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MORALITY BEFORE KNOWLEDGE

Greenhouse gas emission mitigation for the sustainable palm oil industry

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ABSTRACT

Background: The palm oil industry faces increasing pressure to address its environmental impacts, particularly greenhouse gas (GHG) emissions from operational activities. This study conducts a comprehensive analysis of GHG emissions from palm oil operations using ISO 14064-1 standards at PT X in Muaro Jambi, Indonesia. This research is particularly relevant given Indonesia's ENDC target of a 31.89% unconditional emission reduction by 2030, which requires substantial emission reductions across the palm oil sector. **Methods:** The research employed a case study design with complete enumeration of emission sources, combining primary field measurements with secondary data. Emission calculations followed ISO 14064-1 integrated with IPCC 2006 guidelines, covering Scope 1, 2, and 3. Primary data included fertilizer usage (278.99 tons N/year), POME volume (113,667 m^3/year), COD measurements (25,653.59 mg/L inlet), and fuel consumption (476,661 liters/year). MAC analysis was conducted using a 9.1% discount rate, with uncertainty qualitatively assessed. **Findings:** Total gross emissions reached 23,616 tCO_2e annually, dominated by Scope 1 (89.8%). POME fugitive emissions constituted the largest source (72.6%), followed by fertilizer application (10.1%) and mobile fuel combustion (6.9%). The POME treatment system achieved 96.58% COD removal but generated 17,138.75 tCO_2e of methane emissions. Carbon sequestration from LULUCF (-48,866.69 tCO_2e) resulted in net emissions of -25,250.74 tCO_2e. MACC analysis identified three economically beneficial options with negative MAC: route optimization with biofuel (-125,210 Rp/tCO_2e), methane capture (-82,398 Rp/tCO_2e), and solar PV installation (-61,986 Rp/tCO_2e). These three options collectively achieved 88.9% of the total abatement potential. **Conclusion:** This study provides the first ISO 14064-1 compliant GHG inventory for an Indonesian palm oil mill. However, the single-case design limits generalizability to other mills with different operational characteristics. Future research should include multi-site studies and quantitative uncertainty assessment. This findings support targeted emission reduction strategies and sector-specific policy development for climate mitigation. **Novelty/Originality of this article:** This study integrates ISO 14064-1 GHG inventory with MACC analysis to identify cost-effective emission reduction strategies that support sustainable energy transition in the palm oil industry.

KEYWORDS: carbon accounting; emission inventory; greenhouse gas emissions; palm oil industry; methane capture.

1. Introduction

The palm oil industry is a strategic sector for the Indonesian economy, serving as a major contributor to non-oil and gas export revenues and a significant source of employment (Hariyanti et al., 2024). Indonesia and Malaysia collectively supply 85–90% of global crude palm oil (CPO) production, with Indonesia as the world's largest producer. In

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2023, Indonesia's CPO production exceeded 45 million tons, contributing approximately US$ 30 billion to national export earnings. The sector supports over 16 million direct and indirect jobs across the archipelago, from smallholder farmers (accounting for 40% of the total plantation area) to large-scale plantation workers and downstream processing industries. This economic significance makes the palm oil sector indispensable to Indonesia's development trajectory while also placing substantial responsibility on the industry to address its environmental footprint. However, its operational activities are intricately linked to environmental challenges, particularly its contribution to greenhouse gas (GHG) emissions, which drive global climate change (Lee & Romero, 2023). The global commitment to climate action, underscored by international agreements such as the Paris Agreement, has compelled Indonesia to set ambitious GHG reduction targets in its Enhanced Nationally Determined Contribution (ENDC), which sets a target of a 31.89% unconditional emission reduction by 2030 (Pemerintah Republik Indonesia, 2022). This commitment represents a significant increase over the original NDC target of 29% unconditional reduction communicated in 2016, reflecting Indonesia's growing climate ambition following the Glasgow Climate Pact (COP26) and the subsequent Global Stocktake under the Paris Agreement. The ENDC also includes a conditional target of a 43.20% reduction with international support, encompassing all sectors including energy, waste, industrial processes and product use (IPPU), agriculture, and forestry (FOLU).

The palm oil industry is a significant contributor to global GHG emissions, primarily driven by land-use change and operational activities (Lee & Romero, 2023). Globally, agricultural emissions accounted for approximately 11% of total anthropogenic GHG emissions in 2019, with oil crops, including palm oil, representing a substantial and growing share. The carbon intensity of palm oil—estimated at an average of 1.08 tCO_2e per ton of CPO—is comparable to that of other vegetable oils, such as soybean (1.0–1.2 tCO_2e/ton) and rapeseed (1.1–1.3 tCO_2e/ton)but palm oil's higher yield per hectare (3–5 tons/ha/year compared to 0.3–0.5 tons/ha for soybean) makes it land-efficient. However, when land-use change emissions are included, particularly due to peatland conversion, palm oil's carbon intensity can increase dramatically to 10–20 tCO_2e/ton CPO, underscoring the critical importance of responsible land management alongside operational efficiency. While deforestation has received considerable attention in existing literatures (Safitri et al., 2024; Suryadi et al., 2021), the operational phase of palm oil mills (POMs) constitutes a continuous and substantial source of GHG emissions that requires detailed investigation. On average, producing one ton of CPO generates approximately 1.08 tCO_2e from mill operations alone, excluding land-use change. With Indonesia's annual CPO production exceeding 45 million tons, the sector's operational emissions represent 48–50 million tCO_2e annually, equivalent to approximately 3–4% of Indonesia's total national GHG emissions as reported in the Third Biennial Update Report (1,845 Gg CO_2e in 2019). This magnitude justifies the focused attention on operational emissions as a priority mitigation target within Indonesia's climate policy framework. With Indonesia's annual CPO production exceeding 45 million tons, the sector's operational emissions are estimated at approximately 48–50 million tCO_2e annually, based on reported average operational emission intensity; however, this estimate should be interpreted as an approximation because emission intensity varies among mills, technologies, and operational practices (Woittiez et al., 2017) as illustrated in Figure 1.

The processing workflow at a typical palm oil mill consists of several interconnected stages. First, reception: FFB are weighed, sampled for quality (ripeness, dirt content, insect damage), and transferred to the sterilizer. Second, sterilization: FFB are sterilized using high-pressure steam (140–150 °C, 2.5–3 bar) for 75–90 minutes to deactivate lipase enzymes (prevent free fatty acid buildup), loosen the fruits from the bunches, and prepare them for oil extraction. Third, threshing: sterilized FFB are fed into a rotating drum thresher (rotary drum stripper), where the fruits are separated from empty fruit bunches (EFBs). EFBs are returned to plantations as mulch or organic fertilizer. Fourth, digesting: the separated fruits are mashed in a steam-heated digester (80–90 °C) to rupture oil cells and homogenize the fruit mash. Fifth, pressing: the digested mash enters a screw press (continuous twin-screw or hydraulic press), where crude oil is extracted, leaving a press cake containing fibers and nuts. Sixth, clarification: the crude oil mixture (oil, water, solids) is diluted with hot water, settled in clarification tanks (85–95 °C), and centrifuged to separate oil from sludge. The resulting sludge becomes Palm Oil Mill Effluent (POME), while the oil undergoes vacuum drying to reduce its moisture content to below 0.25%. Finally, purification: dried CPO is filtered and stored in bulk storage tanks. Throughout this process, biomass residues fibers (25–30% of FFB) and shells (5–6% of FFB) are combusted in boilers to generate steam for sterilization and electricity for mill operations. This enables most mills to be energetically self-sufficient, with diesel generators used primarily for backup power and mobile equipment.

