Methane in Malaysia:

A Report on Sources, Data, and Research Needs

Yusri Yusup, Ph.D.

Mohd Talib Latif, Ph.D.

Nor Diana Abdul Halim, Ph.D.

Mohd Shahrul Mohd Nadzir, Ph.D.

Haris Hafizal Abd Hamid, Ph.D.

Murnira Othman, Ph.D.

Maggie Ooi Chel Gee, Ph.D.

Ehsan Jolous Jamshidi, M.Sc.

Choong Kah Hua, B.Tech.

Report No. 01/2025

December 2025

Available at: https://indtech.usm.my/index.php/info-gateway/downloads/92-research?download=650:methane-in-malaysia-v01-2025

Corresponding Author:
Yusri Yusup
Email: yusriy@usm.my

Suggested Citation:
Yusup, Y., Latif, M.T., Abdul Halim, N.D., Mohd Nadzri, M.S., Abdul Hamid, H.H., Othman M., Ooi, M., Jamshidi, E.J., and Choong, K.H. 2025. *Methane in Malaysia: A Report on Sources, Data, and Research Needs* (Report No. 01/2025). School of Industrial Technology, Universiti Sains Malaysia.
https://indtech.usm.my/index.php/info-gateway/downloads/92-research?download=650:methane-in-malaysia-v01-2025

Funding Acknowledgement
This report was funded by the Environmental Defense Fund (EDF).
The authors gratefully acknowledge EDF's support in enabling the research and analysis presented herein.

Executive Summary

This study aims to identify critical research gaps in current knowledge on methane emissions in Malaysia. Employing an integrated approach that combines meta-analysis, natural language processing, data survey, and multi-criteria decision analysis, the research uncovers 16 knowledge gaps derived from an extensive review of existing literature and methane monitoring initiatives. Notably, research on methane emission factors in Malaysia exhibits a sectoral bias, with an overemphasis on Agriculture, Forestry, and Other Land Use, and Waste, potentially overlooking comprehensive emissions data across all sectors. Furthermore, the Fourth Biennial Update Report (BUR4) highlights an over-reliance on Tier 1 emission factors in the energy sector, which may compromise the accuracy of emission estimates.

A significant lack of up-to-date activity data, coupled with issues like the omission of natural gas venting data and reliance on outdated surveys, challenges accurate emission assessments. Regarding methane monitoring, while efforts have been made, Malaysia faces obstacles in establishing consistent baselines due to operational issues and infrequent monitoring stations. Additionally, despite the potential for advanced monitoring through remote sensing technologies, research in this domain is still limited.

In terms of greenhouse gas (GHG) reporting, Malaysia leans heavily on Tier 1 emission factors and occasionally borrows data from neighbouring countries. Regulatory standards for methane control remain non-mandatory, and issues of data availability persist, including limited public accessibility, confidentiality concerns, and operational challenges. Challenges in reducing methane emissions in Malaysia span financial constraints, stakeholder engagement, data sharing limitations, and the slow adoption of renewable energy in the private sector. The lack of established guidelines and a limited focus on methane research further compound these challenges.

To address these multifaceted challenges, the study introduces a framework that categorises knowledge gaps into high and low severity levels. High-level initiatives stress the importance of comprehensive interdisciplinary research to facilitate stakeholder engagement and effective solutions. Recommendations include spatiotemporal monitoring through advanced technology, site-level sampling, and enhanced data sharing to elevate monitoring and reporting precision. In contrast, low-level knowledge gaps advocate for the development of a Methane Inventory Database and the selection of a secure storage platform for methane emission data. These measures aim to streamline accurate data collection, support research endeavours, and foster collaboration.

This report presents a comprehensive assessment on methane emissions in Malaysia, offering a roadmap for collaboration, precise measurement, and effective strategies in the global effort to combat climate change.

Table of Contents

Executive Summary....3
List of Figures....6
List of Tables....7
1. Methane as A Greenhouse Gas: Properties, Sources, and Climate Impact....8
The Global and Malaysian Methane Research Landscape....8
The Need for Improved Methane Measurement and Reporting in Malaysia....10
Report Objectives....10
2. Methodological Framework for Methane Data Gap Analysis....10
Identification of the Initial Gap....12
Meta-Analysis....12
Natural Language Processing....13
Data Survey....13
Multi-Criteria Decision Analysis....15
3. Published Reporting Levels of Methane....16
Emission Reporting in The Fourth Biennial Update Report (BUR4)....16
Emission Reporting: Tiers 1 to 3 Emission Factors Adoption....22
Emission Reporting: Activity Data Sources....28
Current and Ongoing Methane Measurement Work....29
Methane Monitoring....29
Methane Data Availability....37
Challenges in Introducing More Methane Measurements....39
The Severity Level of Gap Findings....41
What's next: Moving Forward....44
4. Conclusions....48
Acknowledgements....50
References....51
Appendices....57
Appendix A: Published Emission Factor....57
Appendix A -1: Energy | Fuel Combustion Activities | Combined Heat and Power Generation....69
Appendix A -2: AFOLU | Livestock | Enteric Fermentation....71
Appendix A - 3: AFOLU | Pineapple Cultivation....72

Appendix A - 4: AFOLU | Drained Organic Soil | Sago Plantation 75
Appendix A - 5: AFOLU | Peat lands | Oil Palm Plantation 76
Appendix A - 6: AFOLU | Peat lands | No vegetation 81
Appendix A - 7: AFOLU | Peat lands | Mixed Peat Swamp Forest 82
Appendix A - 8: AFOLU | Peat lands | Alan Batu Forest (Undisturbed) 84
Appendix A - 9: AFOLU | Peat lands | Alan Bunga Forest (Relatively Disturbed) 90
Appendix A - 10: AFOLU | Peat Fires 96
Appendix A - 11: AFOLU | Rice Cultivation 97
Appendix A - 12: AFOLU | River Basins 99
Appendix A - 13: Waste | Wastewater Treatment and Discharge - Industrial 100
Appendix B: Data Survey 101
Appendix B - 1: List of Stakeholders identified. 101
Appendix B - 2: Responses per Sector 103
Appendix C: Drone Services 114

List of Figures

Fig. 1. Research workflow: Tier 1 denotes the default IPCC values (Rypdal et al. 2006). Agencies include government and private entities; NLP denotes Natural Language Processor. 11
Fig. 2. Summary of the data collected from email surveys and interviews...15
Fig. 3. Methane emission distribution categorised into different sectors: (a) Waste, (b) Energy, (c) AFOLU (Livestock), (d) AFOLU (Land Use) and (e) IPPU (Malaysia, 2022). 18
Fig. 4. Publicly available datasets. 21
Fig. 5. Level of emission factor for four main sectors namely, Energy, Industrial Processes and Product Used (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), and Waste with their subcategories.............25
Fig. 6. Summary of gap findings in Malaysia's current published reported level regarding the emission factor. 28
Fig. 7. Summary of gap findings in Malaysia's current published reporting level regarding activity data. .29
Fig. 8. Methane continuous monitoring stations in Malaysia operated by Department of Environment (DOE), Malaysia Meteorological Department (METMalaysia), and the Natural Environment Research Council with a collaboration of Universiti Malaya (NERC-UM). Since 1996, the DOE has set up 26 stations with methane monitoring instruments. However, the methane monitoring by the DOE stopped in 2010. Then the NERC-UM started to monitor methane ambient concentration continuously in 2015 but only at one station located in Bachok, Kelantan. Meanwhile, the METMalaysia started monitoring in 2022. The location includes (1) Cameron Highlands, Pahang; (2) Langkawi, Kedah; (3) Sarawak; and (4) Lembah Danum, Sabah in 2022. The instrument is the ABB LGR Analyser, reporting in ppm. 32
Fig. 9. Summary of gap findings in Malaysia's current methane measurement. 36
Fig. 10. Summary of gap findings in Malaysia's current methane data availability...................................38
Fig. 11. Summary of gap findings in challenges in introducing more methane measurement in Malaysia. 40
Fig. 12. The severity level of the gap findings in methane measurements in Malaysia. 41
Fig. 13. Climate Change Institutional Arrangements and Thematic Working Groups (Malaysia 2022). ...104

List of Tables

Table 1 Emission factor is defined by three levels, based on IPCC 2006 Guidelines. 8
Table 2 The list of criteria used to determine the severity of the gap findings. 16
Table 3 Methane emissions by sectors and Tiers. AFOLU - Livestock under Tier 1 excludes the enteric fermentation for other cattle, while Waste under Tier 1 level excludes the waste for Palm Oil Mill Effluent (POME). Both uses Tier 2 Emission Factors. 23
Table 4 Methane measurement methods with data coverage in Malaysia. 30
Table 5 Previous studies in Malaysia that conducted methane mapping. 34
Table 6 Methane data availability in Malaysia...37
Table 7 Challenges and difficulties encountered by different groups of stakeholders in Malaysia. 39
Table 8 The potential research plan based on the high-level severity gap of knowledge in methane measurements in Malaysia. 44
Table 9 The potential research plan based on the low level of severity gap of knowledge in methane measurement in Malaysia...46

Table A - 1 Extracted emission factor from published journal article. Dark khaki (yellow) indicates Tier 1 while green indicates Tier 2 and Crayola (yellow) indicates Tier 3. 57

Table A - 1 - 1 Methane emission factor for various combustion technologies. 69

Table B - 1 - 1 List of stakeholders identified. Last updated in December 2023. 101

Table C - 1 - 1 Drone services available. Last updated in December 2023. 114

1. Methane as A Greenhouse Gas: Properties, Sources, and Climate Impact

The increasing concentration of greenhouse gases, or GHGs, in the Earth's atmosphere has become a pressing concern for scientists, policymakers, and the global community. While carbon dioxide (CO_2) has long been the primary focus of climate change discussions, methane's potency as a short-lived climate pollutant demands immediate attention (Bollinger et al. 2021). Methane (CH_4) accounts for approximately 16% of the total greenhouse gas emissions (Xu et al. 2021, Rafalska et al. 2023).

Methane is a colourless, odourless gas and a primary component of natural gas. It is released into the atmosphere through both natural processes and human activities. While natural sources, such as wetlands and termites (Parker et al. 2018, Nauer et al. 2018), contribute significantly to methane emissions, anthropogenic activities like agriculture, livestock production, fossil fuel extraction, and waste management have escalated methane concentrations to unprecedented levels (Leifer et al. 2013, Heede and Oreskes 2016, Ito et al. 2019, Glasson et al. 2022, Liu et al. 2023). Furthermore, in tropical conditions, such as in Malaysia and Southeast Asia, methane can be released by large areas of wetlands and agricultural plots (Deshmukh et al. 2020).

The consequences of elevated methane levels are far-reaching and complex, influencing climate and atmospheric chemistry. Despite its shorter-than-CO_2 atmospheric lifetime, the global warming potential of methane is approximately 28 to 36 times more potent (by 100 years) and significantly higher (by 20 years) than CO_2 (UNECE 2023). Thus, methane is a critical greenhouse gas that contributes to global warming. The methane radiative forcing effect and its potential to amplify climate change make understanding and addressing emissions of methane crucial to the development of effective climate mitigation strategies.

Since emission is the key quantity in methane monitoring, it needs to be estimated first. It can be calculated by multiplying activity data and emission factor. According to the IPCC 2006 guidelines, emission factor is defined by three levels, from the basic (Tier 1) to the most advanced (Tier 3), as shown in **Table 1**.

Table 1
Emission factor is defined by three levels, based on IPCC 2006 Guidelines.

Emission Factor Level	Definition
Tier 1	Default, representative, not specific to any country
Tier 2	Mass balance
Tier 3	Site and plant specific with equipment and technology used

The Global and Malaysian Methane Research Landscape

The emergence of global climate change pollutants like CH_4 threatens the well-being, economic stability, security, and essential food and water supplies of billions of people. This issue stands out as one of the foremost challenges confronting the world today, as acknowledged by the Intergovernmental Panel on Climate Change in 2018 (IPCC 2018).

The tangible impacts of climate change are becoming increasingly evident through extreme weather occurrences like heatwaves, intense rainfall, floods, and droughts that have endangered various aspects of human life, including health, security, livelihoods, access to food and water, infrastructure, and economic advancement. Acknowledging this, 196 nations worldwide embraced the Paris Agreement in December 2015. The primary objective of this agreement is to strive for measures that curtail the escalation of global temperatures, aiming to keep the temperature increase within 1.5°C (United Nations 2015). Therefore, more attention should be paid to CH_4 by regularly evaluating the scientific foundations of climate change, its consequences, future risks, and potential measures for adaptation and mitigation.

The atmospheric concentration of methane was relatively stable in the early 2000's but started to rise in 2007 and accelerating after 2014 (Cheng and Redfern 2022). Hence, emissions and concentrations of CH_4 are continuing to increase, making CH_4 the second most important human-induced greenhouse gas after CO_2. For instance, although CH_4 global emissions during 2008-2017 was estimated at around 576 Tg CH_4 yr^{-1} (Saunois et al. 2020), the CH_4 global emission rates have increased significantly to be over 600 Tg CH_4 yr^{-1} now (Saunois et al. 2025).

Significant sources of atmospheric CH_4 come from anthropogenic and natural sources, including fossil fuels, landfills, agriculture, and wildfires (Bastviken et al. 2023). Wetlands produce about 30% of methane emissions, including ponds, lakes, and rivers. Meanwhile, agriculture produces another 20% due to livestock, waste management and rice cultivation. Oil, gas, and coal extraction activities release an additional 30%. The remaining methane emissions come from minor sources such as wildfires, biomass burning, permafrost, termites, dams, and the ocean (Saunois et al. 2016).

The Malaysian Department of Environment measured methane in the ambient air from 1997 until 2010 at 20 stations around Malaysia. Methane also has been measured by the Malaysian Department of Meteorology at Global Atmosphere Watch (GAW) stations. Published studies on methane emissions within Malaysia have been more related to methane as a source of renewable energy from palm oil waste (Yacob et al. 2006, Sumathi et al. 2008, Subramaniam et al. 2010, Loh et al. 2017, Tan and Lim 2019). Researchers from the Sarawak Tropical Peat Research Institute (TROPI), among others, have dominated the study of CH_4 emissions of from tropical peats (Chaddy et al. 2021, Busman et al. 2023).

For anthropogenic sources, fugitive CH_4 emissions from oil and gas industries are thought to be the major sources in Malaysia. In 2016, CH_4 emissions totalled 57,211 gigagrams (Gg) CO_2 eq (Malaysia 2020). The highest emission was from fugitive emissions from the oil and gas industries, which accounted for 25,308 Gg CO_2 eq (44%) of the CH_4 emissions, followed by emissions from industrial wastewater treatment and discharge amounting to 13,928 Gg CO_2 eq (24%), and solid waste disposal sites at 11,214 Gg CO_2 eq (20%). About 99% of industrial wastewater treatment and discharge emissions were from palm oil mill effluent (POME). The latest study by researchers (Rangga et al. 2023) highlighted that the average direct CH_4 emissions of landfilled waste were 109,000 tonnes yr^{-1}, equivalent to 2,740,000 tonnes of CO_2 yr^{-1}. However, these emissions rates are estimated using emissions factors.

The Need for Improved Methane Measurement and Reporting in Malaysia

Methane is a potent greenhouse gas, contributing to a global warming potential many times greater than CO_2, and poses a significant environmental challenge. Accurate quantification of these methane emissions is essential for informed policymaking and targeted mitigation efforts. However, efforts to accurately quantify and mitigate methane emissions in Malaysia are hindered by several critical knowledge gaps and outdated data sources within national and international emission inventories.

Based on the Fourth Biennial Update Report (BUR4) in 2022, the current approach to estimating methane emissions in Malaysia primarily relies on emissions factors derived from international datasets and models rather than direct quantitative measurements, since level of emissions factor reported are mostly from Tier 1. This over-reliance on emissions factors presents a pressing problem that requires attention and resolution.

To address this pressing issue, a comprehensive research gap study is required to understand the methane sources, measurement method, and reporting levels of methane emissions in Malaysia. Thus, this study aims to determine research gap in current methane knowledge, particularly focusing on methane emissions studies in Malaysia, as developing an accurate and up-to-date understanding of methane emissions in Malaysia is not only essential for meeting international reporting commitments but also for effectively mitigating greenhouse gas emissions and minimising the country's contribution to global climate change.

Report Objectives

To bridge the gap in the Malaysian methane measurement and reporting knowledge-base, the report set out to,

1. Identify current reporting levels of methane emissions in the national inventory and other emission inventories, and where there are country-specific knowledge gaps or out-of-date data being used in both emission factors and activity data.
2. Identify current and ongoing methane measurement work to address identified knowledge gaps.
3. Suggest potential research topics to improve knowledge of methane emissions in Malaysia.

2. Methodological Framework for Methane Data Gap Analysis

This study has two methodological phases, as shown in **Fig. 1**. The initial phase concerns the initial gap identification. To further understand Malaysia's methane emission in four sectors, namely energy, Industrial Processes and Product Used (IPPU); Agriculture, Forestry and Other Land Use (AFOLU), and waste, this research examines the latest Fourth Biennial Update Report (BUR4), which is developed based on the United Nations Framework on Climate Change (UNFCCC) Decision 2/CP .17. (Malaysia 2022).

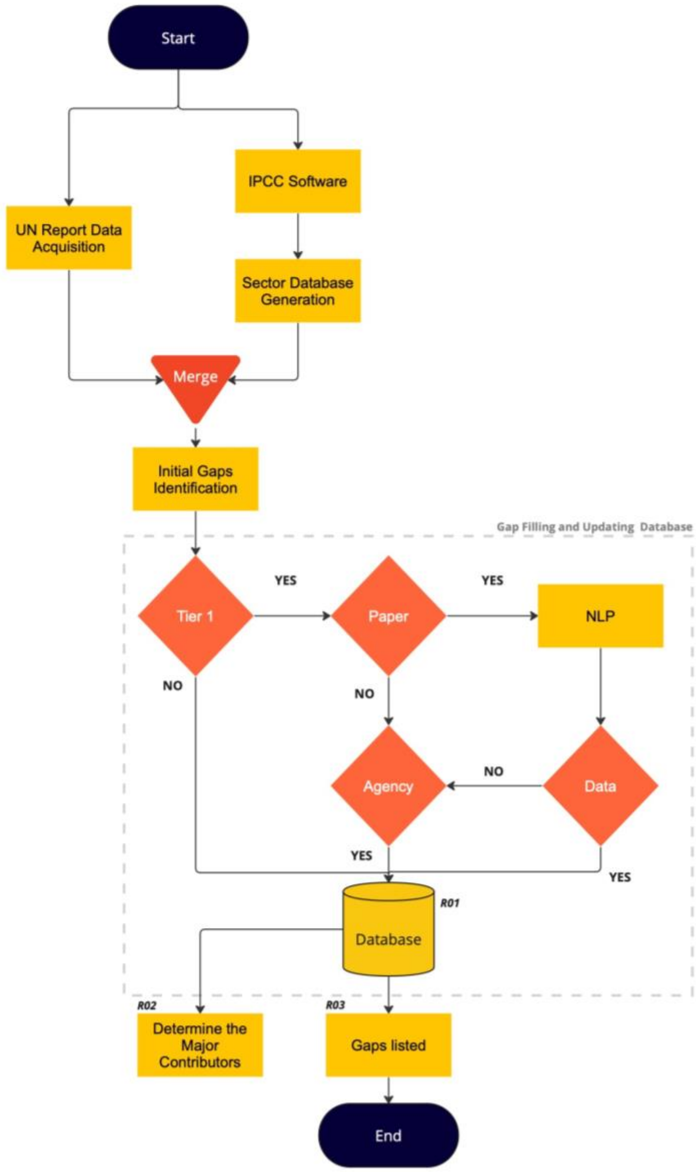


Fig. 1. Research workflow: Tier 1 denotes the default IPCC values (Rypdal et al. 2006). Agencies include government and private entities; NLP denotes Natural Language Processor.

The reported data is then integrated into the IPCC database, followed by a search through multiple established databases using keywords associated with initial data gaps. Literature sources of emissions are identified by applying keywords linked with these gaps, and the gathered information is consolidated to highlight knowledge and data gaps.

Publicly available databases and reports concerning CH_4 emissions in Malaysia are collected from various sources, encompassing both government and private entities. These sources include the Ministry of Natural Resources, Environment, and Climate Change (NRECC), the Malaysian Department of Environment (DOE), the Malaysian Palm Oil Board (MPOB), PETRONAS, the Sarawak Tropical Peat Research

Institute (TROPI), landfills, ports, power plants, diverse industries, agricultural activities like enteric fermentation, wastewater treatment plants, and the national emission inventory. The analysed data covers continuous ambient air quality data from 1997 to 2010 obtained from the Department of Environment (DOE), emission data from the Ministry of Natural Resources, Environment and Climate Change (NRECC), and other relevant industries.

In Phase 2, data consolidation, processing, and analysis were performed on all the databases and reports collected. Using the capabilities of the Natural Language Processing (NLP) Model, the focus shifted to filtering journal articles and databases gathered in Phase 1, facilitating their subsequent in-depth assessment. This phase involved data collection, processing, consolidation, and analysis using a combination of Python along with artificial intelligence methodologies. These methodologies enabled the estimation of methane emissions, emphasising regions where emission data remained scarce. The results yielded by the analytical procedures were interpreted to determine the extent of the knowledge gap in methane study in Malaysia. This assessment subsequently served as a benchmark for further methane emissions studies.

Identification of the Initial Gap

Data was acquired from the Fourth Biennial Update Report (BUR) under the United Nations Framework Convention on Climate Change. The data source corresponds to the year 2019. The Methodological Tiers and Type of Emission Factors were obtained from *Table A-1: Methodological Tiers and Type of Emission Factors*, which provides information on whether the emission factors are default or country-specific.

Meanwhile, the Summary of Emission Factors was extracted from *Table A-2: Summary of Emission Factors Used*. For identification purposes, *Table A-8: Summary Table for GHG Inventory Year 2019* was utilised to classify methane emission sources as not applicable (NA), not occurring (NO), or not estimated (NE). The sectors and their respective categories were retrieved from the software developed by the Intergovernmental Panel on Climate Change (IPCC), known as the IPCC-TFI Inventory Software (available at iges.or.jp), accessed in April 2023 (IPCC-TFI 2023). The collected data was populated into the sector database generation to assess the initial gap. The identified gap refers to the level of Emission Factors at Tier 1 based on the IPCC 2006 Guidelines or categories marked as NE.

Meta-Analysis

This study is limited to the publicly available literature on methane emission and emission factors specific to Malaysia. The databases used for literature extraction are Google Scholar, Elsevier, Research Gate and Open Knowledge Map. Methane Flux in Malaysia (45 results out of 1,080,000 papers related to methane flux).

The period of the search was from 2003 to 2023.

- Methane + Malaysia (70,700 results)

- Methane Emission Factor + Malaysia (36,100 results)
- Methane + Greenhouse Gas Inventories + Malaysia (20,000 results)
- Methane Flux (1,080,000 results)

The keywords used are “Methane + Malaysia”, “Methane Emission Factor + Malaysia”, “Methane Emission + Greenhouse gas inventories + Malaysia”, and “Methane Flux”. The scope was widened to a tropical country with a similar climate to fill the identified gaps, for example, Thailand, Indonesia, and China. The selection criteria adopted are based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) checklist. PRISMA 2020 provides a structured and transparent framework for planning, conducting, and reporting systematic reviews, ensuring methodological consistency and reproducibility (Zubair et al. 2023). It is an updated guideline that provides a transparent and rigorous framework for conducting systematic reviews and meta-analyses, emphasising straightforward research questions, comprehensive search strategies, transparent reporting, and bias assessment in included studies.

Natural Language Processing

This study employs a combination of Python libraries and advanced NLP technologies to automate the examination of scholarly articles about methane. The code initiates the process by initiating a range of queries targeted at specific data elements within the articles, including aspects like methodology, geographical context, and fundamental concepts. The utilisation of the textract library facilitates the extraction of text from PDF documents, followed by the organisation of the extracted textual data to isolate relevant segments. The script divided the extracted text into coherent and manageable sections using a character-based text division approach.

A pre-trained language model, which can be GPT-3 or GPT-4, is then loaded for query-based analysis. The textual chunks undergo similarity searches via FAISS (Facebook AI Similarity Search) based on OpenAI's embeddings. These similar text chunks are processed through the language model to answer the pre-defined queries in a structured JSON format. Additionally, the code allows for environment variable configuration to access OpenAI's API and offers options for error handling.

The workflow streamlines the review process, enabling us to sift through many papers and extract pertinent information efficiently. This automated mechanism aids in the rapid identification of relevant papers, thereby expediting the research process.

