia	**3594.51**	**18,453,420**	**66.05**

It is worth noting that the theoretical emissions are only indicative of emissions during CPO production when no emissions reduction technologies are deployed. However, in the current industry practice, Malaysian oil palm estates and palm oil mills have adopted different plantation management practices and palm-based biomass utilisation technologies, resulting in lowered emissions levels.

5. Emissions reduction technologies

This section analyses various technologies that can potentially be employed for processing palm-based biomass and POME. Fig. 8 shows alternative emissions reduction technologies in palm oil plantation and mill.

In the current industry practice, PMF and PKS are used as solid fuel for CHP system to produce steam and power to fulfill the requirements of the mill. Any excess PKS can be co-fired in coal power plants; while POME can be anaerobically digested for biogas production and eventually power generation *via* gas engine. Besides, the generated EFB can be processed *via* diverse technologies such as briquetting, pelletisation, composting, fermentation, gasification, and pyrolysis. In addition, oil palm fronds can function as mulch, thereby reducing the chemical fertilisers usage in the plantations.

In general, all emissions reduction technologies can be classified as nature-based solutions and engineered solutions. Nature-based solutions are those that aim to restore nature's carbon sink while engineered solutions refer to those that lead to emissions avoidance or emissions removal. For instance, nature-based solution can be application of biochar in the plantation where carbon is stored in the soil. On the other hand, engineered solutions refers to technologies that reduce emission. For example, utilisation of biomass as a substitute for fossil fuels in power generation. Table 5 shows the solution category of the considered emissions reduction technologies.

An overview of operational data (i.e. feed, output, conversion factor, energy demand, steam demand) for each abatement technology is provided in Table 6. Note that the conversion factor for each technology is benchmarked to 1 t/h of FFB processing capacity. This is performed to standardise the outputs that can be generated from the technologies from processing the FFBs. The respective cost data for these technologies are presented in Table 7. Based on these cost data, the cost values in terms of per unit of product and FFB throughput are presented in Appendix.

The emissions reduction capabilities of these technologies are determined by accounting for the following:

- Emissions mitigated by the product produced from the technology,
- Emissions avoidance from the current disposal practice, and
- Emissions from the energy used for process operation at the technology.

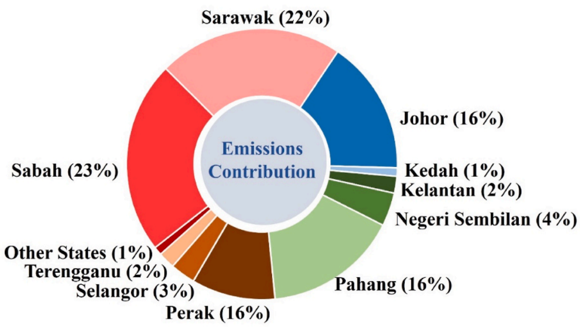

Fig. 7. State-wise distribution of the emissions from upstream and midstream segment.