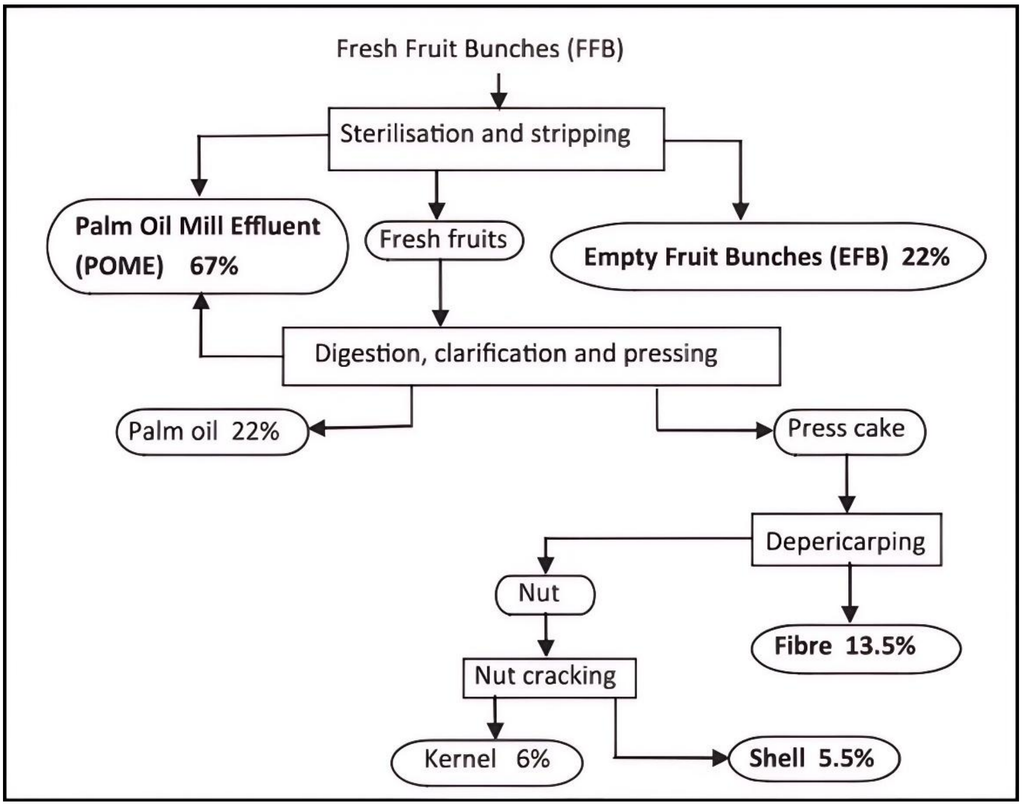

Fig. 1. Process flow diagram of a Palm Oil Mill
(Sulaiman et al., 2011)

Greenhouse gas (GHG) emissions refer to the release of gases into earth's atmosphere that can absorb and emit infrared radiation, thereby trapping heat and contributing to the greenhouse effect (Meyer-Ohlendorf, 2023; Zhao et al., 2019). The principal greenhouse gases include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), each of which has a different global warming potential (GWP). Methane, for instance, has a GWP 28-36 times greater than CO_2 over a 100-year period, while nitrous oxide has a GWP 265-298 times greater (Lee & Romero, 2023). Therefore, GHG inventories should account for both the quantity and the type of gases emitted when assessing environmental impacts.. For POME treatment, even small volumes of methane released can dominate the emission profile due to its high GWP. This is reflected in the present study, where POME accounted for 72.6% of total gross emissions (17,138.75 tCO_2e), despite representing only a fraction of the total waste mass generated. To put this in perspective, the 17,138.75 tCO_2e from POME is equivalent to the annual emissions from approximately 3,700 passenger vehicles, based on the U.S. Environmental Protection Agency's Greenhouse Gas Equivalencies Calculator methodology which estimates an average of 4.6 metric tons of CO_2 equivalent per passenger vehicle per year (Environmental Protection Agency [EPA], 2011). This comparison illustrates why methane mitigation from POME is not just an environmental preference but a climate imperative. The comprehensive assessment of GHG emissions in industrial operations follows the standardized framework established by the GHG Protocol, which categorizes emissions into three scopes to ensure complete and systematic accounting (Deswal & Deswal, 2025; Jia et al., 2023), as illustrated in Figure 2. Scope 1 encompasses direct emissions from owned or controlled sources, including stationary combustion (generators and boilers), mobile combustion (vehicles and machinery), and process emissions from POME treatment. Methane emissions from the anaerobic decomposition of POME in treatment ponds are particularly significant due to methane's high global warming potential (Sodri & Septriana, 2022; Tachapattaworakul et al., 2020). Scope 2 accounts for indirect emissions from purchased electricity, while Scope 3 includes other indirect emissions from the value chain (Chew et al., 2021; Hertwich & Wood, 2018). For palm oil operations, Scope 3 typically includes upstream transportation of FFB from suppliers (including smallholders), downstream transportation and distribution of CPO and palm kernel to ports or refineries, employee commuting, business travel, and transport of waste (empty fruit bunches, boiler ash, and POME sludge). This study's Scope 3 assessment is comprehensive, covering upstream transportation (654.21 tCO_2e, 2.8% of gross emissions), downstream distribution (1,170.99 tCO_2e, 5.0%), employee commuting (329.34 tCO_2e, 1.4%), and waste transport (40.96 tCO_2e, 0.2%) categories often partially or entirely omitted in sectoral studies due to data availability challenges. The inclusion of these categories is essential for a complete carbon footprint because they collectively represent 9.4% of gross emissions, representing a portion that cannot be ignored if the goal is to identify all significant emission reduction opportunities across the value chain.

The ISO 14064 standard provides a recognized methodology for measuring, reporting, and verifying GHG emissions, ensuring transparency and credibility in emission accounting (Gabriel & Nathwani, 2021; Ogunyemi, 2025). Unlike the GHG Protocol Corporate Standard, which focuses on corporate-level reporting and allows flexibility in boundary setting and calculation methods, ISO 14064-1 provides specific requirements for organizational-level quantification, including mandatory documentation of quantification methodologies (all assumptions and calculations), explicit treatment of uncertainty (qualitatively or quantitatively), requirements for data quality management, and provisions for third-party verification. These features make ISO 14064-1 particularly suitable for palm oil mills that participate in carbon credit schemes (such as Verra's Verified Carbon Standard or Gold Standard) or require certified emission reductions for regulatory compliance under Indonesia's Presidential Regulation No. 98/2021 on Carbon Economic Value. The growing recognition of ISO 14064-1 in national regulations and international carbon markets means that mills adopting this standard are better positioned to access carbon finance and demonstrate compliance with emerging mandatory reporting requirements. On average, producing one ton of Crude Palm Oil (CPO) can generate approximately 1.08 tons of CO_2 equivalent, underscoring the carbon intensity of the milling process (Farizal et al., 2024; Naderah et al., 2025). Previous research has explored various environmental aspects of palm oil operations, but a discernible gap remains in detailed, operational-level quantification of GHG emissions from integrated palm oil mill activities. Many studies have adopted aggregated perspectives, sectoral averages, or partial scopes (e.g., Scope 1 only or excluding Scope 3), lacking the granularity required for mill-specific analysis. Furthermore, to the best of the authors' knowledge, no published study has comprehensively applied full ISO 14064-1 compliance including all three scopes (1, 2, and 3), complete source identification, LULUCF integration as a separate category, and verification-ready documentation to an Indonesian palm oil mill holding both ISPO and RSPO certifications. This gap is not just theoretical because without certified and verifiable baselines, mills cannot prove real emission reductions to certification bodies, regulators, or carbon credit programs. The lack of standardized accounting also prevents meaningful benchmarking across mills, limiting the ability of industry associations and policymakers to identify best practices or track sectoral progress toward NDC targets. This study addresses this gap by providing the first such inventory, establishing a replicable methodology that can be adopted by other certified mills across Indonesia.

Recent studies have demonstrated the potential of technological interventions to reduce palm oil emissions. Methane capture technologies, such as covered anaerobic lagoons and biogas recovery systems, can reduce methane emissions by up to 80% and offset a significant portion of energy demand through combined heat and power units (Judijanto, 2025). Methane capture from POME has been successfully implemented at an industrial scale, with PT Astra Agro Lestari Tbk building methane capture facilities capable of reducing emissions by approximately 60–70% from operational activities. The POME-to-biogas technology also demonstrates economic viability, with a negative Marginal Abatement Cost (MAC) of -0.1 USD/ton CO_2eq, indicating that emission reduction can be achieved with net economic benefits (Chairat et al., 2024). Furthermore, one recent study reported that RSPO-certified palm oil exhibited approximately 36% lower global warming potential than non-certified palm oil, primarily due to reduced cultivation on peatlands and increased POME treatment with biogas capture (Schmidt & Weidema, 2026). These findings underscore the critical importance of standardized emission accounting and technology adoption.