Data Survey

The initial phase of stakeholder engagement involves identifying related stakeholders with a comprehensive assessment to pinpoint individuals, groups, or organisations with a high possibility of emitting or utilising methane during their activities. Following the identification of these stakeholders, the subsequent step involves actively seeking out appropriate contacts within these entities. This step involves browsing existing networks, databases, or platforms to establish connections that facilitate meaningful engagement. The focus then shifts towards determining the person in charge within each stakeholder group. This individual is entrusted with decision-making authority and possesses the necessary insights to drive the engagement process forward. Upon ascertaining the correct point of contact, the most effective mode of communication, often through email, is employed to initiate dialogue, share information, and lay the foundation for productive interactions that align with the objectives of stakeholder engagement. Appendix B-1 lists further details of contacts are listed. Four questions are asked in the report as follows:

- **Ongoing Methane Monitoring Initiatives**: Do you have any ongoing methane monitoring initiatives within your company? If yes, we are interested to know more about the methodologies, technologies, and systems used, as well as the scope and geographical coverage of these initiatives.
- **Ongoing Methane Emission Related Initiatives:** Do you have any ongoing methane emission initiative related to policy enforcement, a methane pledge action plan, or any start-off action plan on methane emission? For example, methane flux or eddy covariance.
- **Methane Emission or Concentration Data**: Do you have any methane emission or concentration data that your company has collected? Regarding methane emission or concentration data, we kindly request your cooperation in indicating whether your company's data is publicly available or confidential. Understanding the availability of the data will assist us in evaluating the feasibility of incorporating it into our research.
- **Challenges or Barriers in Reducing Methane Emissions:** What are the major challenges or barriers your company faces in reducing methane emissions? Your insights will help us better understand the complexities and develop effective strategies.

This research collected data from email surveys and interviews with identified stakeholders. The email surveys involve sending a list of questions via email to identified stakeholders, who then respond with written answers. On the other hand, the interviews involve direct conversations with individuals or groups, during which open-ended questions are asked to elicit detailed responses. Refer to Appendix B-1 for detailed information about the identified stakeholders.

About 26 identified stakeholders participated in the data collection through email surveys and interviews, as shown in **Fig. 2.** Summary of the data collected from email surveys and interviews. There are 14 government sector representatives and 12 private sector representatives. The average response time since the first email sent is 14 days. Based on the collected data, 17 stakeholders have responded, nine have yet to respond, and a follow-up email has been sent to alert the stakeholders. The four categories of responses from the stakeholders who responded are as follows:

a) responded with a complete answer (n = 7),

b) responded but needs further clarification (n = 4),

c) responded but rejected (n = 2),

d) responded but needed time to gather information and data (n = 4).

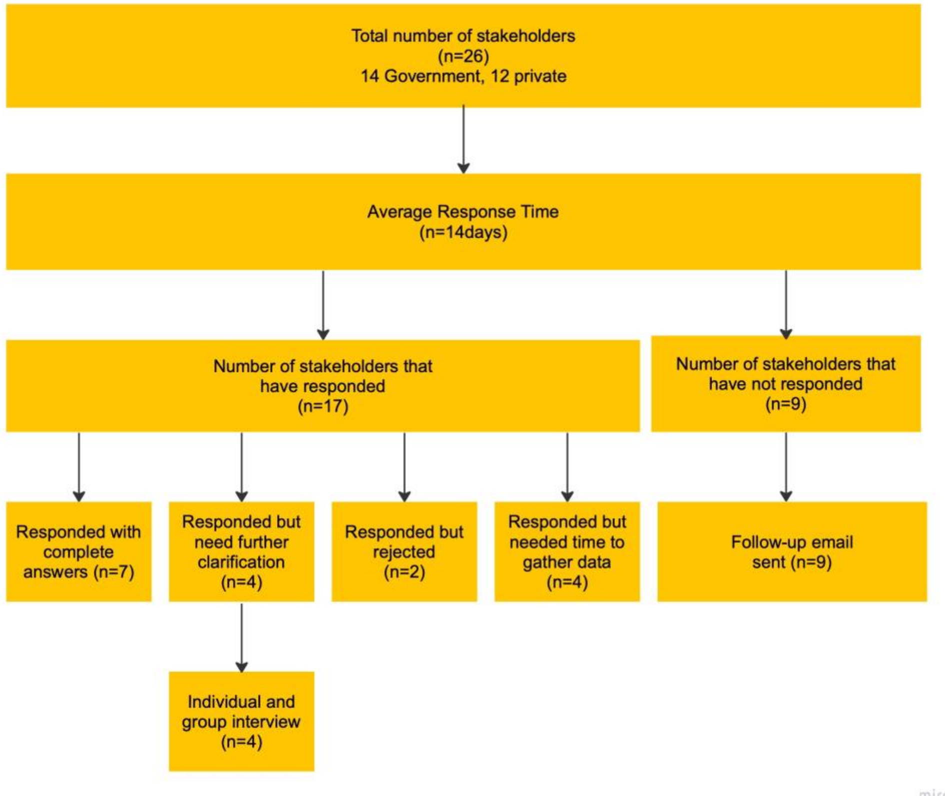


Fig. 2. Summary of the data collected from email surveys and interviews.

Multi-Criteria Decision Analysis

This research performed a Multi-criteria Decision Analysis (MCDA), a statistical analysis to rank the severity of the gap findings in methane emissions research and works in Malaysia. Multi-Criteria Decision Analysis (MCDA), also known as Multi-Criteria Decision Making (MCDM), is a structured decision-making methodology that helps to evaluate and select the best recommendations of future research plan from a set of gap findings. This analysis is normally used in the situations where decisions involve multiple criteria or factors, and there may be trade-offs between these criteria.

Table 2 shows the list of criteria used to determine the severity of the gap findings in methane emissions research and works in Malaysia. There are nine criteria including cost, quality, time, reliability, regulatory compliance, innovation, strategic alignment, accessibility, and scalability. These criteria are grouped into two categories which are beneficial (quality, reliability, regulatory compliance, innovation, strategic alignment, accessibility, and scalability) and non-beneficial criteria (cost and time). The alternatives or options in this analysis referred to the list of gaps obtained from the result findings that focused on knowledge gaps. The criterion is using the same weighting scale as,

1 – Very low negative impact;

2 – Low negative impact;

3 – Medium negative impact;

4 – High negative impact;

5 – Very high negative impact.

Each of gaps have been assigned weights to each criterion to reflect its relative severity level by using the findings from the data survey that were conducted. Then, the data has been normalised by using min-max scaling method before the construction of decision matrix with rows representing gaps and columns representing criteria. The score for each gap is calculated by multiplying the normalised values by the corresponding criteria weight and summing the total score for each gap, as equation below.

Table 2
The list of criteria used to determine the severity of the gap findings.

Criteria	Explanation
Cost	Evaluate financial implications of each gap findings.
Quality	Evaluate the performance of quality of each alternative based on how it will affect the future methane emissions works.
Time	Evaluate time duration implications of each gap findings.
Reliability	Evaluate the likelihood of each gap findings to cause without failures or breakdowns.
Regulatory Compliance	Evaluate the impact of gap findings in regulations.
Innovation	Evaluate the impact of gap findings in technological advancement.
Strategic Alignment	Evaluate how well each gap findings align with the research objectives.
Accessibility	Evaluate how each gap findings related to accessibility and inclusivity.
Scalability	Evaluate the ability of each gap findings to changes in demand or scope.

The gap findings from this research are ranked based on their scores. Higher scores indicate the severity of the gap in reducing methane emissions in Malaysia. The sensitivity analysis has been conducted to assess the robustness of these results. These results act as a baseline in suggesting the potential research topics that can improve knowledge of methane emissions in Malaysia.

3. Published Reporting Levels of Methane

Emission Reporting in The Fourth Biennial Update Report (BUR4)

The fourth Biennial Update Report (BUR4) follows the emissions categorisation guidelines recommended by the Intergovernmental Panel on Climate Change (IPCC), which classify emissions into four sectors:

Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry, and Other Land Use (AFOLU), and Waste.

Among these sectors, Waste stands out as the largest contributor to greenhouse gas emissions, with a significant share of 1,113.31 Gg, accounting for 51.8% of the total emissions. The Energy sector also plays a substantial role, contributing 739.75 Gg, which represents 34.1% of the total emissions. This emphasises the critical importance of addressing emissions within the Energy sector to achieve substantial reductions in overall greenhouse gas emissions. Meanwhile, the AFOLU sector, which includes activities related to agriculture and land use, accounts for 162.07 Gg, equivalent to 8% of the total emissions. In contrast, emissions from the IPPU sector are low at 14.08 Gg, making up just 0.6% of the total emissions.

Within the waste sector, emissions are categorised into several subcategories, each contributing differently to the overall methane emissions profile. The largest contributor is Wastewater Treatment and Discharge, accounting for a substantial 645.98 Gg of emissions, which is approximately 57.9% of the total waste sector emissions. POME (Palm Oil Mill Effluent) emerges as the primary contributor, accounting for a substantial 572.31 Gg of emissions within this subcategory. Following that, Solid Waste Disposal is the next notable contributor, releasing 467.24 Gg of emissions, constituting approximately 41.9% of the total waste sector emissions with Unmanaged Waste Disposal Sites accounts for 86% of the emission. This subcategory stresses the significance of addressing emissions arising from solid waste disposal practices, such as landfilling. In contrast, Incineration and Open Burning of Waste generate low emissions at 0.08 Gg, representing around 0.007% of the total waste sector emissions. Similarly, Biological Treatment of Solid Waste shows minimal emissions, with only 0.01 Gg, contributing less than 0.001% to the total waste sector emissions.

The energy sector is subdivided into two key categories: Fuel Combustion Activities and Fugitive Emissions from Fuels. Within the Fugitive Emissions from Fuels category, which accounts for a substantial 96% of the total emissions from the energy sector at 714.64 Gg, Oil and Natural Gas appear as the predominant contributors, totalling 713.69 Gg. This subcategory is further divided into two noteworthy components: Oil, contributing 430.04 Gg, encompassing venting (403.83 Gg 10^{-6} m^{-3}) and flaring (26 Gg 10^{-6} m^{-3}) emissions, and Natural Gas, contributing 283.65 Gg, including flaring emissions (1.53 Gg 10^{-6} m^{-3}). Within the Fuel Combustion Activities category, the most substantial contributor is the transport sector, specifically road transportation, which generates 20.74 Gg of methane emissions out of the total.

In the AFOLU sector, emissions total 162.07 Gg, with contributions from various subcategories. At the forefront of these emissions is Rice Cultivation, which stands out as the most substantial contributor, releasing 90.76 Gg of emissions. This category is alone approximately 56.1% of the total emissions within the AFOLU sector. Following closely behind is the Livestock subcategory, contributing 70.56 Gg of emissions to the AFOLU sector. This subcategory encompasses a range of emissions sources, with a noteworthy part being Enteric Fermentation, responsible for 48.98 Gg of emissions, which accounts for around 30.2% of the sector's emissions. Within this subcategory, cattle alone contribute 38.98 Gg to methane emissions. Additionally, Manure Management contributes 21.58 Gg of emissions, making up approximately 13.3% of the sector's emissions. Notably, swine emissions account for a large portion of this subcategory at 13.22 Gg. Lastly, Burning, responsible for 0.75 Gg of emissions, making up approximately 0.5% of the sector's emissions. While burning contributes the least in terms of emissions quantity and percentage, it is still a relevant factor in the overall emissions landscape within the AFOLU sector.

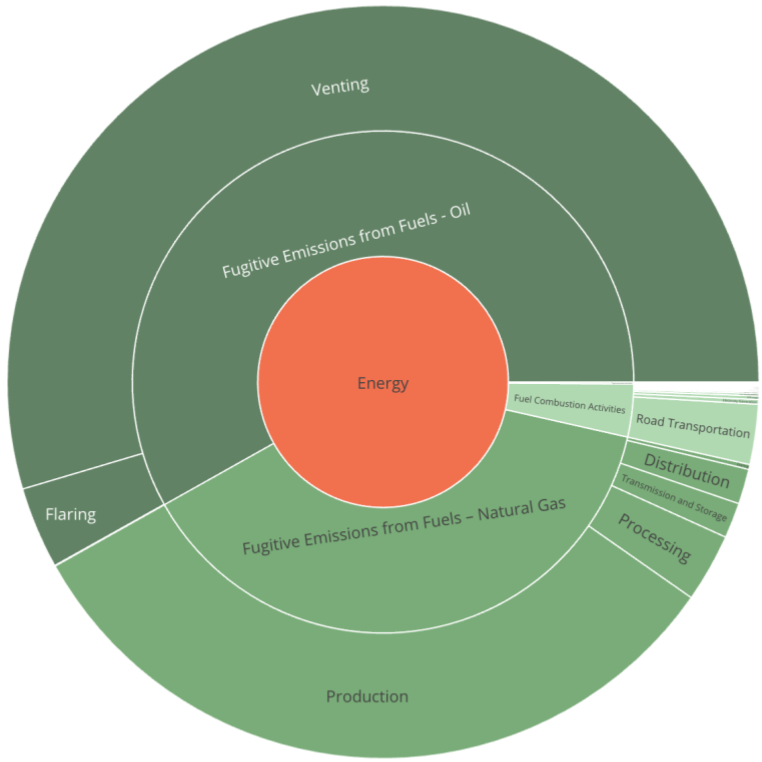
Industrial Processes and Product Use contribute a 14.08 Gg of methane emissions with Chemical Industry as the dominant contributor generating 13.11 Gg of emissions, which accounts for 93% of the emission within the IPPU sector. This subcategory encompasses various chemical processes, with a specific focus on Petrochemical and Carbon Black Production, responsible for all the emissions in this subcategory. Metal Industry accounts for the remaining emissions, contributing 0.97 Gg. Within this subcategory, emissions are further divided between Iron and Steel Production (0.41 Gg) and Ferroalloys Production (0.56 Gg). The most apparent gap in the IPPU Sector is the absence of emission estimates for several subcategories, as indicated by "NE" (Not Estimated), which are Paraffin Wax Use, Pulp and Paper Industry and Food and Beverages Industry. Without emission data for these subcategories, it is challenging to assess their contributions to the overall methane emissions within the sector. Obtaining or estimating emissions for these subcategories would provide a more comprehensive understanding of the sector's emissions profile.

The distribution of methane emissions is illustrated according to the different sectors in **Fig. 3**.

(a)

Fig. 3. Methane emission distribution categorised into different sectors: (a) Waste, (b) Energy, (c) AFOLU (Livestock), (d) AFOLU (Land Use) and (e) IPPU (Malaysia, 2022).

(b)



(c)

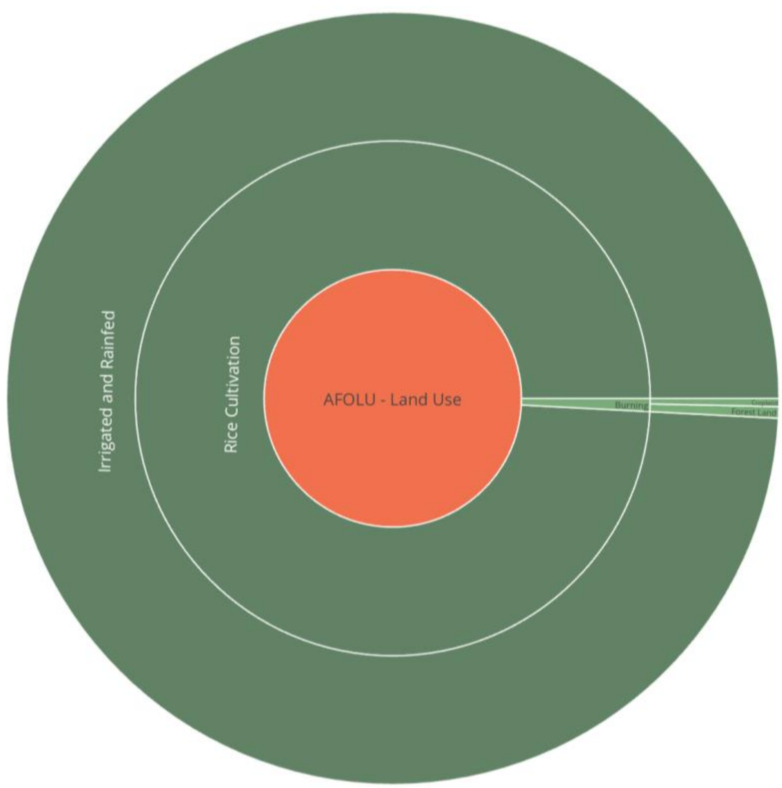
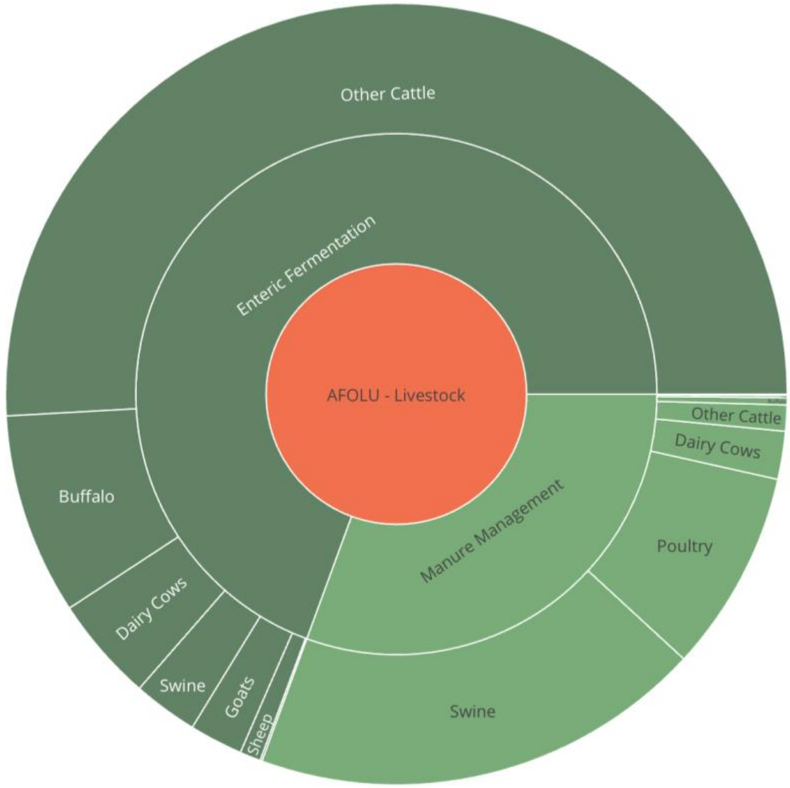


Fig. 3. (continued)

(d)



(e)

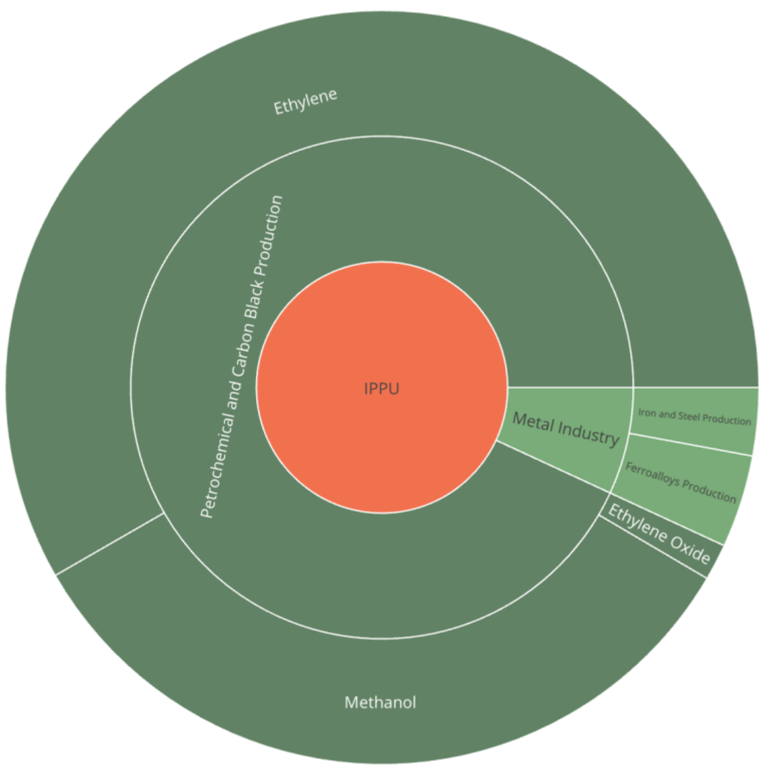


Fig. 3. (continued)

Several databases report methane emissions in Malaysia based on IPCC guidelines, including the International Energy Agency (IEA), Climate Watch Data, and EDGAR. **Fig. 4** illustrates how six relevant databases are related for research on methane values in Malaysia.

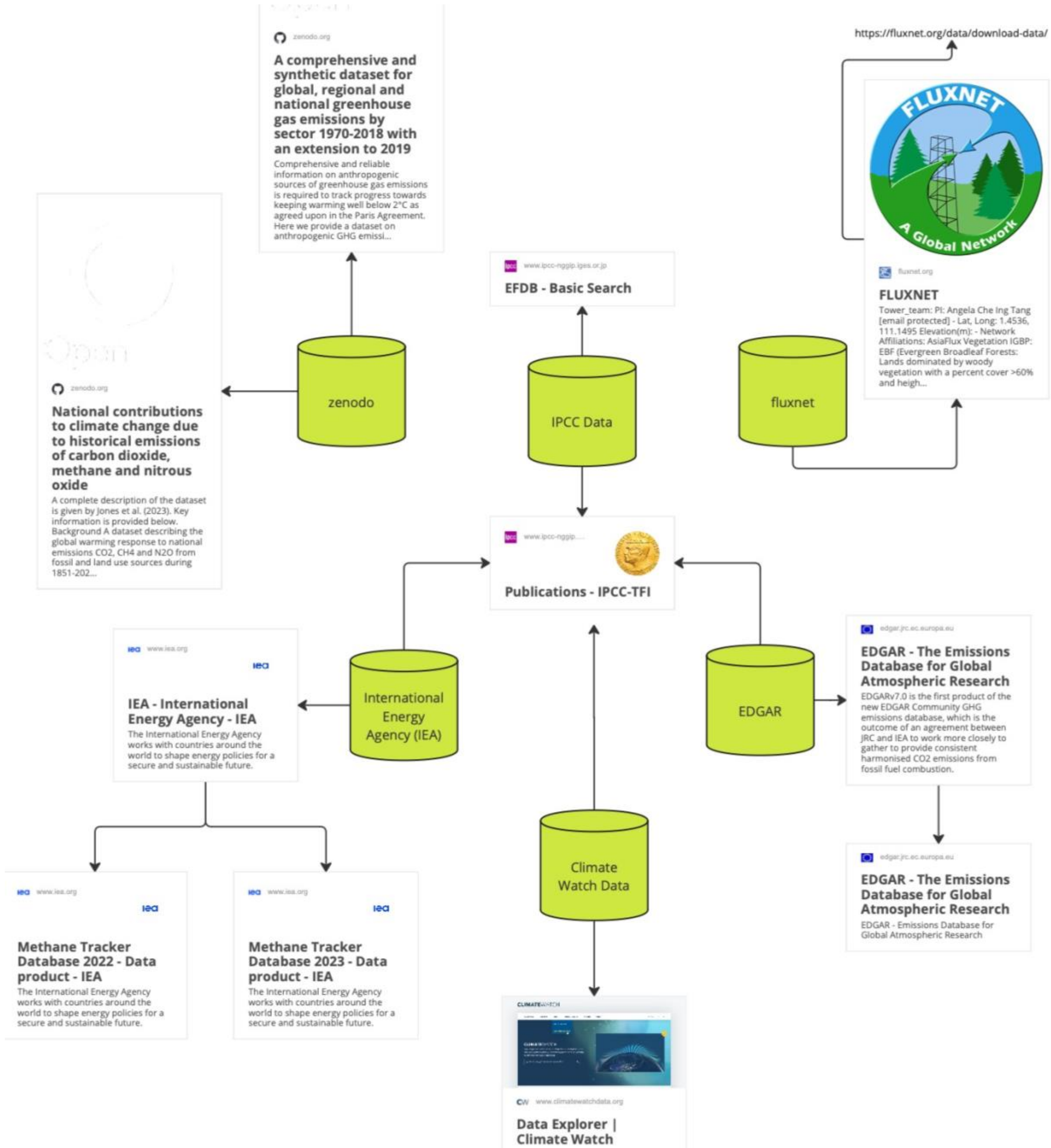


Fig. 4. Publicly available datasets.

The IEA Methane Tracker Databases offer recent methane emissions data categorised by sectors, spanning multiple years. The 2022 database provides data for 2018-2019 and 2021, while the 2023 version covers 2019-2021 and 2022. The data is presented in the CSV (comma-separated values) format with units in kilotonnes (kt). Energy-related greenhouse gas emissions data are sourced from the World Energy Balance, while other estimates are adopted from the BUR of the respective year.

For a comprehensive dataset covering a significant time frame (1990-2020) on greenhouse gas emissions across various sectors, Climate Watch Data offers data in the CSV format with units in megatonnes (Mt) CO_2 eq, sourced from Climate Watch, PIK, and UNFCCC-NAI.

