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Cost Assessment of Emission Mitigation Technology for the Palm Oil Sector in Indonesia

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ABSTRACT

Indonesia must establish a policy on the application of technology for mitigating greenhouse gas emissions because it is the nation that produces the most palm oil. When evaluating different technologies, policymakers should consider how much the technology will cost compared to the potential emissions abated, in terms of marginal abatement cost (MAC), which reflects priorities in the form of marginal abatement cost curves (MACC). The objective of this research is to evaluate and estimate the ranking of MAC from eight mitigation technologies used in Indonesia's palm oil sector between 2020 and 2030. The least MAC is given as technology ranked first, namely the high-capacity boiler, with a value of $-19.61/tonne CO_2eq followed by the high-efficiency steam turbine with $-7.2/tonne CO_2eq, and the POME-to-biogas technology with $-0.1/tonne CO_2eq. Additionally, the MAC of five additional technologies is positive, suggesting that implementation expenses were incurred. Subsequently, a sensitivity analysis is performed to see which technology ranks are impacted by interest rate fluctuations. Biogas upgrading technology is therefore liable to changes in the discount rate, which occur at different values. Other mitigation technologies, however, are also increasing their parameters, although less significantly than biogas upgrading, therefore this has no bearing on mitigation technology ranking.

INTRODUCTION

The world is grappling with a pressing issue concerning fossil energy, as the detrimental environmental effects of its extraction and consumption become increasingly apparent. The combustion of fossil fuels, such as coal, oil, and natural gas, releases vast amounts of carbon dioxide and other greenhouse gases into the atmosphere, contributing significantly to climate change. This global predicament has spurred countries to adopt multifaceted approaches to mitigate the adverse impacts of fossil energy. Several nations have invested heavily in renewable energy sources like solar, wind, and hydropower, aiming to diversify their energy portfolios and reduce reliance on fossil fuels. Additionally, international collaborations and agreements, such as the Paris Agreement, have sought to unite countries in collective efforts to limit global temperature rise. Governments are implementing policies to incentivize clean energy initiatives, promote energy efficiency, and phase out subsidies for fossil fuels. The transition to sustainable energy is not without challenges, including economic considerations and the need for technological advancements. However, the global commitment to addressing the fossil energy problem underscores the urgency of finding innovative solutions to secure a more sustainable and environmentally responsible energy future.

In January 2022, Indonesia has been making notable strides in contributing to sustainable development, recognizing the imperative of balancing economic growth with environmental and social considerations. One key aspect is the country's commitment to reducing carbon emissions and combating climate change. Indonesia has implemented policies and initiatives to address deforestation and promote sustainable forestry practices. Efforts such as the moratorium on new licenses for primary forests and peatlands, as well as the establishment of the REDD+ program (Reducing Emissions from Deforestation and Forest Degradation), aim to preserve the country's rich biodiversity and mitigate carbon emissions. Furthermore, Indonesia has been actively promoting renewable energy sources to diversify its energy mix and decrease reliance on fossil fuels. Initiatives include the development of geothermal, solar, and wind energy projects, with a focus on increasing the share of renewables in the overall energy grid. The government has also launched programs to enhance energy efficiency and reduce the environmental impact of industries.

Currently, Indonesia is also the largest producer of palm oil globally, and the industry has played a pivotal role in the country's economic development, contributing to job creation and export revenue. Each year, the country generates around thirty million tons of palm oil, accounting for 4.5% of its GDP and employing 3 million people (Edwards 2019). International demand for palm oil products has contributed significantly to those positive impacts. The cultivation of oil palm, coupled with the subsequent processing of fresh fruit bunches (FFBs) into crude palm oil (CPO) and various derivative products, has created a robust supply chain that spans agricultural activities, processing facilities, and downstream industries.

However, the expansion of palm oil plantations has been associated with deforestation, habitat loss, and increased greenhouse gas (GHG) emissions. The conversion of large areas of tropical forests, particularly peatlands, into palm oil plantations is a major driver of GHG emissions. The production of palm oil leads to a variety of concerns regarding the environment. It has already been confirmed throughout the manufacturing chain, most notably methane (CH_4) emissions coming from wastewater in open-water ponds during the milling cycle (Stichnothe & Bessou 2017).

These circumstances prompted consumer awareness and international pressure throughout the palm oil industry to shift toward more sustainable practices. The government has implemented policies and regulations to curb deforestation, including moratoriums on new licenses for primary forests and peatlands. The use of mitigation technology (MT) to enhance mill efficiency and limit environmental impacts is essential for the industry to minimize its contribution to GHG emissions and support a more sustainable and responsible future for palm oil production in Indonesia. To assess the allocation of energy-related options and identify which resources are essential for climate measures, the Marginal Abatement Cost (MAC) is used to incorporate both economic and technical aspects of accomplishing GHG emission reduction targets.

To demonstrate the relationship involving abatement quantity and MAC, policymakers utilized the Marginal Abatement Cost Curve (MACC), a visual instrument that highlights the performance measures of economic effectiveness of a variety of GHG mitigation options like an established performance measures of maximum tracking error for machine tools application (Chiew et al. 2017). Fig. 1 shows an example of MACC with five MTs.