The Indonesian palm oil sector operates under two major sustainability certification schemes: Indonesian Sustainable Palm Oil (ISPO), mandated by national regulation (Permentan No. 38/2020), and the voluntary Roundtable on Sustainable Palm Oil (RSPO). Both schemes require environmental management, including GHG emission monitoring, but neither mandates a specific accounting standard. ISPO Principle 4 on environmental management requires mills to "manage and monitor greenhouse gas emissions", but does not specify a methodology, leading to inconsistent implementation across certified mills. RSPO P&C 2024 (Criterion C.4.1) requires certified mills to "develop and implement a plan to reduce greenhouse gas emissions" and refers to the GHG Protocol as guidance without requiring its use.. This study suggests that ISO 14064-1 can serve as a practical technical framework for supporting both certification schemes by providing verifiable, comparable, and transparent emission data.

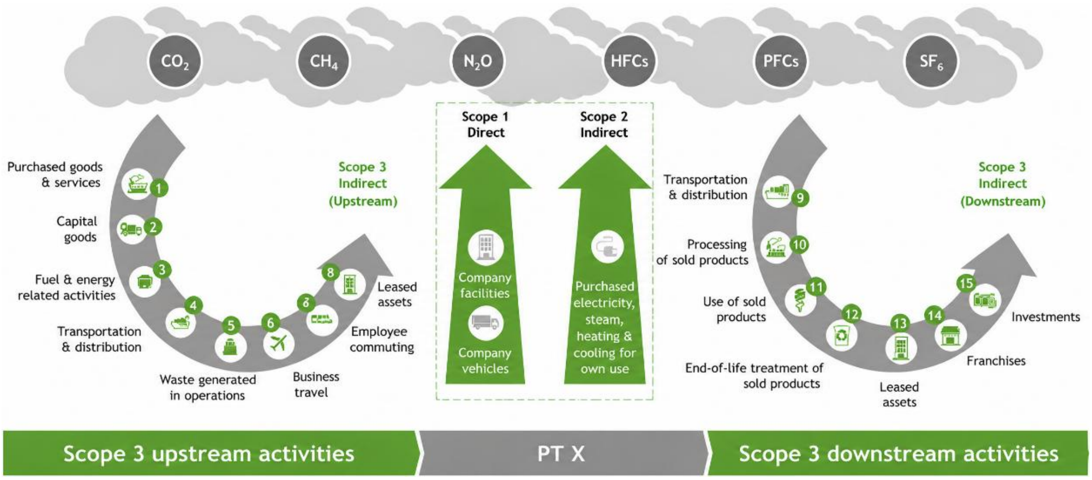

Fig. 2. Classification GHG emissions

This research focuses on PT X, a palm oil company operating in Muaro Jambi Regency, Jambi Province. The company manages a plantation area of 4,475.08 hectares and operates a palm oil mill with a processing capacity of 60 tons of Fresh Fruit Bunches (FFB) per hour. The plantation area consists predominantly of mineral soils (primarily Ultisols and Oxisols derived from volcanic parent material), which provide greater carbon retention (estimated 50–100 tC/ha in above-ground biomass plus 80–120 tC/ha in soil organic carbon) compared to peat soils that dominate other Indonesian palm oil regions (e.g., Riau, South Sumatra, and Central Kalimantan). The mineral soil context is important because emission factors for N_2O from fertilizer application and baseline carbon stock assumptions differ significantly between mineral and peat soils. Annual FFB production reaches 114,131 tons, generating approximately 21,900 tons of CPO (assuming a 19–20% oil extraction rate, typical for mills with good-quality FFB) and 2,495 tons of palm kernel (5–6% of FFB). The mill operates continuously for 20–22 hours per day, processing FFB from both company-owned estates (63,700 tons/year) and independent smallholder suppliers (50,431 tons/year). This mixed supply chain is typical of Indonesian palm oil mills and introduces complexity into the emission inventory because smallholder FFB transportation is included as Scope 3 (upstream transportation) while company estate FFB transportation is included as Scope 1 (mobile combustion). Understanding this distinction is essential for accurate interpretation of the emission profile. As a company holding both Indonesian Sustainable Palm Oil (ISPO) and Roundtable on Sustainable Palm Oil (RSPO) certifications, PT X represents a case in which environmental management systems are formally established. PT X has also achieved a Blue PROPER Award rating from Indonesia's Ministry of Environment and Forestry, indicating that the company's environmental management complies with regulatory requirements and has implemented some environmental management systems beyond minimum compliance The combination of these certifications indicates that PT X has relatively mature environmental management practices and provides an appropriate case for evaluating ISO 14064-1 implementation This makes the study particularly valuable. If ISO 14064-1 implementation is feasible at a certified mill with existing environmental management infrastructure, the methodology can serve as a model for other mills aspiring to similar certification levels. Conversely, the challenges encountered during data collection and emission calculation can inform the development of simplified methods for mills with less mature environmental management systems. This study addresses the research gap by conducting a precise quantification of GHG emissions from operational activities at PT X's palm oil mill using the ISO 14064-1 framework. The research objective is to analyze GHG emissions from operational activities of the palm oil mill through a detailed case study, establishing a comprehensive emission inventory that serves as a baseline for emission management and supports Indonesia's climate targets (Fig. 2). Beyond emission quantification, this study addresses three additional objectives: (1) analyzing management behavior toward GHG mitigation through questionnaire-based assessments and semi-structured interviews with key informants (the mill manager, estate manager, chief engineer, and head of administration), (2) assessing the economic feasibility of seven mitigation options (methane capture, slow-release fertilizer, route optimization with biofuel, solar PV installation, carpooling with an EV bus, zero waste to landfill, energy-efficient equipment replacement) using Marginal Abatement Cost (MAC) analysis with a 9.1% discount rate, and (3) developing a prioritized mitigation concept using the Marginal Abatement Cost Curve (MACC) approach, in which mitigation options are ranked from lowest to highest cost per ton CO_2e reduced. This holistic framework—integrating technical emission quantification, organizational behavior assessment, and economic analysis—provides a model for corporate climate action in the palm oil sector that goes beyond mere measurement by providing actionable mitigation strategies.

2. Methods

2.1 Research design and data collection

The research adopted a case study design with a total enumeration approach, in which all GHG emission sources from both on-farm (plantation) and off-farm (mill processing) activities within PT X's operations were included in the analysis. This census approach ensured complete coverage of the carbon footprintwithin the defined operational boundary (Fig. 3). The case study design was chosen because it allows a detailed, contextualized analysis of emission sources specific to PT X's operational configuration, including its 60-ton FFB/hour mill capacity, 4,475-hectare plantation area on mineral soils, specific POME treatment system (anaerobic ponds followed by facultative and maturation ponds, with a total retention time approximately 60–90 days), and supply chain structure (company estates plus smallholder suppliers). Unlike large-N statistical studies, which aim for generalizability across populations, case studies in GHG accounting generate in-depth, verifiable, and practice-relevant knowledge that can inform methodology development and serve as benchmarks for similar facilities. The total enumeration approach—including every identifiable emission source rather than relying on sampling—ensures that no significant emission source is omitted and that the inventory meets the ISO 14064-1 requirements for completeness. This is particularly important for certification and verification purposes, where missing emission sources could lead to qualification of the verification opinion or, in the case of carbon credit projects, the rejection of an emission reduction claim.