The EDGAR Database provides extensive greenhouse gas emissions data spanning several decades (1970-2021) from various sources, available in multiple formats including Text, NetCDF, and Image, with units given in tonnes, using the IPCC Guidelines. EDGAR is useful in segregating emissions at the subcategory level.

The IPCC Database is suitable for inventory compilers, offering data for selected years in the Excel format and presenting various parameters following the IPCC Guidelines. This database provides values with background documentations like peer-reviewed journal papers. However, it should be noted that the database for Malaysia is mostly for Agriculture and Waste.

Zenodo is another database that hosts two datasets including comprehensive and synthetic dataset for global, regional, and national greenhouse gas emissions by sector from 1970 to 2018 with an extension to 2019 and the national contribution to climate change due to historical emissions of CO_2, CH_4, and nitrous oxide. Both datasets focus on historical greenhouse gas emission.

The last database, FLUXNET is different from other databases as it provides in-situ eddy covariance flux data in the Maludam National Park for 2014 to 2015. Measurement data can be used for inverse modelling with known meteorological condition, estimating the location of the source. However, the available databases are likely to offer limited improvements in current reporting for Malaysia, as datasets such as IEA primarily focus on the energy sector, and FLUXNET provides only the flux data. The BUR for Malaysia is based on national statistics, while datasets like EDGAR and IEA may rely on more generic data.

Emission Reporting: Tiers 1 to 3 Emission Factors Adoption

The key sectors for methane emissions in Malaysia are Waste, Energy and AFOLU (Malaysia, 2022). Of all the categories, only 2 of 306 are country-specific emission factors: Enteric Fermentation within the AFOLU sector and the Palm Oil Mill Effluent (POME) within the Waste sector.

The prominence of Tier 1 emission factors within the energy sector of Malaysia emphasises the need for heightened efforts to enhance the accuracy of methane emission reporting within this domain. Tier 1 emission factors, while providing a standardised approach to emissions calculation, may need more precision to capture the nuanced variations inherent in diverse energy-related activities. The utilisation of such factors suggests a collective need to refine the emissions estimation process by incorporating more country-specific data and accounting for the particulars of the country's energy landscape.

Interview findings from the Ministry of National Resources, Environment and Climate Change (NRECC) reveal persistent challenges in improving emission factors. The NRECC cites obstacles such as limited data accessibility and a complex process for obtaining permissions, including confidentiality statements to report. These challenges shed light on the intricacies of emissions reporting and highlight the need for more streamlined data collection methods and enhanced cooperation among stakeholders. These efforts are essential for achieving greater accuracy in reporting methane emissions within the energy sector.

The breakdown of methane emissions, measured in Gg and categorised by various sectors and tiers, is presented in **Table 3**. Tier 1 emissions total 1,420.98 Gg, constituting 70% of the overall emissions, while Tier 2 emissions total 608.22 Gg, representing the remaining 30%.

It is worth noting that Tier 1 emissions for AFOLU - Livestock are notably lower than Tier 2 emissions within the same category. This discrepancy suggests that other livestock sources or Enteric Fermentation in cattle might contribute significantly to these emissions. This distribution emphasises the importance of higher-tier emission factors in providing a more comprehensive and accurate representation of methane emissions.

Furthermore, the cumulative contributions of just two subcategories already reach the 30% threshold (**Table 3**). This observation highlights the need for greater precision in emissions accounting and reinforces the importance of implementing higher-tier methodologies to refine our understanding of methane emissions across various sectors.

Table 3

Methane emissions by sectors and Tiers. AFOLU - Livestock under Tier 1 excludes the enteric fermentation for other cattle, while Waste under Tier 1 level excludes the waste for Palm Oil Mill Effluent (POME). Both uses Tier 2 Emission Factors.

Level	Details	Emissions (Gg)	Percentage (%)
Tier 1	Energy	739.75	36.5
	IPPU	14.08	0.7
	AFOLU - Livestock	34.65	1.7
	AFOLU - Land	91.51	4.5
	Waste	540.99	26.7
	Total	**1420.98**	**70**
Tier 2	AFOLU - Livestock (Enteric Fermentation)	35.91	1.8
	Waste - POME	572.31	28.2
	Total	**608.22**	**30**
Tier 1 and Tier 2	Energy	739.75	36.5
	IPPU	14.08	0.7
	AFFOLU - Livestock	70.56	3.5
	AFOLU - Land	91.51	4.5
	Waste	1113.3	54.9
	Total	**2029.2**	**100**

Tier 1 Emission Factors account for a substantial portion (33.01%) by utilising standardised factors for emissions calculation, while the category of Data Unavailable (9.15%) highlights sectors lacking emission data. Meanwhile, the Not Occurring category (27.45%) represents sectors where emissions do not arise due to the absence of relevant activities. These, alongside other categories like Multiple Categories Emission Factors (14.05%) and Not Estimated Emission Factors (5.23 %) collectively provide a comprehensive framework for understanding emissions distribution. The distribution of level of emission factor according to four sectors is shown in **Fig. 5**.

The BUR4 is the primary information source in illustrating the degree of reporting regarding the methane emission factor. The result of screening through published journal articles, including methane flux measurement, suggests improvement from the Tier 1 to the Tier 2 emission factor. The findings are appended in Appendix A, together with Tier 1 values. The level of emission factor is categorised into Tier 1, 2 and 3 according to the General Guidance of the IPCC Guidelines for National Greenhouse Gas Inventories.

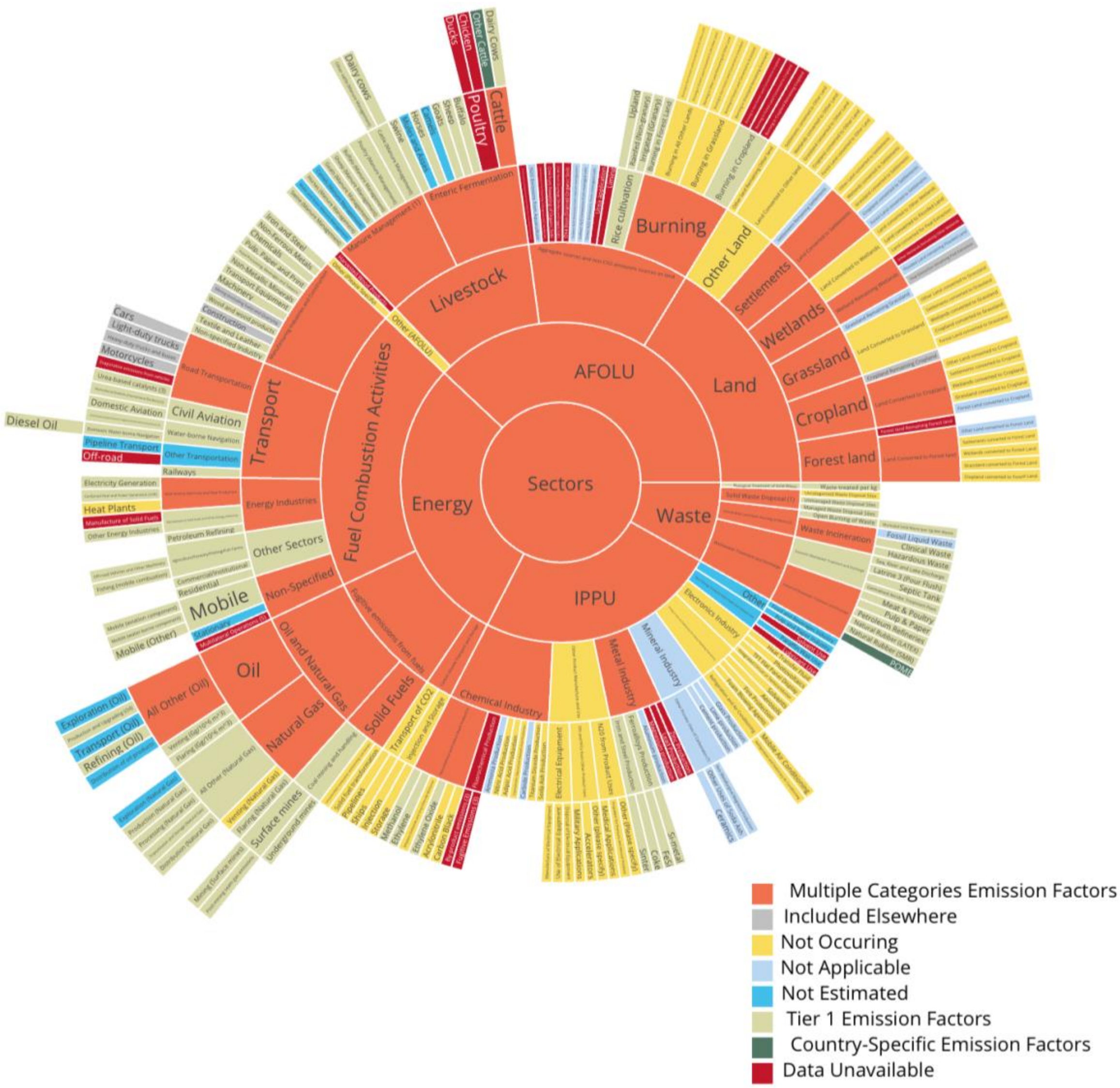


Fig. 5. Level of emission factor for four main sectors namely, Energy, Industrial Processes and Product Used (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), and Waste with their subcategories.

The Malaysian methane emission factors is skewed towards the AFOLU and Waste sector. This is due to the AFOLU and Waste sectors being supported by academia through institutional research. Other sectors are under-represented because of varying reasons. For example, the Energy sector only reports total emissions and not emission factors, making Tier 2 or 3 emission factors unavailable, while other sectors, like the IPPU sector, not having stakeholder interest and thus, less resources to conduct emission factor research.

However, the energy sector is estimated to be the largest source of methane emissions. It primarily utilises Tier 1 emission factors for reporting. The exception to this trend is the subcategory of Electricity Generation and Combined Heat and Power Generation, which employs Tier 2 and Tier 3 factors. Notably, this adoption of higher-tier factors was led by the government-owned company, Tenaga Nasional Berhad.

In a study conducted by researchers (Zakaria et al., 2021), specific plant-based emission factors were investigated across ten gas and coal power plants, taking into account technology specifications. This study aimed to provide a deeper understanding of methane emissions within the Combined Heat and Power Generation subcategory. Although these findings have not yet been incorporated into the latest BUR, it is anticipated that the next report will incorporate these higher-tier emission factors, contingent upon the availability of activity data required for estimation.

Notably, the National Renewable Energy and Climate Change (NRECC) organisation has requested this research to enhance the accuracy of emission factors. However, as shown in **Fig. 3**, the expected proportion of methane emissions from this sub-category within the energy sector is comparatively small compared to fugitive methane emissions from oil and gas. Therefore, the impact on methane emissions reporting will be negligible.

This highlights the energy sector's research landscape, characterised by a significant emphasis on regulation and policy. The sector often grapples with complex policy and regulatory challenges, necessitating substantial resources and encouraging interdisciplinary collaboration. Consequently, research within the energy sector often unfolds over longer timeframes before yielding concrete results, which can pose a challenge when compared to more accessible areas such as agriculture and waste-related research. Moreover, the pronounced influence of commercial interests in the energy sector, driven by private enterprises engaged in proprietary research, may influence the preference for Tier 1 emission factors. This is because proprietary data may not be as readily accessible as research conducted in the public sector. An interview with the NRECC has revealed an ongoing collaboration with PETRONAS aimed at improving emission factors for the flaring subcategory.

BUR4 has adopted two Tier 2 emission factors in the AFOLU sector, particularly enteric fermentation and industrial wastewater treatment and discharge in the Waste sector. Engaging the experts in the field, researchers presented the development of a country-specific emission factor for cattle enteric fermentation with full adherence towards the formula of IPCC guidelines (Azizi et al. 2017).

The agriculture sector is the backbone of Malaysia's economy. Exports of agricultural products like palm oil have contributed significantly to Gross Domestic Product (GDP), where total agricultural exports increased from RM118.7 billion in 2020 to RM154.5 billion in 2021 (Department of Statistics 2022). Palm oil, rubber, cocoa, and wood products account for around half of the economic output while other significant contributors include tropical fruits and rice.

In the context of pineapple cultivation, the papers by researchers (Lim Kim Choo and Ahmed 2017, Luta et al. 2021, Dhandapani et al. 2023) reported emission factors associated with fertiliser use, land management practices, and waste decomposition. As for sago and oil palm plantations, the works of scientists (Melling et al. 2005, Wong et al. 2020, Cooper et al. 2020, Azizan et al. 2021) explored methane fluxes related to soil conditions, water management, and biomass decomposition.

Regarding peatlands, emission factors and CH_4 fluxes are likely to be influenced by the type of peatland (No Vegetation, MPS, Primary, and Secondary), as studied by various researchers (Melling et al. 2005, Wong et al. 2018, Ishikura et al. 2019, Cooper et al. 2020, Azizan et al. 2021, Busman et al. 2023). These studies explored the impact of land use changes, microbial activity, and other factors on peatland CH_4 emissions.

Additionally, rice cultivation, examined in a group of researchers ((Fazli and Man 2014) and a government department (Nuclear Agency Malaysia 2023) is known for its association with CH_4 emissions due to flooded fields and anaerobic conditions. These papers focus on emission factors based on water management, rice variety, and other cultivation practices. As explored by Bange et al. (2019) river basins relate to CH_4 flux studies in disturbed and undisturbed river basins due to presence or absence of anthropogenic activities.

Lastly, CH_4 emission factor due to the occurrence of peat fires as discussed by researchers (Smith et al. 2018) that examined the sudden release of methane due to combustion and its subsequent impact on methane flux dynamics in affected regions. The gaps in Malaysia's Current Published Reporting level regarding the emission factor are depicted in **Fig. 6**.

Gap Findings in Malaysia's Current Published Reporting Level – Emission Factor

G1

Research on methane emission factors in Malaysia exhibits a notable bias towards the Agriculture, Forestry, and Other Land Use (AFOLU) and Waste sectors. While these sectors are undoubtedly significant sources of methane emissions, it is essential to maintain a balanced approach in research to comprehensively address emissions across all sectors.

G2

In the Fourth Biennial Update Report (BUR4), it is worth noting that all the emission factors adopted by the energy sector fall under the Tier 1 category. These factors account for 36.5% of the total emissions, indicating a significant reliance on default methods for emissions assessments. For instance, Malaysia has used emission factors from Thailand to estimate emissions from rice paddy areas. While it is common to adopt emission factors from regions with similar climates, more accurate estimations could be achieved by incorporating local details, such as emission factors with and without organic amendments. The predominance of Tier 1 factors may, therefore, limit the precision of emission estimates.

G3

Limited availability of published literature to support the advancement of emission factors in the energy sector to Tier 2 or Tier 3. There seems to be a stringent requirement to adopt higher-tier factors in terms of reporting, which may be a contributing factor to the predominance of Tier 1 factors.

G4

The limited degree of engagement among stakeholder groups in Malaysia has impacted the development of research on methane emission factors. Despite government efforts to engage industries and research universities in this endeavor, there has been a lack of tangible progress.

Fig. 6. Summary of gap findings in Malaysia's current published reported level regarding the emission factor.

Emission Reporting: Activity Data Sources

The National Energy Balance (NEB) serves as the primary national data provider for the energy sector, offering statistics and survey data concerning electricity generation and transportation. NEB has actively collaborated with major emitters, such as PETRONAS, Petron ExxonMobil, IOI Plantations and KLK Plantations, to enhance the accuracy of activity data.

Regarding transportation, surveys involving important stakeholders for their respective stakeholders were conducted. For example, data from NEB, from 2017 to 2019, is incorporated into the PETRONAS and Economic Planning Unit (EPU) crude oil production analysis for venting. For the railway category, insights from the primary rail operator, Keretapi Tanah Melayu Berhad (KTMB) were sought, while the water-related categories included survey data from the Maritime Department, Malaysia. Survey data acted as the baseline data from around 2014 to 2015.

The activity data provider for the Industrial Processes and Product Use (IPPU) sector mainly includes national associations, departments, and industries. As for the Agriculture, Forestry and Other Land Used (AFOLU) sector, the activity data, including statistics for paddy and livestock, were adopted from authoritative and official publication. The latest available data was taken from Agrofood Statistics 2020 and Department of Agriculture (DOA) 2022, which came from the latest economic census. International statistics like Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT) were also used to fill in missing information.

Unlike any other sectors, waste sector includes journal articles as one of their data sources (Vijaya et al. 2008, 2010) other than national agencies like Malaysian Palm Oil Board (MPOB) or national sewerage company, Indah Water Konsortium. It should be noted that the survey data used as the activity data, illustrating the total waste per day for solid waste, is based on 2012 and can be considered as a data gap.

SWCorp, the national body responsible for management and enforcement of solid waste disposal and public cleansing regulations, addresses this, and the next Biennial Report will be anticipated to consist of the latest survey data from November 2022 until June 2024 on waste characterisation, improving the data quality. However, it is recommended that similar survey should be conducted every three years to provide a more accurate and updated statistics on Waste Composition and Characterisation (National Solid Waste Management Department, 2013). The gap findings related to the activity data used in the fourth BUR reporting are highlighted in **Fig. 7**.

Gap Findings in Malaysia's Current Published Reporting Level – Activity Data

G5

The BUR4 exhibits a lack of consistency in baseline data across different emission categories. This inconsistency complicates the accurate comparison of emissions across sectors, hindering our ability to prioritize mitigation efforts effectively.

G6

There is an absence of available activity data for certain emission sources. For instance, the venting of natural gas remains unaccounted for due to unavailable data. This omission undermines our comprehensive understanding of emissions sources and their significance.

G7

Reliance on outdated activity data, particularly from surveys, may lead to inaccuracies. For example, using 2012 data to estimate daily solid waste production is unlikely to be an accurate reflection of activity data for the reporting period of 2019.

Fig. 7. Summary of gap findings in Malaysia's current published reporting level regarding activity data.

Current and Ongoing Methane Measurement Work

Methane Monitoring

Methane monitoring is the systematic process of observing, measuring, and tracking the concentrations and emissions of methane gas in various environments and sectors. There is a need for accurate monitoring of methane to understand its sources, distribution, and trends, enabling informed decision-making for mitigation strategies.

Methane monitoring involves measurement techniques, source identification, emissions estimation, and data analysis. Various measurement techniques are employed, ranging from ground-based measurements using stationary monitoring stations or portable instruments, to satellite-based observations that provide a broader view of methane sources across larger areas.

Methane monitoring in Malaysia has mainly used ground-based measurements from stationary monitoring stations, as shown in **Table 4**. Monitoring techniques have included chamber, eddy covariance and in-situ measurements.

Table 4
Methane measurement methods with data coverage in Malaysia.

Institute	Location	Parameter	Sampler & Detector	From
Government Department of Environment (DOE)	Across Malaysia 26 stations	Ambient concentration	Air sampling and gas chromatograph with flame ionisation detector (GC-FID)	1996 -2010
Government: Malaysian Meteorological Department (METMalaysia)	Across Malaysia 5 stations	Ambient concentration	Air sampling & laser absorption spectroscopy	2022
Government: Sarawak Tropical Peat Research Institute (TROPI)	Maludam National Park, Sarawak 3 stations (AFOLU)	Surface flux (Mass per area per time)	Gas chamber & gas chromatograph with flame ionisation detector (GC-FID) Spectroscopy - eddy covariance	-
Government: Malaysian Palm Oil Board (MPOB)	Oil palm fields (e.g., Keratong, Pekan, Pahang). Three stations (AFOLU)	Surface flux (Mass per area per time)	Gas chamber & gas chromatograph with flame ionisation detector (GC-FID) Spectroscopy - eddy covariance	2015
Government: Malaysian Agricultural Research and Development Institute (MARDI)	MARDI Peat Research Station at Saratok, Sarawak, Malaysia	Surface flux (Mass per area per time)	Gas chromatography (Agilent 7890A) Flame ionisation detector (FID)	2012
Government: Nuclear Agency Malaysia-Department of Agriculture	Sungai Burong, Selangor	Surface flux (Mass per area per time)	Gas stored in Labco Vials. LGR Laser Spectrometer	2022

Table 4 (continued)

Institute	Location	Parameter	Sampler & Detector	From
Industry: PETRONAS	PETRONAS facilities 1 station	Ambient concentration	Air sampling & infrared methane sensor - thermopile detector	-
Researcher & Government: Natural Environment Research Council with a collaboration of Universiti Malaya (NERC-UM)	Bachok Marine Research Station (BMRS), Kelantan 1 station	Ambient concentration	Air sampling & laser absorption spectroscopy	2015
Researcher: Kyoto University	Pasoh Forest Reserve, Negeri Sembilan 1 station (AFOLU)	Surface flux (Mass per area per time)	Gas chamber & gas chromatograph with flame ionisation detector (GC-FID) Spectroscopy - eddy covariance	2006

At various times, Malaysia has had 31 continuous stationary monitoring stations across Peninsular Malaysia, Sarawak, and Sabah where 26 stations were operated by the Department of Environment (DOE), 4 stations were managed by the Malaysian Meteorological Department (METMalaysia), and 1 station managed by the Natural Environment Research Council with a collaboration of Universiti Malaya (NERC-UM) as shown in **Fig. 8**. These stations were designed to continuously measure ambient methane concentrations in different parts of Malaysia. The instruments used by DOE to measure the ambient methane concentration included in-situ air sampling with gas chromatograph with flame ionisation detector (GC-FID).

However, all 26 stations by DOE discontinued operations in 2010, after 15 years of operation. The available ambient methane concentration data by DOE is only from 1996 until 2010. Since then, no continuous ambient methane monitoring is recorded until the continuous ambient methane monitoring in Malaysia was resumed by METMalaysia in 2022. Hence, there is a 12-year gap of ambient methane monitoring operation.

METMalaysia is using in-situ air sampling and laser absorption spectroscopy to measure the ambient methane concentration in 4 stations that are in (1) Cameron Highlands, Pahang; (2) Langkawi, Kedah; (3) Sebangkoi, Sarawak; and (4) Lembah Danum, Sabah. Based on map in **Fig. 8**, the location of METMalaysia's stations is located far from the urban areas. The latest ambient methane concentration data by METMalaysia is available to purchase from 2022 until now.

Although a station by the NERC-Universiti Malaya started to measure methane ambient concentration in 2015, there was only one station, operated covering the area of Bachok, Kelantan in east coast of Peninsular Malaysia. Based on these findings, Malaysia has disadvantages in establishing a baseline of atmospheric methane over the last decade, due to the large data gap.

Fig. 8. Methane continuous monitoring stations in Malaysia operated by Department of Environment (DOE), Malaysia Meteorological Department (METMalaysia), and the Natural Environment Research Council with a collaboration of Universiti Malaya (NERC-UM). Since 1996, the DOE has set up 26 stations with methane monitoring instruments. However, the methane monitoring by the DOE stopped in 2010. Then the NERC-UM started to monitor methane ambient concentration continuously in 2015 but only at one station located in Bachok, Kelantan. Meanwhile, the METMalaysia started monitoring in 2022. The location includes (1) Cameron Highlands, Pahang; (2) Langkawi, Kedah; (3) Sarawak; and (4) Lembah Danum, Sabah in 2022. The instrument is the ABB LGR Analyser, reporting in ppm.

Other than the 31 continuous stationary monitoring stations operated by the DOE, METMalaysia and NERC-UM, there are other stationary monitoring stations operated by government bodies and research institutes, including the Sarawak Tropical Peat Research Institute (TROPI) (three stations), Malaysian Palm Oil Board (MPOB) (three stations), and Government Malaysian Agricultural Research and Development Institute (MARDI) (1 station). However, the stationary stations operated by TROPI, MPOB and MARDI are Eddy Covariance stations, which measure the surface flux of methane solely from a specific sector (e.g., peatlands or palm oil areas) and over a limited area (typically 0.01 km^2). In addition, the stationary sites operated by MPOB are known to measure methane on a project basis only, rather than continuous monitoring.

Additional stakeholders contributing to this endeavour include PETRONAS and Kyoto University, each operating one monitoring station. These stations result from collaborative efforts among governmental agencies, industrial sector entities, and research institutes. The Nuclear Agency Malaysia-Department of Agriculture have performed a methane monitoring by using portable instruments in the study location; however, the frequency of sampling and monitoring are again based on a project-by-project basis.

Methane monitoring helps accelerate source identification and emissions estimation. These sources can include natural processes like wetlands and geological seepage and human activities, such as agriculture, fossil fuel extraction, waste management, and energy production. Research institutes like TROPI have conducted methane monitoring focusing on the peatlands in Maludam National Park, Sarawak, to estimate the methane emissions from the AFOLU category. The MPOB employs similar methods to estimate methane emissions from the AFOLU category by monitoring oil palm fields at the Keratong, Pekan, and Pahang stations.