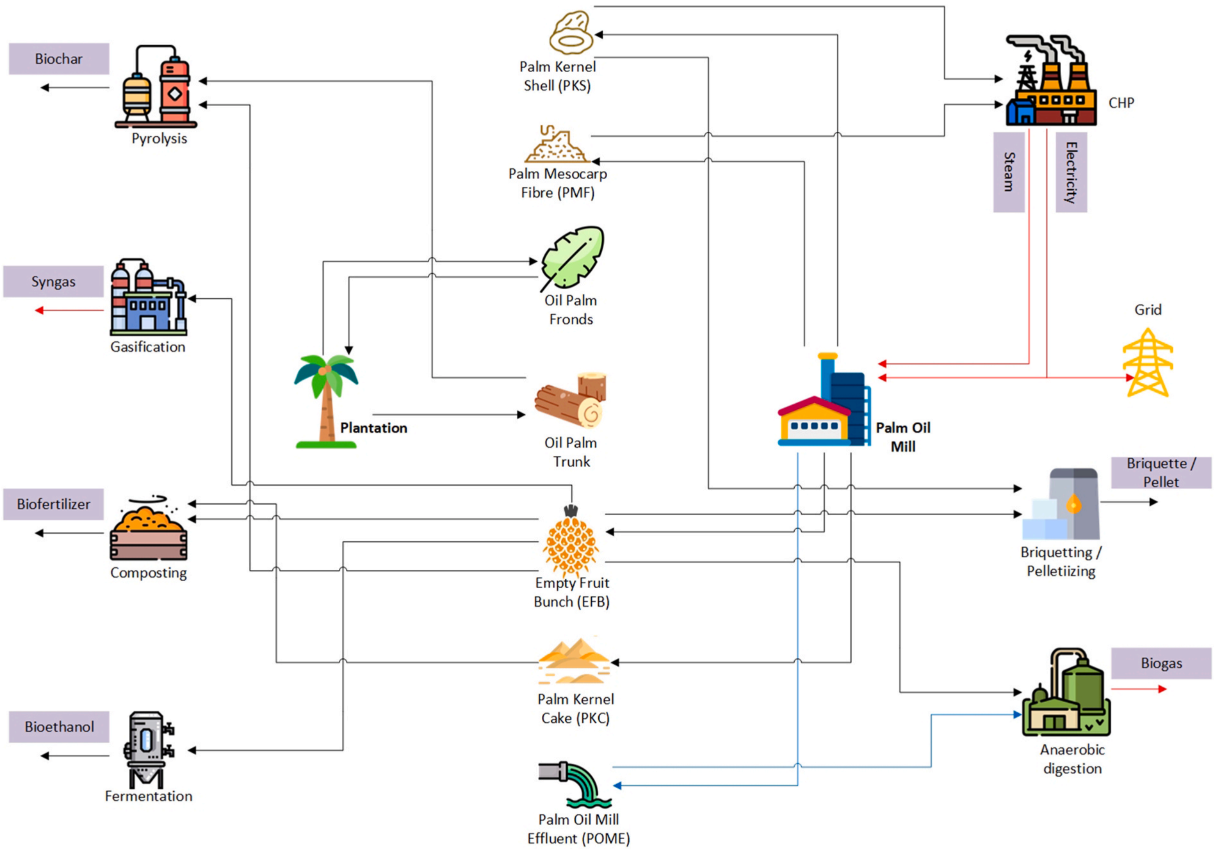

Fig. 8. Overview of current and emerging emissions reduction technologies.

Table 5
Solution category of emissions reduction technologies.

Abatement technologies	Solution category	Remarks
CHP system	Engineered	Emissions avoidance by fossil fuel substitution
Direct cofiring in coal plants	Engineered	Emissions avoidance by fossil fuel substitution
POME Anaerobic digestion	Engineered	Emissions avoidance by landfill disposal and fossil fuel substitution
EFB-Briquette	Engineered	Emissions avoidance by fossil fuel substitution
EFB-Pellet	Engineered	Emissions avoidance by fossil fuel substitution
EFB-Bioethanol	Engineered	Emissions avoidance by fossil fuel substitution
EFB-Biofertilizer	Nature	Emissions avoidance by chemical fertiliser substitution
EFB-Syngas	Engineered	Emissions avoidance by fossil fuel substitution
EFB-Biochar	Nature	Soil carbon storage.
Fronds-Mulching	Nature	Emissions avoidance by chemical fertiliser substitution

For example, EFB can be processed to briquettes *via* briquetting technology. The briquettes can be used to substitute coal as fuel for power generation. The current disposal of EFB as mulching results in methane emissions. Such emissions can be avoided by converting EFB into briquette and utilised as fuel. Through such action, GHG emissions from disposal of EFB and emissions from coal at power plant can be reduced. Likewise, the emissions reduction capability for each of the technologies is estimated and outlined in Table 8.

Technology readiness assessment for each of the technologies is evaluated based on Technology Readiness Level (TRL) chart. TRL is a method used to assess the maturity of a given technology, ranging from the conceptualisation (TRL 1) to a proven deployment (TRL 9). It provides a standardised way to understand the development stage of a technology and its readiness for practical implementation. TRL was originally developed by the US National Aeronautics and Space Administration (NASA) for effective assessment and communication regarding the maturity of new technologies. The breakdown of the TRL levels as detailed by Héder [36] is shown in Appendix. TRL assessment can help in gauging the deployment of emission reduction technologies in decarbonisation of the palm oil sector. TRL assessment for each of the considered technologies are provided in Table 9.

Table 6
Review of current and emerging emissions reduction technologies.

Abatement technologies	Feed	Output	FFB Throughput	Conversion Factor[d]		Energy Demand (kWh/Feed)	Steam Demand (kg/Feed)
CHP system	PMF, PKS	Power Steam	1 t/h	20.80 450	kWh kg	–	–
Direct co-firing in coal power plants	PKS	Power		44.88	kWh	–	–
Anaerobic Digestion	POME	Biogas → Power		38.10	kWh	28[a]	–
Briquetting	EFB	Briquette → Power		171.02	kWh	17.39[b]	124.2[b]
Pelletisation	EFB	Pellet → Power		136.60	kWh	22.43[b]	313.95[b]
Fermentation	EFB	Bioethanol		21.39	kg	69.52[b]	–
Composting	EFB	Biofertiliser		55.2	kg	9.94[c]	100[c]
Gasification	EFB	Syngas → Power		95.36	kWh	62[c]	100[c]
Slow Pyrolysis	EFB	Biochar		25.3	kg	62[c]	–

[a] Foong et al. [27].
[b] Yeo et al. [24].
[c] Ng & Ng [20].
[d] Conversion factor refers to the output produced from unit quantity (1 t/h) of FFB processed.

Table 7
Technology – Cost data.

Abatement technologies	Unit capacity	Capital cost (USD/unit)	Operating cost (USD)
CHP system - Boiler & Turbine	5 MW	2,500,000	0.02/kWh
POME Anaerobic digestion[a] - Biogas production - Gas engine	5400 m^3 1 MW	2,050,000 315,000	31,000/y 25,200/y
EFB-Briquette[b] - Briquette Plant	3 t/h	680,000	32/t briquette
EFB-Pellet[b] - Pellet Plant	2 t/h	450,000	34/t pellet
EFB-Bioethanol[b]	10,000 l/d	1,269,166	2,869,000/y
EFB-Biofertiliser[c]	1 t/h	800,000	55/t compost
EFB- Gasification[c] - Shredding & Drying - Gasifier	1 t/h 100 kW	592,000 192,000	13.5/t EFB 20/t EFB
EFB-Biochar[c] - Shredding & Drying - Pyrolysis	1 t/h 1 t/h	592,000 192,000	13.5/t EFB 20/t EFB

[a] Foong et al.[27].
[b] Yeo et al. [24].
[c] Ng & Ng [20].