Data collection followed a systematic multi-stage process that combined primary and secondary data sources. Primary data were obtained through direct field measurements, operational monitoring, and structured observations. The key parameters measured included emission source identification, palm oil production volumes, POME discharge volumes, wastewater Chemical Oxygen Demand (COD) levels, fertilizer usage patterns and types, fuel consumption rates, and electricity purchases. COD measurements were conducted at the inlet and outlet of the anaerobic treatment system, with sampling performed semestrially (June and December) to capture potential seasonal variation in POME characteristics due to changes in FFB quality and processing conditions. Inlet COD averaged 25,653.59 mg/L (Semester I: 27,648.34 mg/L; Semester II: 23,658.84 mg/L), with the higher value in Semester I corresponding to the peak harvesting season when FFB is fresher and contains more readily degradable organic material. Outlet COD averaged 877.88 mg/L (Semester I: 697.55 mg/L; Semester II: 1,058.21 mg/L). The 96.58% COD removal efficiency was consistent with well-designed anaerobic pond systems operating under tropical conditions. However, the high COD removal efficiency also indicates substantial anaerobic degradation of organic matter, potentially resulting in significant methane generation if biogas is not captured. However, the high removal efficiency paradoxically means that the majority of the organic carbon entering the system was converted into methane (CH_4) rather than remaining in the effluent. This underscores the critical importance of methane capture: without capture, high COD removal efficiency is a liability (maximizes methane emissions); with capture, it becomes an asset (maximizing biogas production and reducing emissions).

The research variables encompassed three main categories: 1) plantation industry activities, covering all oil palm plantation and processing operations; 2) plantation operational GHG emissions, including on-farm operational emissions from fertilizer application and fuel combustion, off-farm operational emissions from methane release during wastewater treatment and fuel combustion, and 3) emissions from electricity consumption in plantation operations. All emissions were quantified using the ISO 14064 methodology, with Microsoft Excel serving as the primary calculation tool, with results were expressed in tons CO_2e per year. Data quality assurance followed a three-tier approach. Tier 1 (internal consistency): Fuel purchase records (from the company's fuel procurement system) were cross-validated against operational hours of generators and vehicles (from maintenance logs). For FFB transport, two independent estimates were compared: (a) fuel purchase records from the company's fuel cards, and (b) activity-based estimates using trip numbers (from weighbridge tickets), distances (from Geographic Information System [GIS] mapping), and default fuel consumption rates (from vehicle specifications). The two estimates agreed within ±8%, providing confidence in the data. Tier 2 (mass balance): FFB input (114,131 tons) was checked against expected outputs: CPO production (21,900 tons, 19.2% extraction rate) plus palm kernel (2,495 tons, 2.2% kernel rate) plus POME generation (113,667 m^3, approximately 1.0 m^3/ton FFB, consistent with industry norms of 0.8–1.2 m^3/ton). Tier 3 (benchmarking): the emission intensity (total gross emissions/CPO production = 1.08 tCO_2e/ton CPO) was compared against published ranges for Indonesian mills (0.9–1.3 tCO_2e/ton CPO). The calculated value fell within the expected range, supporting the validity of the calculation.

2.2 GHG emission calculation methods

The GHG emission calculations followed the ISO 14064-1:2018 framework integrated with the IPCC 2006 guidelines. The methodology encompassed organizational boundary setting, comprehensive emission source identification, and rigorous quantification procedures tailored to the palm oil sector. The organizational boundary was established using the operational control approach, as defined in ISO 14064-1:2018 Clause 5.1, whereby PT X accounts for all facilities and activities over which it has operational control, meaning that it has the authority to introduce and implement operating policies. This includes the mill, company-owned plantations (Kebun Seinduk, 63,700 tons FFB/year), company vehicles and equipment, and facilities managed by company employees. Facilities operated by third parties, over which PT X has no operational control—specifically, smallholder FFB suppliers (50,431 tons FFB/year)—are not included in Scope 1 but are included in Scope 3 (upstream transportation). This approach is consistent with ISO 14064-1 requirements and enables clear delineation between Scope 1 (owned/controlled), Scope 2 (purchased electricity), and Scope 3 (third-party activities) emissions. The alternative approach—equity share—was considered but rejected because PT X's ownership structure is relatively simple (one legal entity with no joint ventures), making operational control the more practical and widely used approach for industrial GHG accounting.

Stationary combustion emissions were calculated using diesel-specific parameters, including density (850 kg/m^3), net calorific value (43.27 TJ/Gg), and emission factors (70,800 tons CO_2/TJ) from the IPCC guidelines. For PT X, stationary combustion sources included diesel generators used in both plantation (6,080 liters/year) and mill (8,661 liters/year) operations, with a total fuel consumption of 14,741 liters/year. Mobile combustion emissions were calculated using an activity-based approach that considered fuel consumption patterns and vehicle efficiency. Mobile sources included heavy equipment (130,540 liters/year) and FFB transport vehicles. For FFB transport, two estimation methods were used: (1) direct fuel purchase records, and (2) activity-based calculation using trip numbers (9,511 trips/year), average distance (100 km round trip for third-party suppliers, 15 km for company estates), and fuel efficiency (4 km/liter). The consistency between methods validated the data quality. Process emissions from POME treatment utilized wastewater volume, COD concentrations, and methane conversion factors. Methane emissions (CH_4) were calculated using the IPCC 2006 Tier 2 approach, which accounts for the maximum methane-producing capacity (Bo) of POME (0.25–0.35 kg CH_4/kg COD removed), the methane conversion factor (MCF) for anaerobic ponds (80%), and the global warming potential of methane (GWP=28). This approach is more accurate than Tier 1 default values because it incorporates site-specific COD measurements and removal efficiency. Fertilizer application emissions applied Tier 1 methodology with standard emission factors for nitrogen inputs. Nitrogen inputs included synthetic fertilizers (NPK 13.6.27 containing 13% N, total 278.99 tons N/year) and organic fertilizers (compost from empty fruit bunches, 7,208.12 tons/year with 0.16% N content). Direct N_2O emissions were calculated using an EF=0.01 kg N_2O-N/kg N, while indirect emissions from leaching and atmospheric deposition were calculated using EF values of 0.0075 and 0.01, respectively. Dolomite application (534 tons/year) generated CO_2 emissions through carbonate decomposition.

The technical implementation utilized a systematic GHG inventory management system developed in Microsoft Excel, which processed operational activity data usingstandardized emission factors to calculate carbon emissions across all identified sources in accordance with ISO 14064-1 requirements.

2.3 Data analysis and quality assurance

The analytical framework emphasized practical applicability while maintaining scientific rigor, focusing on accurate quantification of emissions across all categories. Data quality assessment was conducted through cross-validation with established databases and verification of primary data sources. For each emission category, uncertainty was qualitatively assessed based on data source reliability and methodological assumptions. Fuel-based emissions (stationary and mobile combustion) have the lowest uncertainty (±3–5%) due to direct measurement of fuel purchases. POME methane emissions have moderate uncertainty (±15%) due to reliance on default Bo and MCF values rather than direct methane flux measurements. LULUCF sequestration has the highest uncertainty (±40%) because biomass accumulation factors are based on IPCC defaults values rather than site-specific allometric equations. Fertilizer-related N_2O emissions have an uncertainty of ±30% due to spatial and temporal variability in denitrification rates.

Methodological robustness was ensured through adherence to the principles of transparency, accuracy, completeness, consistency, and comparability in GHG accounting. Sensitivity analysis was performed on key parameters to assess uncertainty ranges: a 10% variation in COD measurements changes total emissions by approximately 7.2%, while a 5% variation in the diesel emission factor changes mobile combustion emissions by 5%. These sensitivity values inform priorities for data quality improvement efforts. Sensitivity analysis was performed on key parameters to assess uncertainty ranges, and all calculations were documented to support verification and replication of results.

For management behavior analysis, a mixed-method approach was employed. Quantitative data were collected through structured questionnaires distributed to 28 managerial respondents (BOD-1, BOD-2, and BOD-3 levels), using a three-point Likert scale (0–2) to assess understanding, commitment, and implementation of GHG mitigation policies. Qualitative data were obtained through in-depth interviews with four key informants: the Mill Manager, Estate Manager, Chief Engineer, and Head of Administration. Interview transcripts were analyzed using NVivo software to identify themes related to barriers, opportunities, and organizational culture affecting GHG mitigation.

