Heliyon 10 (2024) e27265

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A holistic mitigation model for net zero emissions in the palm oil industry

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A R T I C L E I N F O

Keywords:
Mitigation model
Sustainability assessment
Carbon assessment
Optimization modelling
Palm oil
Net zero emissions

A B S T R A C T

Achieving net zero emissions to ensure a sustainable future has become increasingly urgent in light of climate change. The palm oil industry in Malaysia plays a significant role in the country's economy but has faced criticism for its environmental impact, particularly in terms of sustainability and greenhouse gas emissions. While the government has implemented policies and initiatives to promote sustainable palm oil production and reduce emissions, there remains a need for a comprehensive and integrated mitigation strategy to help make an informed decision to improve the performance. To address the limitations of the current framework, this study proposes an Integrated Mitigation Strategy Model which incorporates established frameworks of Palm Oil Mill Carbon Accounting (POMCFA) and Sustainability Index (POMSI). This model has been developed based on the superstructure approach, considering a set of mitigation options to improve weak indicators identified through assessments. The selection of these options is informed by a theoretical review of existing literature on factor changes and their impact on emissions reduction. The model is further validated through case studies, ensuring its robustness and reliability. Based on the case study, it reveals that palm oil mill effluent, diesel consumption, and water consumption contribute the most to carbon dioxide equivalent emissions. In terms of sustainability scoring, the environmental aspect obtains the lowest scores compared to social and economic aspects. Weaknesses identified include dust concentration, palm oil mill effluent, and boiler emissions. Using the heuristics of factor changes equation, the mitigation model suggests implementing high-technology boilers as the optimal solution for these weaknesses. With the theoretical and empirical support behind the choice of variables, our model provides a valuable tool for decision-making in achieving net-zero emissions and sustainable palm oil production.

1. Introduction

Achieving net zero emissions is crucial to mitigate climate change's impacts and ensure a sustainable future for the planet [1]. Numerous countries globally have pledged to reach net zero emissions as a response to climate change and for a sustainable future,

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https://doi.org/10.1016/j.heliyon.2024.e27265
Received 17 May 2023; Received in revised form 18 February 2024; Accepted 27 February 2024
Available online 2 March 2024

including the United Kingdom, Japan, Canada, and New Zealand [2]. Eight ASEAN nations have pledged to attain net zero greenhouse gas emissions or reach carbon neutral status by 2050 to align with the 1.5 °C goal established by the Intergovernmental Panel on Climate Change [3]. Indonesia has promised net zero by 2060, while only the Philippines has not set a net-zero target [4]. These goals reflect the commitment of ASEAN countries, including Malaysia, to address the effects of climate change and strive for sustainability.

Malaysia's government has set ambitious targets to reduce greenhouse gas emissions and to promote sustainable development, including the goal of achieving net zero emissions by the end of this century [5]. One of the key initiatives is the use of electric vehicles, and investing in energy efficiency and sustainable transportation [6]. In the palm oil industry, the government has implemented several policies and initiatives to promote sustainable palm oil production and reduce emissions from the palm oil sector [7]. This shows that the government is committed to pursuing the development of sustainable production in line with the ASEAN Roadmap towards Net Zero Emissions.

The palm oil industry in Malaysia plays a significant role in the country's economy but it has also been criticized for its impact on the environment, particularly in terms of sustainability and greenhouse gas emissions [8]. Palm oil mills, as a major component of the palm oil production process, are significant contributors to the country's greenhouse gas emissions [9]. The energy-intensive nature of the palm oil milling process, which often involves the burning of fossil fuels, releases significant amounts of greenhouse gases. In addition, the waste generated by palm oil mills, if not properly managed, can also contribute to emissions through the production of methane. Malaysia has taken steps to address these concerns, this includes the Malaysian Sustainable Palm Oil (MSPO) certification scheme, which sets standards for sustainable palm oil production, and the Malaysian Palm Oil Certification Council (MPOCC), which oversees the certification of palm oil mills and growers [10] Additionally, the Malaysia Palm Oil Board (MPOB) and the Roundtable on Sustainable Palm Oil (RSPO) are committed to reducing greenhouse gas emissions from the palm oil sector by 30% by 2020 and many mitigation plans have been planned to achieve the goals [11]. Four primary treatment approaches can effectively address emissions in the palm oil industry. These four treatment methods encompass the treatment of empty fruit branches (EFB), fiber combustion, oil extraction enhancement, and treatment of palm oil mill effluent (POME). The following section will examine the advantages and disadvantages of measurement.

EFB constitutes a significant byproduct of the palm oil extraction procedure, necessitating appropriate disposal methods. Improper disposal practices of oil palm trunks and empty fruit bunches lead to the release of substantial quantities of greenhouse gases. The utilization of palm waste for the production of solid biofuels holds promise in its ability to support initiatives aimed at reducing carbon emissions. Several studies have been performed to assess the efficacy of the treatment and its potential for enhancing economic and environmental aspects associated with the EFB.

A comprehensive framework combining life cycle assessment and the Greenhouse Gas Protocol has been established to accurately measure the direct and indirect carbon emissions associated with the densification of oil palm trunks and empty fruit bunchs [12]. The method covers the whole life cycle of the process, from its inception to the point of production, and focuses on three pellet facilities located in Indonesia and Malaysia. The production of empty fruit bunch pellets has the potential to cut emissions by a significant margin, ranging from 62.0% to 74.1% when compared to the alternative method of landfilling the empty fruit bunch.

The existing techniques employed for composting empty fruit bunches (EFB) are critically evaluated and a concise synthesis of research findings on the impact of EFB compost on the growth of oil palm seedlings is presented [13]. The diverse range of techniques employed in composting empty fruit bunches (EFB) demonstrates that EFB compost has the potential to serve as a viable planting substrate for oil palm seedlings. The improvement of the physicochemical qualities, particularly the nutrient content, suggests that these materials possess the necessary characteristics to serve as a good planting medium for the generation of oil palm seedlings.

EFB can be converted into other useful products such as bioethanol. The economic feasibility of bioethanol production from empty fruit bunches (EFB) is assessed through the utilization of an ASPEN suite simulator for the process simulation [14]. The findings revealed an internal rate of return of 15% and a payback period of approximately seven years. Prevaporation technologies are applied in this study to convert the raw material into bioethanol.

The composting treatment of palm oil waste is studied and systematic literature research is conducted to get a thorough understanding of its possible uses [15]. The findings demonstrated that composting, which is regarded as a sustainable technology for preserving the environment, human safety, and economic value, provided the best treatment for palm oil waste. The best method, which requires a minimum of 14 days, uses an in-vessel method with a controlled composting chamber. In contrast to the windrow system, it necessitates strict control and yields a final product with a high microbial colony form both indoors and outdoors.

Apart from the EFB remaining, the combustion of fiber during the palm oil extraction process should be optimized to mitigate air pollutant emission. During the combustion of fibers, several air pollutants are emitted, including nitrogen oxides (NOx), particulate matter (PM), sulfur dioxide (SO2), and volatile organic compounds (VOCs). Each air pollutant requires specific treatment measures to effectively mitigate its impact on the environment and human health. SO2 and VOCs can be removed by using wet scrubber technology and a thermal incinerator. Wet scrubbing demonstrates enhanced economic and applicative merit in its capacity to effectively eliminate both sulfur dioxide (SO2) and nitrogen oxides (NOX) concurrently [16]. Particulate matter can be effectively eliminated through the utilization of wet scrubbers, which operate by entrapping these particles within liquid droplets. Thermal incinerators are applied to remove VOCs. The VOCs or HAPs are oxidized by heating them to a precise temperature in a thermal oxidizer. The process of oxidation converts harmful contaminants into carbon dioxide and water. Thermal oxidizers are ideal for applications with particulates and a high concentration of volatile organic compounds.

Selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) can be applied to reduce the NOx. SCR is a chemical reaction that occurs in the presence of a catalyst, while SNCR is a process that does not rely on the use of a catalyst. SCR is generally recognized as a more efficient method for reducing NOx emissions. However, it is important to note that SCR systems entail higher costs due to the initial investment and ongoing maintenance required for the catalyst. There exist additional variables that can potentially influence the choice between the two options, including the presence of other constituents in the flue gas that could potentially harm the catalyst, as well as logistical considerations such as the availability of sufficient space for the installation of an SCR reactor. NOx air pollutants also can be mitigated by using technology such as low NOx burner and nonthermal plasma.

The PM is also a component of the emissions generated by the palm oil industry. Prolonged exposure to particulate matter pollution originating from palm oil mills is associated with the development of chronic respiratory diseases, cardiovascular diseases, and increased mortality rates [17]. Particulate matter measuring less than 2.5 μm (PM2.5) exerts a more significant influence compared to particles with a size of 10 μm. There are three distinct technologies available for the containment of particulate matter (PM) particles, namely cyclones, baghouses, and electrostatic precipitators. A cyclone application is proposed for enhanced fine particle separation in palm oil mills, with the specific aim of improving the separation efficiency of PM2.5 particles [17]. Another method to remove PM is the deployment of baghouse. When air passes through a filter medium, such as a bag or cartridge, the particles adhere to the external surface of the filter, allowing the clean gas to pass through. The typical method employed for the removal of accumulated dust on the exterior surface of filters involves the application of a compressed air pulse. An electrostatic precipitator is operated by allowing a stream of dusty air to traverse a precipitator enclosure that is subjected to an electric field, typically established using plates or wires. As the dust particles pass by the charged plates or wires, they undergo a corona effect, resulting in the acquisition of a positive charge. The phenomenon of dust particles with positive charges being drawn towards a collection of negatively charged plates results in the adhesion of the dust particles to the plates. The mechanical component of the apparatus entails striking these plates at consistent intervals, thereby inducing the descent of dust particles into a receptacle.

Other than treating and reducing air pollutants, enhancing the oil extraction rate can be employed as a strategy to mitigate emission pollutants by augmenting the yield of the product. The current status of the palm oil milling process and the factor affecting the rate and improvement methods is discussed in this study [18]. The study suggests that there are two primary methodologies for enhancing milling efficiency which is recovering the residual oils from waste stream or minimizing the oil loss by improving the oil extraction. Solvent extraction has been limited due to the safety and environmental concerns thus, enzyme technology looks promising in improving the oil extraction. Another study has been conducted to identify the benefits and drawbacks of the technology for recovering palm oil [19]. These technologies included static setting, decanter, evaporation and ultrasound splitting. The papers also reviewed the important parameter in testing the quality of palm oil which is free fatty acid (FFA), moisture, impurities content and deterioration of bleachability index (DOBI). The study results also demonstrate that researchers primarily prioritize the examination of FFB grading, heat treatment, extraction, and oil recovery within the context of palm oil milling, as the key unit activities under investigation.

Palm oil mill effluent (POME), the side product from the process is abundant and it will emit more air pollutants if they are not treated correctly**.** The substantial quantity of POME currently poses an environmental hazard, necessitating the implementation of an appropriate treatment process to mitigate its organic potency in compliance with prescribed discharge thresholds before its release into the environment [20]. POME can be treated by using an anaerobic biofilm reactor, composting and biogas production.

The recent improvement in the treatment of POME using anaerobic biofilm reactors is reviewed in a study [20]. The study summarizes that the anaerobic biofilm system has the ability to create high-quality effluent in compliance with the standard discharge constraint and allow the generation of the biogas which is a value-added product. However, the system may have a clogging issue at the biofilm and require further optimization towards the zeros waste concept.