Table 8
Abatement Technology – Emissions reduction capability.

Abatement technologies	Feed	Output	Emissions Reduction (kg CO_2/t FFB)	Cost of emissions reduction (USD/t CO_2)
CHP system	PMF, PKS	Power & Steam	169.66	4
POME Anaerobic digestion	POME	Biogas → Power	265.35	36
EFB-Briquette	EFB	Briquette → Power	329.68	13.58
EFB-Pellet	EFB	Pellet → Power	231.55	14.92
EFB-Bioethanol	EFB	Bioethanol	172.04	208.20
EFB-Biofertiliser	EFB	Biofertiliser	124.87	13.27
EFB-Syngas	EFB	Syngas → Power	209.31	36.53
EFB-Biochar	EFB	Biochar	217.61	3.48

6. Opportunities and challenges for net-zero status

The established theoretical emissions for CPO production amount to 3594.51 kg CO_2/t CPO (see Section 4.1). It is noted that the theoretical emissions value is not reflective of the current Malaysian scenario. During the theoretical emissions estimation, it is assumed that none of the generated biomass from the plantation and palm oil mill are recovered. However, in the current practice, some of the biomass are utilised in CHP system. This section commences by assessing the gap to attain a net-zero state, considering the

Table 9
TRL assessment of emissions reduction technologies.

Abatement technology	TRL score	Remarks
CHP system	9	The CHP system is well established technology used in palm oil mills
Direct cofiring in coal plants	9	Cofiring of PKS in coal power plant is well established industrial practice.
POME Anaerobic digestion	9	The POME biogas system has been successfully installed and operational in palm oil mills.
EFB-Briquette	7	The EFB briquette production is demonstrated in an operational environment, but the technology is not fully developed and optimised specific to EFB processing.
EFB-Pellet	7	The EFB pellet production is demonstrated in an operational environment, but the technology is not fully developed and optimised specific to EFB processing.
EFB-Bioethanol	7	EFB-bioethanol pilot plant is operational and validated.
EFB-Biofertilizer	5	EFB-biofertiliser production is demonstrated in relevant operational environment.
EFB-Syngas	4	The EFB-syngas production feasibility is analysed at laboratory scale.
EFB-Biochar	4	The EFB-biochar production feasibility is analysed at laboratory scale.

current extent of technology adoption in plantations and palm oil mills, which is reflective of the current status of emissions during CPO production in Malaysia. Subsequently, the emerging technologies' potential in facilitating the transition to a net-zero target for CPO production is outlined.

6.1. Current status in malaysian plantations and mills

The Malaysian palm oil sector has consistently deployed technologies to reduce emissions, aligning with its commitment to sustainable palm oil production since decades ago. The Feed-in Tariff scheme in 2011 promoted the adoption of CHP systems in palm oil mills. In addition to the CHP system providing internal steam and power requirements at the mill, any excess power can also be exported to the national grid. Typically, the entire PMF and about 57 % of PKS generated at the mill are used to meet steam and power requirements at the mill. This can offset 20.84 % of the baseline emissions. The remaining PKS is generally used for co-firing in coal

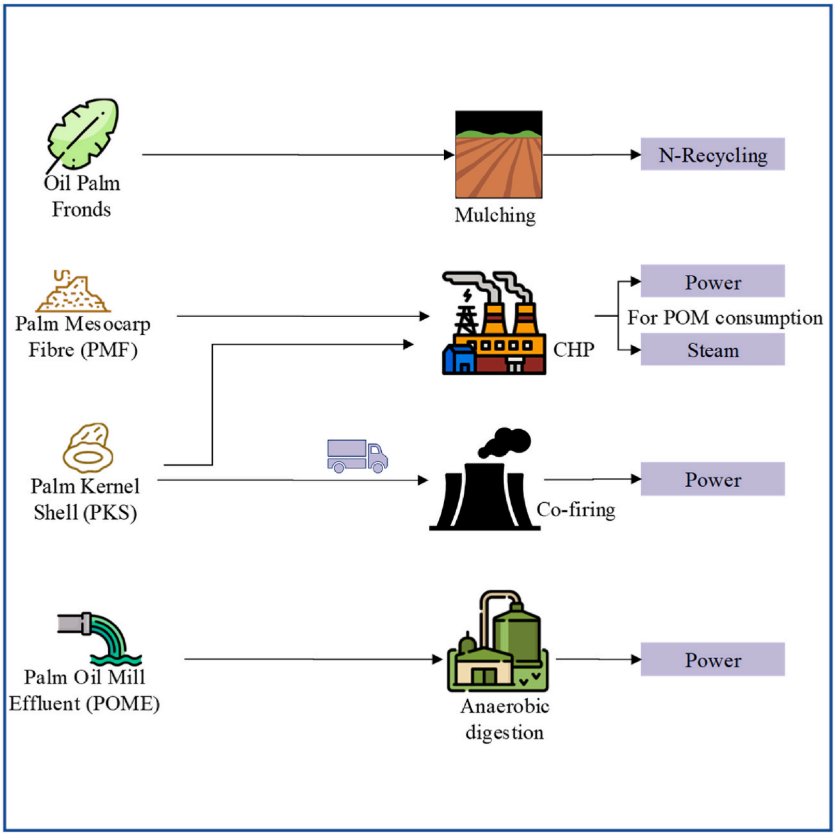

Fig. 9. Technology pathways – current status.