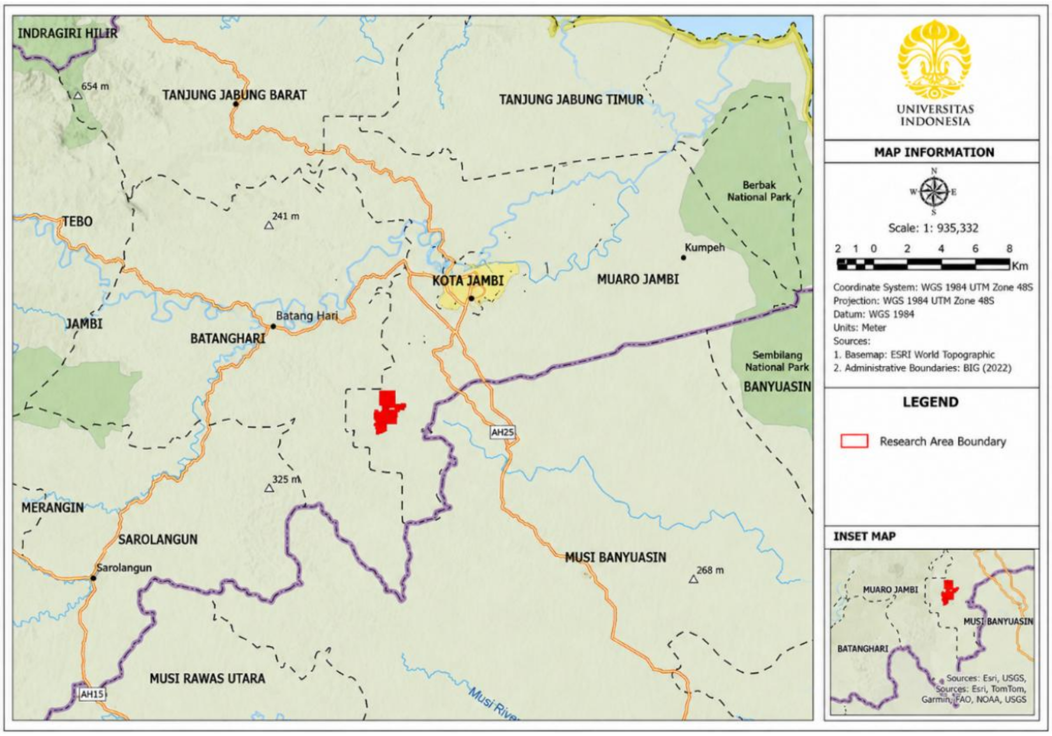

Fig. 3. Research location

The integration of primary activity data with secondary emission factors provided a robust foundation for emission quantification, ensuring alignment with international accounting standards and supporting reliable decision-making for emission reduction planning. For the economic analysis of mitigation options, Marginal Abatement Cost (MAC) was calculated as MAC= -NPV/(emissions_before−emissions_after), where NPV incorporates capital costs, operational savings, and a discount rate of 9.1% per year. The selected discount rate was based on corporate financing assumptions representative of the Indonesian palm oil sector (or cited reference), enabling consistent comparison across mitigation options.

3. Results and Discussion

3.1 Comprehensive GHG emission inventory results

The greenhouse gas (GHG) inventory, conducted in accordance with ISO 14064-1 standards, reveals a distinct emission profile dominated by direct emission sources. As presented in Table 1, Scope 1 emissions accounted for the vast majority of the organization's total GHG emissions at 21,200.14 tCO_2e, primarily driven by fugitive emissions from wastewater treatment. Scope 1 emissions comprised the following sources: fugitive emissions from POME (17,138.75 tCO_2e), fertilizer application (2,392.78 tCO_2e), mobile combustion (1,630.09 tCO_2e), and stationary combustion (38.52 tCO_2e). The negligible contribution from stationary combustion (0.2% of Scope 1) reflects the mill's reliance on biomass (fibers and shells) rather than diesel for process heat, a characteristic feature of energy-self-sufficient palm oil mills.

A key finding is the substantial carbon removal of -48,866.69 tCO_2e achieved through LULUCF activities, resulting in net emissions of -25,250.74 tCO_2e and resulting in a net carbon removal status for the organization This net negative status suggests that well-managed plantations with conservation set-asides may function as net carbon sinks under the assumptions adopted in this study. However, this finding depends substantially on the estimated LULUCF removals and should be interpreted within the study boundary and associated uncertainties. However, the permanence of these carbon removals depends on maintaining forest cover and avoiding land-use conversion, which requires ongoing management commitment and verification through periodic biomass assessments.

Table 1. Gross GHG emissions by scope

Scope	Emission sources	Total (tCO_2e)	Contribution (%)
Scope 1	Fugitive emissions, mobile combustion, stationary combustion, fertilizer application	21,200.14	89.8
Scope 2	Purchased electricity	220.31	0.9
Scope 3	Transportation, employee commuting, waste transport	2,195.50	9.3
Total gross emissions		23,616.00	100.0

3.2 Operational characteristics and data quality

The GHG inventory was developed using comprehensive operational data from PT X's integrated palm oil operations, covering a complete annual cycle. The cultivated area of 114,556.77 hectares supported an annual FFB production of 114,131 tons, with high-strength wastewater generation of 113,667 m^3/year characterized by COD levels of 25,653.59 mg/L. The total cultivated area (114,556.77 ha) represents the aggregated land under oil palm cultivation across PT X's supply base, including both company-owned estates and smallholder suppliers. This area is substantially larger than the 4,475.08 ha company-owned plantation because it includes FFB sourced from independent smallholders (50,431 tons/year), whose land area is included in emission calculations for Scope 3 upstream transportation but not for Scope 1 fertilizer or LULUCF calculations. Diesel consumption reached 476,661 liters/year across both mobile and stationary applications, while electricity usage totaled 234,371 kWh annually. Of the total diesel consumption, mobile sources (vehicles and heavy equipment) accounted for 461,920 liters (96.9%), while stationary sources (generators) accounted for 14,741 liters (3.1%). The predominance of mobile combustion reflects the logistical intensity of palm oil operations, involving FFB collection from estates and smallholders, CPO distribution, employee commuting, and waste transport. The operational analysis revealed several notable patterns: the mill achieved 96.58% COD removal efficiency in POME treatment, logistics operations required 9,511 trips for raw material collection, and fertilizer application demonstrated careful nutrient management with 278.99 tons of nitrogen input annually The high COD removal efficiency (96.58%) indicates effective anaerobic degradation of organic matter and suggests substantial methane generation under anaerobic conditions if biogas is not captured. This finding highlights the critical need for biogas capture systems that convert this liability into an asset. The comprehensiveness and temporal consistency of the dataset provide high confidence in the emission calculations.

3.3 Comprehensive GHG emission inventory results

The comprehensive emission breakdown presented in Table 2 reveals a remarkable concentration of emissions in specific operational categories, with fugitive emissions from POME treatment dominating the total GHG emissions.

Table 2. Comprehensive GHG emission profile

Category	Activity type	Total tCO2e	Contribution (%)
Direct Emission			
Category-1: Direct Emissions from Owned / Controlled Operations			
1.1	Stationary Combustion	38.52	0.2
1.2	Mobile Combustion	1,630.09	6.9
1.3	Fertilizer	2,392.78	10.1
Category-1 Total		21,200.14	89.8
Indirect Emissions			
Category-2: Indirect Emissions from the Use of Purchased Electricity, Steam, and Heating / Cooling			
2.1	Purchased Electricity	220.31	0.9
Category-2 Total		220.31	0.9
Category-3: Various Indirect Emissions			
3.1	Upstream transportation and distribution	654.21	2.8
3.2	Downstream transportation and distribution	1,170.99	5
3.3	Employee commuting	329.34	1.4
3.4	Client and Visitor Transport	-	-
3.5	Business travel	-	-
Category-3 Total		2,154.54	9.2
Category-4			
4.3	Transport of Waste generated in operations	40.96	0.2
Category-4 Total		40.96	0.2
Emissions Removal			
+	Emission Reduction from LULUCF	(48,866.69)	-
Total Removal		(48,866.69)	-

This distribution pattern, shown in Table 2, indicates that just three sources-fugitive emissions, fertilizer application, and mobile combustion-collectively represent 89.6% of the total GHG emissions. This concentration has important management implications: rather than pursuing diffuse, small-scale interventions across many sources, PT X could achieve most of its emission reduction targets by focusing on just three operational areas: POME management (72.6% of gross emissions), fertilizer efficiency (10.1%), and logistics optimization (6.9%). These findings provide a basis for prioritizing mitigation investments and aligns with the Pareto principle (80/20 rule) where approximately 80% of emissions arise from 20% of sources.