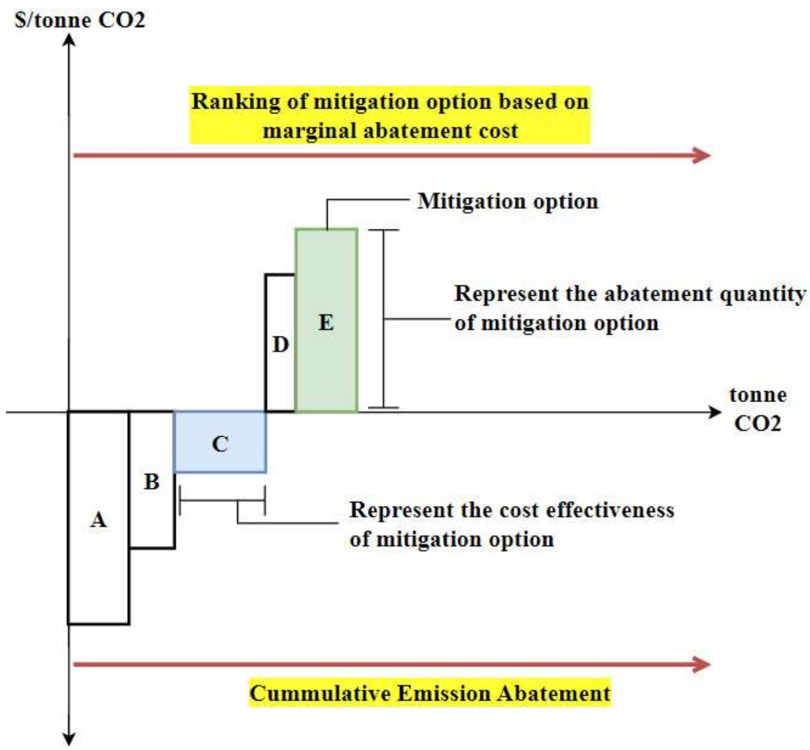

Fig. 1: Illustration of five mitigation technologies in MACC.

On the x-axis, the abatement quantity is presented, representing the volume of GHG emissions reductions achievable through diverse mitigation activities. This axis is organized from left to right, signifying an increasing scale of emission reduction efforts. Each point along the x-axis corresponds to a specific mitigation option, ranging from low-cost measures on the left to more expensive alternatives on the right. Conversely, the y-axis represents the Marginal Abatement Cost, measuring the cost incurred to achieve each additional unit of emission reduction. The MAC is expressed in monetary units and is arranged from bottom to top, indicating an ascending cost scale. As one moves upward along the y-axis, the cost of achieving additional emission reductions rises, reflecting diminishing returns on investment. The MACC, therefore, slopes upward, highlighting the economic efficiency of each mitigation option. The intersection of the MACC with the x-axis denotes measures that are both environmentally effective and economically viable without incurring additional costs. This crucial point indicates a balance between cost-effectiveness and emission reduction goals. By offering a visual representation of the costs associated with different mitigation measures, the MACC assists decision-makers in identifying the most economically efficient strategies to achieve specific emission reduction targets.

In Indonesia, only a few industries are relatively conscious of how much potential for mitigation exists and how much it would cost to realize this potential (Pambudi et al. 2018). Calculating the abatement costs of CO_2 is a key step to realizing CO_2 emission reduction (Duan et al. 2018) and can be summarized that MAC curves are a widely used method to support policy recommendations on carbon mitigation. To the best of the authors' knowledge, there is currently only one study available on the MAC curve and its application for the assessment of GHG emission reduction solutions for their costs in Indonesia. MAC applications have been used for energy, transport, residence, and agriculture, but are still not widely used in the palm oil sector, particularly in Indonesia. Extension to developing countries would bring greater challenges to MAC research. Thus, this study aims to fill this gap by using the concept of the "CO_2 abatement cost" to construct a bottom-up model to capture both the cost-effective and the technical potential for CO_2 emission reduction in the Indonesian palm oil sector. Research and development for CO_2 emission reduction in the palm oil production sector is also needed to ensure sustainable palm oil development. Reducing GHG emissions all along the production chain can help to reduce global impact while generating additional energy and farm income at the local