The implementation of biogas capture and utilization serves as a viable and effective approach to enhance the sustainability and economic viability of palm oil mills through the adoption of cleaner production practices. The potential of capturing the biogas emitted from the palm oil mills in Malaysia is evaluated [21]. The study reveals that a potential reduction of approximately 75% in GHG emissions could be attained for each metric ton of crude palm oil produced from a palm oil mill that incorporates biogas capture technology. Annually, the capture of biogas from all palm oil mills in Malaysia has the potential to yield a total of 1750 million cubic meters, resulting in greenhouse gas savings of approximately 19.5 million metric tons of carbon dioxide equivalent. The technical, economic, and environmental dimensions of biogas power generation derived from POME at the designated research location in Bangka are evaluated [22]. The findings indicate that the biogas facility located at the designated research site can effectively decrease COD levels in POME by as much as 91%. Additionally, this plant has the capability to generate a monthly biogas output of 325,292 m3, consisting of approximately 55% methane content. The results also suggested buying POME from other sites to ensure there is no insufficient POME for the process as a low amount of POME will reduce the profit of the process.

The emission mitigation has been discussed and they all can help to mitigate the pollutant but they may increase the cost dramatically at the same time. The monitoring and optimization of emissions from industrial areas necessitate a careful balance between the pollutants being emitted and the associated costs of implementing mitigation equipment. Several models have been created to decrease costs to meet emission target requirements.

A mathematical optimization model is presented to ascertain the most optimal pathway for achieving circularity in the utilization of palm-based biomass, specifically palm oil mill effluent (POME) and refinery wastes, in conjunction with other sectors [23]. The results of the multi-objective analysis indicate a potential economic output of USD 151.36 million, net CO2 emissions of 804,946.60 tCO2, and landfill waste reduction of 80.17%. In scenario cases where carbon emission is prioritized, the findings indicate a net CO2 emission of 825,478.10 t. It is significant to note that the optimized pathway transports the least amount of biomass and waste and uses the least amount of energy for processing. The model, however, places more emphasis on the process pathway that will help choose the final product than it does on the pathway for emission mitigation technology. The model only focuses on carbon emissions but not all air pollutants.

The study attempt included the formulation of a mathematical framework to ascertain the most efficient course of action for the POME process [24]. This model was constructed using a mixed integer programming approach and subsequently solved utilizing the General Algebraic Modeling System. According to the model, the optimal pathway would yield a payback period of 6 years, accompanied by a total capital investment cost amounting to USD 2,934,564. This model successfully identified the pathway for purifying the biogas but not the whole palm oil process treatment. The model also does not include carbon emission or other air pollutant as the constraint.

The techno-economic viability of the sustainable circular economy is determined through the development of a mathematical model that illustrates the biomass network, taking into account the recycling process [25]. The model has considered various technologies involved in the palm oil process, including pelletizing, briquetting, fermentation, fiber making, and other relevant techniques. The findings indicate that the linear economy model is more profitable, however, the circular economy model exhibits promise in reducing 39.292% of imported steam and 13.469% of imported electricity. Additionally, the circular economy model demonstrates a slight decrease of 0.642% in gross profit compared to the linear economy model. The primary objective of the model is to prioritize the establishment of a sustainable circular economy, with less emphasis placed on addressing air pollutant emissions. The model does not include the emission as a constraint or a parameter.

There is a study conducted to create a comprehensive optimization model for the synthesis of a sustainable production system of bio-CH4 from POME, with a focus on economic and environmental performance [26]. Given the inherent conflicts between the aforementioned considerations, the optimization model employs a multiple-objective optimization approach, specifically a fuzzy optimization approach, to effectively balance and resolve these objectives.

The environmental consequences of RSPO-certified and non-certified palm oil production are assessed by conducting a comprehensive Life Cycle Assessment (LCA) on 1 kg of RBD palm oil up to the factory gate [27]. The analysis focuses on palm oil produced in Indonesia and Malaysia in the year 2016, intending to identify the potential advantages and disadvantages associated with RSPO certification. The Life Cycle Assessment (LCA) that adheres to ISO 14040/14044 standards encompasses both a consequential and an attributional LCA methodology. The model carries out a detailed life cycle assessment but does not evaluate the technology to reduce greenhouse gas emissions.

The pathway development of the energy sector will not only economic growth but also environmental issues [28]. The examination of the equilibrium between traditional energy sources and alternative energy sources has been a subject of scholarly investigation. The present study examines the association among CO2 emissions, economic growth, alternative energy sources, and institutional quality in the context of E7 nations [29]. The investigation uses the environmental Kuznets curve as a theoretical framework to analyze this relationship between the energy sources and the economic perspective. The findings indicate that policymakers must strengthen their dedication to environmental quality, particularly in relation to promoting sustainable growth and transitioning from fossil fuel reliance to cleaner energy alternatives. Table 1 summarizes the description of each model and its research gaps. However, achieving an appropriate mitigation strategy is indeed a complex task, as it involves balancing economic, social, and environmental concerns. The implementation of mitigation strategies and the adoption of sustainable planning practices are of utmost importance in order to effectively reduce the adverse effects of industrial production on the environment [30]. An integrated sustainability index and carbon accounting framework are necessary for making accurate decisions on mitigation steps in the palm oil industry [31]. This approach can provide a comprehensive overview of the industry's environmental impact and identify areas where emissions can be reduced. A number of mitigation model assessments in palm oil areas have been performed as shown in Table 1 [32–34]. Nevertheless, the literature shows a lack of an integrated mitigation model developed between sustainability and carbon footprint assessment. There are several studies which are only focusing on the environmental aspect and not sustainability as a whole [35,36]. An extensive study integrating a mitigation model with sustainability and carbon assessment in palm oil mills was conducted [37]. However, there remains a lack of a clear comparative analysis regarding the relationship between the suggested mitigation model and the improvement of sustainability and carbon assessment in the context of palm oil mills. The model from this study only focuses on evaluating the techno-economic viability of biomass networks considering the recycling process but does not involve the emission of pollutants [25]. The model is able to determine the best end product and determine their life cycle emission but the model does not look into the process selection [23]. These models included certain processes from the palm oil mill to evaluate their pollution emission and economic perspective but did not include the raw material until the end product [24,26]. In the study, a detailed life-cycle emission assessment is carried out and identifies the emission source, but the model is not designed to optimize the pollutant emission.

From the review, it can be pointed out that the existing mitigation planning in the palm oil industry is still not comprehensive and mostly relies only on one of the aspects either sustainability or carbon footprint, rather than addressing both aspects. This highlights the need for further research and development to improve the accuracy and efficiency of mitigation planning in the industry. This includes the utilization of optimization models for the calculation and monitoring of carbon emissions and sustainability performance. The novelty of this study lies in the development of a comprehensive integrated mitigation model with the capability to simultaneously optimize overall sustainability performance and ensure that emissions remain within an acceptable range. This integrated model can be a valuable tool for decision-making related to mitigation plans by considering both sustainability and carbon emissions aspects. It brings together various factors and data to provide a comprehensive understanding of the potential impact of different actions and strategies allowing for more informed and effective decisions to be made. Therefore, this paper aims to develop an Integrated Mitigation Strategy Model that incorporates the Carbon Accounting and Sustainability Index as a key tool to achieve Net Zero Emissions targets in a specific study case which is the palm oil industry.

***Table 1**
review of current mitigation strategy model for sustainability and carbon Emission.

Author	Description	Research gap	Application
[23]	To determine the best strategy to achieve circularity in palm-based biomass use, including POME and refinery wastes, in cooperation with other industries.	Not including all air pollutants. Rely on end product selection rather than technology throughout the process.	Palm oil Industry
[24]	To determine the optimal pathway for handling the POME	Focus only on the biogas from the POME and not the palm oil process.	Palm oil Industry
[25]	To evaluate the techno-economic viability of biomass network considering the recycling process	Do not include the emission constraint and focus only on the economy perspective	Palm oil Industry
[26]	To optimize the process of biomethane from the POME and study its economic and environmental performance	Limited to only the biogas and emission	Palm oil Industry
[27]	Conduct a Life Cycle Assessment to evaluate the environmental impact of RSPO-certified and non-certified palm oil production.	Detail life-cycle emission assessment is carried out but the process pathway is not optimized.	Palm oil Industry
[29]	Evaluate the balance between environmental and economic growth by using environmental	The study focuses only on CO_2 emission but not other air pollutants and no optimization has occurred.	Industry field
[32]	Contribution to supplier selection and demand allocation by analyzing different sustainable procurement strategies using mathematical modeling	Carbon assessment is not been included or integrated with the sustainability parameter	Procurement
[33]	Development of sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework	Carbon Footprint assessment and mitigation strategy are not included in the framework.	Palm Oil industry
[34]	To develop an Integrated Carbon Accounting and Mitigation Framework for Greening the Industry	Sustainability assessment not included Mitigation selection is limited	Nickel electroplating industry
[35]	Environmental impact assessment of palm oil produced in Thailand	Assessment limited to the environmental impact of palm oil production	Palm Oil Industry
[36]	Developed a new systematic tool known as the Green Industrial Performance Scorecard (GIPS) to assess the green level of the palm oil industry.	Applicable to assessed environmental aspect only Weightage is not included A mitigation strategy is not included	Palm oil industry
[38]	A sustainability performance assessment framework for palm oil mills	The carbon footprint assessment and mitigation strategy model is not included in the framework	Palm Oil Industry
[39]	To develop a Sustainability Assessment Framework in the Hydropower sector using a mathematical model	The mathematical model is developed to quantify the key performance of sustainability. However, no carbon emission assessment and mitigation strategy was included in the study.	Hydropower sector
[40]	A holistic low-carbon city indicator framework for sustainable development	Focused on carbon assessment The best achievement was taken as a benchmark, without any reference to standards/regulations/policies Using the entropy method to calculate the weightage. The economic aspect is not taken into consideration No mitigation strategy included	Low carbon city
[41]	Mathematical Modelling of Sustainable Procurement Strategies: Three Case Studies	Development of Mathematical Modelling for Sustainable Procurement Strategies. However, carbon emission assessment has not been included in the model parameter.	Procurement
[42]	To reconsider environmental sustainability in the business model of industrial manufacturing	Lack of quantification of environmental assessment	Industrial manufacturing
[43]	To integrate quantitative material input and semi-quantitative decisions on environmental weaknesses in the single-serve coffee value chain	Assessment is limited to environmental performance and does not include sustainability as a whole	Coffee value chain
[44]	Discussion on advantages, challenges, and the implications of additive manufacturing on sustainability in terms of the sources of innovation, business models, and the configuration of value chains.	A qualitative assessment of the additive manufacturing sustainability. Mitigation is not a strategy included.	Additive manufacturing
[45]	Life cycle assessment framework for the environmental evaluation and decision-making of automobile paint shops	Assessment limited to environmental performance and mitigation strategy is not been included	Automobile paint shops
[46]	Sustainability Index for the Automotive Industry	Policies or regulations are not put into calculation thus no statistical value to compare with regulations. Mitigation strategy and carbon footprint assessment are not included.	Automotive Industry
[47]	Developed an integrated sustainability index for small-holder dairy farms in Rajasthan, India	Policies or regulations are not put into calculation thus no statistical value to compare with regulations A mitigation strategy is not included	Dairy farm
[48]	Developed an Environment Performance Index for the state level in Malaysia	Assessment limited to environmental performance A mitigation strategy is not included	State/Country
[49]	Selection and identification of the indicators for quickly measuring sustainability in micro and small furniture industries	Weightage is not included	Furniture Industry
[50]	Developed a Sustainability Assessment Model (SAM) to bring all the sustainability aspects into a single method for the automobile industry	Weightage is not included	Automobile

2. Methodology

This section presents the methodology which has been divided into 5 main parts. Part 1 presents the development of POMCFA and focuses on quantifying and reporting the carbon emissions of the mill. Part 2 and Part 4 shows the POMCFA and POMSI analysis conducted to export finding (weaknesses) which will be integrated into Part 5. Part 3 presents the development of POMSI focuses on quantifying and reporting sustainability performance towards the national guidelines. In this paper only a brief explanation of Part 1 – Part 4 is introduced, the details value of this part can be referred to the previous work as in the previous article [31,38]. In this study, the focus is to establish the integration of mitigation strategy planning with previous work of POMCFA and POMSI as described in Part 5. Fig. 1 shows the methodology flowchart for this study.