power plants. The emissions reduction that can be achieved by PKS cofiring at coal power plants within 100 km radius is 6.18 %. Recently, biogas capture plants in palm oil mills are facilitated when the government made it mandatory for all mills to have biogas capture under the Palm Oil National Key Economic Area of the National Economic Transformation program. POME anaerobic digestion for biogas capture and power generation can contribute to ~37.47 % reduction of the theoretical emissions. Besides, the mulching of oil palm fronds in plantations is a common plantation management practice, which could result in emissions reduction of 4.31 %. Therefore, the current adoption of technologies in plantations and palm oil mills (shown in Fig. 9) – mulching, CHP system, POME biogas-based power generation, and PKS co-firing result in a 68.80 % emissions reduction based on the baseline scenario. The gap to achieve net-zero status in CPO production is estimated as 31.20 % of the theoretical emissions. Consequently, the current emissions level for CPO production in Malaysia is determined as 1121.49 kg CO_2/t CPO. Table 10 presents the emissions reduction that is achieved by the adoption of current technologies. Meanwhile, Fig. 10 shows the waterflow chart, which indicates a cumulative emissions reduction achieved as technologies are added and the current emissions level. It is a useful representation for understanding how the emissions reduction is achieved by a series of technology additions. The red colour in the figure indicates the theoretical emissions, the blue colour indicates the cumulative emissions reduction achieved by the addition of each successive abatement technology and finally the yellow colour represents the gap to net-zero status.

6.2. Opportunities to net-zero status via EFB management options

The current technological landscape handles the PMF, PKS, and POME generated within the mill, but EFB utilisation remains limited in the Malaysian palm oil sector. This section delves into an evaluation of various technological alternatives for EFB processing. These include briquetting, pelletisation, composting, fermentation, gasification, and pyrolysis. The assessment is conducted within two distinct scenarios. Scenario 1 envisions that surplus PKS is directed toward co-firing in coal power plants, while Scenario 2 assumes the entirety of PKS is allocated to the CHP system, supporting the energy requirements for EFB processing technologies. Figs. 11 and 12 provide visual representations of Scenario 1 and Scenario 2, respectively. The emissions reduction from each of the EFB processing technologies under both scenarios are presented in Table 11. A negative value in the table indicates a net sequestration while a positive value refers to net emissions. Visual representation of emissions reduction capabilities for each of the pathways in Scenario 1 and Scenario 2 can be found in Figs. 13 and 14. The emissions reduction achieved by each of the technologies are benchmarked with current emissions levels (Section 6.1) to represent the net-zero status.

In Scenario 1, the utilisation of EFB-briquette and EFB-pellet pathways yields the attainment of net-zero emissions in CPO production. Notably, the EFB-briquette pathway surpasses net-zero by 19 %, while the EFB-pellet pathway exceeds it by 1.51 % when benchmarked to theoretical emission value. Conversely, the reduction gaps to accomplish net-zero status for EFB-biofertilizer, EFB-bioethanol, EFB-syngas, and EFB-biochar pathways are 6.85%, 13.60%, 1.59%, and 0.41% respectively. It is worth highlighting that the EFB-biochar pathway is fairly close to achieve the net-zero objective.

In Scenario 2, the excess steam and power generated from the CHP system can be supplied to support the utility consumptions in each EFB processing technology. Much like in Scenario 1, EFB-briquette and EFB-pellet pathways successfully reach the net-zero objective in Scenario 2. Consequently, the EFB-briquette pathway surpasses net-zero by 15.87 %, and the EFB-pellet pathway exceeds it by 5.47 %. Furthermore, the EFB-biochar pathways also accomplish the net-zero target while the EFB-syngas pathway exhibits a marginal gap of 0.77 % from net-zero target. Nevertheless, despite the additional utility supplied from the CHP system, the EFB-biofertilizer and EFB-bioethanol pathways still exhibit a 9.36 % and 7.83 % emissions reduction gap, respectively (i.e. unable to achieve net-zero status).

It is important to highlight that the allocation of PKS to the CHP system has resulted in only slight improvements in the emissions reduction potential of the EFB-pellet, EFB-syngas, EFB-bioethanol, and EFB-biochar pathways as compared to Scenario 1. Notably, the emissions reduction capacity of the EFB-briquette and EFB-biofertiliser pathway has decreased by 2.55 % and 5.01 % relative to Scenario 1. It is worth noting that the EFB-briquette and EFB-pellet pathways have achieved net-zero targets in both scenarios and has potential for large scale implementation.

The above discussed emissions reduction potential in Table 11 and cost of emissions reduction in Table 8 for the different pathways are illustrated for a 60 t/h palm oil mill. Considering the annual operating hours of the palm oil mill to be 5000 h, the annual emissions can be estimated as 215,670.60 tCO_2/y. Table 12 presents the total annual emissions reduction potential and its associated cost for the different pathways.