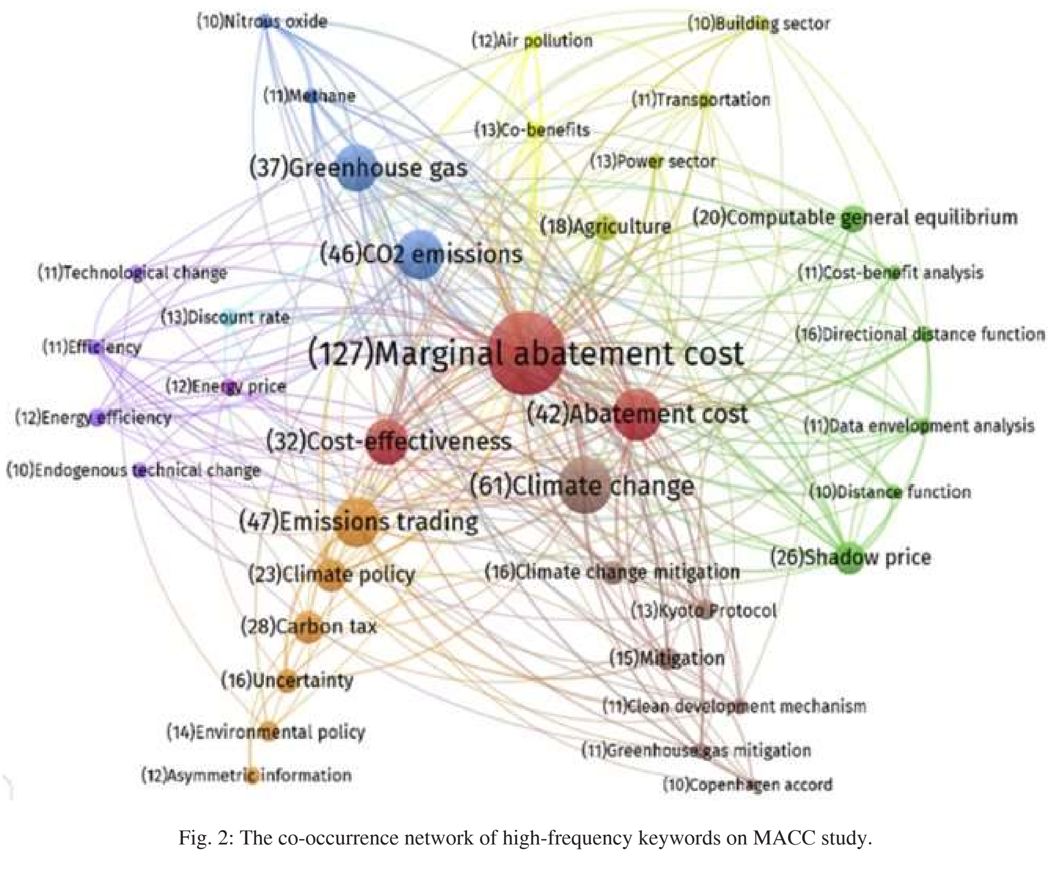

Fig. 2: The co-occurrence network of high-frequency keywords on MACC study.

level. The results are intended to help researchers and policymakers evaluate palm oil policies before 2060 and to develop new policies which in line with national and global climate mitigation targets.

MAC STUDIES IN PAST

Recently, research on the Marginal Abatement Cost Curve (MACC) has been widely used by policymakers in climate change issues, which reveals that MACC is an important analysis tool for decision-making on climate change. The trend shows that the volume of research on MACC has generally been increasing from 1993 to 2022, indicating a popular trend in MACC research, mainly because of the wide application of MACC to evaluate the effects of the Kyoto Protocol and carbon trading as shown in Fig. 2. The co-occurrence network is drawn around high-frequency keywords (with a frequency exceeding 10) in the MACC field.

The MAC study field of interest is divided into three primary groups determined by the keyword frequency findings: decision-making aims, MAC applications, and stakeholder type. In essence, the three categories represent the growing popularity of MAC-related research interest. Table 1 provides an overview of MAC's progress in research for the last ten years, based on credible journal sources, with an emphasis on applications across many industries to support the greenhouse emission reduction strategy.

MACC is applied in many different industries but is more common in high-emission industries, such as transportation, renewable energy, industry, power generation, and agriculture. MACC is also used for a series of sectors, such as the industrial, transportation, residential, commercial, and power generation sectors. Determined national MAC averages in four sectors: household, services, transportation, and EE solutions. The use of MACC for industrial aggregates is common in smaller contexts, such as cities or provinces. The efficacy and cost-effectiveness of various reduction strategies in waste management, energy, transport, and buildings were evaluated in London. Similarly, the cost-effectiveness and abatement potential of seventy measures belonging to the same four sectors were also examined in New York City. Seventy measures from the same four sectors were studied to determine their reduction potential and cost-effectiveness. MACCs have also been constructed for 58 cross-sector abatement technologies in Shanghai to

Table 1: MAC Research Trends.

Authors	Stakeholder		Sector (Country)	Methodologies	GHG Emission (Period)
	G	I			
(Kesicki 2013)	√		Transportation (UK)	Energy System Model (UK MARKAL) and Decomposition Analysis	CO_2 (2000-2050)
(Promjiraprawat et al. 2014)	√		Residential and building (Thailand)	Asia-Pacific Integrated Model	CO_2 (2005-2050)
(Tomaschek 2015a)	√		Transportation (South Africa)	TIMES-GEECO model	CO_2 (2007-2040)
(Contreras 2016)		√	Building (Spain)	Finance-accounting	CO_2 (N/A)
(Zhang et al. 2017)	√		Rural households (China)	Levelized Production Cost (LPC)	CO_2 (2015-2035)
(Luu et al. 2018)	√		Energy (Vietnam)	Finance-accounting	CO2 (2015-2020)
(Johnsson et al. 2019)		√	Wood industry (Sweden)	Energy key performance indicators	CO_2 (2010-2018)
(Chen 2020)	√		Power (China)	Micro-technology and macro-industry model	CO_2 (2015-2030)
(Janzen et al. 2020)		√	Oil sands (Canada)	Market penetration model and Finance-accounting	CO_2 (2019-2050)
(Lameh et al. 2022)utilization, and sequestration (CCUS	√		Power (N/A)	Mini-MAC	CO_2 (2020-2040)
This study (2024)		√	Palm oil Mill (Indonesia)	Finance-accounting	CO_2 (2020-2030)

G: Government, I: Industry

analyze GHG emission reductions and capital investments in 2015 and 2020 (Ibrahim & Kennedy 2016, Jiang et al. 2022, Tomaschek 2015b, Xiong et al. 2016).