2.1. Part 1: development of Palm Oil Mill Carbon Footprint and accounting (POMCFA) integrated with sustainability index

Step 1. Plant Familiarisation

POMCFA was developed to provide a quantitative and effective approach for presenting the complex sustainability data of a palm oil mill. It is meant to inform related agencies as well as the public on the status of the sustainability practice of mills. Palm oil mill operation is analyzed to identify the mill component, system, and operational data before the selection of relevant indicators.

Step 2. Identify the indicator and parameter of the carbon source

POMCFA aims to assess the emission of palm oil mills using an index score. It consists of three assessment layers, which are indicator, parameter, and aspect. The indicators are selected based on relevance, performance orientation, transparency, data quality, data sustainability, and data custodian [48]. In this study, the selection of indicators is based on current carbon reporting such as MYCarbon. The final decision is taken through a series of engagements with subject experts of palm oil mills, subject to data availability. Every parameter and indicator unit is based on per 1 MT fresh fruit bunch (FFB) production. The emission result of POMCFA is also based on this unit. This is in parallel with the statement by Klaarenbeeksingel that emissions related to operations at the plantation and the mill are generally applied on a per tonne CPO or FFB basis.

Step 3. Carbon Mapping

In this next step, with the establishment of the POMCFA database, carbon mapping is conducted to identify carbon emission sources by each stream and operation unit.

Step 4. Collecting monthly consumption or generation of data for each mapped stream

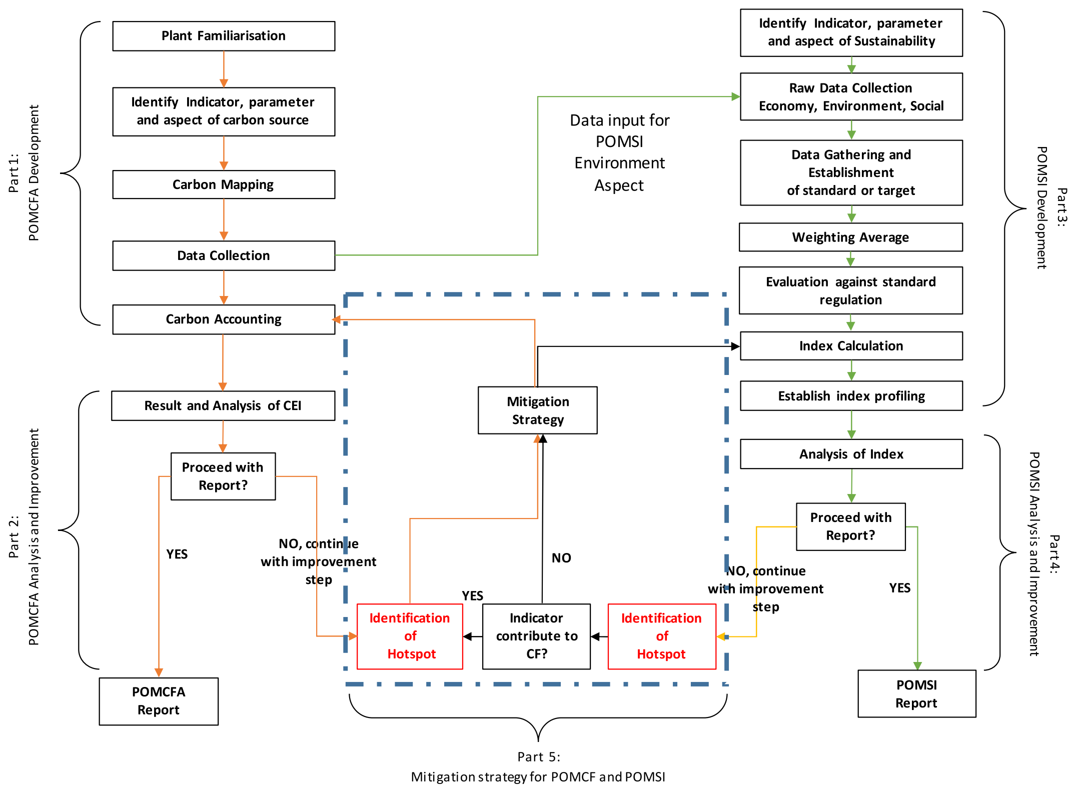

Fig. 1. Overall methodology.

Based on the mapping, the monthly consumption or generation of parameters will be identified for each parameter. The indicator for each stream is also determined. Importantly, the data will also be used as input into the POMSI environment. This will reduce the process of entering data and any redundancy can be avoided.

Step 5. Carbon Emission Accounting

In this step, the emission factor must first be determined. Based on the carbon parameter, the emission factor will be obtained from related carbon reporting authorities such as MYCarbon, IPCC, etc. In this study, an aggregate factor for multiple gases is provided in kg or t of CO_2 equivalent (CO_2e) emissions referred to as $EFCO_2e$. The emission factor unit was also revised so it would be standardized with the carbon footprint parameter unit for the purpose of comparing orders of magnitude. Next, emission calculation is conducted by multiplying the emission factor ($EFCO_2e$) with the monthly consumption or generation (D) indicator to quantify the amount of CO_2e emitted for each indicator (tCO_2e). Then, the value is summed up by indicator (tCO_2e_i), parameter (tCO_2e_p), operation unit (tCO_2e_{uo}), or stream (tCO_2e_s). The details equation of this step can be referred to in Appendix 1. The emission is then analyzed by carbon emission profile (%). The result was analyzed based on indicator, parameter, operation unit, and stream. To calculate the carbon emission profile (%) for the indicator, the tCO_2e of each indicator was divided by $otCO_2e$ and multiplied by 100. To calculate the carbon emission profile (%) for the parameter, the total CO_2e (tCO_2e) of each parameter was divided by the overall total CO_2e ($otCO_2e$) and multiplied by 100. Similarly, to calculate the carbon emission profile for stream and unit operation, the tCO_2e of each was divided by $otCO_2e$ and multiplied by 100. Appendix 1 shows the equation used to calculate the carbon emission profile, which applies to all variables (indicator, parameter, operation unit, and stream).

2.2. Part 2: Palm Oil Mill Carbon Footprint analysis and improvement

Step 6. Carbon Emission Profile Result and Analysis

Based on the calculation, the carbon emission profile (%) is developed to assess the carbon emission level. The result was analyzed based on indicator, parameter, stream, and operation unit. The result will also be analyzed together with the POMSI result to formulate further improvement strategies.

Step 7. Report generation

A report is generated as the assessment result for documentation, database, etc.

Step 8. Identifying Hotspot

Based on the result and analysis, the hotspot (the part contributing to the most carbon) will be identified and appropriate improvements proposed. The carbon emission score is recalculated to simulate the feasibility of improvements and to show the significance of carbon reduction after the application of the improvements. Once the selected improvement has been chosen, an improvement report will be generated based on the latest calculation. However, if the user does not accept the improvements, the user can opt to use the original report. This option is illustrated in the flowchart of Fig. 2.

2.3. Part 3: development of the Palm Oil Mill Sustainability Index (POMSI)

The development of a sustainability index for palm oil mills requires ten steps: 1) identifying the indicator, parameter, and aspect of palm oil mill sustainability; 2) raw data collection; 3) data gathering and establishment of target; 4) determination of weighting average of the parameter; 5) evaluation against standard regulation; and 6) index calculation. Steps 7–10 are outlined in Section 2.4 below.

2.4. Part 4: Palm Oil Mill Sustainability Index analysis and improvement

In this part, the steps continue from: 7) establish index profiling, 8) analysis of index, 9) report generation, and 10) identification of hotspots. Based on the sustainability index profile and analysis, areas of weaknesses (hotspots) are identified and improvements to the hotspots are proposed. The sustainability performance score will be recalculated to evaluate the effectiveness of the proposed improvement. However, this assessment is not comprehensive enough, as it lacks a carbon emission analysis and carbon accounting. Therefore, integration of POMCFA and POMSI is needed for a more holistic assessment.

2.5. Part 5: integrated mitigation strategy selection model for POMCFA and POMSI

This section presents the integration of a mitigation strategy selection tool with the Palm Oil Mill Carbon Footprint (POMCFA) and Palm Oil Mill Sustainability Index (POMSI) assessment. It provides an overview of the development of the mitigation strategy selection model for POMCFA and POMSI. The study considers a set of mitigation strategies that can potentially be implemented to improve the weak indicators identified from the assessments of POMCFA and POMSI. A superstructure was developed that features several mitigation options to improve the indicators. The next step of the mitigation strategy selection focused on data gathering from the existing POMCFA and POMSI databases, particularly data retrieved from recent studies on factor changes to the mitigation options. Later, the mathematical models to develop the mitigation strategy selection model for POMCFA and POMSI were formulated. The mathematical models were formulated according to the superstructure coded into GAMS and then verified using the case studies. Then, the selected mitigation options were used to simulate a new score for POMCFA and POMSI. This model, presented in Fig. 2, shows the methodology framework.

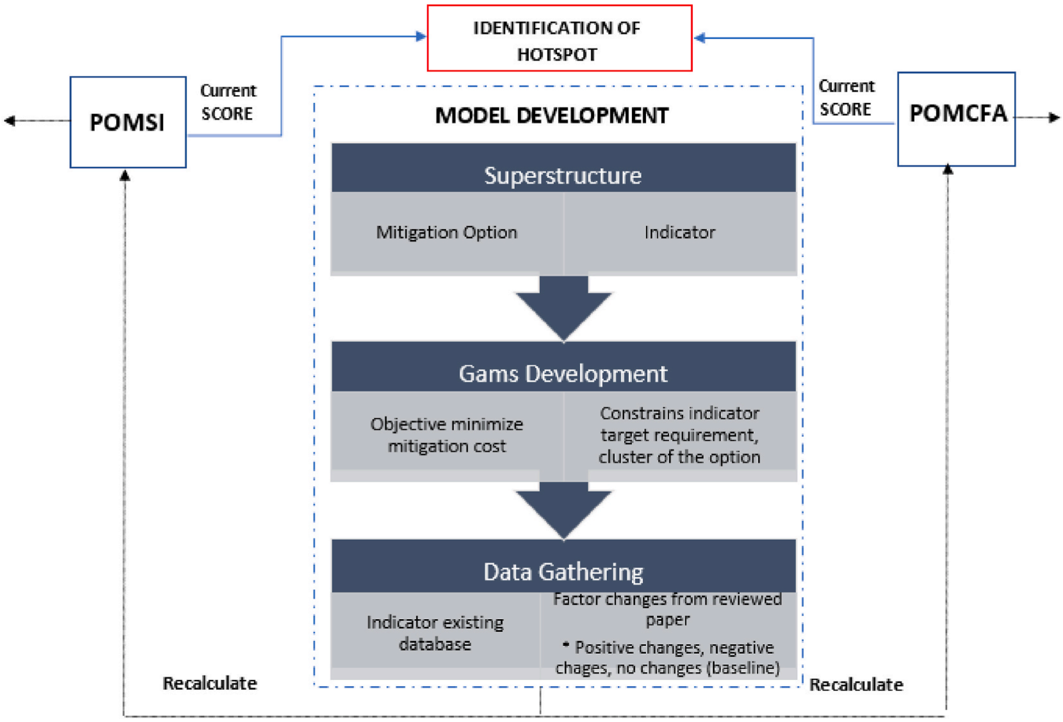

Fig. 2. Integrated mitigation strategy selection model framework.

2.5.1. Identification of integrated hotspot for POMCFA and POMSI

Based on the result and analysis, the hotspot (the part or section in the process contributing to the most GHG emission) was identified and appropriate improvements were proposed. The GHG emissions score was recalculated to simulate the feasibility of improvements and to show the significance of GHG emissions reduction after the application of the improvements. Once the selected improvement was chosen, an improvement report was generated based on the latest calculations. Even so, this step can only consider GHG emission reduction strategies and neglects some aspects such as the economic aspect. Moreover, sustainability is not portrayed as a whole. A more holistic integration method is discussed in Part 5 of Section 2.5.