Data collected from monitoring stations across Malaysia can be obtained for free upon request from the DOE, or it can be purchased from METMalaysia. However, some information can only be obtained through published reports or journal articles due to the raw data confidentiality status. Previous studies by researchers (Razali and Yeow 2014, Topa et al. 2023)Click or tap here to enter text. have utilised the methane data by analysing it to identify patterns, trends, and potential hotspots of methane emissions in Malaysia. The findings from these previous studies help in understanding how emissions vary over time, geography, and sectors in Malaysia.

As part of methane monitoring, methane mapping is crucial in determining the concentration trends of methane over time and across different geographical locations. Methane mapping refers to creating detailed spatial representations or maps of methane concentrations in a specific area, typically using remote sensing technologies, such as satellites, aircraft, drones, or ground-based sensors (Hollenbeck et al. 2021, Scheller et al. 2022). Methane mapping is important in climate research, environmental monitoring, and policymaking because it helps identify locations with high emissions, assess the impact of various sources on methane concentrations, and measure the efficiency of emission reduction efforts.

This research managed to identify previous studies conducted in Malaysia that focused on methane mapping by using advanced techniques and technologies, including satellites, drones, and ground-based sensors as shown in **Table 5.** According to the findings, there are only a limited number of methane studies that have performed methane mapping in Malaysia. In the latest study conducted by researchers (Hashim et al., 2023), methane mapping in real time was conducted using an unmanned aerial vehicle (UAV)-based sniffing system (Sniffer4D), a specialised sensor technology integrated into a drone. This study focused on determining the methane ambient concentration in the industrial areas in Peninsular Malaysia. The results of using UAV-based Sniffer4D revealed that the mapped UAV methane concentration reported a good agreement with the in-situ observations with an RMSE of 6 mg m^{-3}. UAVs may provide a more cost-effective, accurate, and safe approach to finding greenhouse gas leaks than existing technology (Barchyn et al. 2017).

Table 5
Previous studies in Malaysia that conducted methane mapping.

Research	Location	Methodology
Hashim et al. 2023	Industrial areas (Pasir Gudang and Tanjung Langsat) in Peninsular Malaysia	• Used an unmanned aerial vehicle-based (UAV) sniffer sensor to visualise and analyse three-dimensional (3D) methane pollution data in real time. • The sniffer4D sensor, a detection and mapping system sensor for data collection of greenhouse gas concentration, was attached to the UAV, a drone for measuring methane over relatively large industrial areas (Pasir Gudang and Tanjung Langsat). • The UAV drone was flown at an altitude of 100 m.
Ng and Hashim 2023	Industrial areas in Peninsular Malaysia	• Used multiple types of satellite data to map methane trends during the COVID−19 pandemic control order in Peninsular Malaysia. • Level 2 data of total column-average dry-air mole fraction of methane (denoted as XCH_4, respectively) from GOSAT, GOSAT-2 and TROPOMI were used. • Data for the entire period of the lockdown (18th March to 3rd May) of 2019, 2020, and 2021 for all satellites were employed, where only data for 2020 and 2021 were used due to data availability.

Table 5 (continued)

Research	Location	Methodology
Rajab et al. 2012	Peninsular Malaysia	• Used Atmospheric Infrared Sounder (AIRS) data from 2003 until 2009 for methane mapping over Peninsular Malaysia. • The AIRS Level 3 data was obtained from NASA's Aqua Satellite. AIRS is a continuously operating cross-track scanning sounder consisting of a telescope that feeds a scale spectrometer. • The AIRS instrument views the atmospheric infrared spectrum in 2378 channels with a nominal spectral resolving power ranging from 1086 to 1570 covering more than 95% of the earth's surface and returning about three million spectra daily, in the 3.74–4.61 µm, 6.20–8.22 µm and 8.8–15.4 µm infrared wavebands at a nominal spectral resolution, also includes four visible/near-IR (Vis/NIR) channels between 0.40 and 0.94 µm, with a 2.3–km FOV.

Other than using a drone and sensor, methane mapping can also be conducted using satellite technology. A study by Ng and Hashim (2023) used multiple types of satellite data to map methane ambient concentration during the COVID−19 pandemic movement control order (MCO) or lockdown in selected industrial areas in Peninsular Malaysia. The methane mapping in this study was performed by using Level 2 data of the total column-average dry-air mole fraction of methane from GOSAT, GOSAT-2, and TROPOMI. Methane concentrations in industrial areas in Peninsular Malaysia during the lockdown were mapped successfully with satellite data from GOSAT, GOSAT-2, and TROPOMI. By comparing data during the MCO period from 2019 to 2021, methane concentrations indicated an increasing trend from year to year, and MCO had little influence on it, largely reflecting global trends in atmospheric methane.

Although this study demonstrated that satellite data can be employed for mapping of methane of large areas, the data were not used to determine emission rates.

Another study by Rajab et al. (2012) used Atmospheric Infrared Sounder (AIRS) data from 2003 until 2009 for methane mapping over Peninsular Malaysia. The AIRS Level 3 data was obtained from NASA's Aqua Satellite. AIRS is a continuously operating cross-track scanning sounder consisting of a telescope that feeds a scale spectrometer. This satellite technology can map methane, especially in determining seasonal weather conditions. In addition, this study confirmed that methane concentration over Peninsular Malaysia is increasing along the latitude of the troposphere over different regions. However, there is a disadvantage of using AIRS sample in methane mapping for estimating methane emissions since the AIRS samples of methane in the mid-upper troposphere has minimal relevance for methane emissions monitoring at the surface.

According to the findings of this research, no aircraft methane mapping research has been conducted in Malaysia. Although a study in Malaysia has explored the possibility of using remote sensing technologies such as satellites, drones, and ground-based sensors, the amount of study is considered limited and still at the early stage. The local services to use drones in measuring and mapping methane in Malaysia are also limited and upon request. Only two companies are known to provide these services: IKM Testing Malaysia and Alam Sekitar Malaysia Sdn. Bhd. Furthermore, previous Malaysian studies only focused on determining changes in methane concentrations and did not use the spatiotemporal methane map to estimate methane emissions using modelling techniques. Thus, there is room to explore and utilise the capabilities of remote sensing technologies not only for mapping methane concentration trends but also for estimating the methane emissions.

There is also potential for Malaysia to conduct comprehensive research that combines atmospheric measurements with other data sources that can be obtained from satellite technologies, including land use, industrial activities, and livestock populations by using advanced modelling techniques, like inverse modelling, to attribute the observed methane concentrations to specific source categories.

In addition, methane mapping that produces a spatiotemporal methane map can indeed aid in calculating methane emissions through inverse modelling as a spatiotemporal methane mapping provides the necessary methane concentrations data to better understand methane emissions, their sources, and their variations in the atmosphere over time and space, where these concentration measurements are essential inputs for inverse modelling (Bergamaschi et al. 2022). The discrepancies in Malaysia’s current methane measurements are listed in **Fig. 9**.

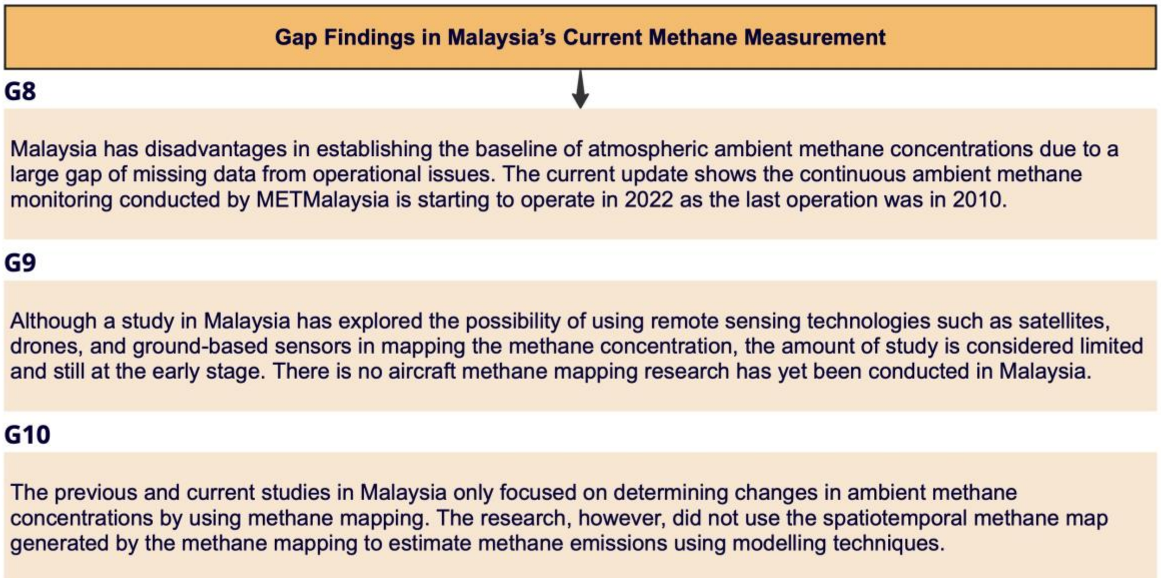


Fig. 9. Summary of gap findings in Malaysia's current methane measurement.

Methane Data Availability

Data availability refers to the accessibility and readiness of data for use when needed. Malaysia measures methane in ambient methane concentrations and surface fluxes. The methane data availability is based on the data collected from the continuous monitoring of methane concentrations either from ground-based monitoring stations, Eddy Covariance stations, and from portable measurements. **Table 6** shows the methane data available in Malaysia.

Table 6

Methane data availability in Malaysia.

Type of data	Source	Duration	Data Availability
Ambient concentration	Government Department of Environment (DOE)	1996 -2010	By request
	Government: Malaysian Meteorological Department (METMalaysia)	2022	Purchasable
	Industry: PETRONAS	-	Not public
	Researcher & Government: Natural Environment Research Council with a collaboration of Universiti Malaysia (NERC-UM)	2015	Public
Surface flux (Mass per area per time)	Government: Sarawak Tropical Peat Research Institute (TROPI)	-	By request but published
	Government: Malaysian Palm Oil Board (MPOB)	2015	Not public but published
	Government: Malaysian Agricultural Research and Development Institute (MARDI)	2012	Public
	Government: Nuclear Agency Malaysia-Department of Agriculture	2022	Not public
	Researcher: Kyoto University	2006	Not public but published

The methane ambient concentration in Malaysia has been measured and collected by the DOE, METMalaysia, NERC-UM, and industrial stakeholder, like PETRONAS. However, the availability status of the data is varied based on the data sources. The methane ambient concentration data from the government bodies and research institute can be obtained upon request, which some of the data are purchasable, such as from METMalaysia.

As an industrial and private company in the energy sector, PETRONAS has kept tabs on the sites' methane concentrations and emissions, but the data is not publicly available. On the other hand, Petron has decided not to include methane emissions in their reports and daily monitoring, mainly because the measured methane emissions account for less than 1% of the inventory.

Surface flux data of methane in Malaysia has been measured and collected by government bodies and research institutes, including TROPI, MPOB, MARDI, Nuclear Agency Malaysia-Department of Agriculture, and Kyoto University. Most of the data can be obtained from their published annual report and journal articles. However, the data is not publicly available and ready to be utilised for other purposes, like reanalysis. The available data begin as early as 2006 (Kyoto University), but unfortunately, most of the surface flux measurements in Malaysia are not continuously monitored and instead are on a project-by-project basis. The summary of gap findings in Malaysia's current methane data availability is exemplified in **Fig. 10**.

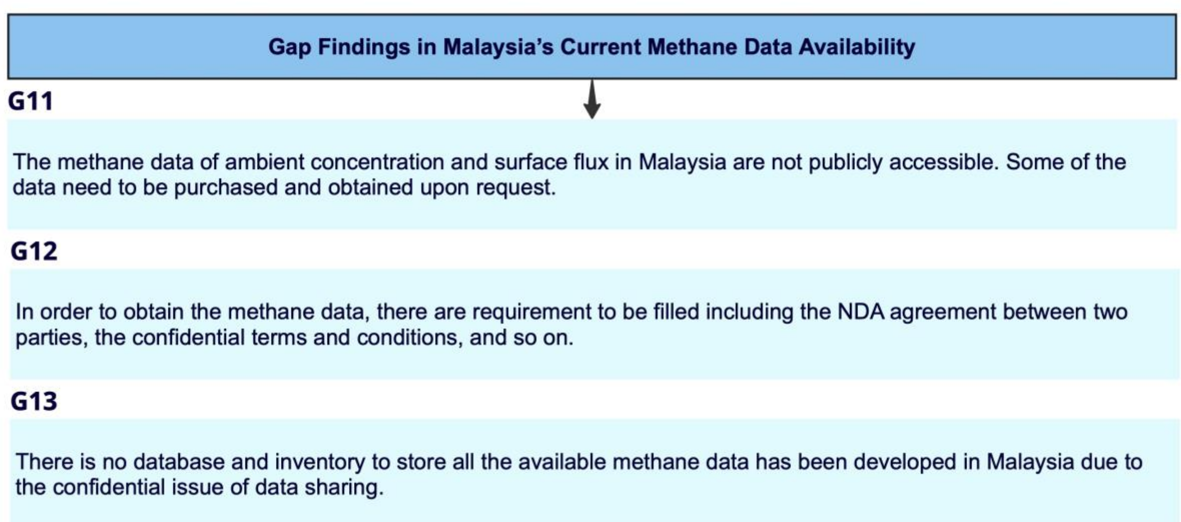


Fig. 10. Summary of gap findings in Malaysia's current methane data availability.

Challenges in Introducing More Methane Measurements

Reducing methane emissions in Malaysia, as in many countries, poses several challenges due to the complex nature of methane sources, diverse economic activities, and the lack of coordinated efforts. Based on the findings of this research, the challenges, and difficulties in introducing more methane measurements faced by Malaysia can be divided into three levels of stakeholder categories, including the ministry or government agencies, the industrial sectors, and universities or research institutes. From the **Table 7**, there are a few gap-findings obtained in measuring methane.

Table 7

Challenges and difficulties encountered by different groups of stakeholders in Malaysia.

Level		Challenges and difficulties
Ministry/ government agencies	i.	Lack of involvement from stakeholders to develop Country Specific Emission Factor (CSEF), where the academia or industries are needed.
	ii.	Hard-to-emphasise the need for emission factor research especially methane emissions since there is low engagement with academicians and industrial stakeholders.
	iii.	Most of the data is confidential, where there is the need to sign a non-disclosure agreement (NDA), and the data is solely used for greenhouse gas reporting.
	iv.	Different standards used in reporting for the Oil and Gas Sustainability Report make retrieving data hard to interpret, which can lead to the possibility of double-counting.
	v.	No established acts or guidelines for mandatory reporting of greenhouse gas emissions.
	vi.	Continuous monitoring of methane concentration and surface flux requires continuous financial support for operational, maintenance, and management.
Industrial sectors	i.	The private sector often faces cost considerations when implementing methane reduction measures. Balancing economic viability with environmental goals can be a challenge since the industrial sector, like the oil and gas sector is targeting to reduce 50% of methane emissions by 2050.
	ii.	Adaptation of renewable energy requires time and cost to reduce methane emissions.
Universities/ Research institutes	i.	The complexity of emission sources and the lack of methane flux measurement.
	ii.	Low research funds, lack of automation, and technology limitations due to excessive costs for advanced technologies. For example, the reduction of methane in the faecal waste sector involves expensive facilities (e.g., biodigesters).

The challenges in introducing more methane measurements in Malaysia are highlighted in **Fig. 11**.

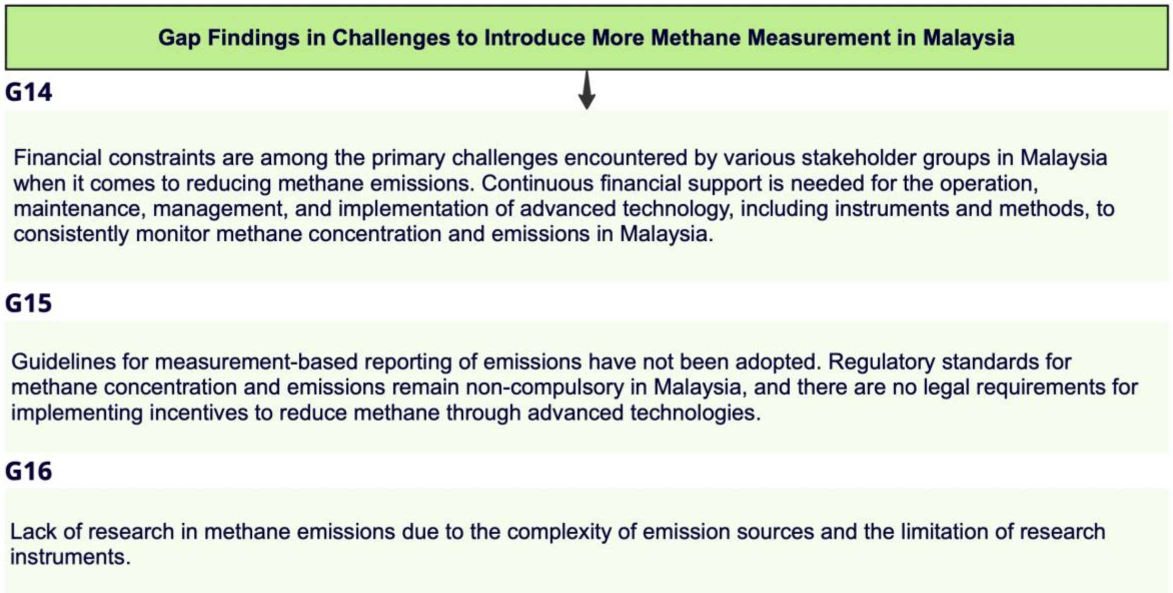


Fig. 11. Summary of gap findings in challenges in introducing more methane measurement in Malaysia.

The Severity Level of Gap Findings

Understanding the extent of methane emissions, identifying their sources, and bridging the gap in current works and efforts are crucial steps in addressing this issue of methane in Malaysia. The severity of gaps in current works and efforts of methane emissions in Malaysia especially focusing on knowledge gaps is a matter of increasing concern due to its significant implications for both the nation's environment and its commitment to international climate agreements.

Malaysia, like many countries, faces a complex challenge in managing and reducing methane emissions, which arise from a variety of sources across different sectors. As indicated in **Fig. 12**, approximately 16 gaps have been discovered based on the results of the gap analysis conducted for this research.

The multi-criteria decision analysis (MCDA) was then performed based on nine criteria's (cost, quality, time, reliability, regulatory compliance, innovation, strategic alignment, accessibility, and scalability) on the 16 gaps to rank the severity level of the gap findings. The criteria's contributing to the determination of severity levels consider responses obtained from the stakeholders including government, industry players, and researchers. However, it's important to note that the ordering may fluctuate due to subjective judgment.

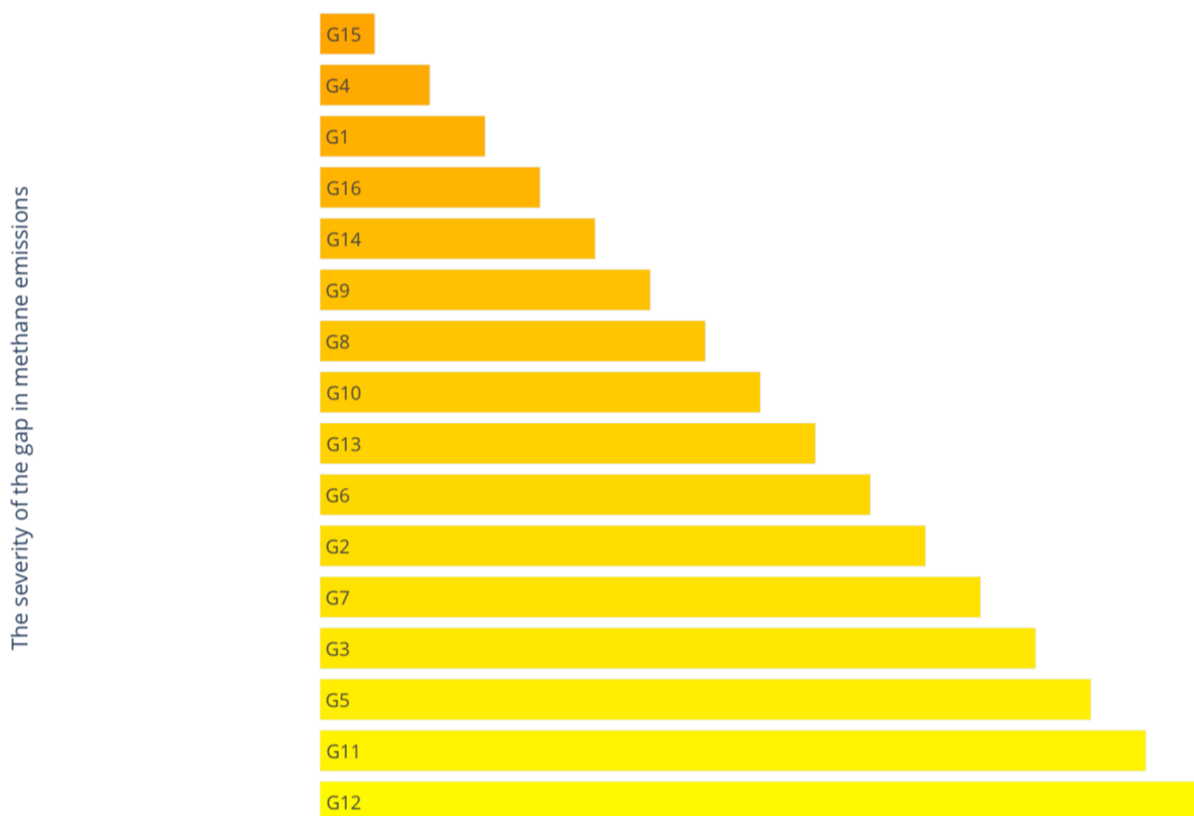


Fig. 12. The severity level of the gap findings in methane measurements in Malaysia.

High severity	G15	No established regulatory acts and guidelines for mandatory greenhouse gas (GHG) reporting
	G4	Limited engagement among stakeholders led to lack of tangible progress
	G1	Unbalance research approach across all sectors
	G16	Lack of research in methane emissions due to the complexity of emission sources and the limitation of research instruments
	G14	No continuous financial support for the operation, maintenance, management and implementation of advanced technology, especially in research and development
	G9	Usage of advanced technology in monitoring is considered limited and still at the early stage
	G8	Huge gap of missing data due to operational issue in ground-based monitoring station
	G10	Current methane mapping has yet to estimate emissions using modelling techniques
Low severity	G13	No database and inventory to store all the available data
	G6	Absence of activity data for certain emissions sources
	G2	The reliance on Tier 1 factors in greenhouse gas (GHG) reporting may limit the accuracy of emissions estimates
	G7	Reliance on outdated activity data may raises accuracy concerns
	G3	Limited availability of published literature to support advancement of emissions factors to Tier 2 or Tier 3 in most of the sectors
	G5	Lack of consistency in baseline data across different emissions categories in greenhouse gas (GHG) reporting
	G11	Limited access of data sharing due to the concentration and emission data are not publicly accessible
	G12	Requirement to sign the NDA for data sharing request

Fig. 12. (continued)

Based on **Fig. 12**, the severity level of gap findings grows as the level of the pyramid increases, with two levels of severity from the low level to the high level. The low severity of gaps generally denotes a gap that is less critical and of limited impact that does not pose an immediate or substantial risk in introducing more methane measurements. The low severity gaps may not demand immediate attention but should be addressed over time to prevent them from becoming more significant. The high severity gaps indicate the gaps that have substantial negative impacts, which might potentially lead to major problems in pursuing more methane measuring efforts. The high severity gaps require immediate attention and intervention to prevent any potential difficulties in reducing methane emissions.

The **high severity gaps** of the pyramidal diagram in consist of eight gaps (**G15, G4, G1, G16, G14, G9, G8**, and **G10**) related to methane measurements, particularly methane concentration and emission monitoring by various stakeholders in Malaysia. The highest level of severity in methane measurement in Malaysia refers to G15, the lack of established acts and guidelines for greenhouse gas reporting. The lack of established acts and guidelines for reporting methane emissions has influenced the participation of stakeholders in Malaysia in methane measurements and reduction. The lack of extensive collaboration among stakeholders, such as government entities, industrial sectors, and research institutions, has resulted in an imbalanced research strategy across all sectors pertaining to methane sources. The limited research on methane emissions across many sectors may be attributed to the complexity of emission sources and the constraints imposed by research instruments. However, it is crucial to conduct research of methane in all sectors to effectively address and mitigate these emissions in a comprehensive manner.

Although Malaysia has continuously monitored the methane ambient concentration using ground-based monitoring and Eddy Covariance stations, there are still gaps in the data due to operational issues and the diversity of monitoring stations and locations. While Malaysia is currently investigating the utilisation of advanced technology, such as drones and satellites, it is important to note that the capability for such monitoring is currently limited and in its preliminary stages.