6.3. Challenges of implementing emissions reduction pathways

While the various pathways explored offer prospects for achieving net-zero status in plantations and palm oil mills, their practical implementation is accompanied with the following challenges:

- **Emerging Technology Readiness**: The relatively low TRL scores of many emerging technologies introduce uncertainties concerning their cost-effectiveness and emissions reduction potential at a commercial scale.
- **Import Dependence**: The absence of local manufacturers for efficient high-pressure steam generators necessitates the import of equipment required for biomass-based power generation and CHP systems [15]. It is also reported that the technologies for biogas production in Malaysia through the anaerobic digestion technique have been imported from the Germany [37].
- **Infrastructure Constraint**: Limited access to the necessary infrastructure, such as grid connectivity and transportation networks, hinders the export of excess energy and bio-products generated from the technologies, reducing the potential benefits.

Table 10
Emissions reduction in current technologies.

Abatement technology	Emissions reduction	
	(kg CO_2/t CPO)	(% of baseline)
Mulching of fronds	155.91	4.31 %
CHP system	749.98	20.84 %
Direct cofiring of PKS in coal plants	222.13	6.18 %
POME Anaerobic digestion	1346.95	37.47 %

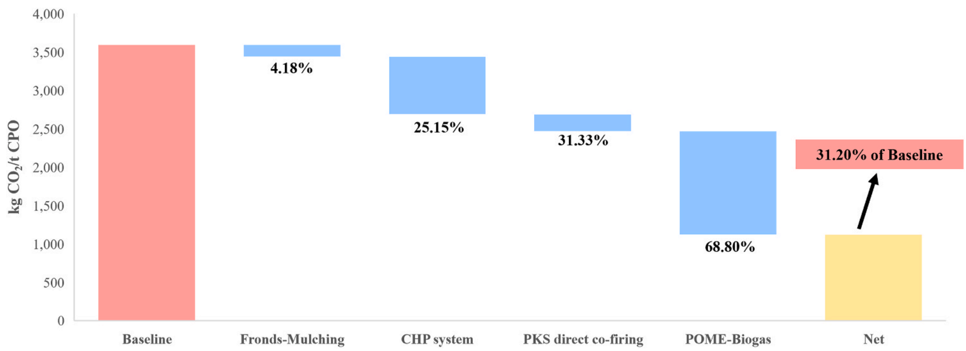

Fig. 10. Emissions reduction – current status.

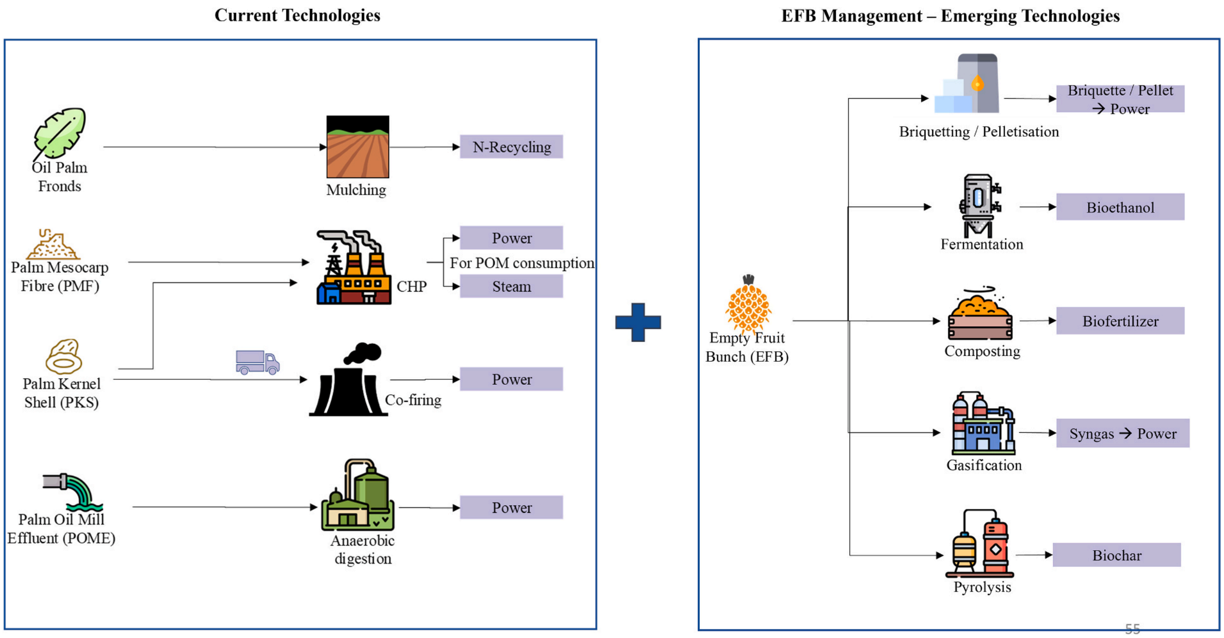

Fig. 11. Scenario 1 – Technology pathways.

- **Capital Requirement**: The emissions reduction technologies require significant upfront investments, posing barrier, especially for small and medium-sized mills with limited financial resources.
- **Biomass Logistics Challenges**: Efficient technology operation relies on a consistent supply of biomass feedstocks. Besides, high transportation and storage costs for palm-based biomass and uncertainty regarding biomass quality variation over time pose significant challenges.
- **Lack of Urgency**: Operators' lack of urgency and understanding among operators concerning net-zero targets and their long-term benefits can impede progress.