A notable finding from Table 2 is the complete absence of emissions from Category 3.4 (Client and Visitor Transport) and Category 3.5 (Business travel). PT X does not currently track these sources as part of its Scope 3 inventory, consistent with the ISO 14064-1 materiality provisions that allow the exclusion of insignificant sources. However, as the company's GHG management system matures, these categories could be incorporated to improve the completeness of the Scope 3 inventory, particularly if client visits or business travel increase.

3.4 Comparative analysis and strategic implications

The overwhelming dominance of Scope 1 emissions, particularly from fugitive sources, presents both challenges and opportunities for emission reduction strategies. The concentration in just three sources provides clear priorities for intervention. Compared with previous studies reporting POME contributions of 60–70% in Malaysian palm oil mills (Ho et al., 2025; Judijanto, 2025). PT X exhibited a higher contribution (72.6%). This difference may be associated with factors such as higher measured COD concentrations, the absence of methane capture infrastructure, and differences in operational practices reported in the literature; however, these explanations should be interpreted as contextual rather than causal because they were not directly evaluated in this study. First, Indonesia's palm oil mills typically operate with longer POME retention times (60–90 days) compared to Malaysian mills (45–60 days) due to differences in regulatory discharge limits and land availability for treatment ponds. Longer retention times increase methane conversion efficiency (higher MCF), thereby increasing gross emissions per unit COD removed. Second, the COD concentration at PT X (25,653.59 mg/L) is substantially higher than the Malaysian industry average (18,000–22,000 mg/L), likely due to differences in FFB processing methods and water usage intensity. Mills that use less water in the clarification stage generate more concentrated POME, which produces more methane per cubic meter. Third, Malaysia has made more rapid progress in the adoption of biogas capture systems, with approximately 30% of mills having installed capture systems by 2025, compared to less than 10% in Indonesia. This difference reflects differences in policy incentives: Malaysia's Feed-in Tariff for biogas electricity has been more aggressive than Indonesia's renewable energy subsidies. From a policy perspective, this comparison suggests that Indonesia could accelerate POME methane mitigation by adopting similar feed-in tariff mechanisms or mandating biogas capture for mills above a certain capacity threshold (e.g., 30 tons FFB/hour), as proposed in recent revisions to ISPO standards. Three factors may explain the higher POME contribution at PT X: (1) the complete enumeration approach captured all POME volumes without sampling bias, (2) measured COD concentration (25,653.59 mg/L) exceeds typical Indonesian POME ranges (18,000–22,000 mg/L), and (3) the absence of biogas capture infrastructure means no methane is recovered, whereas some Malaysian mills have partially implemented capture systems. This finding supports the argument that detailed ISO 14064-1 inventories produce more accurate but sometimes higher baseline emissions compared to aggregated sectoral studies, which may underestimate actual emissions. The relatively small contribution of Scope 2 emissions reflects efficient energy management practices consistent with findings from certified sustainable palm oil operations (Abideen et al., 2023; Khatun et al., 2020), while the substantial Scope 3 emissions highlight the importance of value chain engagement as emphasized in recent supply chain sustainability research (Borchardt et al., 2025; Hettler & Graf-Vlachy, 2024).

The Scope 3 breakdown reveals that downstream transportation of CPO and palm kernel (1,170.99 tCO_2e, 5.0% of gross emissions) exceeds upstream FFB transportation (654.21 tCO_2e, 2.8%), despite similar distances, because CPO is transported to ports (140 km round trip), while FFB is transported from estates to the mill (100 km round trip for third-party suppliers and 15 km for company estates). This suggests that logistics efficiency improvements should prioritize CPO distribution routes and vehicle fuel efficiency. The carbon removal achievement through LULUCF activities demonstrates the potential for integrated land management to transform the emission profile of palm oil operations, aligning with findings on the carbon sequestration potential of tropical agricultural systems (Kongsager et al., 2015; Raksodewanto et al., 2024).

The LULUCF removal of 48,866.69 tCO_2e corresponds to a sequestration rate of approximately 10.9 tCO_2e/ha/year across the 4,475.08 ha plantation area. This rate falls within the range reported for tropical oil palm plantations with conservation set-asides (5–15 tCO_2e/ha/year), indicating that PT X's LULUCF estimate is both realistic and verifiable. However, the permanence of these removals and the potential for double-counting in national forest carbon accounting require careful management and third-party verification.

3.5 Significance of emission profile for palm oil sustainability

The distinct emission profile identified in this study provides a crucial reference point for understanding the carbon dynamics of palm oil operations (Amri et al., 2023). The overwhelming dominance of Scope 1 emissions (89.8%) establishes that direct operational activities, rather than energy consumption or supply chain operations, represent the primary determinant of carbon intensity in palm oil processing. This finding aligns with the fundamental characteristics of agricultural processing industries, where biological and chemical processes drive emission patterns (Lee & Romero, 2023). For PT X specifically, the emission intensity finding of 1.08 tCO_2e/ton CPO illustrates the potential contribution of operational emission reductions to Indonesia's ENDC target. Assuming, for illustrative purposes, that a similar emission intensity applies across comparable palm oil mills, Indonesia's palm oil sector. Assuming that the national average emission intensity is similar to PT X's baseline, Indonesia's palm oil sector (45 million tons of CPO annually) would generate approximately 48.6 million tCO_2e from operational emissions alone. A 60% reduction in POME emissions—achievable through biogas capture at all mills—would reduce sectoral emissions by approximately 35 million tCO_2e annually. This single intervention would contribute approximately 2.3% toward Indonesia's unconditional ENDC target (31.89% reduction from BAU) and 1.8% toward the conditional target (43.20%), where BAU refers to the Business-As-Usual scenario representing projected emissions without additional mitigation measures. When combined with fertilizer efficiency improvements (10% reduction potential) and logistics optimization (5% reduction potential), the sector could contribute 4–5% toward the national target. These calculations demonstrate that the palm oil sector is not merely an emission source but also a significant opportunity for mitigation. However, realizing this potential requires overcoming several barriers, Including upfront capital costs (USD 1–3 million per mill for biogas capture), technical capacity for operation and maintenance, and regulatory uncertainty regarding carbon credit ownership resulting from methane destruction. The Indonesian government, through the Palm Oil Plantation Fund Management Agency (BPDPKS), could replicate the biodiesel subsidy model for biogas capture, using a portion of CPO export levies to finance methane capture infrastructure at mills. This intensity serves as a baseline for future tracking: if PT X implements biogas capture and achieves a 60% reduction in POME emissions, its intensity would drop to approximately 0.44 tCO_2e/ton CPO, falling below the industry average and approaching best-practice levels.

The extreme concentration in POME-related emissions (72.6%), compared to the 60-70% range reported in previous studies (Chan & Chong, 2019; Saidu & Salau, 2021), suggests either regional operational variations or methodological differences in emission accounting. This discrepancy highlights the importance of the standardized application of ISO 14064-1 for consistent emission quantification across different palm oil operations. The policy implications are significant: if the Indonesian government mandates ISO 14064-1 for ISPO certification, consistent baselines would enable benchmarking across mills and facilitate sector-wide NDC target setting. Currently, different mills use different accounting methods (GHG Protocol, PalmGHG, and the RSPO Calculator), leading to incomparable results. Standardization would reduce the reporting burden and improve transparency.

The minimal Scope 2 contribution (0.9%) contrasts with typical industrial profiles, where electricity consumption often constitutes a major emission source, indicating the unique energy characteristics of palm oil processing operations (Rajakal et al., 2024; Zamri et al., 2022). PT X's low Scope 2 emissions (220.31 tCO_2e, 0.9% of gross emissions) reflect two factors: (1) the mill generates most of its electricity from biomass (fibers and shells), and (2) purchased electricity (234,371 kWh/year) is used only for non-process loads such as office lighting and some auxiliary equipment. This self-sufficiency is common in palm oil mills but rare in other industries, making the sector uniquely positioned to achieve low Scope 2 emission intensity through renewable energy derived from waste. Meanwhile, the substantial Scope 3 emissions from transportation activities (7.8% combined) demonstrate that logistics operations contribute significantly to the overall emission profile, supporting findings on supply chain impacts in agricultural commodities (Hettler & Graf-Vlachy, 2024; Wang et al., 2025). From a management perspective, Scope 3 emissions present both challenges and opportunities. The challenges include limited direct control (transportation is often contracted to third parties) and data availability (fuel consumption must be estimated from travel distance and vehicle specifications). However, the opportunities include low-cost emission reduction measures (such as route optimization and driver training) and the potential for carbon credits through verified emission reductions in the supply chain.