In the energy sector, many studies conducted in large emitting countries and developed countries show that MAC varies widely between countries, and the average technology abatement cost of wind power technology in China is 75 Chinese Yuan/tCO_2e or 11 USD/tCO_2e. This figure is much lower than the average abatement cost of EE technology in thermal power plants in the same country, which is 316.51 Chinese Yuan/tCO_2e, or 48 USD/tCO_2e (Xiong et al. 2016). Using wind power as an example, the abatement costs for wind power technology in Austria are even negative, amounting to −31 EUR/tCO_2e (or −37 USD/tCO_2e) (Jiang et al. 2022). The different circumstances of these countries, such as resource potential, generation capacity, and generation costs, account for the varying ranges of abatement costs.

Based on the studies review, for the last several years, it is widely known that different stakeholders and the MAC approach have been explored and applied in various sectors by previous scholars. However, to the best of the author's knowledge, the approach of finance-accounting method for industrial stakeholders in the application of the palm oil sector is still limited and infrequent. Therefore, the current study attempts to assess the marginal costs of GHG emission mitigation technology abatement in Indonesian palm oil mill manufacturing operations. Particularly within the domain of the Indonesian palm oil industry, this study represents a pioneering effort aimed at bridging this evident gap in MACC implementation by undertaking a rigorous evaluation of energy-related mitigation options. The study's findings from empirical research have the potential to provide significant contributions to the development of evidence-based policy recommendations. This will assist in ensuring the adoption of well-informed decisions regarding the most effective use of national and regional resources for climate change mitigation initiatives.

METHODS AND DATA

Scope Setting

This scope includes the establishment of time intervals, geographic limits, and emission sectors. Compared to other Indonesian provinces, Riau province has produced the most CPO, supplying over one-fifth of the total national production. Samples from four palm oil mills that differed in capacities, ownership, and years of operation in relation to greenhouse gas emissions were assessed to gain the ranking of MAC. Geographic boundaries encompassing the years 2020 to 2030 are found in the Rokan Hulu Region and are defined by the administrative boundaries between the cities of Tandun, Kepenuhan, Ujung Batu, and Pasir Pengaraian.

Identification and Evaluation of Mitigation Alternatives

The extraction and processing of palm oil involves several processes that result in GHG emissions, and every phase has the opportunity to increase GHG efficiency. Technology aimed at lowering greenhouse gas emissions in palm oil mills has primarily concentrated on increasing waste reuse. Examples involve composting mill waste, which is then used as fertilizers on plantations, and utilizing biogas as a source of energy generated by facilities that capture methane from POME.

Indirect and direct MTs that lower GHG emissions in mills are covered in the following subsection. A similar set of criteria, including the potential for reducing greenhouse gas emissions and cost aspects, were applied to evaluating the identified MTs. It is significant to take into consideration that the use of MT in a mill may encourage the reduction of GHG emissions elsewhere or make a difference in a larger context. For instance, methane-captured biogas can be used as captive power or to replace fossil fuel-based electricity generation on the grid.

Research Design

The study flowchart presented in Fig. 3 illustrates a systematic research technique that is segmented into three primary stages to develop and analyze the MACC relevant to the palm oil industry.

In the initial phase of problem formulation, the commencement of this process entails the systematic acquisition of secondary data, primarily facilitated through an extensive literature review, focusing on elucidating the application of the MACC methodology within the industrial domain, with a specific emphasis on its implementation within the palm oil sector. Subsequently, this scholarly inquiry delineates the precise problem to be addressed, thereby laying the foundational framework for the formulation of research objectives. The process then proceeds to the critical task of delineating the most appropriate MACC approach, a decision-making endeavor that is rigorously aligned with the stipulated research objectives. Should the initially chosen MACC approach prove incongruent with the predefined research objectives, a systematic iterative process ensues, wherein alternative approaches are meticulously considered and evaluated until an optimal alignment between the selected approach and the research objectives is achieved? This methodological rigor