Addressing these challenges is vital for the successful adoption and deployment of emission-reducing technologies within the palm

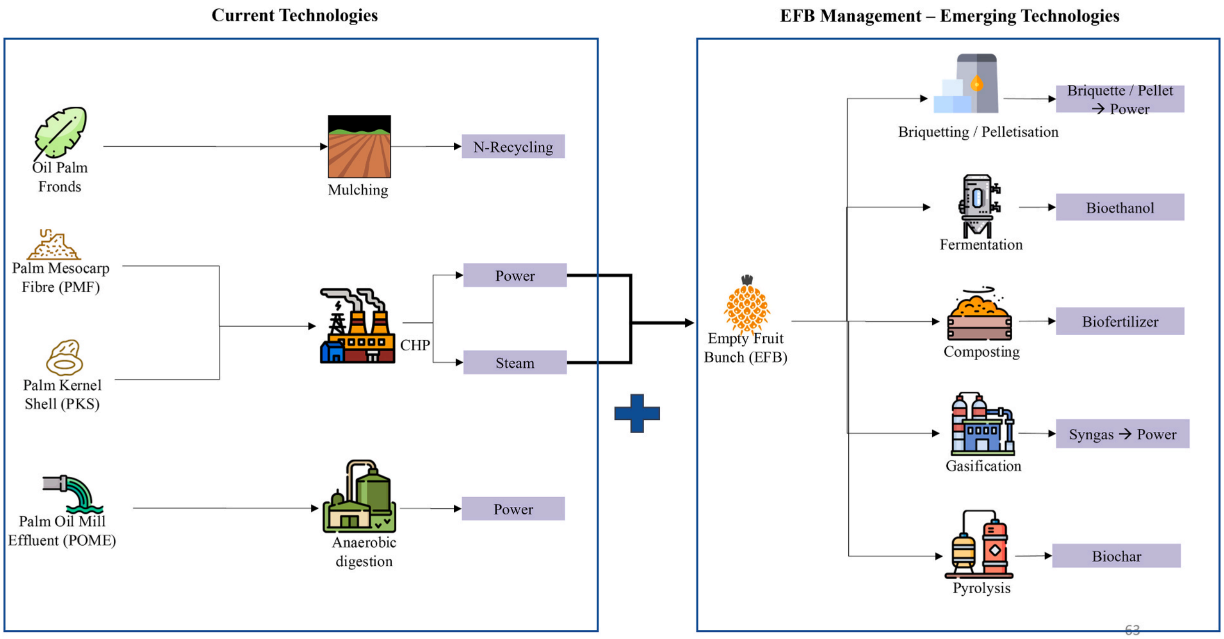

Fig. 12. Scenario 2 – Technology pathways.

Table 11
Emissions reduction in emerging technologies.

Abatement technology	Emissions reduction (kg CO_2/t CPO)	Gap to net-zero (kg CO_2/t CPO)
Scenario 1		
EFB-Briquette	1804.44	-682.96
EFB-Pellet	1177.20	-55.71
EFB-Bioethanol	875.26	246.22
EFB-Biofertiliser	632.63	488.85
EFB-Syngas	1064.33	57.15
EFB-Biochar	1106.75	14.74
Scenario 2		
EFB-Briquette	1799.05	-570.45
EFB-Pellet	1425.22	-196.62
EFB-Bioethanol	892.16	336.45
EFB-Biofertiliser	947.15	281.45
EFB-Syngas	1200.93	27.68
EFB-Biochar	1246.94	-18.33

*Note that the values accounted for the different EFB-pathways that is integrated with other existing technologies, i.e., frond mulching, CHP, and anaerobic digestion (see Figs. 11 and 12).

oil sector.

6.4. Recommendations

The analysis conducted sheds light on significant opportunities for the Malaysian palm oil sector to transition towards net-zero emissions. To capitalise on these opportunities and address the challenges identified, several recommendations can be considered:

- **Research & Development**: While emerging technologies hold promise, the low technology readiness level (TRL) scores pose uncertainties. Therefore, investing in research and development to raise the TRL of these technologies and demonstrate their feasibility on a larger scale is crucial. Collaborative efforts among industry players, researchers, and government agencies can accelerate technology maturation.
- **Promote Local Equipment Manufacturing**: Given the import dependence for equipment, supporting local manufacturers to develop and produce such equipment can enhance self-sufficiency, reduce costs, and encourage technology adoption.
- **Enhance Infrastructure**: Establishing robust grid connectivity and transportation networks is essential for effective export of excess energy generated from biomass conversion.