Furthermore, Malaysia has not yet conducted the estimation of emissions utilising advanced modelling approaches and data collected from drones, satellites, and ground-based monitoring stations. This approach has the potential to significantly enhance the accuracy of methane emission estimates. All these gaps can be related to financial constraints, the instability of the operation, maintenance, management, and implementation of advanced technology in measuring methane concentration and emissions continuously.

The **low severity gaps** are related to the limitations faced by Malaysia in reporting high-precision and accurate methane emissions due to the limited data available and its lack of dissemination. There are eight gaps (**G13, G6, G2, G7, G3, G5, G11,** and **G12)** listed in **Fig. 12**. Incomplete and missing activity data from specific emissions sources has resulted in reliance on outdated activity data and variability in baseline data in greenhouse gas reporting, increasing dependency on Tier 1 factors, which may limit the accuracy and precision of emissions estimation. The reasons for these gaps are related to the scarcity of reliable published literature and methane concentration and emissions data, which led to the challenging advancement to Tier 2 or Tier 3 as most of the data is not publicly available and require a non-disclosure agreement (NDA), one of the many complicated and time-consuming processes involved in acquiring the data. The current methane data is also difficult to access for all sectors since they are not equally monitored or researched. The lack of a centralised methane database or inventory in Malaysia has also made it more difficult to share and collect data. The impact of these gaps influences the accuracy and precision of methane emissions reporting, which is critical for tracking emission trends as part of Malaysia's commitment to the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement in decreasing methane emissions.

Although reporting methane emissions are essential for Malaysia as an effort to reduce global methane emissions, ensuring the accurate and precise measurement of methane emissions from all sectors should be prioritised in Malaysia. The investment in database and inventory development for methane reporting purposes may not be justifiable if the data are characterised by significant gaps and unreliability, resulting from uneven monitoring practices and limited utilisation of technology. All gaps should be addressed holistically, to achieve comprehensive and sustainable solutions in reducing the methane emissions in Malaysia.

What's next: Moving Forward

The severity level of gap findings serves as a baseline for recommending future research. The potential research plans were categorised based on the severity of the knowledge gap findings in attempts to reduce the methane emissions in Malaysia as shown in **Table 8** for the high-level and **Table 9** the low level.

Table 8

The potential research plan based on the high-level severity gap of knowledge in methane measurements in Malaysia.

High-Level Severity	
Gap	**Potential Research Plan**
G15, G4, G1 and G16	**Comprehensive Interdisciplinary Research Across All Sectors** Comprehensive interdisciplinary research can play a significant role in engaging stakeholders and reducing methane emissions in Malaysia to promote stakeholder interaction between the ministry, government agencies, industrial sectors, and university/research institute researchers. Interdisciplinary research brings together experts from different fields to collaborate on understanding the problem holistically and finding effective and more coordinated solutions. For example, 1) A study of "Integrated Strategies for Methane Emission Reduction: A Cross-Industry Approach in Malaysia". This interdisciplinary research that combines Palm Oil Mill Effluent (POME) and oil and gas sectors can drive more effective and sustainable methane emissions reduction efforts. It can involve environmental scientist, government agencies, industrial sectors representatives, technology experts, and policy makers. 2) A study of "Integrated Strategies for Mitigating Methane Emissions from Natural Gas Flaring in the Malaysian Oil and Gas Sector." This interdisciplinary research can contribute to reducing methane emissions from flaring in oil and gas sector by promoting flare gas recovery technologies and emissions control measures. It can involve environmental scientist, oil and gas representatives, technology experts, health and safety experts, local authorities, government bodies, and policy analysts. 3) A study of "Assessment and Mitigation of Methane Emissions in the Urban Environment: A Case Study in Kuala Lumpur, Malaysia". This interdisciplinary research project focuses on understanding and reducing methane emissions in the urban environment. It can involve experts from environmental scientist, social scientist, economist, government agencies (Department of Environment, Malaysian Meteorological Department, etc), industrial sectors, Kuala Lumpur City Hall to address the complex nature of methane emissions in an urban setting. 4) A study of "Sustainable Agricultural Methane Mitigation (SAMM) Initiative". The SAMM Initiative is a comprehensive interdisciplinary research project aimed at addressing methane emissions in the AFOLU sector, specifically focusing on agricultural activities in a region or country. It can involve environmental scientist, social scientist, economist, government bodies, such as the Agricultural Department of Malaysia, livestock expert, forest expert and policy analysts. Addressing methane emissions is a complex issue that involves various sectors. However, it is necessary to allocate equal attention to all sectors of sources to thoroughly investigate the methane. It can also promote collaboration and shared responsibility among stakeholders, leading to more sustainable solutions for mitigating methane emissions and addressing climate change. This interdisciplinary research efforts should be comprehensive and well-documented to support the development of effective and enforceable methane reporting and measurement regulations.

Table 8 (continued)

High-Level Severity	
Gap	**Potential Research Plan**
G9, G8, and G10	**Spatiotemporal Monitoring using Advanced Technology (Satellite, Drone, and Aircraft)** Spatiotemporal monitoring using advanced technology, such as satellites, drones, and aircraft, can play a significant role in reducing methane emissions in Malaysia by providing accurate and timely data on emission sources, trends, and hotspots. Drones and aircraft can collect direct measurements of methane concentrations near the source, providing precise emission estimates for individual facilities or locations. Remote sensing instruments on satellites can estimate methane concentrations in the atmosphere, enabling the quantification of emissions on a regional or national scale by using inverse modelling techniques. Drones equipped with multispectral cameras can monitor agricultural fields for signs of excessive methane emissions, such as flooded rice paddies. This information can guide farmers in adopting more methane-friendly practices especially in AFOLU sector. Satellite data can provide insights into land-use changes, helping policymakers assess the impact of land use on emissions and implement sustainable land management practices. Besides, the satellite data can help to improve the accuracy and precision of activity data. **Network for Methane Flux Towers** To improve the monitoring of methane emissions in Malaysia, it is recommended to relocate monitoring stations closer to the sources of emissions, such as industrial areas and oil and gas facilities based on the findings from the spatial emissions sources analysis. This will provide a more comprehensive view of methane emissions across the country, enhancing our ability to address greenhouse gas emissions effectively. Installing methane flux sensors at all monitoring stations is also crucial to broaden the coverage of methane emissions measurements. Consistent funding for station maintenance is paramount to ensure the functionality and longevity of the monitoring stations, drawing inspiration from successful models in other countries. Making methane emission data publicly available will further support research and foster international cooperation. Sharing methane data across borders can encourage collaboration on emissions reduction strategies and climate change mitigation. Lastly, the collected methane emission data can aid in improving Malaysia's emissions inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC).
G15	**Site-level Sampling to Attain the Gold Standard Established by the Oil and Gas Methane Partnership (OGMP) 2.0** PETRONAS has publicly disclosed its full compliance with OGMP 2.0 across all operational oil and gas entities in Malaysia. This demonstrates a significant commitment within the industry to curbing methane emissions through comprehensive initiatives. Prominent companies in the sector, including PETRONAS and Shell are increasingly aligning themselves with the second level of OGMP 2.0 compliance. At this stage, emissions are reported within consolidated and simplified source categories, organised according to the upstream, midstream, and downstream segments of the oil and gas production process. The shared objective of these companies is to attain site-level measurements for methane emissions and to employ specific emission factors and activity factors. This refined approach promises a more precise understanding of emissions sources and trends. However, it is widely recognised within the industry that the foremost challenge in achieving these objectives lies in the financial implications associated with their execution. The focus on reducing methane emissions is imperative for the industry to secure additional funding to expedite the process and attain site-level measurements. This, in turn, will provide a more accurate understanding of emissions, facilitating the determination of the most effective reduction strategies. This raises questions about whether the absence of requirements for site-level measurements in greenhouse gas reporting is allowing the industry to slow down in pursuing these crucial goals. Mandating site-level measurements could encourage all oil and gas companies to actively participate in reducing methane emissions while gaining recognition for their efforts.

Table 9

The potential research plan based on the low level of severity gap of knowledge in methane measurement in Malaysia.

Low-Level Severity	
Gap	**Potential Research Plan**
G13, G6, G2, G7, G3, and G5	**Development of Methane Inventory Database** A fundamental cornerstone in addressing methane emissions is the creation of a comprehensive Methane Inventory Database. This database plays a pivotal role in the effective monitoring and management of greenhouse gas emissions. The project is proposed to unfold in three distinct phases: Phase 1: Emission Factor Database The development of an emissions factor database entails the establishment of a repository housing emissions factor. These factors quantify the amount of greenhouse gas pollutants, such as methane or carbon dioxide, released per unit of activity or other relevant parameters. This database's primary objective is to centralise emissions factors for various emission sources and sectors. It primarily focuses on the creation and cataloguing of emissions factors, often as a precursor to constructing an emissions inventory. These emissions factors are essentially numerical values utilised for estimating emissions based on activity data. They are typically expressed as emissions per unit of activity, such as kilograms of methane emitted per hectare of rice cultivation. The aim is to forge a user-friendly and readily shareable emissions factor database, which can be efficiently crafted using tools like Microsoft Excel. The Intergovernmental Panel on Climate Change (IPCC) also offers Excel-based worksheets derived from guideline calculations. The database may be organised by sector, sub-sector, and pollutant. Its primary purpose is to serve as a resource for researchers, policymakers, and environmental professionals, equipping them with emissions factors for different sectors and sources. This resource facilitates the estimation of emissions for specific activities or industries. Phase 2: Activity Data Database This phase involves the aggregation of activity data related to emissions sources, complementing the emissions factors, and providing a comprehensive understanding of emissions. Phase 3: Methane Inventory Database The development of a Methane Inventory Database aligns with the framework proposed by the U.S. Environmental Protection Agency (USEPA), as evaluated in September 2023. This framework encompasses four essential stages in inventory development: (1) scoping and planning the inventory, (2) collecting data and quantifying greenhouse gas emissions, (3) formulating a greenhouse gas inventory management plan, and (4) monitoring and reporting progress. This framework closely adheres to the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC), which is guided by IPCC recommendations and tailored for city-level emissions assessment that can be scaled to the national level. Additionally, the International Local Government Greenhouse Gas Emissions Analysis Protocol (IEAP) shares analogous concepts with these guidelines. It defines emissions within specific boundaries, scopes emissions across three levels, and establishes baseline years. The initiation of a Methane Inventory Database can commence at the city level, following a bottom-up approach, encompassing the definition of emission levels across various industry sectors. Data collection will originate from the emission factor database (Phase 1) and activity data database (Phase 2), simplifying the integration process and reducing the risk of asynchrony. However, one of the most formidable challenges in constructing such a comprehensive database is the scarcity of readily available datasets. Addressing this challenge necessitates engagement with local authorities and raising their awareness of the pivotal role they play as data providers.

Table 9 (continued)

Low-Level Severity	
Gap	**Potential Research Plan**
G11 and G12	**Storage Platform for Methane Inventory Database** Data sharing is essential in research and development especially in methane measurement in Malaysia. The restriction on data sharing has had an impact on several gaps, particularly in the reporting of methane emissions. Selecting a storage platform for a methane inventory database that can be accessed by all stakeholders with or without a Non-Disclosure Agreement (NDA) requires a careful balance of data security and accessibility. Research related to choosing a storage platform for a methane inventory database typically falls under the domain of data management, environmental science, and information technology. For example, a study of "Evaluation and Implementation of a Secure Storage Platform for Methane Emission Inventory Data." This study has the potential to provide a valuable contribution towards identifying the most suitable data storage platform for a methane inventory database. The aim is to identify a platform that fulfils the essential criteria of secure and efficient storage of the database, while also allowing for dissemination to all stakeholders with or without an NDA. Conducting comprehensive research and potentially collaboration with experts in environmental data management, information technology, and data security is vital to ascertain that the chosen storage platform is in accordance with the requirements and focal points of methane inventory database. Prior to the implementation of any platform, it is imperative to get guidance from legal professionals to ascertain the necessity of NDAs and the appropriate methods for their implementation to safeguard sensitive data, in addition to ensuring compliance with pertinent regulatory frameworks.

4. Conclusions

The future of emissions management and mitigation holds promising opportunities for further progress. This research offers a comprehensive approach to address methane emissions in Malaysia by leveraging the identified knowledge gaps, which have been categorised based on their severity levels. These research plans provide practical solutions for mitigating methane emissions.

The high-level initiatives stress the significance of fostering interdisciplinary research and active engagement among stakeholders from various sectors, including government bodies, industrial sectors, and researchers. Collaborative efforts are key to finding effective solutions. Furthermore, the utilisation of advanced technology, such as satellites, drones, and aircraft for spatiotemporal monitoring, is recommended to obtain precise data on emission sources and trends. The relocation of monitoring stations closer to emission sources and providing public access to methane emission data further enhance the accuracy of monitoring and reporting.

Low-level knowledge gaps are addressed by proposing the development of a Methane Inventory Database, consisting of three crucial phases: the Emission Factor Database, the Activity Data Database, and the Methane Inventory Database. These phases are designed to facilitate precise data collection, monitoring, and reporting of methane emissions. However, the scarcity of readily available datasets highlights the importance of engaging local authorities to provide the necessary data.

Another aspect of addressing low-level knowledge gaps is the selection of a secure storage platform for the methane emission data. This emphasises the need for a platform that balances data security and accessibility to support research and development.

Malaysia has adopted the Tier 2 emission factor within the Agriculture and Waste sector, emphasising the need to assess and validate other sources of emissions data, particularly concerning is the Palm Oil Mill Effluent (POME) emissions. The validation process draws upon multiple studies (Vijaya Subramaniam & Choo, 2012; Vijaya et al., 2008), and these findings contribute to a more precise understanding of POME emissions, ensuring that Tier 2 emissions factor-based calculations are grounded in empirical evidence. However, it's important to remain mindful of adopting updated factors as technology specifications change. Collaboration with countries already employing Tier 2 methodologies, such as Singapore, Thailand, and Vietnam, offers substantial potential for enhancing Malaysia's methane inventory, recognising the unique challenges faced by Southeast Asian nations.

When it comes to Tier 3 methodologies, an important example is the published literature addressing subcategories like Electricity Generation and Combined Heat and Power Generation. It is worth noting that despite the availability of this literature, Tier 3 methodologies have not been adopted in the latest Biennial Update Report (BUR). This discrepancy raises questions about why Tier 3 methodologies were omitted and how this issue can be addressed. Engaging with countries that have successfully implemented Tier 3, such as Singapore, can provide valuable insights into overcoming these challenges and working toward more comprehensive methane emissions assessments.

The combined approach of exploring emission factors and facilitating collaborative sessions with stakeholders sets a forward-looking trajectory for addressing methane emissions. By embracing these recommendations, we can take significant strides towards a more sustainable and environmentally conscious future.

Acknowledgements

This research was supported by the Environmental Defense Fund. The researchers also thank the valuable insights from Ministry of Natural Resources, Environment and Climate Change (NRECC), PETRONAS, Sarawak Energy, and Indah Water Konsortiums during the interviews. The researchers also thank all the participating institutes and companies for their contributions to this study, including the Malaysian Meteorological Department (METMalaysia), Malaysian Nuclear Agency and Department of Agriculture Malaysia, Malaysian Agricultural Research and Development Institute (MARDI), Department of Environment (DOE), Sarawak Tropical Peat Research Institute (TROPI), Environmental Research Division, Top Glove and Malakoff.

References

Azizan, S. N. F., Y. Goto, T. Doi, M. I. F. Kamardan, H. Hara, I. McTaggart, T. Kai, and K. Noborio. 2021. Comparing GHG emissions from drained oil palm and recovering tropical peatland forests in Malaysia. Water 13:3372.

Azizi, A. A., M. Mardhati, M. S. Mohd Fairuz, A. T. Shaidatul Azdawiyah, A. B. Nurul Ain, J. Fauzi, A. R. Mohamad Hariz, and A. Reisinger. 2017. Local emission factors estimates for methane emission from cattle enteric fermentation using IPCC tier-2 methodology. Malaysian Journal of Animal Science 20:1–10.

Bange, H., C. Hock Sim, D. Bastian, J. Kallert, A. Kock, A. Mujahid, and M. Müller. 2019. Nitrous oxide (N2O) and methane (CH4) in rivers and estuaries of northwestern Borneo. Biogeosciences 16:4321–4335.

Barchyn, T. E., C. H. Hugenholtz, S. Myshak, and J. Bauer. 2017. A UAV-based system for detecting natural gas leaks. Journal of Unmanned Vehicle Systems 6:18–30.

Bastviken, D., C. C. Treat, S. R. Pangala, V. Gauci, A. Enrich-Prast, M. Karlson, M. Gålfalk, M. B. Romano, and H. O. Sawakuchi. 2023. The importance of plants for methane emission at the ecosystem scale. Aquatic Botany 184:103596.

Bergamaschi, P., A. Segers, D. Brunner, J. M. Haussaire, S. Henne, M. Ramonet, T. Arnold, T. Biermann, H. Chen, S. Conil, M. Delmotte, G. Forster, A. Frumau, D. Kubistin, X. Lan, M. Leuenberger, M. Lindauer, M. Lopez, G. Manca, J. Müller-Williams, S. O'Doherty, B. Scheeren, M. Steinbacher, P. Trisolino, G. Vítková, and C. Yver Kwok. 2022. High-resolution inverse modelling of European CH4 emissions using the novel FLEXPART-COSMO TM5 4DVAR inverse modelling system. Atmospheric Chemistry and Physics 22:13243–13268.

Bollinger, E., J. P. Zubrod, F. Y. Lai, L. Ahrens, S. Filker, A. Lorke, and M. Bundschuh. 2021. Antibiotics as a silent driver of climate change? A case study investigating methane production in freshwater sediments. Ecotoxicology and Environmental Safety 228:113025.

Busman, N. A., L. Melling, K. J. Goh, Y. Imran, F. E. Sangok, and A. Watanabe. 2023. Soil CO2 and CH4 fluxes from different forest types in tropical peat swamp forest. Science of the Total Environment 858:159973.

Chaddy, A., L. Melling, K. Ishikura, K. J. Goh, Y. Toma, and R. Hatano. 2021. Effects of long-term nitrogen fertilization and ground water level changes on soil CO2 fluxes from oil palm plantation on tropical peatland. Atmosphere 12:1340.

Cheng, C. H., and S. A. T. Redfern. 2022. Impact of interannual and multidecadal trends on methane-climate feedbacks and sensitivity. Nature Communications 13:1–11.

Cooper, H. V., S. Evers, P. Aplin, N. Crout, M. P. Bin Dahalan, and S. Sjogersten. 2020. Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. Nature Communications 11:1–8.

Department of Statistics. 2022, October 25. Selected Agricultural Indicators, Malaysia. https://www.dosm.gov.my/portal-main/release-content/selected-agricultural-indicators-malaysia-2022.

Deshmukh, C. S., D. Julius, C. D. Evans, Nardi, A. P. Susanto, S. E. Page, V. Gauci, A. Laurén, S. Sabiham, F. Agus, A. Asyhari, S. Kurnianto, Y. Suardiwerianto, and A. R. Desai. 2020. Impact of forest plantation on methane emissions from tropical peatland. Global Change Biology 26:2477–2495.

Dhandapani, S., S. Evers, D. Boyd, C. D. Evans, S. Page, F. Parish, and S. Sjogersten. 2023. Assessment of differences in peat physico-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands. Catena 230.

Fazli, P., and H. C. Man. 2014. Comparison of methane emission from conventional and modified paddy cultivation in Malaysia. Agriculture and Agricultural Science Procedia 2:272–279.

Glasson, C. R. K., R. D. Kinley, R. de Nys, N. King, S. L. Adams, M. A. Packer, J. Svenson, C. T. Eason, and M. Magnusson. 2022. Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants. Algal Research 64:102673.

Heede, R., and N. Oreskes. 2016. Potential emissions of CO2 and methane from proved reserves of fossil fuels: An alternative analysis. Global Environmental Change 36:12–20.

Hollenbeck, D., D. Zulevic, and Y. Chen. 2021. Advanced leak detection and quantification of methane emissions using sUAS. Drones 5:117.

IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Page (Masson-Delmotte, P. Z. V., H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), Eds.). Cambridge University Press.

IPCC-TFI. 2023, August. IPCC Inventory Software. Intergovernmental Panel on Climate Change.

Ishikura, K., R. Hirata, T. Hirano, Y. Okimoto, G. X. Wong, L. Melling, E. B. Aeries, F. Kiew, K. S. Lo, K. K. Musin, J. W. Waili, and Y. Ishii. 2019. Carbon dioxide and methane emissions from peat soil in an undrained tropical peat swamp forest. Ecosystems 22:1852–1868.

Ito, A., Y. Tohjima, T. Saito, T. Umezawa, T. Hajima, R. Hirata, M. Saito, and Y. Terao. 2019. Methane budget of East Asia, 1990–2015: A bottom-up evaluation. Science of the Total Environment 676:40–52.

Leifer, I., D. Culling, O. Schneising, P. Farrell, M. Buchwitz, and J. P. Burrows. 2013. Transcontinental methane measurements: Part 2. Mobile surface investigation of fossil fuel industrial fugitive emissions. Atmospheric Environment 74:432–441.

Lim Kim Choo, L. N., and O. H. Ahmed. 2017. Methane emission from pineapple cultivation on a tropical peatland at Saratok, Malaysia. Sustainable Agriculture Research 6:64–74.

Liu, T., S. Hu, Z. Yuan, and J. Guo. 2023. Simultaneous dissolved methane and nitrogen removal from low-strength wastewater using anaerobic granule-based sequencing batch reactor. Water Research 242:120194.

Loh, S. K., A. B. Nasrin, S. Mohamad Azri, B. Nurul Adela, N. Muzzammil, T. Daryl Jay, and R. A. Stasha Eleanor. 2017. Biogas capture - a means of reducing greenhouse gas emissions from palm oil mill effluent. Oil Palm Bulletin 75:27–36.

Luta, W., O. H. Ahmed, L. Omar, R. K. J. Heng, L. N. L. K. Choo, M. B. Jalloh, A. A. Musah, and A. Abdu. 2021. Water table fluctuation and methane emission in pineapples (Ananas comosus (l.) merr.) cultivated on a tropical peatland. Agronomy 11:1148.

Malaysia. 2020. Third Biennial Update Report Under the United Nations Framework Convention on Climate Change. UNFCC.

Malaysia. 2022. Fourth Biennial Update Report Under the United Nations Framework Convention on Climate Change. UNFCC.

Melling, L., R. Hatano, and J. G. Kah. 2005. Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. Soil Biology and Biochemistry 37:1445–1453.

Nauer, P. A., L. B. Hutley, and S. K. Arndt. 2018. Termite mounds mitigate half of termite methane emissions. Proceedings of the National Academy of Sciences of the United States of America 115:13306–13311.

Ng, H. L., and M. Hashim. 2023. Mapping trends of carbon dioxide and methane during movement control order in industrial areas in Peninsular Malaysia using GOSAT, GOSAT-2, OCO-2, OCO-3, and TROPOMI satellites data. Pages 273–278 International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives. International Society for Photogrammetry and Remote Sensing.

Nuclear Agency Malaysia. 2023. Greenhouses Gases Evaluation Programs on Farmer Rice Field in Collaboration with Department of Agriculture Sungai Burong, Selangor, Malaysia.

Parker, R. J., H. Boesch, J. McNorton, E. Comyn-Platt, M. Gloor, C. Wilson, M. P. Chipperfield, G. D. Hayman, and A. A. Bloom. 2018. Evaluating year-to-year anomalies in tropical wetland methane emissions using satellite CH4 observations. Remote Sensing of Environment 211:261–275.

Rafalska, A., A. Walkiewicz, B. Osborne, K. Klumpp, and A. Bieganowski. 2023. Variation in methane uptake by grassland soils in the context of climate change – A review of effects and mechanisms. Science of The Total Environment 871:162127.

Rajab, J. M., M. Z. Matjafri, and H. S. Lim. 2012. Methane interannual distribution over Peninsular Malaysia from atmospheric infrared sounder data: 2003-2009. Aerosol and Air Quality Research 12:1459–1466.

Rangga, J. U., S. N. S. Ismail, I. Rasdi, and K. Karuppiah. 2023. Contribution of waste segregation to GHG emissions, land usage, and health risk of NMVOC exposure: a study in Malaysia. Journal of Material Cycles and Waste Management 25:181–197.

Razali, A. M., and P. M. Yeow. 2014. Pemetaan kepekatan metana di Semenanjung Malaysia. Jurnal Pengukuran Kualiti dan Analisis 10:99–110.

Rypdal, K., N. Paciornik, S. Eggleston, J. Goodwin, W. Irving, J. Penman, and M. Woodfield. 2006. Chapter 1 - Introduction to the 2006 Guidelines.