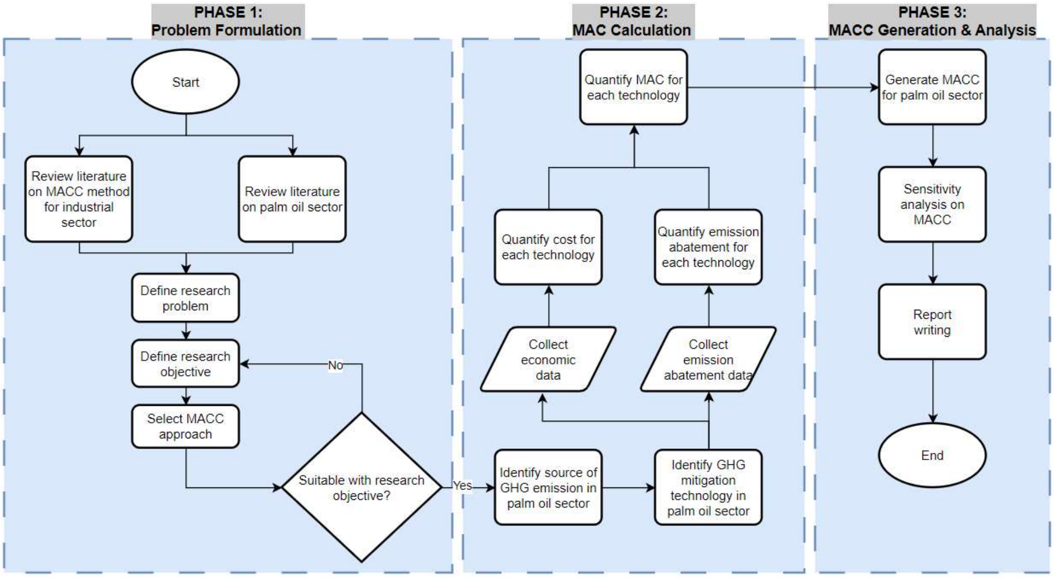

Fig. 3: The present research flowchart.

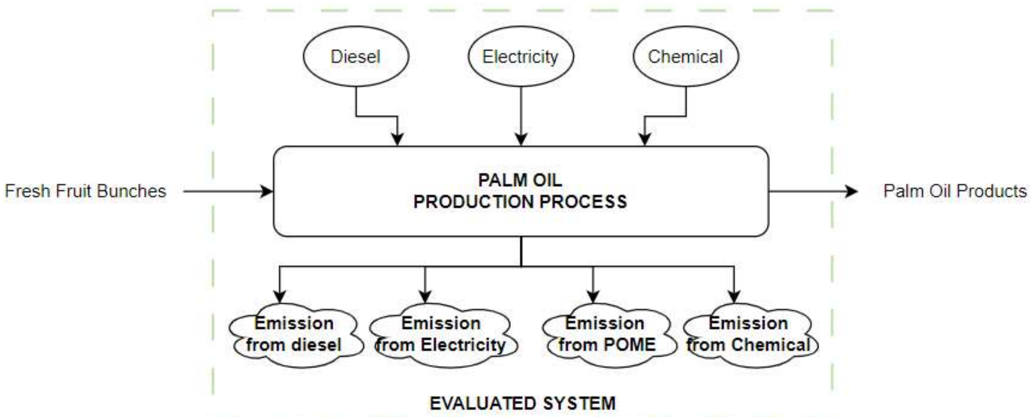

Fig. 4: Scope of the evaluated system in palm oil mill.

ensures that the ensuing research endeavors are conducted with a coherent and purposeful alignment toward the attainment of the established objectives, thereby enhancing the efficacy and robustness of the investigative process.

The subsequent phase of the study encompasses a comprehensive examination aimed at delineating the sources of greenhouse gas emissions prevalent within the palm oil sector. The burning of fossil fuels, Palm Oil Mill Effluent (POME), and the use of grid energy are the primary contributors to emissions that are identified throughout the milling stages (Fig. 3). These emissions arise from burning fossil fuels that are used for a variety of operational functions, such as machinery operation and steam production. They also come from the anaerobic digestion of POME to create biogas and the grid-based electricity that is obtained to meet the energy demands of milling operations (Acobta et al. 2023).

Building upon this foundational understanding, the research endeavors progress to the quantification of MAC attributed to each discerned technological intervention. This intricate undertaking necessitates the meticulous collection and analysis of economic data pertinent to each technological avenue, facilitating the precise quantification of associated costs. Following the current study, the difference between the cost of producing palm oil in the MT condition and the baseline condition, divided by the difference between the GHG emissions in the baseline condition and the MT condition, is the marginal abatement cost of utilizing one MT. The MAC equation can be written as follows:

$$MAC_{MT(i)} = \frac{TC_{MT(i)} - TC_{BAU}}{TE_{BAU} - TE_{MT(i)}} \quad \ldots(1)$$

Where $MAC_{MT(i)}$ is the marginal abatement cost of utilizing selected MT ($/ton CO_2eq), $TC_{MT(i)}$ is the total cost of applying selected MT in palm oil production ($) and TC_{BAU} is the total cost in the baseline condition ($). TE_{BAU} is the quantity of GHG emissions (ton CO_2eq) in the baseline condition and $TE_{MT(i)}$ is the quantity of GHG emissions (ton CO_2eq) with selected MT in palm oil production. The total cost consists of capital expenditure (capex) and operational expenditure (opex) for baseline condition and utilizing a single MT in palm oil mill, which can be expressed as follows:

$$TC_{MT(i)} = \sum_{t=1}^{n} \frac{CAPEX_{MT(i)}^{t} + OPEX_{MT(i)}^{t}}{(1+r)^{t}} \quad \ldots(2)$$

$$TC_{BAU} = \sum_{t=1}^{n} \frac{CAPEX_{BAU}^{t} + OPEX_{BAU}^{t}}{(1+r)^{t}} \quad \ldots(3)$$