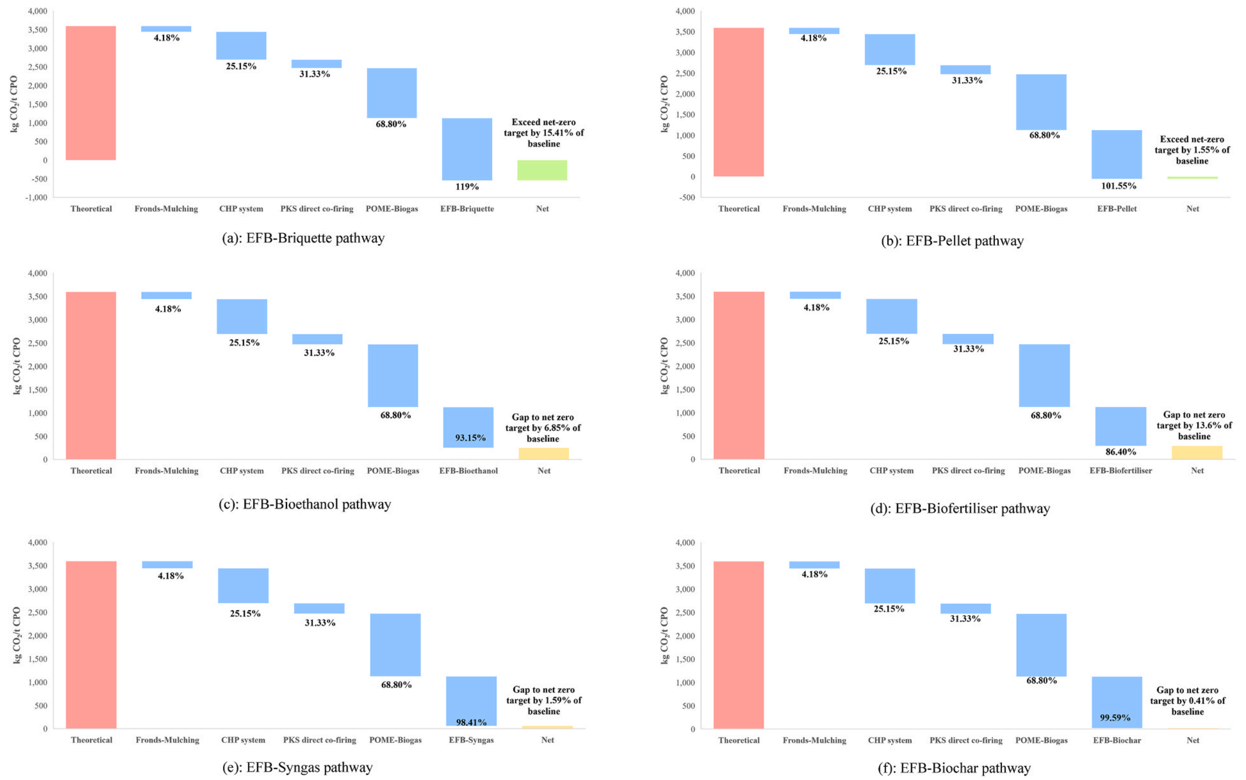

Fig. 13. Emissions reduction capability of pathways – Scenario 1.

- **Provide Financial Support**: Facilitating access to financing, grants, or incentives for palm oil mills, especially small and medium-sized ones, can alleviate the financial burden of adopting biomass conversion technologies. This can stimulate wider technology adoption across the industry. Bursa Malaysia is expected to roll out the voluntary carbon market scheme otherwise known as Bursa Carbon Exchange (BCX). BCX is a platform that aims to facilitate the trading of high-quality carbon credits *via* standardised carbon contracts. Corporates or hard-to-abate sectors (e.g. cement, steel, oil, and gas) may purchase these credits to offset their carbon footprint while the sale of carbon credits, in return, will help to finance and drive the development of domestic emissions reduction and removal projects.
- **Policy and Regulations:** Policy and regulations are critical in driving the adoption of emissions reduction technologies in the palm oil sector. Since setting targets in the Paris agreement, Malaysia has formulated and rolled out several policies and regulations for reducing emissions. For instance, Malaysia recently implemented the Malaysian Sustainable Palm Oil (MSPO) certification scheme. MSPO requires stakeholders in the sector to implement emissions reporting and monitoring, with the view of emissions reduction or mitigation plans. In addition, Bursa Malaysia's environmental, social and governance framework regulates public-listed companies to meet its emissions reduction obligations. Aside from this, Malaysia launched its National Biomass Action Plan (NBAP) 2023–2030, to empower and promote biomass and renewable energy industry. With Bursa Malaysia's BCX initiative, it will help in incentivising the industry to adopt emissions reduction technologies. However, the focus and attention must be directed to determining how effective these policies and regulations are in encouraging stakeholders in the sector.
- **Optimise Supply Chain**: Efficient supply chain management is vital for biomass-related businesses. Developing streamlined processes for collection, transportation, and storage of biomass materials can enhance the feasibility of technology adoption.

Implementing these recommendations will not only facilitate a more sustainable palm oil sector but also contribute significantly to Malaysia's net-zero emissions target.

7. Conclusion

This work analyses the current status of emissions levels and opportunities for net-zero status at Malaysian oil palm plantations and palm oil mills. The study identified several sources of GHG emissions and the theoretical emissions representing a scenario of no biomass utilisation at plantation and mill were estimated to be 3594.51 kg CO_2/t CPO. Current technology adoption within the Malaysian palm oil sector, including mulching, CHP systems, POME anaerobic digestion, and direct co-firing of PKS has already resulted in 68.80 % reduction in theoretical emissions. However, EFB is largely underutilised in the current industry practice. This work examined the various pathways for EFB utilisation under different two scenarios: Scenario 1, where PKS is employed in CHP