Saunois, M., P. Bousquet, B. Poulter, A. Peregon, P. Ciais, J. G. Canadell, E. J. Dlugokencky, G. Etiope, D. Bastviken, S. Houweling, G. Janssens-Maenhout, F. N. Tubiello, S. Castaldi, R. B. Jackson, M. Alexe, V. K. Arora, D. J. Beerling, P. Bergamaschi, D. R. Blake, G. Brailsford, V. Brovkin, L. Bruhwiler, C. Crevoisier, P. Crill, K. Covey, C. Curry, C. Frankenberg, N. Gedney, L. Höglund-Isaksson, M. Ishizawa, A. Ito, F. Joos, H. S. Kim, T. Kleinen, P. Krummel, J. F. Lamarque, R. Langenfelds, R. Locatelli, T. Machida, S. Maksyutov, K. C. McDonald, J. Marshall, J. R. Melton, I. Morino, V. Naik, S. O'Doherty, F. J. W. Parmentier, P. K. Patra, C. Peng, S. Peng, G. P. Peters, I. Pison, C. Prigent, R. Prinn, M. Ramonet, W. J. Riley, M. Saito, M. Santini, R. Schroeder, I. J. Simpson, R. Spahni, P. Steele, A. Takizawa, B. F. Thornton, H. Tian, Y. Tohjima, N. Viovy, A. Voulgarakis, M. Van Weele, G. R. Van Der Werf, R. Weiss, C. Wiedinmyer, D. J. Wilton, A. Wiltshire, D. Worthy, D. Wunch, X. Xu, Y. Yoshida, B. Zhang, Z. Zhang, and Q. Zhu. 2016. The global methane budget 2000-2012. Earth System Science Data 8:697–751.

Saunois, M., A. Martinez, B. Poulter, Z. Zhang, P. A. Raymond, P. Regnier, J. G. Canadell, R. B. Jackson, P. K. Patra, P. Bousquet, P. Ciais, E. J. Dlugokencky, X. Lan, G. H. Allen, D. Bastviken, D. J. Beerling, D. A. Belikov, D. R. Blake, S. Castaldi, M. Crippa, B. R. Deemer, F. Dennison, G. Etiope, N. Gedney, L. Höglund-Isaksson, M. A. Holgerson, P. O. Hopcroft, G. Hugelius, A. Ito, A. K. Jain, R. Janardanan, M. S. Johnson, T. Kleinen, P. B. Krummel, R. Lauerwald, T. Li, X. Liu, K. C. Mcdonald, J. R. Melton, J. Mühle, J. Müller, F. Murguia-Flores, Y. Niwa, S. Noce, S. Pan, R. J. Parker, C. Peng, M. Ramonet, W. J. Riley, G. Rocher-Ros, J. A. Rosentreter, M. Sasakawa, A. Segers, S. J. Smith, E. H. Stanley, J. Thanwerdas, H. Tian, A. Tsuruta, F. N. Tubiello, T. S. Weber, G. R. Van Der Werf, D. E. J. Worthy, Y. Xi, Y. Yoshida, W. Zhang, B. Zheng, Q. Zhu, Q. Zhu, and Q. Zhuang. 2025. Global methane budget 2000-2020. Earth System Science Data 17:1873–1958.

Saunois, M., A. R. Stavert, B. Poulter, P. Bousquet, J. G. Canadell, R. B. Jackson, P. A. Raymond, E. J. Dlugokencky, S. Houweling, P. K. Patra, P. Ciais, V. K. Arora, D. Bastviken, P. Bergamaschi, D. R. Blake, G. Brailsford, L. Bruhwiler, K. M. Carlson, M. Carrol, S. Castaldi, N. Chandra, C. Crevoisier, P. M. Crill, K. Covey, C. L. Curry, G. Etiope, C. Frankenberg, N. Gedney, M. I. Hegglin, L. Höglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K. M. Jensen, F. Joos, T. Kleinen, P. B. Krummel, R. L. Langenfelds, G. G. Laruelle, L. Liu, T. MacHida, S. Maksyutov, K. C. McDonald, J. McNorton, P. A. Miller, J. R. Melton, I. Morino, J. Müller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R. J. Parker, C. Peng, S. Peng, G. P. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W. J. Riley, J. A. Rosentreter, A. Segers, I. J. Simpson, H. Shi, S. J. Smith, L. Paul Steele, B. F. Thornton, H. Tian, Y. Tohjima, F. N. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T. S. Weber, M. Van Weele, G. R. Van Der Werf, R. F. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B. Zheng, Q. Zhu, Q. Zhu, and Q. Zhuang. 2020. The global methane budget 2000-2017. Earth System Science Data 12:1561–1623.

Scheller, J. H., M. Mastepanov, and T. R. Christensen. 2022. Toward UAV-based methane emission mapping of Arctic terrestrial ecosystems. Science of the Total Environment 819:153161.

Smith, T. E. L., S. Evers, C. M. Yule, and J. Y. Gan. 2018. In situ tropical peatland fire emission factors and their variability, as determined by field measurements in Peninsula Malaysia. Global Biogeochemical Cycles 32:18–31.

Subramaniam, V., and Y. M. Choo. 2012. Greenhouse gas emissions for the production of crude palm kernel oil - a gate-to-gate case study. Journal of Oil Palm Research 24:1511–1517.

Subramaniam, V., C. Y. , M. May, H. H., T. Z., Y. A., and P. C. Wei. 2010. Life cycle assessment of the production of crude palm oil (part 3). Journal of Oil Palm Research 22:895–903.

Sumathi, S., S. P. Chai, and A. R. Mohamed. 2008. Utilization of oil palm as a source of renewable energy in Malaysia. Renewable and Sustainable Energy Reviews 12:2404–2421.

Tan, Y. D., and J. S. Lim. 2019. Feasibility of palm oil mill effluent elimination towards sustainable Malaysian palm oil industry. Renewable and Sustainable Energy Reviews 111:507–522.

Topa, M. R., M. T. Latif, M. Othman, C. G. Maggie Ooi, N. Mohd Hanif, M. S. Mohd Nadzir, H. H. Abd Hamid, A. A. Ahmad Mohtar, and J. Liew. 2023. Rekod jangka panjang kepekatan metana di Malaysia. Sains Malaysiana 52:1359–1370.

UNECE. 2023. The Challenge. Methane Management. https://unece.org/challenge.

United Nations. 2015. Paris Agreement.

Vijaya, S., A. Ma, and Y. M. Choo. 2010. Capturing biogas: a means to reduce green house gas emissions for the production of crude palm oil. American Journal of Geoscience 1:1–6.

Vijaya, S., A. N. Ma, Y. M. Choo, and N. S. Nik Meriam. 2008. Life cycle inventory of the production of crude palm oil - a gate to gate case study of 12 palm oil mills. Journal of Oil Palm Research 20:484–494.

Wong, G. X., R. Hirata, T. Hirano, F. Kiew, E. B. Aeries, K. K. Musin, J. W. Waili, K. S. Lo, and L. Melling. 2018. Micrometeorological measurement of methane flux above a tropical peat swamp forest. Agricultural and Forest Meteorology 256–257:353–361.

Wong, G. X., R. Hirata, T. Hirano, F. Kiew, E. B. Aeries, K. K. Musin, J. W. Waili, K. S. Lo, and L. Melling. 2020. How do land use practices affect methane emissions from tropical peat ecosystems? Agricultural and Forest Meteorology 282–283:107869.

Xu, X., Z. Xia, Y. Liu, E. Liu, K. Müller, H. Wang, J. Luo, X. Wu, J. Beiyuan, Z. Fang, J. Xu, H. Di, and Y. Li. 2021. Interactions between methanotrophs and ammonia oxidizers modulate the response of in situ methane emissions to simulated climate change and its legacy in an acidic soil. Science of the Total Environment 752:142225.

Yacob, S., M. Ali Hassan, Y. Shirai, M. Wakisaka, and S. Subash. 2006. Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment. Science of the Total Environment 366:187–196.

Zakaria, S., R. D. R. Ahmad, A. R. Abbas, and M. F. M. Batcha. 2021. Greenhouse Gas Emission Intensity Assessment for Power Plants in Peninsular Malaysia. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 88:14–26.

Zubair, M., S. Chen, Y. Ma, and X. Hu. 2023. A systematic review on carbon dioxide (CO2) emission measurement methods under PRISMA guidelines: transportation sustainability and development programs. Sustainability 15:4817.

Appendices

Appendix A: Published Emission Factor

Table A - 1

Extracted emission factor from published journal article. Dark khaki (yellow) indicates Tier 1 while green indicates Tier 2 and Crayola (yellow) indicates Tier 3.

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Diesel oil	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Residual Fuel Oil	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Bituminous	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Sub-Bituminous Coal	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Sub-Bituminous Coal	Tier 2		0.09		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Lignite	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Lignite	Tier 2		0.04		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Natural Gas	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Natural Gas	Tier 2		0.09		kg TJ^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Biomass (Other Primary Solid Biomass)	Tier 1		30		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Electricity Generation	Biogas (Other Biogas)	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Gas/Diesel Oil Boiler	Tier 3		0.9		kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Residual Fuel Oil Boiler	Tier 3		0.8		kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Pulverized Bituminous	Tier 3		0.7		kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Combustion Boilers	Tier 3	0.7	0.9	0.8	kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Natural Gas Boilers	Tier 3		1		kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Natural Gas Gas-Fired Gas Turbines >3M W	Tier 3		4		kg TJ^{-1}	A - 1

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appendix
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Natural Gas Large Dual Fuel Engines	Tier 3		258		kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Natural Gas Combined Cycle	Tier 3		1		kg TJ^{-1}	A - 1
IPCC	Energy	Fuel Combustion Activities – Combined Heat and Power Generation	Biogas (Other Biogas)	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Petroleum Refining	Crude Oil (Liquid Fuel)	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Other Energy Industries	Natural Gas	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	Natural Gas	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	Motor Gasoline	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	Gas/Diesel oil	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	Residual Fuel Oil	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	LPG	Tier 1		3		kg TJ^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	Other kerosene	Tier 1		1		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Iron and Steel	Sub-bituminous coal	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Domestic Aviation	Jet kerosene	Tier 1		0.5		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Road Transportation	Gasoline	Tier 1		33		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Road Transportation	Diesel Oil	Tier 1		3.9		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Road Transportation	Natural gas	Tier 1		92		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Road Transportation	Biodiesel	Tier 1		3		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Railways	Diesel Oil	Tier 1		4.15		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Domestic Water-borne Navigation	Diesel Oil	Tier 1		7		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Domestic Water-borne Navigation	Residual Fuel Oil	Tier 1		7		kg TJ^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	Energy	Fuel Combustion Activities – Commercial /Institutional	Diesel Oil	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Commercial /Institutional	Residual Fuel Oil	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Commercial /Institutional	LPG	Tier 1		5		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Commercial /Institutional	Natural Gas	Tier 1		5		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Residential	Other kerosene	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Residential	LPG	Tier 1		5		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Residential	Natural Gas	Tier 1		5		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Agriculture/ Forestry/Fishing/Fish Farms (Stationary)	Motor Gasoline	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Agriculture/ Forestry/Fishing/Fish Farms (Stationary)	Diesel oil	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Agriculture/ Forestry/Fishing/Fish Farms (Stationary)	Residual Fuel Oil	Tier 1		10		kg TJ^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	Energy	Fuel Combustion Activities – Agriculture/ Forestry/Fishing/Fish Farms (Off-road Vehicles and Other Machinery)	Residual Fuel Oil	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Agriculture/ Forestry/Fishing/Fish Farms (Fishing – mobile Combustion)	Motor Gasoline	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Agriculture/ Forestry/Fishing/Fish Farms (Fishing – mobile Combustion)	Diesel Oil	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Aviation Component (Mobile)	Jet kerosene	Tier 1		0.5		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Water Component (Mobile)	Diesel Oil	Tier 1		7		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Other (Mobile)	Motor Gasoline			33		kg TJ^{-1}	-
IPCC	Energy	Fuel Combustion Activities – Other (Mobile)	Diesel Oil			3.9		kg TJ^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	Energy	Fugitive Emissions from Fuels – Underground Coal Mining and Handling	Mining	Tier 1		10		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Underground Coal Mining and Handling	Post-Mining Seam Gas Emissions	Tier 1		2.45		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Underground Coal Mining and Handling	Abandoned Underground Mines	Tier 1		0.343		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Underground Coal Mining and Handling	Mining	Tier 1		0.3		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Surface Coal Mining and Handling	Post-mining seam gas emissions	Tier 1		0.1		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels - Oil	Venting	Tier 1		0.66		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels - Oil	Flaring	Tier 1		0.012		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels - Oil	Production and upgrading	Tier 1		5.9×10^{-7}		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels - Oil	Refining	Tier 1		6.4×10^{-6}		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Natural Gas	Flaring	Tier 1		0.012		kg TJ^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appendix
IPCC	Energy	Fugitive Emissions from Fuels – Natural Gas	Production	Tier 1		2.74×10^{-3}		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Natural Gas	Processing	Tier 1		5.42×10^{-4}		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Natural Gas	Transmission and Storage	Tier 1		2.59×10^{-4}		kg TJ^{-1}	-
IPCC	Energy	Fugitive Emissions from Fuels – Natural Gas	Distribution	Tier 1		1.24×10^{-3}		kg TJ^{-1}	-
IPCC	IPPU	Chemical Industry – Petrochemical and Carbon Black Production	Methanol	Tier 1		2.3×10^{-3}		kg $CH_4 \cdot kg^{-1}$ product	-
IPCC	IPPU	Chemical Industry – Petrochemical and Carbon Black Production	Ethylene	Tier 1		6×10^{-3}		kg $CH_4 \cdot kg^{-1}$ product	-
IPCC	IPPU	Chemical Industry – Petrochemical and Carbon Black Production	Ethylene Oxide	Tier 1		1.79×10^{-3}		kg $CH_4 \cdot kg^{-1}$ product	-
IPCC	IPPU	Metal Industry – Iron and Steel Production	Sinter	Tier 1		7×10^{-5}		kg $CH_4 \cdot kg^{-1}$ product	-
IPCC	IPPU	Metal Industry – Iron and Steel Production	Coke	Tier 1		1×10^{-7}		kg $CH_4 \cdot kg^{-1}$ product	-
IPCC	IPPU	Metal Industry – Ferroalloys Industry	FeSi	Tier 1		1×10^{-3}		kg $CH_4 \cdot kg^{-1}$ product	-
IPCC	IPPU	Metal Industry – Ferroalloys Industry	Si-metal	Tier 1		1.2×10^{-3}		kg $CH_4 \cdot kg^{-1}$ product	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appendix
IPCC	AFOLU - Livestock	Enteric Fermentation	Dairy Cows	Tier 1		68		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Other Cattle	Tier 1		47		kg CH_4 ha^{-1} yr^{-1}	-
Malaysia	AFOLU	Enteric Fermentation	Other Cattle	Tier 2	51.6	65.7	58.65	kg CH_4 $head^{-1}$ yr^{-1}	A - 2
IPCC	AFOLU - Livestock	Enteric Fermentation	Buffalo	Tier 1		55		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Sheep	Tier 1		5		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Goats	Tier 1		5		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Horses	Tier 1		18		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Swine	Tier 1		1		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Poultry - Chicken	Tier 1		-		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Enteric Fermentation	Poultry – Ducks	Tier 1		-		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Dairy Cows	Tier 1		31		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Other Cattle	Tier 1		1.24		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Buffalo	Tier 1		2		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Sheep	Tier 1		0.2		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Goats	Tier 1		0.22		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Horses	Tier 1		2.19		kg CH_4 ha^{-1} yr^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
IPCC	AFOLU - Livestock	Manure Management	Swine	Tier 1		7		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Poultry - Chicken	Tier 1		0.02		kg CH_4 ha^{-1} yr^{-1}	-
IPCC	AFOLU - Livestock	Manure Management	Poultry – Ducks	Tier 1		0.02		kg CH_4 ha^{-1} yr^{-1}	-
Malaysia	AFOLU	Pineapple Cultivation	Open Cultivation/Alternate Wet and Dry	Tier 2	0.0072	1.78	1.03	kg CH_4 ha^{-1} day^{-1}	A - 3
IPCC	AFOLU	Drained Organic Soil	Sago Plantation	Tier 1		26.2 ± 0.0717		kg CH_4 ha^{-1} day^{-1}	-
Malaysia	AFOLU	Drained Organic Soil	Sago Plantation	Tier 2		0.0052944 ± 0.0013632		kg CH_4 ha^{-1} day^{-1}	A - 4
IPCC	AFOLU	Drained Organic Soil	Drained Oil Palm Plantation	Tier 1		0		kg CH_4 ha^{-1} yr^{-1}	-
Malaysia	AFOLU	Peat Lands	Drained Oil Palm Plantation	Tier 2	– 0.000859	0.619	0.06	kg CH_4 ha^{-1} day^{-1}	A - 5
Malaysia	AFOLU	Peat Lands	No vegetation (Bare)	Tier 2		2.05		kg CH_4 ha^{-1} day^{-1}	A - 6
Malaysia	AFOLU	Peat Lands	Mixed Peat Swamp Forest	Tier 2	0.000545	0.0477	0.0241	kg CH_4 ha^{-1} day^{-1}	A - 7
Malaysia	AFOLU	Peat Lands	Alan Batu	Tier 2	0.115	0.282	0.175	kg CH_4 ha^{-1} day^{-1}	A - 8
Malaysia	AFOLU	Peat Lands	Alan Bunga	Tier 2	0.0476	0.114	0.0808	kg CH_4 ha^{-1} day^{-1}	A - 9
IPCC	AFOLU	Aggregate Sources and Non-CO_2 Emissions Sources on Land - Burning	Forest Land	Tier 1		6.8×10^{-3}		kg $CH_4 \cdot kg^{-1}$ dry matter ha^{-1}	-
IPCC	AFOLU	Aggregate Sources and Non-CO_2 Emissions Sources on Land - Burning	Cropland	Tier 1		2.7×10^{-3}		kg $CH_4 \cdot kg^{-1}$ dry matter ha^{-1}	-
IPCC	AFOLU	Aggregate Sources and Non-CO_2 Emissions Sources on Land - Burning	Organic Soil	Tier 1		0.021		kg $CH_4 \cdot kg^{-1}$ dry matter ha^{-1}	-

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appen-dix
Malaysia	AFOLU	Aggregate Sources and Non-CO_2 Emissions Sources on Land - Burning	Organic Soil – Oil Palm Plantation	Tier 2	0.00667	0.02619	0.0110	kg $CH_4 \cdot kg^{-1}$ dry fuel burned	A - 10
IPCC	AFOLU	Rice Cultivation	Irrigated - Continuously Flooded	Tier 1		1.6 with scaling factor of 1		kg CH_4 ha^{-1} day^{-1}	-
Malaysia	AFOLU	Rice Cultivation	Irrigated - Continuously Flooded	Tier 2	0.04115	0.325	0.183	kg CH_4 ha^{-1} day^{-1}	A - 11
Malaysia	AFOLU	Rice Cultivation	Irrigated - Multiple Drainage Period	Tier 2	0.01420	0.2	0.01625	kg CH_4 ha^{-1} day^{-1}	A - 11
Indonesia	AFOLU	Rice Cultivation	Irrigated - Continuously Flooded	Tier 2		0.000836		kg CH_4 ha^{-1} day^{-1}	A - 11
IPCC	AFOLU	Rice Cultivation	Rainfed	Tier 1		1.6 with scaling factor of 0.27		kg CH_4 ha^{-1} day^{-1}	-
IPCC	AFOLU	Rice Cultivation	Upland	Tier 1		1.6 with scaling factor of 0.27		kg CH_4 ha^{-1} day^{-1}	-
Malaysia	AFOLU	Undisturbed River Basins		Tier 2	0.0765	0.259	0.168	kg CH_4 ha^{-1} day^{-1}	A - 12
Malaysia	AFOLU	Disturbed River Basins		Tier 2	0.213	0.301	0.256	kg CH_4 ha^{-1} day^{-1}	A - 12
IPCC	Waste	Solid Waste Disposal	Managed Waste Disposal Site	Tier 1		1		kg $CH_4 \cdot kg^{-1}$ Total MSW	
IPCC	Waste	Solid Waste Disposal	Unmanaged Waste Disposal Site	Tier 1		0.8		kg $CH_4 \cdot kg^{-1}$ Total MSW	
IPCC	Waste	Biological Treatment of Solid Waste	Waste treated per kg	Tier 1		4		kg $CH_4 \cdot kg^{-1}$ Total annual amount treated by biological treatment facilities	
IPCC	Waste	Incineration and Open Burning of Waste	Hazardous Waste	Tier 1		0		kg $CH_4 \cdot kg^{-1}$ Annual Amount of waste incinerated	

Table A - 1 (continued)

Countries	Sectors	Category	Condition	Level	Min	Max	Median	Unit	Appendix
IPCC	Waste	Waste Incineration	Clinical Waste	Tier 1		0		kg $CH_4 \cdot kg^{-1}$ Annual Amount of waste incinerated	-
IPCC	Waste	Open Burning of Waste	Municipal Solid Waste	Tier 1		0.01		kg $CH_4 \cdot kg^{-1}$ Total amount of waste open-burnt	-
IPCC	Waste	Wastewater Treatment and Discharge - Domestic	Centralised Aerobic Treatment Plant	Tier 1		0		kg $CH_4 \cdot kg^{-1}$ BOD	-
IPCC	Waste	Wastewater Treatment and Discharge - Domestic	Septic Tank	Tier 1		0.18		kg $CH_4 \cdot kg^{-1}$ BOD	-
IPCC	Waste	Wastewater Treatment and Discharge - Domestic	Latrine 3 (Pour Flush)	Tier 1		0.252		kg $CH_4 \cdot kg^{-1}$ BOD	-
IPCC	Waste	Wastewater Treatment and Discharge - Domestic	Sea, River, and Lake Discharge	Tier 1		0.036		kg $CH_4 \cdot kg^{-1}$ BOD	-
IPCC	Waste	Wastewater Treatment and Discharge - Industrial	Palm Oil Mill Effluent	Tier 2		0.225		kg $CH_4 \cdot kg^{-1}$ COD	A - 13
IPCC	Waste	Wastewater Treatment and Discharge - Industrial	Natural Rubber (SMR)	Tier 1		0.2		kg $CH_4 \cdot kg^{-1}$ COD	-
IPCC	Waste	Wastewater Treatment and Discharge - Industrial	Natural Rubber (LATEX)	Tier 1		0.036		kg $CH_4 \cdot kg^{-1}$ COD	-
IPCC	Waste	Wastewater Treatment and Discharge - Industrial	Petroleum Refineries	Tier 1		0.125		kg $CH_4 \cdot kg^{-1}$ COD	-
IPCC	Waste	Wastewater Treatment and Discharge - Industrial	Pulp and Paper	Tier 1		0.125		kg $CH_4 \cdot kg^{-1}$ COD	-
IPCC	Waste	Wastewater Treatment and Discharge - Industrial	Meat and Poultry	Tier 1		0.125		kg $CH_4 \cdot kg^{-1}$ COD	-

Data available at the link: https://tidbrepo.usm.my/pid/89a78907-1dd9-49f7-87d3-8d4e8b1baaa5

Appendix A-1: Energy | Fuel Combustion Activities | Combined Heat and Power Generation

Reference

Zakaria, S., Ahmad, R. D. R., Abbas, A. R., & Batcha, M. F. M. (2021). Greenhouse Gas Emission Intensity Assessment for Power Plants in Peninsular Malaysia. ***Journal of Advanced Research in Fluid Mechanics and Thermal Sciences***. 88(2), 14–26.
https://doi.org/10.37934/arfmts.88.2.1426

Summary

This article discusses the assessment of greenhouse gas emission intensity for power plants in Peninsular Malaysia. The study quantifies the emissions from stationary combustion and proposes emission reduction strategies. The highest greenhouse gas emission intensity is observed in coal power plants, while natural gas power plants have lower emissions. The article also presents projected greenhouse gas emissions and emission intensity up to 2025 under different scenarios. The study emphasises the need for optimising power generation efficiency and transitioning to cleaner energy resources to mitigate greenhouse gas emissions.

Field of Study/Sector

Fluid Mechanics and Thermal Sciences, Power Sector

Method

The methodology used in the research paper involved the adoption of the Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard and Intergovernmental Panel on Climate Change (IPCC) methodologies for assessing greenhouse gas emissions from stationary combustion in power plants. The Tier 3 approach was used for estimating methane (CH_4). CH_4 emissions from reservoirs were estimated based on diffusive and bubbling emissions.

Location

Ten gas and four coal power plants in Peninsular Malaysia.

Emission Factor Value

Table A - 1 - 1 Methane emission factor for various combustion technologies.