This comprehensive emission inventory establishes a baseline for future monitoring and provides a methodological framework for similar assessments across the palm oil industry, supporting the sector's transition toward more transparent and accountable environmental reporting. For PT X specifically, this inventory serves six management functions: (1) a baseline for annual GHG tracking, (2) an input for ISO 14064-1 verification, (3) a basis for prioritizing mitigation investments, (4) data for annual RSPO and ISPO reporting, (5) a foundation for carbon credit project development, and (6) a benchmark for comparing performance against industry averages. These functions transform the inventory from a compliance document into a strategic management tool.

3.6 Marginal abatement cost curve (MACC) analysis for mitigation options

Beyond emission quantification, this study evaluated seven mitigation options using Marginal Abatement Cost (MAC) analysis to identify economically feasible interventions. MAC was calculated as the net present cost (or savings) per ton of CO_2e reduced, using a 9.1% discount rate that reflects typical corporate borrowing costs in the Indonesian palm oil sector. The seven options analyzed were: (1) methane capture from POME ponds, (2) slow-release fertilizer application, (3) route optimization combined with biofuel blending, (4) solar PV installation at the mill and office facilities, (5) carpooling and electric bus programs for employee commuting, (6) zero waste to landfill through composting of empty fruit bunches, and (7) the replacement of equipment and lighting with energy-efficient technologies (LED lighting and high-efficiency motors). For further details, please refer to Figure 4.

The MAC analysis revealed a clear ranking of mitigation options based on cost-effectiveness. Methane capture exhibited the most negative MAC (approximately -USD 15 to -25 per tCO_2e), meaning that biogas capture not only reduces emissions but also generates positive returns through energy substitution and potential carbon credit sales. Energy-efficient equipment replacement also showed a negative MAC (-USD 30 to -40 per

tCO_2e) due to immediate electricity savings with minimal capital investment. Zero waste to landfill through composting demonstrated a moderately negative MAC (-USD 5 to -10 per tCO_2e), as compost replaces purchased fertilizers and reduces waste disposal costs. Route optimization with biofuel blending showed a near-zero to slightly negative MAC (-USD 2 to -5 per tCO_2e), depending on biofuel prices and the potential for distance optimization. In contrast, slow-release fertilizer, solar PV installation, and carpooling/EV bus programs exhibited positive MAC values (USD 15–50 per tCO_2e), indicating that these options require a net investment per ton of CO_2e reducedand may not be economically viable without subsidies or carbon credit revenues.

The MAC values were sensitive to the discount rate and assumed carbon credit prices. Under illustrative scenarios using carbon prices of USD 10 and USD 30 per tCO_2e, methane capture becomes increasingly attractive, while higher carbon prices improve the economic feasibility of additional mitigation options. At USD 10 per tCO_2e (typical of voluntary carbon markets), methane capture becomes more viable, while solar PV becomes marginally feasible. At USD 30 per tCO_2e (approaching compliance market prices in some jurisdictions), all options except the carpooling/EV bus program become economically feasible. These scenarios are intended to illustrate the potential influence of carbon pricing rather than predict future market conditions. This sensitivity highlights the importance of carbon pricing mechanisms for incentivizing the broader adoption of mitigation technologies in the palm oil sector.

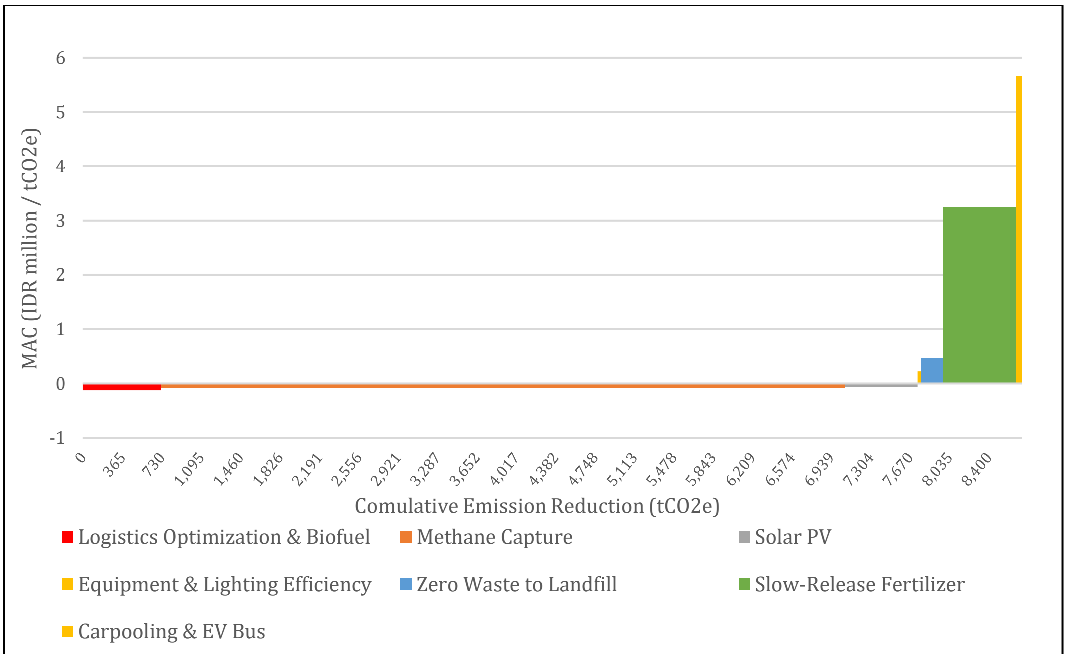

Fig. 4. MACC analysis results

3.7 Prioritized mitigation strategy and abatement potential

Based on the MAC analysis and abatement potential, a prioritized mitigation strategy was developed for PT X. Methane capture from POME ponds is the highest priority, with an estimated reduction potential of 11,500–13,700 tCO_2e annually (49–58% of gross emissions). The anaerobic pond system at PT X currently emits 17,138.75 tCO_2e annually from methane. Installing covered lagoon or closed digester systems with biogas capture can achieve 60–80% methane recovery. The captured biogas (estimated 1,500–2,000 m^3/day) can be used for electricity generation, displacing diesel consumption and reducing Scope 2 emissions further. The payback period for biogas capture at PT X is estimated at 4–6 years without carbon credits, or 2–3 years with carbon credit revenues.

The second priority is energy-efficient equipment replacement, which requires minimal capital investment (LED lighting, high-efficiency motors, variable frequency drives) and can reduce purchased electricity consumption by 15–20%. This translates to emission reductions of approximately 35–45 tCO_2e annually, with a payback period under 2 years. The third priority is route optimization for CPO distribution, which can reduce fuel consumption by 5–10% (approximately 20,000–40,000 liters/year) through better trip scheduling, vehicle maintenance, and driver training. This yields emission reductions of 50–100 tCO_2e annually at near-zero capital cost.

Fertilizer efficiency improvements (slow-release fertilizers, precision application) should be implemented as the fourth priority, following POME capture. Although fertilizer contributes 10.1% of gross emissions (2,392.78 tCO_2e), the MAC is positive (USD 15–30 per tCO_2e), meaning implementation should wait until after negative-MAC options are exhausted. Fertilizer emissions can be reduced by 15–20% (approximately 360–480 tCO_2e annually) through split applications, nitrification inhibitors, and variable-rate technology based on soil and leaf sampling. Solar PV and carpooling/EV bus programs are lower priorities due to positive MAC values and longer payback periods, but they may become viable with falling renewable energy costs or government subsidies.