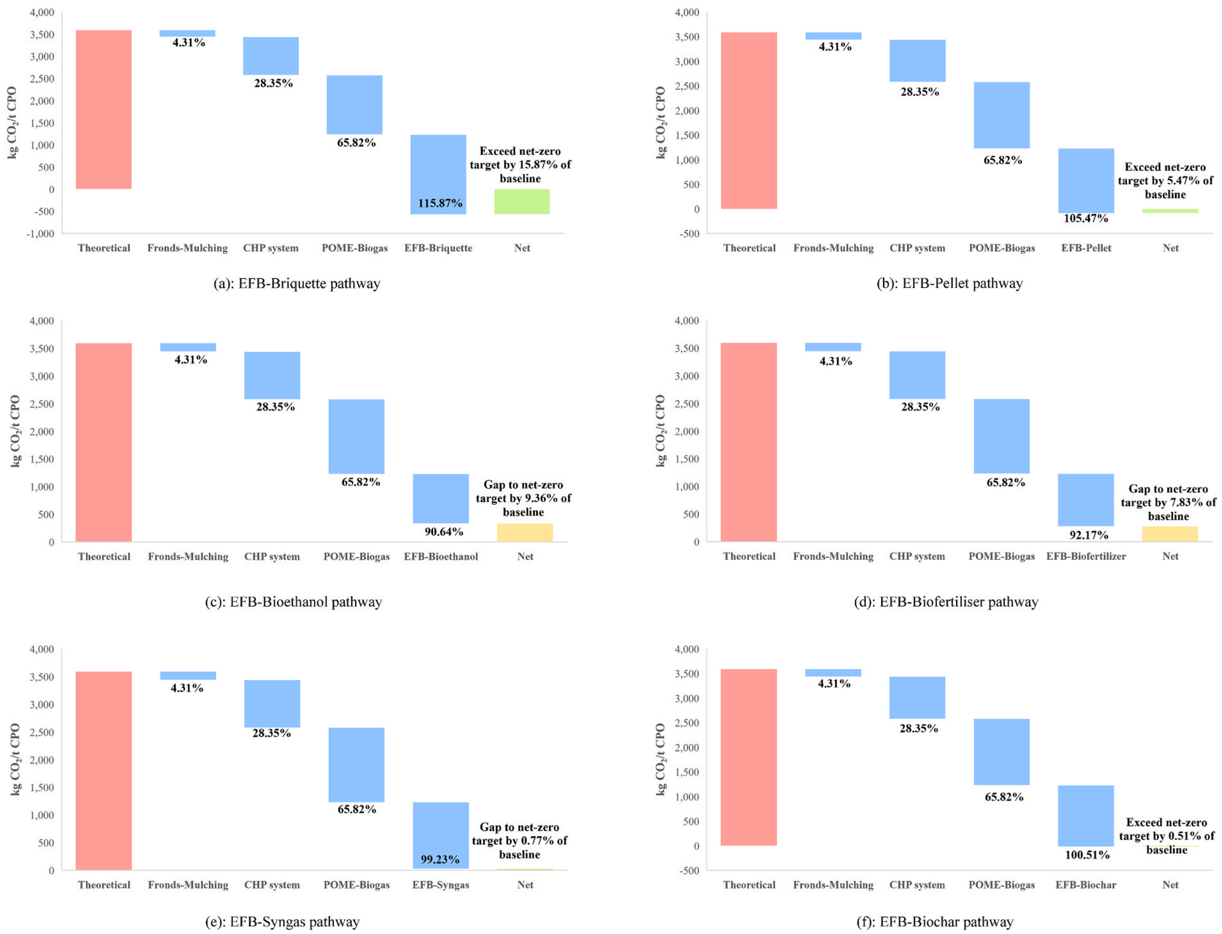

Fig. 14. Emissions reduction capability of pathways – Scenario 2.

Table 12
Illustrative analysis for a 60 t/h palm oil mill.

Abatement technology	Emissions reduction (tCO_2/y)	Cost of emissions reduction (M USD/y)
Scenario 1		
EFB-Briquette	256,648	4.56
EFB-Pellet	219,013	4.14
EFB-Bioethanol	200,897	14.02
EFB-Biofertiliser	186,339	3.59
EFB-Syngas	212,241	5.42
EFB-Biochar	214,786	3.32
Scenario 2		
EFB-Briquette	249,898	4.58
EFB-Pellet	227,468	4.39
EFB-Bioethanol	195,484	14.26
EFB-Biofertiliser	198,784	3.87
EFB-Syngas	214,010	5.75
EFB-Biochar	216,771	3.38

systems with any excess directed toward co-firing, and Scenario 2, in which all PKS is allocated to the CHP system to support EFB processing technologies. Scenario 2, due to its strategic use of excess steam and power supplied by the CHP system, achieved enhanced emissions reductions in various pathways compared to Scenario 1. Most notably, the EFB-briquette and EFB-pellet pathways in Scenario 2 were able to successfully achieve the net-zero objective. The EFB-biochar and EFB-syngas pathways also demonstrated promising potential in achieving the net-zero target. Finally, challenges in implementing the emissions reduction technologies are highlighted with recommendations to capitalise on the opportunities. This study serves as a vital resource for policymakers, industry stakeholders, and researchers, providing a roadmap for the Malaysian palm oil sector to transition toward sustainability, reduce emissions, and contribute to Malaysia's ambitious net-zero targets. As for future extension, this study can be expanded to cover (i) supply chain management in which Scope 3 emissions are incorporated; (ii) supply chain uncertainty by using Stochastic model; and (iii) techno-economic feasibility of each emissions reduction pathway with consideration of its carbon credit potential.

CRediT authorship contribution statement

Jaya Prasanth Rajakal: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Foo Yuen Ng:** Writing – review & editing, Visualization, Validation. **Anna Zulkifli:** Writing – review & editing, Visualization, Validation. **Bing Shen How:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jaka Sunarso:** Writing – review & editing, Writing – original draft, Validation. **Denny K.S. Ng:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Viknesh Andiappan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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