2.5.2. Model development

2.5.2.1. Superstructure for model development. Fig. 3 presents a sustainability indicator considering a set of mitigation options that can potentially be implemented in the palm oil mill. As shown in Fig. 3, the superstructure is constructed to show the relationship between the mitigation option, m, to the mill indicator, n. The mitigation options are generally the possible choices, improvements, technology, or alternatives to improve the weak indicators.

2.5.2.2. Mathematical equations.

i. Objective Function

The optimization model was formulated with an objective function and several constraints. The objective aims to select the mitigations with minimum overall cost (COST) as described by Equation (1). The function C_m, is the cost of mitigation options selected to upgrade the palm oil mill process. Cost considered for C_m are the investment cost (IC), the production cost (PC), and the variable cost (VC) as shown in Equation (2). The values of the options were determined by reviewing various literature works on palm oil mill mitigation planning, which was then converted into factor changes, as explained in Table 2. On the other hand, X_m is both the binary variable and decision variable for this model.

$$Min\ COST = \sum C_{(m)} \times X_{(m)} \tag{1}$$

$$\sum C_m = IC_m + PC_m + VC_m \tag{2}$$

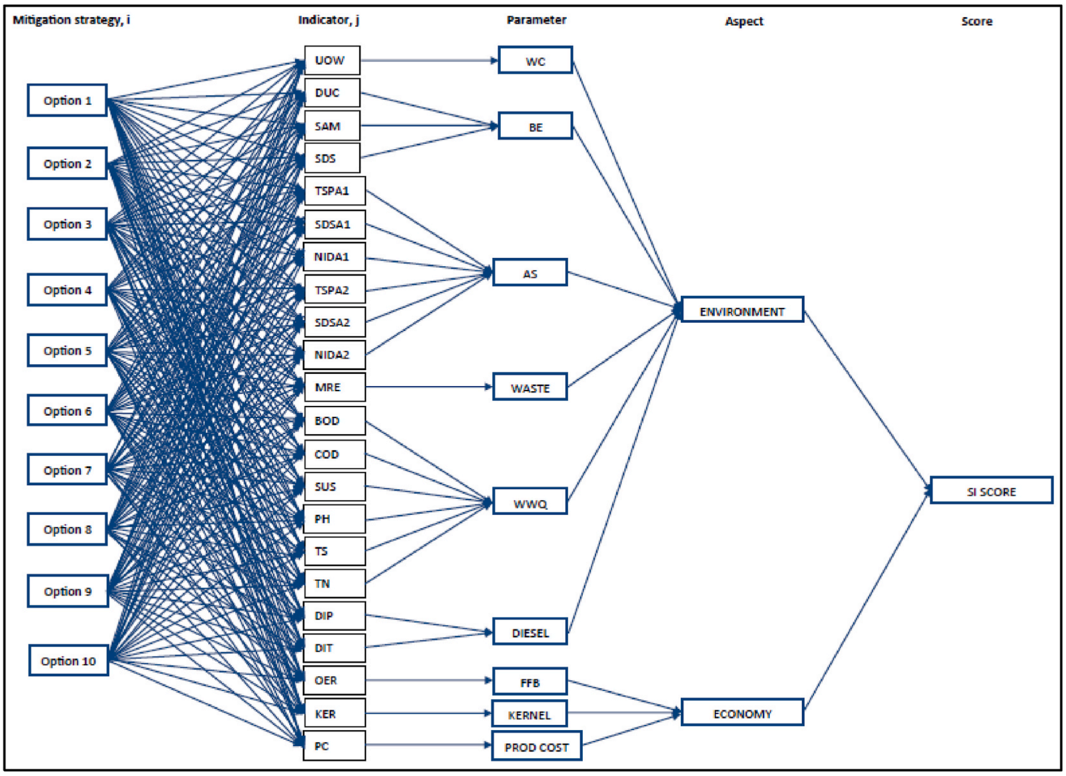

Fig. 3. General model superstructure.

ii. Constraint

To define the relationship between the variable and parameters in this model, several constraints were developed, as explained below.

(a) Indicator requirement.

F_{mn} is the factor changes of the mitigation option, m, to the indicator, n. Meanwhile, W_n is the weightage of the indicator, n, and X_m is a binary variable for the mitigation options. The selection of mitigation option, m, must fulfill the requirement set, Y_n by each indicator, as described by Equation (3).

$$\sum_j F_{mn} \text{ x } X_m \text{ x } W_n \geq Y_n \tag{3}$$

The target increment of each indicator can be manipulated based on necessity or requirement. Y_n is the factor of the target increment required by each indicator for the benchmark to be met. The target was translated into the target indicator factor (Y_j) using Equation (4).

$$Y_n = \frac{target\ increment\ (\%)\ x\ \ W_n}{100} \tag{4}$$

(b) Technology Cluster

Table 2
FC selection.

	No Changes	Reduce	Increase
Emission	–	Positive FC of indicator	Negative FC of indicator
Consumption	–	Positive FC of indicator	Negative FC of indicator
Yield	–	Negative FC of indicator	Positive FC of indicator

Some of the mitigation options, m can be clustered, as they could belong to one group of technology. For example, any alternatives of empty fruit bunches waste treatment is belong to one group or any options of palm oil mill effluent treatment technology also categorized into one group, etc. In this case, only one technology could be selected at one time, as described in Equation (5).

$$\sum_{m} X_m = 1 \tag{5}$$

(c) Data Gathering

The mitigation options, m were determined by reviewing various works on palm oil mill mitigation planning, listed in Appendix F. The mitigation options, which affected the changes in the indicator, were taken as input data and referred to as Factor Changes (FC). However, the FC varies according to terms of units and bases. Thus, standardization of FC was done, as explained below:

Heuristics of Factor Changes.

(d) If the mitigation option makes no changes to the indicator, the factor changes (FC) of the indicator are denoted as null.
(e) If the mitigation option leads to positive changes to the indicator, for example, reduces emission, increases profit, etc., the equation of the FC of an indicator is represented by Equation (6).
(f) If the mitigation option makes negative changes to the indicator, for example, increasing emissions, reducing profit, increasing, cost, etc., the FC indicator is calculated using Equation (7).

$$\text{Positive FC of indicator} = +\frac{\%\text{ of FC}}{100} \tag{6}$$

$$\text{Negative FC of indicator} = -\frac{\%\text{ of FC}}{100} \tag{7}$$

Indicators affected by the mitigation action, however, can be grouped into 3, namely emission, consumption, and yield. The choices of FC can be summarised in Table 2.

2.5.3. Recalculation score of POMCFA and POMSI assessment score

The results of the mathematical models coded into GAMS were used to recalculate a new score for POMCFA and POMSI. Hence, a new score for simulated efficacy and the potential for implementation of the new mitigation options was obtained. This result provides tremendous help to the industry to see a bigger and clearer picture of the initiatives planned to be undertaken.

3. Case study and input data

3.1. Introduction

This section considers a solution to improve the performance of POMCFA and POMSI using the mitigation strategy model. The model suggests the optimal selection to fix the identified hotspot. This case study is an extension of the first case study presented [31]. It adds the selection of the mitigation strategy for the identified hotspot for both assessments. However, this case study only focuses on mill C. Mill C was chosen because it has the lowest performance compared to the other mills, which allows for a clearer case study.

Firstly, the integrated hotspot required for improvements based on the POMCFA and POMSI assessment is identified. Then, a model is developed as a mitigation strategy selection tool to decide optimal mitigation alternatives. The model is formulated as a Mixed Integer Linear Programme (MILP) and implemented in a General Algebraic Modelling System (GAMS). MILP is chosen for its known speedy conversion and being a worldwide optimum well-defined solution approach [51]. On the other hand, GAMS has the ability to note down index equations in pressed form that can produce multiple single equations [52]. In this case study, the optimal selection was analyzed based on several requirements: (1) target indicator improvement, (2) technology cluster, and (3) number of selections. Then, the POMCFA and POMSI were recalculated based on the designated scenario to project a new score based on the improvements.

3.2. Identification of an integrated hotspot for POMCFA and POMSI

In an earlier method, a framework to assess the performance of the palm oil mill was developed. Based on the previous results of POMCFA and POMSI, it can be concluded that several indicators require attention (hotspot). It is apparent from the result of POMCFA that Mill C had the highest CO_2e emissions compared to other mills. The findings of POMCFA are consistent with the findings of the POMSI assessment. Based on the POMSI assessment, most of the mills had one to no severe issues in current practice except for Mill C, which had several major issues. Besides, Mill C was also identified as the poorest-ranking one. Thus, in this case study, the focus of the mitigation strategy is on Mill C.

Several mutual hotspots were identified from the POMCFA and POMSI assessments, which are DUC, SDS, MRE, DP, and EG. The other related hotspots are COD and cTC. Fig. 4 shows the highlighted hotspots of POMCFA and POMSI for further integrated mitigation analysis. The performance of Mill C shows that despite the low emission profile of DUC and SDS according to POMCFA, the comparison analysis of POMCFA and POMSI indicates that the DUC and SDS performance was the poorest of all other mills.

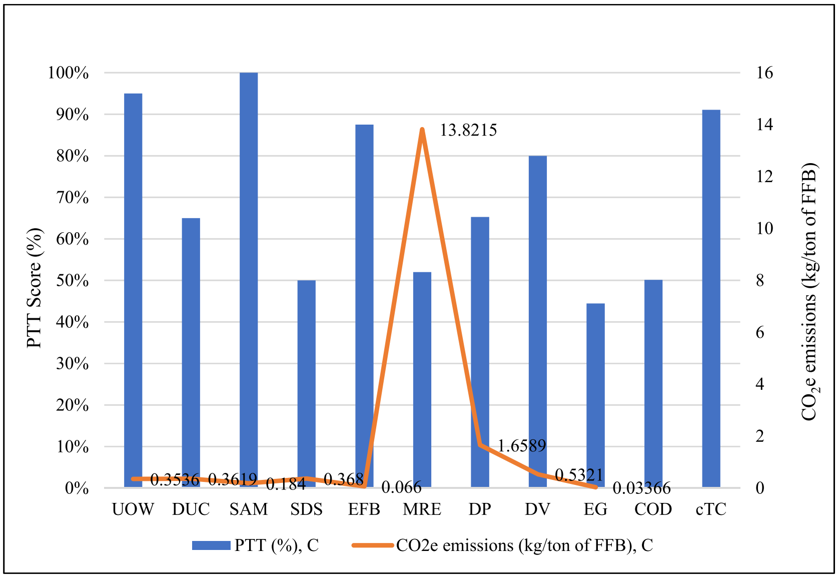

Fig. 4. Integrated result of POMCFA and POMSI of mill C.

It can also be seen that Mill C's emission profile for the MRE indicator dominated the emissions in the POMCFA assessment. A correlation was found in the POMSI assessment where the MRE and COD only scored 52% and 50.14%, respectively. The other indicators that achieved a below-average score were DP and EG, with 65.28% and 44.44%, respectively. From the economic aspect, the parameter of total cost, cTC is 91.07% for current performance. The changes in cTC can be shown after the mitigation strategy has been implemented.

Based on the findings, indicator requirements and technology clustering are identified as the input for the constraints. Here, this model aims to select optimal mitigation options based on the hotspot to decide on better alternatives. The mitigation strategy selection tool model uses GAMS as a solver.