Basic Technology	Configuration	Emission Factors (kg CH_4 TJ^{-1})
Gas/Diesel Oil Boiler	Normal/Tangential Firing	0.9
Residual Fuel Oil Boiler	Normal/Tangential Firing	0.9
Pulverized Bituminous	Dry Bottom, Wall Fired	0.7
Combustion Boilers	Dry Bottom, Tangentially Fired	0.7
	Wet Bottom	0.9

Table A – 1 - 1 (continued)

Basic Technology	Configuration	Emission Factors (kg CH_4 TJ^{-1})
Natural Gas	Boilers	1
	Gas-Fired Gas Turbines >3MW	4
	Large Dual Fuel Engines	258
	Combined Cycle	1

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A-2: AFOLU | Livestock | Enteric Fermentation

Reference

Fairuz, M., Azdawiyah, S., Ain, N., & Hariz, M. (2017). Local emission factors estimate methane emission from cattle enteric fermentation using IPCC tier-2 methodology. ***Malaysian Society of Animal Production***. *20*(2), 1–10.

Summary

This research discusses the uncertainty in estimating methane emissions from livestock in Malaysia. The study highlights the lack of detailed statistical data and local emission factors (EF) measurements, leading to highly uncertain greenhouse gas inventories. The Intergovernmental Panel on Climate Change (IPCC) recommends Tier−1 and Tier-2 methods for estimating emissions, with Tier-2 providing more accurate results. The paper focuses on developing local EFs for mature beef cattle using the IPCC Tier-2 methodology.

Field of Study/Sector

The field of study is greenhouse gas emissions from livestock, specifically methane emissions from mature beef cattle. The sector of this paper is agriculture and environmental science.

Method

The research paper used the IPCC Tier-2 methodology to estimate methane emissions from cattle enteric fermentation. This methodology relies on country-specific data on nutrient requirements, feed intake, and the methane conversion rate for the specific feed type. The researchers calculated the emission factor (EF) using the formula provided by the IPCC guidelines, which considers parameters such as gross energy, net energy required for maintenance, net energy for animal activity, net energy for lactation, net energy for work, net energy required for pregnancy, and the ratio of net energy available in a diet. The EFs were derived through extensive surveys and structured analyses on livestock feed intake and production data to generate better estimates with lower uncertainty range values.

Location

The geographical location of the research was in Serdang, Selangor, Malaysia.

Emission Factor Value

58.65 kg CH_4 head^{-1} yr^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 3: AFOLU | Pineapple Cultivation

Reference

Lim Kim Choo, L. N., & Ahmed, O. H. (2017). Methane Emission from Pineapple Cultivation on a Tropical Peatland at Saratok, Malaysia. ***Sustainable Agriculture Research***. *6*(3), 64. https://doi.org/10.5539/sar.v6n3p64

Summary

The study took place in a peat excavation site in Malaysia. Soil samples were collected and analysed for various chemical and physical properties. The peat soil had low bulk density and high-water holding capacity. The pH was low, indicating a need for liming before cultivation. The soil had high organic carbon and total nitrogen content. Methane emissions from the soil varied with different treatments and seasons.

Field of Study/Sector

Environmental Science, Peatland Ecology (Sustainable Agriculture Research).

Method

Field lysimeters were set up to measure CH_4 emissions from the peat soil under different treatments. The emissions were measured using the closed chamber method, and the gas samples were analysed for CH_4 using gas chromatography. Statistical analysis was conducted to test treatment effects and compare means. The relationships among CH_4 emission, soil temperature, and soil moisture were also analysed using correlation analysis. The period of study for methane emissions in this research was from September 2012 to July 2013. The frequency of sampling methane was conducted at different times of the day, including early morning, morning, mid-morning to afternoon, afternoon, evening, and night. The measurements were carried out in September 2012, November 2012, January 2013, April 2013, and July 2013 to represent both wet and dry seasons. The type of the pineapple is Moris pineapple. The study uses Foliar and compound fertilizers with urea and ammonium sulphate.

Location

MARDI Peat Research Station at Saratok, Sarawak, Malaysia 2.9° N, 101.7° E.

Emission Factor Value

1.78 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Water table (0.5 m – 0.6 m)

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Luta, W., Ahmed, O. H., Omar, L., Heng, R. K. J., Choo, L. N. L. K., Jalloh, M. B., Musah, A. A., & Abdu, A. (2021). Water table fluctuation and methane emission in pineapples (Ananas comosus (l.) merr.) cultivated on a tropical peatland. ***Agronomy***. *11*(8), 1148.
https://doi.org/10.3390/agronomy11081448

Summary

The research study on CO_2 and CH_4 emissions in a tropical peatland subjected to water table fluctuation. The study was conducted under field conditions and simulated lysimeter at the Malaysian Agricultural Research and Development Institute. The Long-term Research Grant Scheme and Translational Research Grant Scheme from the Ministry of Higher Education Malaysia funded the research.

Field of Study/Sector

The field of study is environmental science, specifically focusing on greenhouse gas emissions in a tropical peatland. The sector of this paper is academia, as it is conducted by researchers affiliated with various universities and research institutes in Malaysia.

Method

The methodology involved measuring soil CH_4 emissions from a tropical peatland under pineapple cultivation using a closed chamber method. The CH_4 emissions were quantified using gas chromatography with a thermal conductivity detector. The study included monitoring CH_4 fluxes during the dry and wet seasons, with two cycles for each weather season. The instrument used to measure methane are gas chromatography equipped with a thermal conductivity detector (TCD). The study period included the months of July, August, September, and December 2015. Methane sampling was conducted with two cycles for each weather season.

Location

Sesang, Saratok, Sarawak, Malaysia

Emission Factor Value

0.18 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Compound NPK fertilizers contain ammonium.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Dhandapani, S., Evers, S., Boyd, D., Evans, C. D., Page, S., Parish, F., & Sjogersten, S. (2023). Assessment of differences in peat physico-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands. ***Catena***, *230*(2023), 107255.
https://doi.org/10.1016/j.catena.2023.107255

Summary

This paper assesses the differences in peat physico-chemical properties, surface subsidence, and greenhouse gas emissions between different land uses in Selangor peatlands. Researchers from various universities and research institutions in the UK and Malaysia conducted the study. The paper analyses factors such as moisture, pH, electrical conductivity, redox potential, bulk density, and nutrient concentrations. The results show the impact of different land uses on peat properties and highlight the anthropogenic modification of the peat. The study focuses on the Selangor region in Malaysia and provides valuable insights for land use management and conservation efforts.

Field of Study/Sector

Environmental Science, Peatland Ecology.

Method

The methodology involved weighing the samples into a ceramic crucible and recording the exact weight. The samples were then transferred to an auto sampler in a Skalar primacs series SNC100 TC TN analyser to analyse total C and N content. Greenhouse gas emissions, specifically CO_2 and CH_4, were measured using a Los Gatos ultraportable greenhouse gas analyser with a closed dynamic chamber method. Peat nutrient concentrations were analysed using inductively coupled plasma mass spectroscopy.

Location

--

Emission Factor Value

0.0072 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 4: AFOLU | Drained Organic Soil | Sago Plantation

Reference

Melling, L., Hatano, R., & Kah, J. G. (2005). Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. ***Soil Biology and Biochemistry***, *37*(8), 1445–1453. https://doi.org/10.1016/j.soilbio.2005.01.001

Summary

This paper focuses on measuring and analysing methane emissions in three different ecosystems in Sarawak, Malaysia: mixed peat swamp forest, sago plantation, and oil palm plantation. The study examines the environmental factors that influence methane flux, particularly the effects of drainage and compaction. The paper provides detailed site descriptions and characteristics of the ecosystems and information on the methodology used for methane flux measurements. The results section presents findings on environmental variables and gas fluxes. Overall, the study aims to understand the factors contributing to methane emissions in these ecosystems.

Field of Study/Sector

Environmental science, specifically the study of methane emissions in different ecosystems.

Method

The methodology involved collecting soil gas samples using a stainless-steel pipe with a silicon tube and a three-way stopcock. The samples were collected at different depths and analysed for CH_4 concentration using a gas chromatograph equipped with a flame ionization detector (Hewlett Packard 6890N). Methane fluxes were calculated from the linear increase or decrease in gas concentration in the chamber with time. The study period and frequency of sampling were not specified. The study focused on forest, sago, and oil palm ecosystems. The soil composition or fertilizer used was not mentioned.

Location

The three experimental sites were in the Mukah Division of Sarawak, Malaysia.

Emission Factor Value

0.00529 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Drained soil with water table of − 0.6715 m.

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 5: AFOLU | Peat lands | Oil Palm Plantation

Reference

Melling, L., Hatano, R., & Kah, J. G. (2005). Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. ***Soil Biology and Biochemistry***, *37*(8), 1445–1453. https://doi.org/10.1016/j.soilbio.2005.01.001

Summary

This paper focuses on measuring and analysing methane emissions in three different ecosystems in Sarawak, Malaysia: mixed peat swamp forest, sago plantation, and oil palm plantation. The study examines the environmental factors that influence methane flux, particularly the effects of drainage and compaction. The paper provides detailed site descriptions and characteristics of the ecosystems and information on the methodology used for methane flux measurements. The results section presents findings on environmental variables and gas fluxes. Overall, the study aims to understand the factors contributing to methane emissions in these ecosystems.

Field of Study/Sector

Environmental science, specifically the study of methane emissions in different ecosystems.

Method

The methodology involved collecting soil gas samples using a stainless-steel pipe with a silicon tube and a three-way stopcock. The samples were collected at different depths and analysed for CH4 concentration using a gas chromatograph equipped with a flame ionization detector (Hewlett Packard 6890N). Methane fluxes were calculated from the linear increase or decrease in gas concentration in the chamber with time. The study period and frequency of sampling were not specified. The study focused on forest, sago, and oil palm ecosystems. The soil composition or fertilizer used was not mentioned.

Location

The three experimental sites were in the Mukah Division of Sarawak, Malaysia.

Emission Factor Value

–0.00086 kg CH4 ha^{-1} day^{-1}

Surface Condition

Peat thickness (5.55 m)

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Wong, G. X., Hirata, R., Hirano, T., Kiew, F., Aeries, E. B., Musin, K. K., Waili, J. W., Lo, K. S., & Melling, L. (2020). How do land use practices affect methane emissions from tropical peat ecosystems? ***Agricultural and Forest Meteorology***, *282–283*(2020), 107869. https://doi.org/10.1016/j.agrformet.2019.107869

Summary

This study examines the impact of land use practices on methane emissions in tropical peat ecosystems. The study was conducted in three different sites in Sarawak, Malaysia: an undrained peat swamp forest, a relatively disturbed secondary peat swamp forest, and an oil palm plantation. Various measurements were taken, including air temperature, relative humidity, precipitation, soil temperature, and soil moisture. The study utilised field experiments and eddy covariance techniques to assess net ecosystem CH_4 exchange. The research aims to understand the influence of land use on methane emissions in tropical peat ecosystems.

Field of Study/Sector

Environmental Science, Agricultural and Forest Meteorology

Method

The methodology involved using the eddy covariance technique to measure the ecosystem-scale flux of methane in tropical peat ecosystems. The study sites included undrained peat swamp forests, relatively disturbed peat swamp forests, and oil palm plantations on peat. Flux measurements were conducted using a 3D sonic anemometer/thermometer, an open-path CO_2/H_2O analyser, and an open-path CH_4 analyser. The measurements were taken at each site along fetches of at least 600, 1200, and 4000 m in all directions, respectively. The sensors were installed at the tip of a 1-m-long boom projecting toward the prevailing wind direction. The measurements were recorded every 5 min.

Location

The geographical location of the research sites is in Sarawak, Malaysia. The undrained peat swamp forest (PSF) and disturbed secondary PSF are in the Maludam Peninsula, approximately 29 km apart. The oil palm plantation is situated in Sibu, more than 100 km from the peninsula.

Emission Factor Value

0.06 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Peat thickness (12.7 m)

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Cooper, H. v., Evers, S., Aplin, P., Crout, N., Dahalan, M. P. bin, & Sjogersten, S. (2020). Greenhouse gas emissions result from peat swamp forest conversion to oil palm plantation. ***Nature Communications***, *11*(1), 1–8.
https://doi.org/10.1038/s41467-020−14298-w

Summary

The context discusses the contribution of Southeast Asian peat swamp forests to greenhouse gas emissions, particularly from drainage-based agriculture such as oil palm and pulp wood production. It highlights the importance of including methane (CH_4) and nitrous oxide (N_2O) fluxes in emission calculations and presents improved estimates with uncertainty. The study emphasises the threat to carbon storage in peat swamp forests and the need for sustainable land use practices.

Field of Study/Sector

Environmental science, specifically peatland ecology and greenhouse gas emissions in Southeast Asian swamp forests.

Method

The methodology used in the research paper involved direct measurement of greenhouse gas fluxes at a tropical peatland in North Selangor state, Malaysia. The study selected four stages of conversion from peat swamp forest to oil palm plantation: secondary forest, recently drained but uncleared forest, cleared and recently planted young oil palm plantation, and mature oil palm plantation. Greenhouse gas fluxes, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), were measured at each stage of conversion. The researchers also assessed soil physical properties, carbon storage, and quality to understand the impact of conversion on peat swamp forest. The data collected provided insights into the contribution of the conversion process to greenhouse gas emissions. They highlighted the importance of considering this factor when comparing intact forest and mature oil palm emissions.

Location

The research was conducted in North Selangor state, Malaysia.

Emission Factor Value

Emission factor for young oil palm plantation is 0.216 kg CH_4 ha^{-1} day^{-1} ; Emission factor for mature oil palm plantation is 0.619 kg CH_4 ha^{-1} day^{-1} .

Surface Condition

Water table for young oil palm plantation is – 0.39 m with 2.47 m of peat thickness; Water table for mature oil palm plantation is – 0.21 m with 1.15 m of peat thickness.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Azizan, S. N. F., Goto, Y., Doi, T., Kamardan, M. I. F., Hara, H., McTaggart, I., Kai, T., & Noborio, K. (2021). Comparing GHG emissions from drained oil palm and recovering tropical peatland forests in Malaysia. ***Water***, *13*(23), 3372.
https://doi.org/10.3390/w13233372

Summary

This paper discusses the characteristics of tropical peatland and the emission of greenhouse gases in different sites. The study analyses data from three sites in Malaysia, focusing on soil organic C and N, bulk density, particle density, porosity, and surface organic matter content. The paper also highlights the variations in greenhouse gas emissions, particularly for N_2O and CH_4. The study emphasises the importance of sufficient measurements and long-term monitoring for accurate assessment of greenhouse gas emissions in peatlands.

Field of Study/Sector

Environmental Science, Agriculture.

Method

The methodology used in the research paper involved conducting a 15-month temporal study in the northern Selangor peatlands of peninsular Malaysia. The study is conducted in April-June 2019 with sampling intervals at 0, 10, and 20 min. The study focused on comparing greenhouse gas emissions and environmental parameters in three different land-use types: (1) drained matured oil palm plantation, (2) rewetting-restored forest, and (3) undrained natural forest. Carbon dioxide, N_2O, and CH_4 fluxes were measured using gas chromatography with a flame ionization detector (FID) at biweekly intervals from the soil, along with measurements of in situ environmental factors such as atmospheric temperature, soil temperature, soil moisture, and water table level. The statistical analyses were carried out using Excel 2018, including Pearson's correlation to determine the correlations between greenhouse gas emissions and hydrology parameters variables, and a one-way ANOVA with post hoc test to compare greenhouse gas emissions and environmental parameters at the different sites. The statistical significance level was set at $p = 0.05$.

Location

Northen Selangor peatlands in Peninsular Malaysia.

Emission Factor Value

0.05 ± 0.14 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Dhandapani, S., Evers, S., Boyd, D., Evans, C. D., Page, S., Parish, F., & Sjogersten, S. (2023). Assessment of differences in peat physico-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands. ***Catena***, *230*(2023), 107255.
https://doi.org/10.1016/j.catena.2023.107255

Summary

This paper assesses the differences in peat physico-chemical properties, surface subsidence, and greenhouse gas emissions between different land uses in Selangor peatlands. Researchers from various universities and research institutions in the UK and Malaysia conducted the study. The paper analyses factors such as moisture, pH, electrical conductivity, redox potential, bulk density, and nutrient concentrations. The results show the impact of different land uses on peat properties and highlight the anthropogenic modification of the peat. The study focuses on the Selangor region in Malaysia and provides valuable insights for land use management and conservation efforts.

Field of Study/Sector

Environmental Science, Peatland Ecology.

Method

The methodology involved weighing the samples into a ceramic crucible and recording the exact weight. The samples were then transferred to an auto sampler in a Skalar primacs series SNC100 TC TN analyser to analyse total C and N content. Greenhouse gas emissions, specifically CO_2 and CH_4, were measured using a Los Gatos ultraportable greenhouse gas analyser with a closed dynamic chamber method. Peat nutrient concentrations were analysed using inductively coupled plasma mass spectroscopy.

Location

Peatlands in the State of Selangor, Peninsular Malaysia.

Emission Factor Value

0.0048 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Water table of –0.6715m

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 6: AFOLU | Peat lands | No vegetation

Reference

Luta, W., Ahmed, O. H., Omar, L., Heng, R. K. J., Choo, L. N. L. K., Jalloh, M. B., Musah, A. A., & Abdu, A. (2021). Water table fluctuation and methane emission in pineapples (Ananas comosus (l.) merr.) cultivated on a tropical peatland. ***Agronomy***, *11*(8), 1148.
https://doi.org/10.3390/agronomy11081448

Summary

The research study on CO_2 and CH_4 emissions in a tropical peatland subjected to water table fluctuation. The study was conducted under field conditions and simulated lysimeter at the Malaysian Agricultural Research and Development Institute. The Long-term Research Grant Scheme and Translational Research Grant Scheme from the Ministry of Higher Education Malaysia funded the research.

Field of Study/Sector

The field of study is environmental science, specifically focusing on greenhouse gas emissions in a tropical peatland. The sector of this paper is academia, as it is conducted by researchers affiliated with various universities and research institutes in Malaysia.

Method

The methodology involved measuring soil CH_4 emissions from a tropical peatland under pineapple cultivation using a closed chamber method. The CH_4 emissions were quantified using gas chromatography with a thermal conductivity detector. The study included monitoring CH_4 fluxes during the dry and wet seasons, with two cycles for each weather season. The instrument used to measure methane are gas chromatography equipped with a thermal conductivity detector (TCD). The study period included the months of July, August, September, and December 2015. Methane sampling was conducted with two cycles for each weather season.

Location

Sesang, Saratok, Sarawak, Malaysia

Emission Factor Value

2.05 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Pineapple cultivation

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 7: AFOLU | Peat lands | Mixed Peat Swamp Forest

Reference

Melling, L., Hatano, R., & Kah, J. G. (2005). Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. ***Soil Biology and Biochemistry***, *37*(8), 1445–1453.
https://doi.org/10.1016/j.soilbio.2005.01.001

Summary

This paper focuses on measuring and analysing methane emissions in three different ecosystems in Sarawak, Malaysia: mixed peat swamp forest, sago plantation, and oil palm plantation. The study examines the environmental factors that influence methane flux, particularly the effects of drainage and compaction. The paper provides detailed site descriptions and characteristics of the ecosystems and information on the methodology used for methane flux measurements. The results section presents findings on environmental variables and gas fluxes. Overall, the study aims to understand the factors contributing to methane emissions in these ecosystems.

Field of Study/Sector

Environmental science, specifically the study of methane emissions in different ecosystems.

Method

The methodology involved collecting soil gas samples using a stainless-steel pipe with a silicon tube and a three-way stopcock. The samples were collected at different depths and analysed for CH_4 concentration using a gas chromatograph equipped with a flame ionization detector (Hewlett Packard 6890N). Methane fluxes were calculated from the linear increase or decrease in gas concentration in the chamber with time. The study period and frequency of sampling were not specified. The study focused on three different ecosystems: forest, sago, and oil palm. The soil composition or fertilizer used was not mentioned.

Location

The three experimental sites were in the Mukah Division of Sarawak, Malaysia.

Emission Factor Value

0.00545 ± 0.000323 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Peat thickness with 4.8 m.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Busman, N. A., Melling, L., Goh, K. J., Imran, Y., Sangok, F. E., & Watanabe, A. (2023). Soil CO_2 and CH_4 fluxes from different tropical peat swamp forest types. ***Science of the Total Environment***, *858*(2023), 159973. https://doi.org/10.1016/j.scitotenv.2022.159973

Summary

This paper discusses the measurement of CO_2 and CH_4 fluxes from different forest types in a tropical peat swamp forest. The study examines the effects of environmental factors such as temperature, soil moisture, and light intensity on these fluxes. The research also analyses soil samples' soil physicochemical properties and nutrient contents. Overall, the paper aims to provide a more precise estimation of the contribution of peatlands to greenhouse gas emissions.

Field of Study/Sector

Environmental Science, Peatland Ecology.

Method

The methodology used in the research paper involved collecting and analysing soil samples. Soil samples were collected from three different forest sites: MPS, ABt, and ABg. The soil samples were then analysed for various physicochemical properties, including the contents of phosphorus, potassium, calcium, magnesium, iron, manganese, and zinc. The analysis was conducted using inductively coupled plasma-optical spectroscopy and digesting the soil samples with a mixture of concentrated hydrochloric acid and nitric acid. Statistical analysis was performed using R statistical software version 3.5.1. One-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) were used to analyse differences in soil physicochemical properties and environmental variables. Independent sample t-tests and repeated measure analysis of variance were also conducted to assess differences in greenhouse gas fluxes and environmental variables between different seasons and sites. Linear and multiple regression analysis with backward stepwise inclusion were applied to analyse the relationships between greenhouse gas fluxes and environmental and physicochemical properties. Principal component analysis (PCA) was used to explore the variations in peat soil properties and their relationships with forest types.

Location

The Maludam National Park, Sarawak with coordinates at 1° 25′ 51.41″ N, 111° 07′ 52.06″ E.

Emission Factor Value

0.0476 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Peat thickness with 7.43 m ± 0.08. with vegetation type: *Gonystylus bancanus*, *Dactylocladus stenostachys*, and three Shorea species (*S. platycarpa*, *S. scabrida*, and *S. uliginosa*)

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 8: AFOLU | Peat lands | Alan Batu Forest (Undisturbed)

Reference

Wong, G. X., Hirata, R., Hirano, T., Kiew, F., Aeries, E. B., Musin, K. K., Waili, J. W., Lo, K. S., & Melling, L. (2018). Micrometeorological measurement of methane flux above a tropical peat swamp forest. ***Agricultural and Forest Meteorology***, *256–257*(2018), 353–361. https://doi.org/10.1016/j.agrformet.2018.03.025

Summary

This paper uses the eddy covariance technique to discuss the measurement of methane (CH_4) flux above a tropical peat swamp forest. The study aims to quantify the CH_4 balance of the forest and understand its contribution to the tropical CH_4 budget. The research was conducted over 18 months, from February 201_4 to July 2015. The paper presents the results of seasonal variations in environmental variables and CH_4 flux.

Field of Study/Sector

Agricultural and Forest Meteorology Sector: Environmental Science.

Method

The eddy covariance technique measured CH_4 flux over a larger area, allowing for continuous flux measurement with minimal disturbance. The instrument used for sampling and measuring methane was a closed-chamber system with a CH_4 sensor (CS616, Campbell Scientific Inc.). Environmental variables such as precipitation, groundwater level, soil moisture, air temperature, soil temperature, and daily solar radiation were measured every 10 seconds and recorded every 5 min. The study period ranged from February 2014 to July 2015.

Location

Alan Batu Forest in Maludam National Park, Sarawak

Emission Factor Value

0.282 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Alan Batu forest has a peat thickness of around 10 m, featuring a diverse canopy of dominant tree species like *Shorea albida*, *Lithocarpus sp.*, *Litsea sp.*, and *Dillenia sp.*. The forest floor is rich with their young trees, shrubs, pitcher plants, and pandanus.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Ishikura, K., Hirata, R., Hirano, T., Okimoto, Y., Wong, G. X., Melling, L., Aeries, E. B., Kiew, F., Lo, K. S., Musin, K. K., Waili, J. W., & Ishii, Y. (2019). Carbon Dioxide and Methane Emissions from Peat Soil in an Undrained Tropical Peat Swamp Forest. ***Ecosystems***, *22*(8), 1852–1868. https://doi.org/10.1007/s10021-019-00376-8

Summary

This paper investigates carbon dioxide and methane emissions from peat soil in an undrained tropical peat swamp forest. The study analyses factors controlling soil CO_2 and CH_4 fluxes and quantifies annual cumulative soil respiration and CH_4 emission. The research was conducted in a swamp forest in Sarawak, Malaysia. The study provides insights into the effects of groundwater level on peat decomposition and the overall carbon balance in tropical peat swamp forests.

Field of Study/Sector

Ecology, Environmental Science

Method

The study aimed to investigate the factors controlling soil CO_2 and CH_4 fluxes in an undrained forest on tropical peat. Continuous measurements of soil CO_2 flux, heterotrophic respiration (RH), and soil CH_4 emission were conducted using an automated chamber system for 2 years. The study also included the measurement of precipitation and friction velocity to understand the environmental properties affecting the fluxes.