Where $CAPEX_{MT(i)}^{t}$ is the total capital cost ($) and $OPEX_{MT(i)}^{t}$ is total operational cost ($) when utilizing selected MT with the discount rate, *r*, and in the year of *t*. $CAPEX_{BAU}^{t}$ and $OPEX_{BAU}^{t}$ is total capital cost ($) and operational cost ($) in the baseline conditions with the discount rate, *r*, and in the year of *t*, respectively. The formula assesses the total of Capex and Opex for each type of MT determined by the cost of technology.

Within the present study, a bottom-up MAC approach involving financial accounting was utilized to determine the amount of abatements and corresponding costs on each MT. This methodology is appropriate in comparison to top-up methods, which are focused on analyzing the possible opportunity cost of accomplishing a specific emission reduction goal, due to its computational simplicity and high visibility in ranking cost-effectiveness measures (Huang et al. 2016).

Data is collected and compiled through desk studies and site visits. The data collected is techno-economic data from palm oil mills, with references such as performance reports and publications. For both the BAU and the alternative option, statistical data on investment cost, yearly cost of fuel, periodic operation and maintenance cost, lifespan of the technology, and replacement rates for the alternating solution must be collected.

By assessing the potential savings per ton of abatement against the construction and operating costs, the MAC calculates the net cost of measure implementation. The measures are then categorized and ranked according to their cost-effectiveness after each measure's technical mitigation potential and marginal abatement cost have been measured. Along the x-axis, the mitigation strategies are sorted from smallest to greatest MAC, left to right.

The culminating phase of this research endeavor entails the generation of a tailored curve of marginal abatement cost, specifically tailored to the intricate dynamics of the palm oil sector. This pivotal stage encompasses a meticulous sensitivity analysis conducted upon the resultant MACC, aimed at scrutinizing the impact of parameter variations on the derived outcomes. The conclusion of this phase is marked by the comprehensive compilation of a detailed research report, meticulously encapsulating all pertinent facets of the investigative journey.

Through the dissemination of this comprehensive research report, the culmination of rigorous empirical inquiry, the scholarly community and stakeholders within the palm oil sector are furnished with invaluable insights and evidence-based recommendations pivotal for informed decision-making processes and strategic planning endeavors conducive to fostering sustainable practices and mitigating environmental impacts.

RESULTS AND DISCUSSION

The MACC findings and analysis for mitigating technologies in the palm oil industry are covered in this section. The data sheet was collected using steps involved in the previous section to assess CO_2 emissions in the palm oil industry and develop efficient and cost-effective mitigation technologies. Data collection was focused on investment costs, fixed and variable Operation and Maintenance (O&M) costs, fuel costs, economic lifetime, capacity factor, efficiency or heat rate, specific fuel consumption, fuel prices, and the capacity of the reference palm oil mill.

There are currently eight methods that are capable of being used to lower GHG emissions depending on the conditions in the production process. Improvement aimed at lowering emissions in the mills has primarily concentrated on increasing waste reuse. A few of these include composting mill waste, which can be employed as fertilizer on plantations, and using biogas as a source of energy generated by facilities that capture methane from POME.

The MAC curve is shown in Fig. 5 and Table 2 shows the results of the research's marginal abatement costs for the palm oil industry in Indonesia.

The implementation of CO_2 mitigation technologies in the Rokan Hulu region of Riau, involving four palm oil producers, is projected to yield significant reductions in emissions. Specifically, it is estimated that these initiatives will lead to a reduction of approximately 87,255 tonnes

Table 2: MAC calculations for eight mitigation technologies in the palm oil sector.

Mitigation Technology	Capital cost	Operation and maintenance cost	Annual average CO_2 savings for the project	Project life	NPV	Cumulative savings for all projects	MAC
	($)	($)	(tonnes/year)	(years)	($)	(thousand tonnes/year)	($/tonne CO_2eq)
A	100,000	78,000	8,950	15	-493,274	9.0	-7.2
B	15,000	5,000	15,000	8	-11,675	24.0	-0.1
C	500,000	62,500	4,875	10	115,965	28.8	3.9
D	200,000	20,000	2,390	10	77,109	31.2	5.3
E	120,000	8,000	9,400	15	59,151	40.6	0.8
F	550,000	25,000	27,530	15	359,848	68.1	1.7
G	823,000	91,000	11,630	20	48,266	79.8	0.49
H	343,000	202,500	7,480	10	-901,275	87.3	-19.61

A: High Efficiency Stream Turbine; B: POME-to-Biogas Electricity; C: Co-Composting

D: Solid-Liquid Separation; E: Biomass Waste Utilization; F: Biofuel Production

G: Biogas Upgrading; H: High-Capacity Boiler

of CO_2 emissions per year. This substantial decrease in emissions highlights the effectiveness of the applied mitigation strategies in mitigating the environmental impact of palm oil production activities in the region. When compared to the BAU scenario, wherein no mitigation technologies are implemented, the projected reduction in CO_2 emissions amounts to approximately 11.6%. This comparison underscores the importance and impact of adopting CO_2 mitigation technologies in the palm oil sector. By implementing these measures, palm oil producers can significantly contribute to reducing their carbon footprint and mitigating climate change effects.