3.3. Model development

3.3.1. Superstructure

A superstructure was developed to illustrate the possible mitigation strategy to improve the weak indicator based on the POMCFA and POMSI findings, as shown in Fig. 5. This study presents a sustainability indicator after considering a set of mitigation options that can potentially be implemented in the palm oil mill. Each mitigation strategy, m, has different impacts on the indicators. A total of 22 options for mitigation strategy have been selected in this study as presented in Table 3. To obtain the optimal solution, a series of constraints was curated based on the hotspot identified in the previous assessment. The list of the mitigation strategy, m options, is given in Table 3.

3.3.2. Mathematical equations

3.3.2.1. Objective functions and constraints. In this optimization problem, the objective function was derived to select the minimal cost incurred by the mitigation strategy as shown in Equation (1). The cost considered in Equation (2) includes the investment cost, the production cost, and the variable cost for implementing the mitigation strategy can be referred to in Appendix 2. To define the relationship between the variables and parameters in this model, several constraints were developed as follows.

(g) Target indicator improvement:

In this case study, the target indicator improvement by industry for SDS and PM was assumed to improve by 10% by applying Equation (4). Some parameters may be considered more responsive to changes in the interest aspect and therefore deserve greater weightage (W_n). However, for this case study, it was assumed that all the parameters bear the same weightage; thus 0.09 was set as the W_n value. The target indicator factor (Y_n) was determined using Equation (4) below:

$$Y_n = \frac{target\ increment\ (\%)\ x\ \ W_n}{100}$$

$$Y_n = \frac{10\%\ X\ 0.09}{100}$$

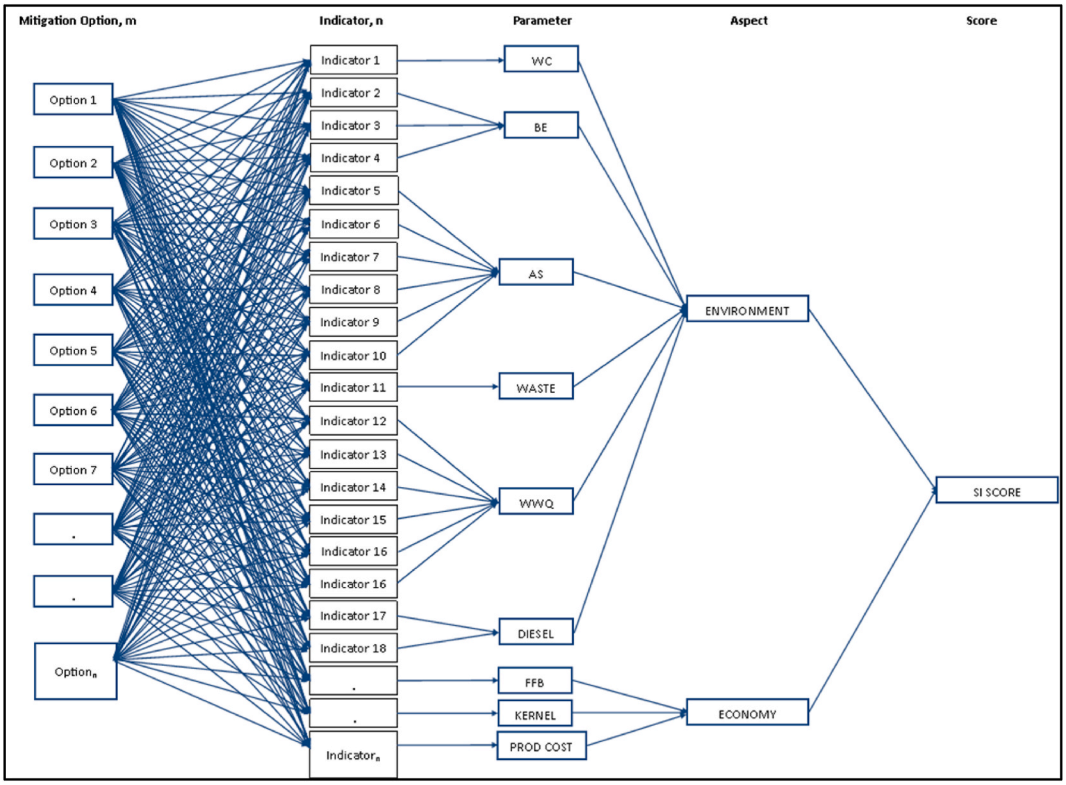

Fig. 5. Superstructure of mitigation strategies for the indicator.

Table 3
Full list of the mitigation strategy, m.

Option	Mitigation Strategy, m	Option	Mitigation Strategy, m
1	EFB combustion	12	Oil recovery from the fiber
2	EFB pellets production	13	Oil recovery from EFB
3	EFB composting plant	14	Oil recovery from POME
4	Ethanol production	15	Cyclones
5	Pellets production	16	Baghouse
6	Composting plant	17	Electrostatic precipitator
7	Selective catalytic reduction	18	Biogas plant
8	Selective noncatalytic reduction	19	Biogas plant upgrading with bioreactor
9	Low NOx burner	20	Pre-heating fiber
10	Nonthermal plasma	21	Wet scrubber
11	Oil recovery from decanter	22	Thermal incinerator

$$Y_n = 0.009$$

However, if more significant improvement is required such as a 50% target increment for CH_4, EG and DP, Equation (2) is modified to get a new target indicator factor (Y_n):

$$Y_n = \frac{50\ \%\ x\ \ 0.09}{100}$$

$$Y_n = 0.045$$

Based on the requirement listed above, the target indicator factor ($\boldsymbol{Y_n}$) can be found in Table 4.

(h) Cluster

The mitigation strategy, m, is classified into seven groups, as listed in Table 5. The cluster has been coded into GAMS by using Equation (5).

All this data was then inserted into GAMS. More details on the GAMS coding are provided in Appendix 3.

Table 4
Summary of target indicator factor (Y_n) for mill C.

Indicator, n	Target indicator Factor (Y_n)
CH_4	*0.045*
SDS	*0.009*
PM	*0.009*
EG	*0.045*
DP	*0.045*

Table 5
Mitigation strategy cluster.

No.	Mitigation Strategy, m	Treatment area
1	EFB combustion	EFB treatment
2	EFB pellets production	
3	EFB composting plant	
4	Ethanol production	
5	Pellets production	
6	Composting plant	
7	Selective catalytic reduction	NO_x control for fiber combustion
8	Selective noncatalytic reduction	
9	Low NOx burner	
10	Nonthermal plasma	
11	Oil recovery from decanter	Oil extraction improvement
12	Oil recovery from the fiber	
13	Oil recovery from EFB	
14	Oil recovery from POME	
15	Cyclones	PM control for fiber combustion
16	Baghouse	
17	Electrostatic precipitator	
18	Biogas plant	POME treatment
19	Biogas plant upgrading with bioreactor	
20	Pre-heating fiber	Pre-heating fiber
21	Wet scrubber	S_2O control for fiber combustion
22	Thermal incinerator	VOC control for fiber combustion

3.3.2.2. Data for factor changes. Based on Fig. 1, Option 1 promotes the implementation of a biogas plant as the mitigation strategy. Based on a review by (Kaewmai et al., 2013), by implementing this option, COD and EG will be reduced by 50%. The remaining indicators will show no changes as a result of this action, where 1 denotes the factor of the indicator.

The mitigation option led to positive changes to COD and EG; thus Equation (6) was applied as follows:

$$\text{Positive factor of indicator} = +\frac{50}{100}$$

$$\text{Positive factor of indicator} = +0.50$$

For Option 3, the EFB combustion implementation will increase the COD emissions by 0.5%, indicating negative changes to the indicator, thus Equation (7) was applied instead as follows:

$$\text{Negativefactorofindicator} = -\frac{0.5}{100}$$

$$\text{Negativefactorofindicator} = -0.005$$

In total, 22 options were considered for the mitigation strategy in this case study. The types of indicators related to the mitigation strategy, factor changes, F_{ij} including the input for each mitigation strategy in terms of cost analysis, are listed in Appendix F. All this data was then inserted into GAMS. More details on GAMS coding are provided in Appendix G.

4. Results and discussion

In this section, the modeling and optimization results generated for the hotspot of Mill C are presented and discussed. The data is input to the MILP model for mitigation and optimized using the GAMS software.

The modeling and optimization results in Table 6 show the optimal mitigation strategy with minimal cost for Mill C, namely biogas plant development and wet scrubber. The results show that the optimal mitigation strategy is to develop a biogas plant matching the findings in the study [20–22] and implement a wet scrubber to the boiler proving what is stated in Ref. [16]. Next, the information on the selected mitigation is used to recalculate the POMSI and POMCF score and the scenario of post-implementation is demonstrated.

Table 6
Output of the mitigation selection model.

Mitigation strategy, m		Mill C
1	EFB combustion	
2	EFB pellets production	
3	EFB composting plant	
4	Ethanol production	
5	Pellets production	
6	Composting plant	
7	Selective catalytic reduction	
8	Selective noncatalytic reduction	
9	Low NOx burner	
10	Nonthermal plasma	
11	Oil recovery from decanter	
12	Oil recovery from the fiber	
13	Oil recovery from EFB	
14	Oil recovery from POME	
15	Cyclones	
16	Baghouse	
17	Electrostatic precipitator	
18	Biogas plant	✓
19	Biogas plant upgrading with bioreactor	
20	Pre-heating fiber	
21	Wet scrubber	✓
22	Thermal incinerator	

4.1. Recalculation of POMCFA and POMSI score

To give the user the flexibility to make a decision, three possible scenarios were considered to analyze the economic impact on the mill, where the POMCFA and POMSI performance in different mitigation scenarios is presented in Table 7. Fig. 6, Fig. 7, and Fig. 8 show the changes in the POMCFA and POMSI performance after the mitigation strategy is implemented.

In Scenario 1, a major reduction from 17.38 to 13.4 kg CO_2e emissions in total emissions, $otCO_2e$ is expected. By implementing biogas capture technology, a decrease in MRE, EG, and DP CO_2e emissions of about 50% is assumed, as shown in Fig. 6. Biogas was used as an alternative plant for electricity and diesel for production and the emission is expected to reduce from 0.034 to 0.017 kg/t of FFB and 1.66 to 0.83 kg/t of FFB for the latter. The biogas technology will also benefit the effluent besides cutting down the amount of CO_2e emissions from 13.82 to 11.32 kg/t of FFB. Another mitigation strategy is to use a wet scrubber, which also causes a reduction in the CO_2e emissions of DUC, SDS, and DP. The previous emissions were reported as 0.36, 0.368 and 13.82 kg CO_2e and are expected to reduce to 0.054, 0.037, and 11.33 kg CO_2e emissions.

This is also supported by the POMSI assessment, where the implementation of these two mitigations caused positive changes in the mill's performance score. The wet scrubber implementation increased the score of DUC and SDS to 100% from only 65% and 50%. By implementing biogas technology, much positive impact on the mill performance was achieved. The score of MRE and COD also increased to 100% since both indicators can be converted to biogas. Biogas would also be a source of energy and converted into electricity, thus it can be an alternative to EG and DP consumption. Hence, this strategy will improve the score of EG and DP from 44% to 65%–77% and 100%, respectively.

However, everything comes with a price; the trade-off of this scenario is the highest cost because two mitigation actions will be implemented. The performance score for the total cost of both mitigation strategies is predicted to reduce to 85.34% from 91.07%, in which the post-mitigation cost will be RM49.02 per tonne of FFB.

Scenario 2 presumes the recovery of the hotspot by only implementing the biogas plant as shown in Fig. 7. This step resulted in substantial emission reduction, namely the MRE emission with a reduction from 13.82 kg/t of FFB to 3.5189 kg/tonne of FFB with post-implementation of the biogas plant. EG CO_2e also showed a 50% reduction from 0.03366 kg/t of FFB to 0.0168 kg/t of FFB. The total CO_2e also reduced from 17.38 to 14.04 kg CO_2e/t of FFB; however, this reduction is slightly lower than Scenario 1. Ideally, by implementing this mitigation strategy, the POMSI score will indicate positive changes in the index performance expected to improve by 5% from the pre-implementation phase to 93.41%. Contrary to expectations, the cost performance was not significantly different between Scenario 1 and Scenario 2, where the performance score of the latter was only 0.001% higher (85.36%), indicating the high cost of the biogas implementation.