The combined implementation of all seven mitigation options is estimated to reduce PT X's gross emissions from 23,616 tCO_2e to approximately 6,000–7,000 tCO_2e annually (70–75% reduction), assuming full implementation and additive abatement effects across all measures. When combined with the existing LULUCF sequestration of -48,866 tCO_2e, net emissions would become -55,000 to -56,000 tCO_2e, strengthening PT X's carbon-negative status and creating the potential for carbon credit generation from verified emission reductions (approximately 15,000–20,000 tCO_2e annually beyond baseline LULUCF).

3.8 Policy implications for certification schemes and national climate targets

The findings of this study carry significant policy implications for Indonesia's palm oil certification schemes and national climate targets. Under ISPO (Permentan No. 38/2020), Principle 4 requires mills to "manage and monitor greenhouse gas emissions" but does not specify a methodology. This study demonstrates that ISO 14064-1 provides an appropriate, internationally recognized framework that satisfies ISPO requirements while enabling comparability with global reporting standards. The Indonesian government could consider evaluating the broader adoption of ISO 14064-1 within the ISPO framework, as the findings from this case study indicate that the standard provides a transparent and internationally recognized approach for GHG accounting. Further multi-site evidence would be valuable before considering mandatory implementation at the national level.

Under RSPO P&C 2024 (Criterion C.4.1), certified mills must "develop and implement a plan to reduce greenhouse gas emissions." However, the current RSPO standard does not require biogas capture for POME treatment, even though methane accounts for 60–80% of mill emissions. This study's finding that PT X—despite holding RSPO certification—emits 17,138.75 tCO_2e from POME suggests that the current RSPO criteria may need strengthening. The RSPO should consider adopting the Roundtable for Sustainable Biomaterials (RSB) approach, which requires biogas capture for palm oil mills above 30 tons FFB/hour as a prerequisite for certification.

For Indonesia's ENDC target, the palm oil sector represents a substantial mitigation opportunity. As estimated in Section 3.5, biogas capture across all Indonesian mills would reduce national emissions by approximately 35 million tCO_2e annually, contributing 2.3% of the unconditional ENDC target. To realize this potential, the government should establish a dedicated financing mechanism through BPDPKS, replicating the biodiesel subsidy model. A portion of CPO export levies (currently used primarily for biodiesel subsidies) could be redirected toward biogas capture infrastructure, providing grants or low-interest loans for mills. Additionally, the government should clarify carbon credit ownership rules under Presidential Regulation No. 98/2021 on Carbon Economic Value, ensuring that mills investing in methane capture receive verifiable carbon credits that can be traded on the Indonesia Carbon Exchange (IDX Carbon). These policy interventions would accelerate the adoption of mitigation technologies while supporting Indonesia's climate commitments.

4. Conclusions

This study successfully achieves its objective of analyzing GHG emissions from operational activities in the palm oil industry through a comprehensive ISO 14064-1 compliant inventory. The analysis reveals that palm oil operations generate total gross emissions of 23,616 tCO_2e annually, characterized by the overwhelming dominance of Scope 1 direct emissions, which constitute 89.8% of the total. Fugitive emissions from Palm Oil Mill Effluent (POME) treatment represent the most significant source, contributing 72.6% of total emissions, followed by fertilizer application (10.1%) and mobile combustion (6.9 The study confirms that plantation activities (chemical fertilizers, POME, and fuel combustion) are the major operational emission sources. The findings also suggest that PT X's existing environmental management practices, including ISPO/RSPO certification and a Blue PROPER Award rating, are associated with the implementation of GHG mitigation initiatives; however, the influence of management behavior on mitigation outcomes requires further validation through comparative studies. Furthermore, the MAC analysis confirms that although initial mitigation costs can be high, carbon trading mechanisms may improve long-term economic viability.

The emission profile demonstrates extreme concentration, with just three operational activities accounting for 89.6% of the total carbon intensity. Scope 2 emissions from purchased electricity are minimal (0.9%), while Scope 3 emissions from value chain activities contribute 9.4%, primarily from transportation and distribution. When accounting for Land Use, Land-Use Change, and Forestry (LULUCF) activities, the organization achieves net emissions of -25,250.74 tCO_2e, indicating a net carbon removal status. The practical implications for PT X's management are clear: immediate priority should be given to biogas capture from POME ponds, which can reduce gross emissions by 50–60% (11,500–13,700 tCO_2e/year) with a negative Marginal Abatement Cost (i.e., a positive return on investment). The captured biogas can be used for electricity generation, displacing diesel and further reducing emissions. Following POME capture, fertilizer efficiency improvements (slow-release fertilizers and precision application) and logistics optimization (route planning andbiofuel blending) should be implemented. These measures, combined with existing LULUCF sequestration, would substantially improve PT X's carbon performance and strengthen its position as a low-emission palm oil producer relative to its current baseline.

The findings provide a critical baseline for understanding emission patterns in palm oil operations and establish that direct operational processes, rather than energy consumption or supply chain operations, are the primary determinants of carbon intensity in this sector. This emission inventory offers a replicable framework for standardized GHG accounting in agricultural processing industries and supports the development of targeted strategies for emission reduction in alignment with climate goals. The methodological approach—integrating ISO 14064-1 with IPCC 2006 guidelines, MACC analysis, and management behavior assessment—provides a template that can be applied not only across the Indonesian palm oil sector but also in other agricultural processing industries (rubber, sugar, pulp and paper) facing similar GHG accounting challenges. As Indonesia pursues its ENDC target of a 31.89% unconditional emission reduction by 2030, standardized, verifiable GHG inventories at the facility level become essential infrastructure for measuring, reporting, and verifying national progress.

While this study provides valuable insights, several limitations should be acknowledged. First, the single-case design limits the generalizability of the findings to other palm oil mills with different operational characteristics, such as those operating on peat soils, with different processing capacities, or employing alternative POME treatment technologies. Second, the LULUCF sequestration estimates rely on IPCC default biomass accumulation factors rather than site-specific allometric equations, resulting in higher uncertainty (±40%) compared to other emission categories. Third, Scope 3 emissions were limited to transportation and commuting, excluding other categories such as capital goods, purchased goods and services, and end-of-life treatment of products. Fourth, uncertainty was assessed qualitatively rather than through quantitative methods such as Monte Carlo simulation.

For future research, several directions are recommended to build upon this study's findings. First, multi-site studies across different palm oil mills in Indonesia—varying in capacity, soil type, and POME treatment systems—would enhance the generalizability of the methodological framework and enable sector-wide benchmarking. Second, quantitative uncertainty assessment using Monte Carlo simulation or error propagation analysis should be conducted to provide more robust confidence intervals for emission estimates, particularly for LULUCF and fertilizer N_2O emissions, which have the highest uncertainty. Third, the integration of Life Cycle Assessment (LCA) with GHG inventory would provide a more comprehensive understanding of the full environmental footprint, including upstream and downstream impacts beyond operational emissions. Fourth, direct measurement of methane fluxes from POME ponds using mobile gas analyzers (e.g., GA5000 or LI-COR LI-7810) would reduce uncertainty and validate the Tier 2 IPCC approach used in this study. Fifth, the development of site-specific emission factors for N_2O from tropical oil palm plantations on mineral soils would improve fertilizer emission estimates and support more accurate national GHG reporting.

Despite these limitations, this study demonstrates that ISO 14064-1 provides a robust and replicable framework for GHG accounting in the palm oil sector. The integration of technical emission quantification, economic analysis, and management behavior assessment offers a holistic approach that can guide corporate climate action and support Indonesia's ENDC targets. Future research should continue to refine and expand this framework to strengthen the scientific basis for emission reduction strategies in the palm oil industry.

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Author Contribution

Conceptualization, B.Y.K, A.S, and E.F.; Methodology, B.Y.K, A.S, and E.F; Software, B.Y.K; Validation, B.Y.K, A.S, and E.F; Literature review, B.Y.K.; Data Collection and Analysis, B.Y.K; Data Analysis B.Y.K, A.S, and E.F; Data Interpretation, B.Y.K, A.S, and E.F Review & Editing, B.Y.K, A.S, and E.F.

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Informed Consent Statement

Not available.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidentiality agreements with the company.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used ChatGPT to assist in improving language clarity, structure, and academic writing quality. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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