Additionally, the calculations reveal that biofuel production technology emerges as the most significant contributor to emission reduction efforts, with an estimated reduction of 27,530 tons of CO_2 per year. This technology alone accounts for approximately 31.5% of the total emissions reduction achieved by the implemented solutions. Following closely behind, technologies such as POME-to-biogas electricity and biogas upgrading collectively contribute 30.5% to the emissions reduction efforts, resulting in a combined reduction of 26,630 tons of CO_2 per year. These three solutions, when considered together, demonstrate the potential to substantially mitigate CO_2 emissions by a combined total of 54,160 tons per year. Moreover, the analysis highlights the collective contribution of the remaining five technologies, which account for approximately 37.9% of the total emissions reduction. Among these, solid-liquid separation technology emerges as the least effective, with a relatively modest reduction of 2,390 tonnes of CO_2 per year, constituting only about 2.7% of the total emissions reduction achieved by all technologies combined.

Furthermore, In the realm of climate change mitigation, the evaluation of marginal abatement costs (MAC) represents a crucial aspect of devising effective emission reduction strategies. Our comprehensive analysis delves deeply into this metric, offering nuanced insights into the cost-effectiveness and economic viability of a range of emission reduction technologies within the palm oil production sector.

Notably, high-efficiency steam turbine technology emerges as a standout performer, boasting a negative MAC of -7.2 ($/tonne CO_2eq). This remarkable finding not only underscores its efficacy in curbing emissions but also highlights its potential to generate substantial cost savings over time. By harnessing the power of advanced steam turbine systems, palm oil producers can not only reduce their carbon footprint but also enhance their bottom line, demonstrating the symbiotic relationship between environmental sustainability and economic prosperity.

Furthermore, the high-capacity boiler technology stands out as a transformative force in emission reduction efforts, with an exceptionally low MAC of -19.6 ($/tonne CO_2eq). This striking figure underscores its unparalleled capacity to drive significant emissions reductions while simultaneously yielding substantial cost benefits. As a cornerstone of sustainable palm oil production practices, high-capacity boilers offer a compelling pathway towards achieving ambitious emission reduction targets while bolstering the economic resilience of the industry.

In contrast, technologies such as POME-to-biogas electricity, solid-liquid separation, and biofuel production exhibit varying degrees of cost-effectiveness, with MACs ranging from marginally negative to moderately positive values. While these technologies offer promising avenues for emissions reduction, their economic viability may be contingent upon factors such as scale of implementation, technological maturity, and market dynamics.

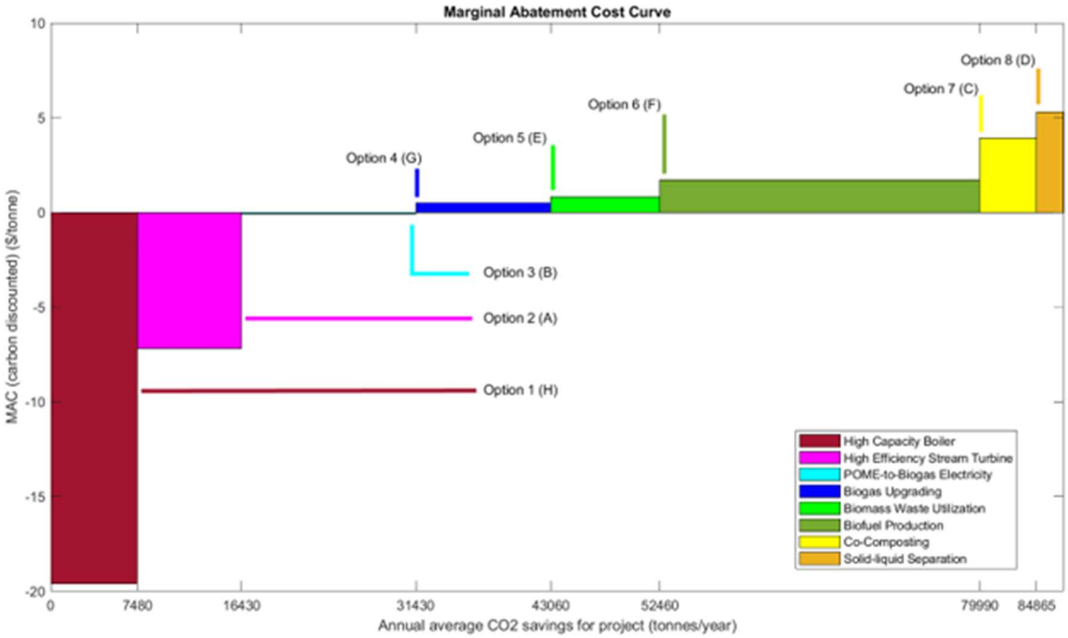

Fig. 5: MACC for the palm oil sector.