Table 7
Mitigation selection scenario.

Scenario	Biogas	Wet Scrubber
1	✓	✓
2	✓	
3		✓

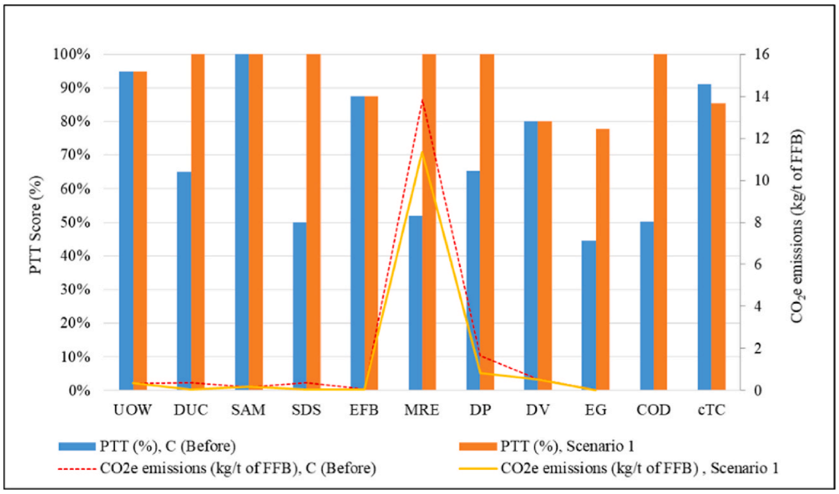

Fig. 6. Scenario 1: Changes in mill C's POMCFA and POMSI performance when both mitigation actions are applied.

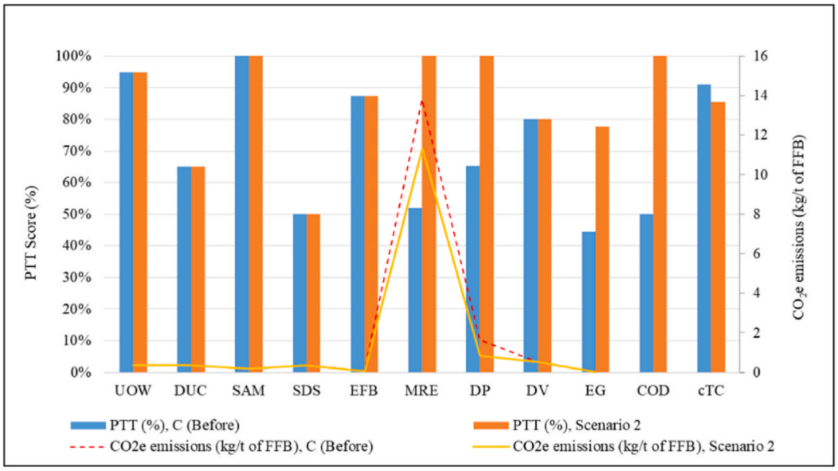

Fig. 7. Scenario 2: Changes in mill C's POMCFA and POMSI performance when biogas mitigation is applied.

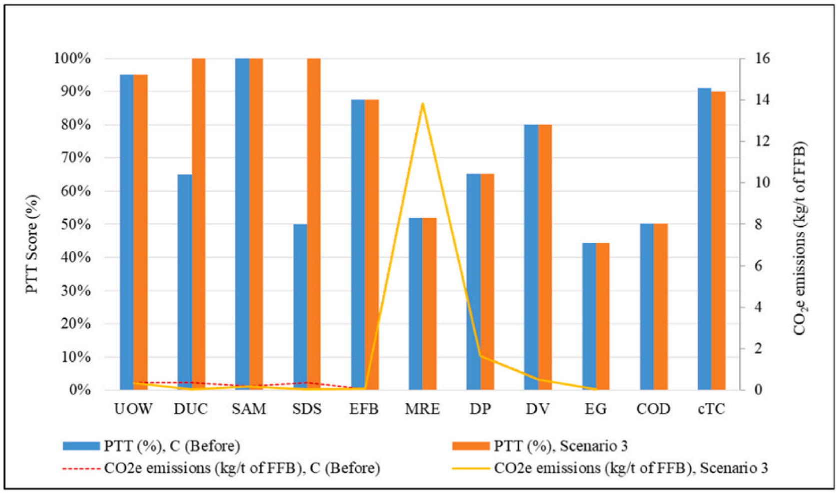

Fig. 8. Scenario 3: Changes in mill C's POMCFA and POMSI performance when the wet scrubber mitigation is applied.

Scenario 3 considers options of wet scrubber and assumes no implementation of a biogas plant and maintains the current practice of the effluent. Under Scenario 3, by implementing the wet scrubber, the efficiency of the boiler was predicted to slightly improve considering the reduction in the $otCO_2e$ from 17.38 kg/t of FFB to 16.74 kg/t of FFB as presented in Fig. 8. However, scenario 3 is observed as the least reduction in $otCO_2e$ in comparison with other scenarios. The POMSI score is presumed to increase from 89.19% to 90.75% but this increment is slightly lower than Scenarios 1 and 2. In terms of cost analysis, this choice would be less expensive than the other two since the cost performance score only dropped by about 1% from 91.07% to 90%.

Based on all three scenarios, the overall POMCFA with the highest $otCO_2e$ reduction is Scenario 1 (17.38 kg/t to 13.4 kg/t of FFB consumption) followed by Scenario 2 (17.38 kg/t to 14.04 kg/t of FFB consumption) and the lowest $otCO_2e$ reduction is Scenario 3 (17.38 kg/t to 16.74 kg/t of FFB consumption). Similar to the POMSI score, the highest increment (89.19%–94.59%) is Scenario 1 followed by Scenario 2 (89.19%–93.4%). The least increment (89.19%–90.75%) was observed in Scenario 3. Contrarily, the cost analysis shows Scenario 3 has the best total cost, cTC performance (95.35%) followed by Scenario 2 and Scenario 1 (90.35% and 90.34%) after the mitigation implementation. The key point of this study is that there is a significant potential to improve palm oil mill performance. This model has been successfully carried out to determine the optimal mitigation selections for Mill C. Mitigation selection is dictated by mitigation cost and target increment set of the weak indicator. From the application, biogas and wet scrubber were found as the solutions for Mill C. Both have been proven to reduce emissions and improve the environmental performance score of Mill C. However, cost analysis would be another key factor to consider whether to pursue the mitigation strategy plan. The information on the predictive emission reductions, the index performance, and the cost analysis provide a clearer picture for the decision-makers to make an optimal choice.

5. Conclusion and policy recommendation

In conclusion, this study presents new contributions to the field of palm oil mills through a comprehensive assessment that addresses carbon footprint accounting and sustainability performance. The framework developed a novel integrated Palm Oil Mill Carbon Accounting (POMCFA) methodology with the Palm Oil Mill Sustainability Index (POMSI) to provide a holistic approach to the mitigation strategy selection tool. The case study conducted on four Malaysian palm oil mills reveals significant findings. The POMCFA methodology allows for systematic carbon footprint accounting by considering indicators, parameters, streams, and unit operations. The results highlight Mill C as having the highest CO_2e emissions and the poorest performance in various aspects such as wastewater, diesel consumption, air quality, and electric consumption. However, it is crucial to note that the POMCFA analysis alone is not sufficient for decision-making, which necessitates the integration of the POMSI. The POMSI evaluates palm oil mill performance based on environmental, economic, and social principles. It provides decision-makers with an overall sustainability performance assessment and identifies areas of weak performance, guiding activities to achieve a more sustainable palm oil mill. Based on this integration, it will serve comprehensive preliminary guide for industries to determine the most suitable mitigation strategies in their journey towards net zero emissions. The integrated mitigation analysis addresses the weaknesses identified in both carbon footprint accounting and sustainability assessment. For Mill C, the optimal mitigation strategy involves the implementation of biogas and a wet scrubber. Recalculating the POMCFA and POMSI scores under different scenarios reveals the trade-offs between emission reduction, environmental score improvement, cost, and overall index performance.

The first scenario where biogas and wet scrubber mitigation were applied, showed the highest performance score increase in DUC, SDS, MRE, COD and EG as they all reached 100% and also achieved the highest $otCO_2e$ reduction. However, the cost performance score decreased from 91.07% to 85.34%. In the second scenario where only biogas plant mitigation was applied, less increase in index performance was achieved at 93.41% with a cost performance score similar to that indicated in the first scenario. Lastly, the third scenario in which only wet scrubber mitigation was applied, showed the least POMSI performance increase of 1.56% to reach 90.75% and the lowest $otCO_2e$ reduction. Yet it was the best compared to others in terms of cost performance with a drop of 1% in cost performance score reaching 90%. According to these findings, palm oil mills can make a clear decision considering the tradeoff between performance scores to choose those following its strategy.

This study enables the palm oil industry to track emissions and measure sustainability performance continuously. The assessments foster competition among mills for improvement and facilitate knowledge-sharing. The mitigation model assists the industry in making informed decisions to enhance performance through optimal solutions, ultimately contributing to the achievement of net zero emissions. In light of the findings in this study, policymakers should consider adopting the integrated approach of carbon assessment and sustainability assessment in their decision-making processes. This approach provides a more holistic and comprehensive understanding of the impacts of different actions and strategies on both environmental sustainability and carbon emissions. This integrated model offers a comprehensive approach to mitigation selection, allowing policymakers to consider the potential impact of different actions and strategies on both carbon emissions and overall sustainability. Policymakers can have access to a wider range of information and metrics that can guide them in making more informed and prioritized actions that not only reduce carbon emissions but also contribute to long-term sustainability goals, such as resource conservation, biodiversity preservation, and social equity. Furthermore, policymakers should actively engage with international sustainability initiatives, such as the Roundtable on Sustainable Palm Oil (RSPO), to ensure alignment with global sustainability goals and standards. By joining forces with international platforms, policymakers can access valuable resources, knowledge, and best practices to drive the transition towards a net zero palm oil sector.

In this study, the parameter's weightage has been assumed equally important thus, it is recommended for the way to go to conduct a thorough study to determine parameter weights according to their importance to the field. Lastly, the mitigation strategy used is limited to the data extracted from the literature. Thus, to improve the accuracy of future studies, it is recommended to collect data from the plant or industry.

Declaration

During the preparation of this work the author(s) used CHATGPT in order to generate sentences in some parts of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Nabila Farhana Jamaludin: Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Zarina Ab Muis:** Supervision, Project administration. **Haslenda Hashim:** Supervision, Project administration. **Ola Yahia Mohamed:** Writing – review & editing. **Lim Lek Keng:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Nabila Farhana binti Jamaludin reports financial support was provided by Universiti Teknologi PETRONAS Department of Chemical Engineering. Nabila Farhana binti Jamaludin reports a relationship with Universiti Teknologi PETRONAS Department of Chemical Engineering that includes: funding grants.

Acknowledgment

This work was supported by Universiti Teknologi PETRONAS and The Murata Science Foundation Grant, 015ME0-346. This assistance has been instrumental in the successful completion of our work, and we sincerely appreciate the contribution to our research endeavors.

Appendix 1

Carbon Emission Calculation Equation

Amount of CO_2e emitted for each indicator: $tCO_2e = EFCO_2e \times D$
Sum amount of CO_2e emitted for each indicator: $tCO_2e_i = \sum$ tCO_2e of each indicator
Sum amount of CO_2e emitted for each parameter: $tCO_2e_p = \sum$ tCO_2e of each parameter
Sum amount of CO_2e emitted for each unit operation: $tCO_2e_{uo} = \sum$ tCO_2e of each unit operation
Sum amount of CO_2e emitted for each stream: $tCO_2e_s = \sum$ tCO_2e of each stream

*emission factor ($EFCO_2e$).
*monthly consumption or generation (D).