This in-depth analysis provides stakeholders with a comprehensive understanding of the intricate trade-offs and opportunities inherent in the pursuit of emission reduction within the palm oil production sector. By leveraging the insights gleaned from our analysis, policymakers, industry stakeholders, and environmental advocates can make informed decisions regarding the adoption and deployment of emission reduction technologies, paving the way for a more sustainable and prosperous future.

The MAC curve is typically displayed as a bar chart, with the horizontal axis representing abatement potential (tonne CO_2eq) and the vertical axis representing marginal abatement costs ($/tonne CO_2eq). The curve can be plotted by using the provided data for "Annual Average CO_2 Savings for Project (tonnes/year)" and "MAC (Carbon Discounted) ($/tonne)" columns. It arranges the projects in ascending order based on their "MAC (Carbon Discounted) ($/tonne)" by presenting the marginal abatement cost while "Annual Average CO_2 Savings for Project (tonnes/year)" was presenting cumulative abatement potential that resulting to identify that offer the most cost-effective abatement options. These projects are located at the lower end of the MACC curve which will enable it to offer greater abatement potential at lower costs, making it more economically viable than other choices for reducing emissions.

The ranking basically can be observed by the MAC value of approximately (($/tonne). The graph shows that High-capacity boiler technology is better other than technologies. This is followed by the High-Efficiency Stream Turbine technology and POME-to-biogas electricity technology that have a negative value of the cost of MAC. The other positive value of marginal abatement cost is defined using the higher cumulative abatement of emission. It shows the Biogas upgrading technology, followed by Biomass waste utilization technology, Biofuel production technology, Co-composting technology, and Solid-liquid separation technology.

Sensitivity Analysis

Sensitivity analysis is a useful tool for determining which factors have the biggest impact on the results and for guiding decision-making by taking many scenarios and possible uncertainties into account. It shows how to assess the investment's cost-effectiveness using a discount rate that can be seen by changes in the outcomes. This aids in decision-makers' comprehension of the degree of risk or uncertainty related to the outcomes and enables them to evaluate the possible effects of changes in important parameters. Table 3 displays the results of a sensitivity study that identified the mitigating technologies as being sensitive to various rates.

The mitigation technology B is still the value in where it doesn't change at any various rates starting at a 10% discount rate. It is demonstrated that mitigation technology G is sensitive to the discount rate, which is increasing at varying rates. However, in contrast to mitigation technology G, other mitigation technologies are also raising their

Table 3: Sensitivity analysis for MAC.

Mitigation Technology	MAC ($/tonne CO_2eq)									
	Discount rate									
	9%	10%	11%	12%	13%	14%	15%	16%	17%	18%
A	-7.3	-7.2	-7.2	-7.1	-7.0	-6.9	-6.8	-6.7	-6.6	-6.5
B	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
C	3.2	3.9	4.6	5.3	6.1	6.8	7.6	8.4	9.2	10.0
D	4.7	5.3	5.8	6.4	7.1	7.7	8.3	8.9	9.6	10.3
E	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.7
F	1.6	1.7	1.9	2.0	2.2	2.3	2.5	2.7	2.8	3.0
G	-0.07	0.49	1.06	1.65	2.25	2.86	3.48	4.11	4.75	5.40
H	-19.93	-19.61	-19.29	-18.96	-18.62	-18.28	-17.94	-17.58	-17.23	-16.87

A: High Efficiency Stream Turbine; B: POME-to-Biogas Electricity; C: Co-Composting

D: Solid-Liquid Separation; E: Biomass Waste Utilization; F: Biofuel Production

G: Biogas Upgrading; H: High-Capacity Boiler

parameter, just not as noticeably, and this does not affect their ranking.

CONCLUSIONS

This study aims to evaluate the eight mitigation technologies that contribute to making the estimated marginal abatement costs (MAC) of Indonesia's palm oil sector from 2020 to 2030. In conclusion, the prospects of implementing CO_2 mitigation technologies in the Rokan Hulu region of Riau are promising, with anticipated substantial reductions in emissions amounting to approximately 87,255 tonnes of CO_2 annually. Among the various technologies, biofuel production emerges as the most impactful contributor, spearheading the emissions reduction efforts with a significant share of 31.5% of the total reduction. This underscores the pivotal role of innovative approaches in biofuel production within the palm oil industry's sustainability agenda.

Following closely behind are POME-to-biogas electricity and biogas upgrading technologies, collectively contributing 30.5% to the emissions reduction endeavor. Their integration into the operational framework of palm oil producers demonstrates a multifaceted approach to emissions reduction, leveraging waste-to-energy solutions for environmental gain.

Moreover, the evaluation of marginal abatement costs reveals compelling insights into the economic feasibility of emission reduction technologies. Notably, high-efficiency steam turbine and high-capacity boiler technologies emerge as cost-effective options, presenting opportunities for both emissions reduction and potential cost savings. This underscores the importance of adopting technologically advanced solutions that align with both environmental and economic sustainability goals. Future research must take into account different perspectives, such as those related to renewable energy technology, carbon taxes, or subsidies, even though the costs of mitigation technologies have been examined in this study.

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