Carbon Emission Profile Equation

$$\text{Carbon emission profile } (\%)\ (\mathrm{i, p, u, s}) = \frac{tCO_2e\ (i, p, u, s)}{otCO_2e} \times 100$$

Appendix 2

Technology Review Used in Case Study

	Mitigation strategy technology, m	Main treatment	Cost ($/ton CPO/year)			Total Cost, C_m	Indicator, n												References
							Emission							Consumption or production				Yield	
			IC_m	PC_m	VC_m	TC_m	CH4	N2O	SO2	NOX	VOC	CO	PM	EFB	Fiber	EG	DIP	CPO	
1	EFB combustion	EFB treatment	61.3	34.6	44.7	140.6	−0.005	−0.15											[53]
2	EFB pellets production		9.3	25.3	−44.4	−9.8								0.9					[54,55]
3	EFB composting plant		2	1.9	−5.3	−1.4								0.9					[56]
4	Ethanol production		258.7		−231.5	27.2													[54]
5	Pellets production		9.3	25.3	−44.4	−9.8													[54,55]
6	Composting plant		2	1.9	−5.3	−1.4													[57,58]
7	Selective catalytic reduction	NO_x control for fiber combustion	2.5	1.5		4		−0.08		0.8									[59]
8	Selective non catalytic reduction		1.9	1.1		3		−0.08		0.4									[60]
9	Low NOx burner		0.6	0.4		1				0.3									[61]
10	Non thermal plasma		3.6	0.9		4.5				0.9									[62,63]
11	Oil recovery from decanter	Oil extraction improvement			−42	−42												0.055	[64,65]c
12	Oil recovery from fiber				−7.6	−7.6												0.01	[64,65]c
13	Oil recovery from EFB				−3.8	−3.8												0.05	(Chavalparit, 2006; DEDE, 2006) c
14	Oil recovery from POME		0.4	0.2	−3.9	−3.3												0.05	[64,65]c
15	Cyclones	PM control for fiber combustion	0.4	0.2		0.6							0.8						[66]
16	Baghouse		0.3	0.1		0.4							0.99						[67]
17	Electrostatic precipitator		1.1	0.6		1.7							0.99						[68]
18	Biogas plant	POME treatment	8.2	5.8	−3.8	10.2	0.50									0.5	0.5		[69]
19	Biogas plant upgrading with bioreactor		7.5	5.8	−2.6	10.7	0.50									0.5	0.5		[70]
20	Pre heating fiber	Pre-heating fiber	0.1	0.1	−3.9	−3.7									0.5				[71]
21	Wet scrubber	S_2O control for fiber combustion	0.5	0.4		0.9			0.9	0.65	0.74		0.85						[72]
22	Thermal incinerator	VOC control for fiber combustion	0.3	0.1		0.4					0.99	0.89	0.88						[73]

Adapted from [53].

Appendix 3

GAMS Script for Mill C's Case Study

```
variable.
Totcost total cost for mitigation selected;
binary variable
x1 mitigation option by EFB combustion
x2 mitigation option by EFB pellets production
x3 mitigation option by EFB composting plant
x4 mitigation option by Ethanol production
x5 mitigation option by Pellets production
x6 mitigation option by Composting plant
x7 mitigation option by Selective catalytic reduction
x8 mitigation option by Selective non catalytic reduction
x9 mitigation option by Low NOx burner
x10 mitigation option by Non thermal plasma
x11 mitigation option by Oil recovery from decanter
x12 mitigation option by Oil recovery from fiber
x13 mitigation option by Oil recovery from EFB
x14 mitigation option by Oil recovery from POME
x15 mitigation option by Cyclones
x16 mitigation option by Baghouse
x17 mitigation option of electrostatic precipitator
x18 mitigation option of biogas plant
x19 mitigation option of biogas plant upgrading with bioreactor
x20 mitigation option by Pre heating fiber
x21 mitigation option by Wet scrubber
x22 mitigation option by Thermal incinerator;
equation
eq1 objective function
eq2 standard requirement for ch4
eq3 standard requirement for so2
eq4 standard requirement for PM
eq5 standard requirement for EG
eq6 standard requirement for DIP
eq7 cluster of EFB treatment
eq8 cluster of NOx control for fiber combustion
eq9 cluster of Oil extraction improvement
eq10 cluster of PM control for fiber combustion
eq11 cluster of POME treatment
eq12 cluster of Pre-heating fiber
eq13 cluster of S2O control for fiber combustion
eq14 cluster of VOC control for fiber combustion
eq15;
eq1. Totcost = e = 140.6*x1 - 9.8*x2 - 1.4*x3 + 27.2*x4 - 9.8*x5 - 1.4*x6 + 4*x7.
+ 3*x8 + 1*x9 + 4.5*x10–4.2*x11–7.6*x12–3.8*x13–3.3*x14 + 0.6*x15.
+ 0.4*x16 + 1.7*x17 + 10.2*x18 + 10.7*x19–3.7*x20 + 0.9*x21 + 0.4*x22;
eq2. 0.09*0.5*x18 + 0.09*0.5*x19–0.09*0.005*x1 = g = 0.045;
eq3. 0.09*0.9*x21 = g = 0.009;
eq4. 0.09*0.85*x21 + 0.09*0.88*x22 + 0.09*0.8*x15 + 0.09*0.99*x16 + 0.09*0.99*x17 = g = 0.009;
eq5. 0.09*0.5*x18 + 0.09*0.5*19 = g = 0.045;
eq6. 0.09*0.5*x18 + 0.09*0.5*x19 = g = 0.045;
eq7. x1 + x2 + x3 + x4 + x5 + x6 = l = 1;
eq8. x7 + x8 + x9 + x10 = l = 1;
eq9. x11 + x12 + x13 + x14 = l = 1;
eq10. x15 + x16 + x17 = l = 1;
eq11. x18 + x19 = l = 1;
eq12. x20 = l = 1;
eq13. x21 = l = 1;
```

eq14. x22 = l = 1;
eq15. x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10 + x11 + x12 + x13 + x14 +x20 = e = 0;
model process/all/;
solve process using MIP minimizing TotCost.

References

[1] Y. Fan, F. Wei, Contributions of natural carbon sink capacity and carbon neutrality in the context of net-zero carbon cities: a case study of hangzhou, Sustainability 14 (5) (2022) 2680. https://doi.org/10.3390/su14052680.
[2] International Energy Agency, Net Zero by 2050 A Roadmap for Global Energy Sector, France, 2021.
[3] Cecillia, Z.: Which ASEAN Countries Will Be the Front-Runners to Decarbonize Their Power Sectors?.
[4] R. Danessa, Philippines Has yet to Establish Net Zero Emission Goal, 2021.
[5] S. Ramli, B. Chew, A. Saptari, Factors in adopting green information technology: a qualitative study in Malaysia, Pertanika J. Sci. Technol. 29 (3) (2021) 1431–1450.
[6] N. Muzir, M. Mojumder, M. Hasanuzzaman, J. Selvaraj, Challenges of electric vehicles and their prospects in Malaysia: a comprehensive review, Sustainability 14 (2022).
[7] Z. Zakaria, A. Rahim, Z. Aman, The future of oil palm smallholders toward greater sustainability: a systematic literature review, Pertanika J. Soc. Sci. Humanit. 30 (1) (2022) 283–306.
[8] N. Ismail, S. Kamal, M. Firdaus, N. Hariri, Export demand of palm oil in Malaysia: analysis using ARDL approach, Asian J. Agric. Rural Dev. 12 (3) (2022) 157–163.
[9] N. Umi Zakiah, S. M Yusof, A.R. Muhammad Daaniyall, U. Chakrin, R. Anitha, The nexus between energy consumption and carbon emission: the case of MALAYSIAN palm oil industry, Oil Palm Ind. Econ. J. 20 (2020) 16–21.
[10] R. Siti Rahyla, M.Y. Suziana, M.A. Mohamad Fadhli, T. Azmil, Seeking for sustainability: actor's perspective on the Malaysian sustainable palm oil certification scheme (MSPO), Malaysian J. Soc. Sp. 17 (2021).
[11] The Edge Markets: Palm Oil Industry Must Be Ready to Accept New Technology Changes, 2022.
[12] Z.L. Chew, E.H. Tan, S.A.L. Palaniandy, K.S. Woon, Z.X. Phuang, An integrated life-cycle greenhouse gas protocol accounting on oil palm trunk and empty fruit bunch biofuel production, Sci. Total Environ. 856 (2023) 159007, https://doi.org/10.1016/j.scitotenv.2022.159007.
[13] N.A. Zakri, S. Adam, A review on the potential of empty fruit bunch (EFB) compost as growing medium for oil palm seedling production, Food Res. 5 (2021) 15–20, https://doi.org/10.26656/fr.2017.5(S4).003.
[14] T.R. Srinophakun, P. Suwajittanont, Techno-economic analysis of bioethanol production from palm oil empty fruit bunch, Int. J. Technol. 13 (2022) 1787–1795, https://doi.org/10.14716/ijtech.v13i8.6131.
[15] J. Supriatna, M.R. Setiawati, R. Sudirja, C. Suherman, X. Bonneau, Composting for a more sustainable palm oil waste management: a systematic literature review, Sci. World J. 2022 (2022), https://doi.org/10.1155/2022/5073059.
[16] M. Zhao, P. Xue, J. Liu, J. Liao, J. Guo, A review of removing SO2 and NOX by wet scrubbing, Sustain. Energy Technol. Assessments 47 (2021) 101451, https://doi.org/10.1016/j.seta.2021.101451.
[17] N. Sylvia, H. Husin, A. Muslim, Yunardi, A. Syahrullah, H. Purnomo, R. Dewi, Y. Bindar, Design and performance of a cyclone separator integrated with a bottom ash bed for the removal of fine particulate matter in a palm oil mill: a simulation study, AIMS Environ. Sci. 10 (2023) 341–355, https://doi.org/10.3934/environsci.2023020.
[18] C. Lye Chew, C. Yong Ng, W. Onn Hong, T. Yeong Wu, Y.-Y. Lee, L. Ee Low, P. San Kong, E. Seng Chan, Improving sustainability of palm oil production by increasing oil extraction rate: a review, Food Bioprocess Technol. 14 (2021) 573–586.
[19] C.L. Chew, L.E. Low, W.Y. Chia, K.W. Chew, Z.K. Liew, E.S. Chan, Y.J. Chan, P.S. Kong, P.L. Show, Prospects of palm fruit extraction technology: palm oil recovery processes and quality enhancement, Food Rev. Int. 38 (2022) 893–920, https://doi.org/10.1080/87559129.2021.1890117.
[20] P.L. Soo, M.J.K. Bashir, L.P. Wong, Recent advancements in the treatment of palm oil mill effluent (POME) using anaerobic biofilm reactors: challenges and future perspectives, J. Environ. Manag. 320 (2022) 115750, https://doi.org/10.1016/j.jenvman.2022.115750.
[21] A.B. Nasrin, A.A. Abdul Raman, N.A. Bukhari, M.A. Sukiran, A. Buthiyappan, V. Subramaniam, A.A. Aziz, S.K. Loh, A critical analysis on biogas production and utilisation potential from palm oil mill effluent, J. Clean. Prod. 361 (2022) 132040, https://doi.org/10.1016/j.jclepro.2022.132040.
[22] A. Sodri, F.E. Septriana, Biogas power generation from palm oil mill effluent (POME): techno-economic and environmental impact evaluation, Energies 15 (2022), https://doi.org/10.3390/en15197265.
[23] J.P. Rajakal, J.Z.H. Hwang, M.H. Hassim, V. Andiappan, Q.T. Tan, D.K.S. Ng, Integration and optimisation of palm oil sector with multiple-industries to achieve circular economy, Sustain. Prod. Consum. 40 (2023) 318–336, https://doi.org/10.1016/j.spc.2023.06.022.
[24] A. Mohtar, L.Y. Lim, Z.A. Muis, H. Hashim, K.Y. Wong, W.S. Ho, Optimising process pathway for palm oil mill effluent to compressed biomethane off-site utilisation, Chem. Eng. Trans. 97 (2022) 529–534, https://doi.org/10.3303/CET2297089.
[25] J.Y.J. Yeo, B.S. How, S.Y. Teng, W.D. Leong, W.P.Q. Ng, C.H. Lim, S.L. Ngan, J. Sunarso, H.L. Lam, Synthesis of sustainable circular economy in palm oil industry using graph-theoretic method, Sustain. Times 12 (2020) 1–29, https://doi.org/10.3390/su12198081.
[26] D.K.S. Ng, S.L.X. Wong, V. Andiappan, L.Y. Ng, Mathematical optimisation for sustainable bio-methane (Bio-CH4) production from palm oil mill effluent (POME), Energy 265 (2023) 126211, https://doi.org/10.1016/j.energy.2022.126211.
[27] J. Schmidt, M. De Rosa, Certified palm oil reduces greenhouse gas emissions compared to non-certified, J. Clean. Prod. 277 (2020), https://doi.org/10.1016/j.jclepro.2020.124045.
[28] F.V. Bekun, Mitigating emissions in India: accounting for the role of real income, renewable energy consumption and investment in energy, Int. J. Energy Econ. Policy. 12 (2022) 188–192, https://doi.org/10.32479/ijeep.12652.
[29] F.V. Bekun, B.A. Gyamfi, S.T. Onifade, M.O. Agboola, Beyond the environmental Kuznets Curve in E7 economies: accounting for the combined impacts of institutional quality and renewables, J. Clean. Prod. 314 (2021) 127924, https://doi.org/10.1016/j.jclepro.2021.127924.
[30] A.M.D.R.F. Jardim, G.D.N.A. Júnior, M.V.D. Silva, A. Dos Santos, J.L.B.D. Silva, H. Pandorfi, J.F.D. Oliveira-Júnior, A.H.D.C. Teixeira, P.E. Teodoro, J.L.M.P. D. Lima, C.A.D. Silva Junior, L.S.B.D. Souza, E.A. Silva, T.G.F.D. Silva, Using remote sensing to quantify the joint effects of climate and land use/land cover changes on the caatinga biome of northeast Brazilian, Remote Sens 14 (2022) 1911, https://doi.org/10.3390/rs14081911.
[31] N.F. Jamaludin, Z.A. Muis, H. Hashim, An integrated carbon footprint accounting and sustainability index for palm oil mills, J. Clean. Prod. 225 (2019) 496–509, https://doi.org/10.1016/j.jclepro.2019.03.312.
[32] E. Khan, M. Chowdhury, P. Royhan, S. Gowan, M. Rahman, M. Mahdavi, A decision model for sustainable informal entrepreneurship in cities, Int. J. Clim. Chang. Strateg. Manag. (2022) 1756–8692. https://doi.org/10.1108/IJCCSM-02-2022-0026.
[33] C.I. Lim, W. Biswas, Sustainability assessment for crude palm oil production in Malaysia using the palm oil sustainability assessment framework, Sustain. Dev. 2016 (2018) 1–17, https://doi.org/10.1002/sd.1872.
[34] H. Hashim, M.R. Ramlan, L.J. Shiun, H.C. Siong, H. Kamyab, M.Z.A. Majid, C.T. Lee, An integrated carbon accounting and mitigation framework for greening the industry, Energy Proc. 75 (2015) 2993–2998, https://doi.org/10.1016/j.egypro.2015.07.609.

[35] K. Saswattecha, C. Kroeze, W. Jawjit, L. Hein, Assessing the Environmental Impact of Palm Oil Produced in Thailand, 2015, https://doi.org/10.1016/j.jclepro.2015.03.037. This.
[36] H. Hashim, S.M.A. Bakar, J.S. Lim, Green industry for low carbon economy: palm oil green assessment tool, Energy Proc. 61 (2014) 2759–2762, https://doi.org/10.1016/j.egypro.2014.12.299.
[37] N.F. Jamaludin, Z.A. Muis, H. Hashim, Integrated mitigation strategy model for carbon accounting and sustainability index to encounter palm oil mill weaknesses holistically, IOP Conf. Ser. Mater. Sci. Eng. 884 (2020), https://doi.org/10.1088/1757-899X/884/1/012012.
[38] N.F. Jamaludin, H. Hashim, Z.A. Muis, Z.Y. Zakaria, M. Jusoh, A. Yunus, S.M. Abdul Murad, A sustainability performance assessment framework for palm oil mills, J. Clean. Prod. 174 (2018) 1679–1693, https://doi.org/10.1016/j.jclepro.2017.11.028.
[39] N.S. Sahimi, F.M. Turan, K. Johan, Development of sustainability assessment framework in hydropower sector, IOP Conf. Ser. Mater. Sci. Eng. 226 (2017) 8–14, https://doi.org/10.1088/1757-899X/226/1/012048.
[40] S. Tan, J. Yang, J. Yan, C. Lee, H. Hashim, B. Chen, A holistic low carbon city indicator framework for sustainable development, Appl. Energy 185 (2017) 1919–1930, https://doi.org/10.1016/j.apenergy.2016.03.041.
[41] T. Aktin, Z. Gergin, Mathematical modelling of sustainable procurement strategies: three case studies, J. Clean. Prod. 113 (2016) 767–780, https://doi.org/10.1016/j.jclepro.2015.11.057.
[42] R. Rajala, M. Westerlund, T. Lampikoski, Environmental sustainability in industrial manufacturing: Re-examining the greening of Interface's business model, J. Clean. Prod. 115 (2016) 52–61, https://doi.org/10.1016/j.jclepro.2015.12.057.
[43] J. Von Geibler, F. Cordaro, K. Kennedy, M. Lettenmeier, B. Roche, Integrating resource efficiency in business strategies: a mixed-method approach for environmental life cycle assessment in the single-serve coffee value chain, J. Clean. Prod. 115 (2016) 62–74, https://doi.org/10.1016/j.jclepro.2015.12.052.
[44] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, J. Clean. Prod. 137 (2016) 1573–1587, https://doi.org/10.1016/j.jclepro.2016.04.150.
[45] J.L. Rivera, T. Reyes-Carrillo, A life cycle assessment framework for the evaluation of automobile paint shops, J. Clean. Prod. 115 (2016) 75–87, https://doi.org/10.1016/j.jclepro.2015.12.027.
[46] M.F. Salvado, S.G. Azevedo, J.C.O. Matias, L.M. Ferreira, Proposal of a sustainability index for the automotive industry, Sustain. Times 7 (2015) 2113–2144, https://doi.org/10.3390/su7022113.
[47] P. Chand, S. Sirohi, S.K. Sirohi, Development and application of an integrated sustainability index for small-holder dairy farms in Rajasthan, India, Ecol. Indic. 56 (2015) 23–30, https://doi.org/10.1016/j.ecolind.2015.03.020.
[48] R. Ahamad (Ed.), Environmental Performance Index for Malaysia 2014, Penerbit UTM Press, 2015.
[49] A.A. Feil, D.M. de Quevedo, D. Schreiber, Selection and identification of the indicators for quickly measuring sustainability in micro and small furniture industries, Sustain. Prod. Consum. 3 (2015) 34–44, https://doi.org/10.1016/j.spc.2015.08.006.
[50] D. Jasiński, J. Meredith, K. Kirwan, A comprehensive framework for automotive sustainability assessment, J. Clean. Prod. 135 (2016) 1034–1044, https://doi.org/10.1016/j.jclepro.2016.07.027.
[51] I. Kantor, J.L. Robineau, H. Bütün, F. Maréchal, A mixed-integer linear programming formulation for optimizing multi-scale material and energy integration, Front. Energy Res. 8 (2020), https://doi.org/10.3389/fenrg.2020.00049.
[52] N. García, R. Ruiz-Femenia, J.A. Caballero, Teaching mathematical modeling software for multiobjective optimization in chemical engineering courses, Educ. Chem. Eng. 7 (2012) e169–e180, https://doi.org/10.1016/j.ece.2012.07.001.
[53] K. Saswattecha, C. Kroeze, W. Jawjit, L. Hein, Options to reduce environmental impacts of palm oil production in Thailand, J. Clean. Prod. 137 (2016) 370–393, https://doi.org/10.1016/j.jclepro.2016.07.002.
[54] Y.L. Chiew, S. Shimada, Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer – a case study of Malaysia, Biomass Bioenergy 51 (2013) 109–124.
[55] O. Chavalparit, W.H. Rulkens, A.P.J. Mols, S. Khaodhair, Options for environmental sustainability f the crude palm oil industry in Thailand through enhancement of industrial ecosystems, Environ. Dev. Sustain. 8 (2006) 271–287.
[56] R.P. Singh, M.H. Ibrahim, N. Esa, M.S. Iliyana, Composting of waste from palm oil mill: a sustainable waste management practice, Rev. Environ. Sci. Bio/Technology. 9 (2010) 331–344.
[57] F. Schuchardt, K. Wulfert, Darnoko, T. Herawan, Effect of new palm oil mill processes on the efb and pome utilization, J. Oil Palm Res. (2008) 115–126.
[58] F. Schuchardt, D. Darnoko, P. Guritno, Composting of empty oil palm fruit bunch (efb) with simultaneous evapoaration of oil mill waste water (pome), in: 2002 International Oil Palm Conference, 2002, pp. 1–9.
[59] M.H. Kim, Formation of N2O in NH3-SCR DeNOxing reaction with V2O5/TiO2-based catalysts for fossil fuels-fired power stations, Korean Chem. Eng. Res. 51 (2013) 163–170.
[60] C. Mendoza-Covarrubias, C.E. Romero, H.-R. Fernando, A. Hans, N2O formation in selective non-catalytic NOx reduction processes, J. Environ. Prot. (Irvine,. Calif). 2 (2011) 1095–1100.
[61] L. Cox, R. Blaszczak, Nitrogen Oxides (NOx) Why and How They Are Controlled, 1999.
[62] EPA, Multipollutant Pollution Control Technology Options for Coal-Fired Power Plant, 2005.
[63] EPA, Using Non-Thermal Plasma to Control Air Pollutants, 2005.
[64] O. Chavalparit, Clean Technology for the Crude Palm Oil Industry in Thailand, 2006.
[65] DEDE, Best Practice Guide on Eco-Efficiency in Oil Palm Industry, 2006.
[66] EPA, Air Pollution Control Technology Fact Sheet - Cyclones, 2003.
[67] EPA, Air Pollution Control Technology Fact Sheet: Fabric Filter-Pulse-Jet Cleaned Type (Referred as Baghouses), 2003.
[68] EPA, Air Pollution Control Technology Factsheet - Dry Electrostatic Precipitator, 2003.
[69] R. Kaewmai, A. H-Kittikun, C. Suksaroj, C. Musikavong, Alternative technologies for the reduction of greenhouse gas emissions from palm oil mills in Thailand, Environ. Sci. Technol. 47 (2013) 12417–12425, https://doi.org/10.1021/es4020585.
[70] A. Pattanapongchai, B. Limmeechokchai, Least cost energy planning in Thailand: a case of biogas upgrading in palm oil industry, Songklanakarin J. Sci. Technol. 33 (2011) 705–715.
[71] DEDE, Best Practice Guide on Waste to Energy in Oil Palm Industry, Bangkok, 2007.
[72] G. Ruitang, X. Gao, Simultaneous removal of SO2 and NO2 by wet scrubbing using aqueous limestone slurry, in: Electrostatic Precipitation, 2009, pp. 602–605.
[73] EPA, Air Pollution Control Technology Factsheet - Thermal Incinerator, 2003.