Location

The study was conducted in Maludam National Park, located at coordinates 1°27'N, 111°9'E, in Sarawak, Malaysia.

Emission Factor Value

0.118 ± 0.108 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Peat thickness approximately 10 m.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Dhandapani, S., Ritz, K., Evers, S., Yule, C. M., & Sjögersten, S. (2019). Are secondary forests second-rate? Comparing peatland greenhouse gas emissions, chemical and microbial community properties between primary and secondary forests in Peninsular Malaysia. ***Science of the Total Environment***, *655*(2019), 220–231. https://doi.org/10.1016/j.scitotenv.2018.11.046

Summary

This paper investigates the differences in greenhouse gas emissions, chemical and microbial community properties between primary and secondary forests in Peninsular Malaysia. The study finds significant differences in peat characteristics, nutrient content, and microbial phenotypic community structure between the two forest types. These differences are correlated with lower CH_4 emissions and higher CO_2 emissions in the secondary forest.

Field of Study/Sector

Environmental Science, Peatland Ecology

Method

The researchers sampled both the wet and dry seasons in a secondary forest and a primary forest in Peninsular Malaysia. In the secondary forest, 150 independent sampling points were selected, with 75 samples collected each season. In the primary forest, 50 samples were taken, with 25 samples collected in each season. From each visit, 5 random samples were taken for PLFA analysis, and 10 random samples were used for nutrient analysis. Greenhouse gas measurements, specifically CO_2 and CH_4 emissions, were measured using a Los Gatos ultraportable greenhouse gas analyser connected to a chamber. The measurements were taken at 25 random points distributed over an area of approximately 100 x 100 m, at least 200 m from the forest edges. The gas analyser was moved 50−70 m from each sub plot, resulting in 25 measurements per visit.

Location

Terengganu state, in the north-eastern part of Peninsular Malaysia

Emission Factor Value

0.588 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Wong, G. X., Hirata, R., Hirano, T., Kiew, F., Aeries, E. B., Musin, K. K., Waili, J. W., Lo, K. S., & Melling, L. (2020). How do land use practices affect methane emissions from tropical peat ecosystems? ***Agricultural and Forest Meteorology***, *282–283*(2018), 353–361.
https://doi.org/10.1016/j.agrformet.2019.107869

Summary

This study examines the impact of land use practices on methane emissions in tropical peat ecosystems. The study was conducted in three different sites in Sarawak, Malaysia: an undrained peat swamp forest, a relatively disturbed secondary peat swamp forest, and an oil palm plantation. Various measurements were taken, including air temperature, relative humidity, precipitation, soil temperature, and soil moisture. The study utilised field experiments and eddy covariance techniques to assess net ecosystem CH_4 exchange. The research aims to understand the influence of land use on methane emissions in tropical peat ecosystems.

Field of Study/Sector

Environmental Science, Agricultural and Forest Meteorology

Method

The methodology involved using the eddy covariance technique to measure the ecosystem-scale flux of methane in tropical peat ecosystems. The study sites included undrained peat swamp forests, relatively disturbed peat swamp forests, and oil palm plantations on peat. Flux measurements were conducted using a 3D sonic anemometer/thermometer, an open-path CO_2/H_2O analyser, and an open-path CH_4 analyser. The measurements were taken at each site along fetches of at least 600, 1200, and 4000 m in all directions, respectively. The sensors were installed at the tip of a 1-m-long boom projecting toward the prevailing wind direction. The measurements were recorded every 5 min.

Location

The geographical location of the research sites is in Sarawak, Malaysia. The undrained peat swamp forest (PSF) and disturbed secondary PSF are in the Maludam Peninsula, approximately 29 km apart. The oil palm plantation is situated in Sibu, more than 100 km from the peninsula.

Emission Factor Value

0.23 ± 0.014 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Peat thickness with 10 m.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Cooper, H. v., Evers, S., Aplin, P., Crout, N., Dahalan, M. P. B., & Sjogersten, S. (2020). Greenhouse gas emissions result from peat swamp forest conversion to oil palm plantation. ***Nature Communications***, *11*(1), 1–8.
https://doi.org/10.1038/s41467-020−14298-w

Summary

The context discusses the contribution of Southeast Asian peat swamp forests to greenhouse gas emissions, particularly from drainage-based agriculture such as oil palm and pulp wood production. It highlights the importance of including methane (CH_4) and nitrous oxide (N_2O) fluxes in emission calculations and presents improved estimates with uncertainty. The study emphasises the threat to carbon storage in peat swamp forests and the need for sustainable land use practices.

Field of Study/Sector

Environmental science, specifically peatland ecology and greenhouse gas emissions in Southeast Asian swamp forests.

Method

The methodology used in the research paper involved direct measurement of greenhouse gas fluxes at a tropical peatland in North Selangor state, Malaysia. The study selected four stages of conversion from peat swamp forest to oil palm plantation: secondary forest, recently drained but uncleared forest, cleared and recently planted young oil palm plantation, and mature oil palm plantation. Greenhouse gas fluxes, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), were measured at each stage of conversion. The researchers also assessed soil physical properties, carbon storage, and quality to understand the impact of conversion on peat swamp forest. The data collected provided insights into the contribution of the conversion process to greenhouse gas emissions. They highlighted the importance of considering this factor when comparing emissions between intact forest and mature oil palm.

Location

The research was conducted in North Selangor state, Malaysia.

Emission Factor Value

1.191 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Water table with –0.06 m and peat thickness of 1.89 m.

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Azizan, S. N. F., Goto, Y., Doi, T., Kamardan, M. I. F., Hara, H., McTaggart, I., Kai, T., & Noborio, K. (2021). Comparing GHG emissions from drained oil palm and recovering tropical peatland forests in Malaysia. ***Water***, *13*(23), 3372.
https://doi.org/10.3390/w13233372

Summary

This paper discusses the characteristics of tropical peatland and the emission of greenhouse gases in different sites. The study analyses data from three sites in Japan and Malaysia, focusing on soil organic C and N, bulk density, particle density, porosity, and surface organic matter content. The paper also highlights the variations in greenhouse gas emissions, particularly for N_2O and CH_4. The study emphasises the importance of sufficient measurements and long-term monitoring for accurate assessment of greenhouse gas emissions in peatlands.

Field of Study/Sector

Environmental Science, Agriculture.

Method

The methodology used in the research paper involved conducting a 15-month temporal study in the northern Selangor peatlands of peninsular Malaysia. The study is conducted in April-June 2019 with sampling intervals at 0, 10, and 20 min. The study focused on comparing greenhouse gas emissions and environmental parameters in three different land-use types: (1) drained matured oil palm plantation, (2) rewetting-restored forest, and (3) undrained natural forest. Carbon dioxide, N_2O, and CH_4 fluxes were measured using gas chromatography with a flame ionization detector (FID) at biweekly intervals from the soil, along with measurements of in situ environmental factors such as atmospheric temperature, soil temperature, soil moisture, and water table level. The statistical analyses were carried out using Excel 2018, including Pearson's correlation to determine the correlations between greenhouse gas emissions and hydrology parameters variables, and a one-way ANOVA with post hoc test to compare greenhouse gas emissions and environmental parameters at the different sites. The statistical significance level was set at $p = 0.05$.

Location

Northern Selangor peatlands in Peninsular Malaysia.

Emission Factor Value

1.44 ± 2.36 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 9: AFOLU | Peat lands | Alan Bunga Forest (Relatively Disturbed)

Reference

Dhandapani, S., Ritz, K., Evers, S., Yule, C. M., & Sjögersten, S. (2019). Are secondary forests second-rate? Comparing peatland greenhouse gas emissions, chemical and microbial community properties between primary and secondary forests in Peninsular Malaysia. ***Science of the Total Environment***, *655*(2019), 220–231. https://doi.org/10.1016/j.scitotenv.2018.11.046

Summary

This paper investigates the differences in greenhouse gas emissions, chemical and microbial community properties between primary and secondary forests in Peninsular Malaysia. The study finds significant differences in peat characteristics, nutrient content, and microbial phenotypic community structure between the two forest types. These differences are correlated with lower CH_4 emissions and higher CO_2 emissions in the secondary forest.

Field of Study/Sector

Environmental Science, Peatland Ecology

Method

The researchers sampled both the wet and dry seasons in a secondary forest and a primary forest in Peninsular Malaysia. In the secondary forest, 150 independent sampling points were selected, with 75 samples collected each season. In the primary forest, 50 samples were taken, with 25 samples collected in each season. From each visit, 5 random samples were taken for PLFA analysis, and 10 random samples were used for nutrient analysis. Greenhouse gas measurements, specifically CO_2 and CH_4 emissions, were measured using a Los Gatos ultraportable greenhouse gas analyser connected to a chamber. The measurements were taken at 25 random points distributed over an area of approximately 100 x 100 m, at least 200 m from the forest edges. The gas analyser was moved 50−70 m from each sub plot, resulting in a total of 25 measurements per visit.

Location

Terengganu state, in the north-eastern part of Peninsular Malaysia

Emission Factor Value

-0.0048 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Wong, G. X., Hirata, R., Hirano, T., Kiew, F., Aeries, E. B., Musin, K. K., Waili, J. W., Lo, K. S., & Melling, L. (2020). How do land use practices affect methane emissions from tropical peat ecosystems? ***Agricultural and Forest Meteorology***, *282–283*(2020), 107869. https://doi.org/10.1016/j.agrformet.2019.107869

Summary

This study examines the impact of land use practices on methane emissions in tropical peat ecosystems. The study was conducted in three different sites in Sarawak, Malaysia: an undrained peat swamp forest, a relatively disturbed secondary peat swamp forest, and an oil palm plantation. Various measurements were taken, including air temperature, relative humidity, precipitation, soil temperature, and soil moisture. The study utilised field experiments and eddy covariance techniques to assess net ecosystem CH_4 exchange. The research aims to understand the influence of land use on methane emissions in tropical peat ecosystems.

Field of Study/Sector

Environmental Science, Agricultural and Forest Meteorology

Method

The methodology involved using the eddy covariance technique to measure the ecosystem-scale flux of methane in tropical peat ecosystems. The study sites included undrained peat swamp forests, relatively disturbed peat swamp forests, and oil palm plantations on peat. Flux measurements were conducted using a 3D sonic anemometer/thermometer, an open-path CO_2/H_2O analyser, and an open-path CH_4 analyser. The measurements were taken at each site along fetches of at least 600, 1200, and 4000 m in all directions, respectively. The sensors were installed at the tip of a 1-m-long boom projecting toward the prevailing wind direction. The measurements were recorded every 5 min.

Location

The geographical location of the research sites is in Sarawak, Malaysia. The undrained peat swamp forest (PSF) and disturbed secondary PSF are in the Maludam Peninsula, approximately 29 km apart. The oil palm plantation is situated in Sibu, which is more than 100 km away from the peninsula.

Emission Factor Value

0.06 ± 0.00575 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Cooper, H. v., Evers, S., Aplin, P., Crout, N., Dahalan, M. P. bin, & Sjogersten, S. (2020). Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. ***Nature Communications***, *11*(1), 1–8.
https://doi.org/10.1038/s41467-020−14298-w

Summary

The context discusses the contribution of Southeast Asian peat swamp forests to greenhouse gas emissions, particularly from drainage-based agriculture such as oil palm and pulp wood production. It highlights the importance of including methane (CH_4) and nitrous oxide (N_2O) fluxes in emission calculations and presents improved estimates with uncertainty. The study emphasises the threat to carbon storage in peat swamp forests and the need for sustainable land use practices.

Field of Study/Sector

Environmental science, specifically peatland ecology and greenhouse gas emissions in Southeast Asian peat swamp forests.

Method

The methodology used in the research paper involved direct measurement of greenhouse gas fluxes at a tropical peatland in North Selangor state, Malaysia. The study selected four stages of conversion from peat swamp forest to oil palm plantation: secondary forest, recently drained but uncleared forest, cleared and recently planted young oil palm plantation, and mature oil palm plantation. Greenhouse gas fluxes, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), were measured at each stage of conversion. The researchers also assessed soil physical properties, carbon storage, and quality to understand the impact of conversion on peat swamp forest. The data collected provided insights into the contribution of the conversion process to greenhouse gas emissions and highlighted the importance of considering this factor when comparing emissions between intact forest and mature oil palm.

Location

The research was conducted in North Selangor state, Malaysia.

Emission Factor Value

0.041 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Rewetting Restored Forest

Conflict of Interest

Reference

Azizan, S. N. F., Goto, Y., Doi, T., Kamardan, M. I. F., Hara, H., McTaggart, I., Kai, T., & Noborio, K. (2021). Comparing GHG emissions from drained oil palm and recovering tropical peatland forests in Malaysia. ***Water***, *13*(23), 3372.
https://doi.org/10.3390/w13233372

Summary

This paper discusses the characteristics of tropical peatland and the emission of greenhouse gases in different sites. The study analyses data from three sites in Japan and Malaysia, focusing on soil organic C and N, bulk density, particle density, porosity, and surface organic matter content. Statistical analyses were conducted using Excel 2018, including Pearson's correlation and one-way ANOVA. The paper also highlights the variations in greenhouse gas emissions, particularly for N_2O and CH_4. The study emphasises the importance of sufficient measurements and long-term monitoring for accurate assessment of greenhouse gas emissions in peatlands.

Field of Study/Sector

Environmental Science, Agriculture.

Method

The methodology used in the research paper involved conducting a 15-month temporal study in the northern Selangor peatlands of peninsular Malaysia. The study is conducted in April-June 2019 with sampling intervals at 0, 10, and 20 min. The study focused on comparing greenhouse gas emissions and environmental parameters in three different land-use types: (1) drained matured oil palm plantation, (2) rewetting-restored forest, and (3) undrained natural forest. Carbon dioxide, N_2O, and CH_4 fluxes were measured using gas chromatography with a flame ionization detector (FID) at biweekly intervals from the soil, along with measurements of in situ environmental factors such as atmospheric temperature, soil temperature, soil moisture, and water table level. The statistical analyses were carried out using Excel 2018, including Pearson's correlation to determine the correlations between greenhouse gas emissions and hydrology parameters variables, and a one-way ANOVA with post hoc test to compare greenhouse gas emissions and environmental parameters at the different sites. The statistical significance level was set at $p = 0.05$.

Location

The geographical location of the research study was the northern Selangor peatlands in peninsular Malaysia.

Emission Factor Value

0.372 ± 0.73 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Busman, N. A., Melling, L., Goh, K. J., Imran, Y., Sangok, F. E., & Watanabe, A. (2023). Soil CO_2 and CH_4 fluxes from different forest types in tropical peat swamp forest. ***Science of the Total Environment***, *858*(2023), 159973. https://doi.org/10.1016/j.scitotenv.2022.159973

Summary

This paper discusses the measurement of CO_2 and CH_4 fluxes from different forest types in a tropical peat swamp forest. The study examines the effects of environmental factors such as temperature, soil moisture, and light intensity on these fluxes. The research also analyses soil physicochemical properties and nutrient contents in the soil samples. Overall, the paper aims to provide a more precise estimation of the contribution of peatlands to greenhouse gas emissions.

Field of Study/Sector

Environmental Science, Peatland Ecology.

Method

The methodology used in the research paper involved the collection and analysis of soil samples. Soil samples were collected from three different forest sites, namely MPS, ABt, and ABg. The soil samples were then analysed for various physicochemical properties, including the contents of phosphorus, potassium, calcium, magnesium, iron, manganese, and zinc. The analysis was conducted using inductively coupled plasma-optical spectroscopy and digesting the soil samples with a mixture of concentrated hydrochloric acid and nitric acid. Statistical analysis was performed using R statistical software version 3.5.1. One-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) were used to analyse differences in soil physicochemical properties and environmental variables. Independent sample t-tests and repeated measure analysis of variance were also conducted to assess differences in greenhouse gas fluxes and environmental variables between different seasons and sites. Linear and multiple regression analysis with backward stepwise inclusion were applied to analyse the relationships between greenhouse gas fluxes and environmental and physicochemical properties. Principal component analysis (PCA) was used to explore the variations in peat soil properties and their relationships with forest types.

Location

1° 27′ 47.89″ N, 111° 09′ 28.64″ E

Emission Factor Value

0.0476 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Vegetation type: *Shorea albida*

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Dhandapani, S., Evers, S., Boyd, D., Evans, C. D., Page, S., Parish, F., & Sjogersten, S. (2023). Assessment of differences in peat physico-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands. ***Catena***, *230*(2023), 107255. https://doi.org/10.1016/j.catena.2023.107255

Summary

This paper assesses the differences in peat physico-chemical properties, surface subsidence, and greenhouse gas emissions between different land uses in Selangor peatlands. Researchers from various universities and research institutions in the UK and Malaysia conducted the study. The paper analyses factors such as moisture, pH, electrical conductivity, redox potential, bulk density, and nutrient concentrations. The results show the impact of different land uses on peat properties and highlight the anthropogenic modification of the peat. The study focuses on the Selangor region in Malaysia and provides valuable insights for land use management and conservation efforts.

Field of Study/Sector

Environmental Science, Peatland Ecology.

Method

The methodology involved weighing the samples into a ceramic crucible and recording the exact weight. The samples were then transferred to an auto sampler in a Skalar primacs series SNC100 TC TN analyser to analyse total C and N content. Greenhouse gas emissions, specifically CO_2 and CH_4, were measured using a Los Gatos ultraportable greenhouse gas analyser with a closed dynamic chamber method. Peat nutrient concentrations were analysed using inductively coupled plasma mass spectroscopy.

Location

Peatlands in the State of Selangor, Peninsular Malaysia.

Emission Factor Value

0.0114 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Water table with –0.4314 m.

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 10: AFOLU | Peat Fires

Reference

Smith, T. E. L., Evers, S., Yule, C. M., & Gan, J. Y. (2018). In Situ Tropical Peatland Fire Emission Factors and Their Variability, as Determined by Field Measurements in Peninsula Malaysia. ***Global Biogeochemical Cycles***, 32(1), 18–31.
https://doi.org/10.1002/2017GB005709

Summary

This paper discusses the variability of greenhouse gas emissions from fires in tropical peatlands in Peninsula Malaysia. The authors conducted field measurements at various sites with different degradation characteristics and burning durations. They aimed to update the emission factors previously summarized by the IPCC and Akagi et al. (2011) by incorporating new findings. The paper provides specific information about the visited sites, including peatland fires and vegetation types.

Field of Study/Sector

The field of study is environmental science, specifically focusing on greenhouse gas emissions from fires in tropical peatlands in Peninsula Malaysia.

Method

The methodology used in the research paper involved field measurements conducted in Peninsula Malaysia. The researchers visited multiple sites in SE Pahang and N Selangor, with different degradation characteristics and burning for different lengths of time. They measured emissions using OP-FTIR (Open-Path Fourier Transform Infrared Spectroscopy) at these sites. The researchers also collected data on the characteristics of the fire sites and conditions studied.

Location

The geographical location of the research study is in southern Peninsula Malaysia, specifically in SE Pahang and N Selangor. The research team also measured Sumatra, an island near Peninsula Malaysia.

Emission Factor Value

0.0110 kg CH_4 kg^{-1} dry fuel burned

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 11: AFOLU | Rice Cultivation

Reference

Fazli, P., & Man, H. C. (2014). Comparison of Methane Emission from Conventional and Modified Paddy Cultivation in Malaysia. **Agriculture and Agricultural Science Procedia**, *2*(2014), 272–279. https://doi.org/10.1016/j.aaspro.2014.11.039

Summary

This study assesses methane emission from modified rice cultivation systems in Malaysia. The cultivation methods studied include two modified systems (MC1 and MC2) and a conventional method (C). The experiment was conducted using the MR219 rice cultivar in experimental plots at the University of Putra, Malaysia. The soil type was silty clay with 51% clay and 43% silt. The study aimed to find solutions to suppress methane emission, as flooded rice fields are major sources of this potent greenhouse gas.

Field of Study/Sector

Agriculture and Agricultural Science

Method

The methodology employed the static chamber method for collecting emitted methane in a comprehensive study conducted on rice plants, specifically MR 219 (Oryza sativa L. ssp. indica). Transparent Plexiglass chambers were utilised for this purpose, and the captured methane was stored in Tedlar bags. The methane concentration within these bags was then determined using a portable gas detector (Crowcon, Oxfordshire England). Over the course of the rice growing season, spanning 110 days, methane emission measurements were undertaken daily at consistent 7-day intervals. The rice cultivating soil exhibited a composition of 51% clay and 43% silt, and a Carbon to Nitrogen ratio of 6.38% to 0.62%.

Location

The research was conducted in experimental plots located in University of Putra, Malaysia, at coordinates 2.9° N, 101.7° E.

Emission Factor Value

Continuous Flooded –0.04115 kg CH_4 ha^{-1} day^{-1}; Alternate Wet and Dry –0.014 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Soil composition: 51% clay, 43% slit with percentage ratio of Carbon to Nitrogen, 6.38% to 0.62%

Conflict of Interest

The author did not declare any conflict of interest.

Reference

Nuclear Agency Malaysia. 2023. Greenhouses Gases Evaluation Programs on Farmer Rice Field in Collaboration with Department of Agriculture Sungai Burong, Selangor, Malaysia.

Summary

In July 2022, Nuclear Malaysia and the Department of Agriculture in Selangor collaborated on a greenhouse gas evaluation program for farmers' rice fields. The aim was to educate farmers about greenhouse gas emissions and improve agricultural policies. The Malaysian Nuclear Agency conducted studies and evaluations in rice fields using two irrigation methods: continuous flooding and alternate wetting and drying (AWD). Sampling was done once a week, and CH_4 and CO_2 gases were stored in Labco Vials. The results showed variations in CH_4 flux between CF and AWD irrigation techniques.

Field of Study/Sector

Agriculture, specifically the evaluation of greenhouse gas emissions in rice cultivation

Method

The methodology used in the research paper involved the evaluation of CH_4 emissions on rice fields under continuous flooding (CF) and alternate wetting and drying (AWD) irrigation techniques. The study crop used was Mardi Sebernas 307. The research was conducted at the Rice Field in the Department of Agriculture, Sungai Burong, Tanjong Karang, Selangor. The experiment had three replications. The plot preparation was done at the rice field, followed by germination of Mardi Sebernas 307 seeds in the germination area. After 1_4 days, the seeds were transplanted to the plot using a transplanter machine. A chamber base was installed at 1 DAT (Days After Transplanting), and the first CH_4 sampling was conducted at 1 DAT. Four splits of N, P, and K fertilizer were applied at specific intervals during the growth period of the rice plants. The CH_4 fluxes were measured and compared between CF and AWD irrigation techniques throughout the planting season.

Location

The geographical location of the research study was the Rice Field in the Department of Agriculture, Sungai Burong, Tanjong Karang, Selangor.

Emission Factor Value

Continuous Flooded −0.325 kg CH_4 ha^{-1} day^{-1}; Alternate Wet and Dry –0.2 kg CH_4 ha^{-1} day^{-1}

Surface Condition

Study crop: Mardi Sebernas 307 with 4 splits of N, P and K fertilizer (25% at 10 DAT, 30% at 27 DAT and 30% at 49 DAT and 15% at 65 DAT).

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 12: AFOLU | River Basins

Reference

Bange, H., Hock Sim, C., Bastian, D., Kallert, J., Kock, A., Mujahid, A., & Müller, M. (2019). Nitrous oxide (N_2O) and methane (CH_4) in rivers and estuaries of northwestern Borneo. ***Biogeosciences***, *16*(22), 4321–4335.
https://doi.org/10.5194/bg−16−4321-2019

Summary

This paper focuses on measuring N_2O and CH_4 concentrations in rivers and estuaries of northwestern Borneo. The study area includes disturbed and undisturbed river basins, with data collected in March 2017. The methods involved water sampling using a Niskin sampler and analysis using gas chromatographic separation. The paper also discusses the influence of environmental factors on the flux densities of N_2O and CH_4.

Field of Study/Sector

Biogeosciences.

Method

The methodology used in the research paper involved collecting discrete samples of surface water at several stations along the salinity gradients of the Rajang, Maludam, Sebuyau, and Simunjan rivers in northwestern Borneo. The samples were taken during two campaigns in March and September 2017, with additional sampling in August 2016 for the Rajang River and March 2017 for the Samunsam and Sematan rivers. Water was collected from a depth of 1 m using a Niskin sampler. Subsamples for N_2O and CH_4 were taken in glass vials and analysed using the static-headspace equilibration method followed by gas chromatographic separation and detection with an electron capture detector.

Location

The geographical location of the study area is northwestern Borneo, specifically the river basins of Rajang, Maludam, Sebuyau, Simunjan, Samunsam, and Sematan.

Emission Factor Value

Disturbed river basin –0.256 kg CH_4 ha^{-1} day^{-1}
Undisturbed river basin –0.168 kg CH_4 ha^{-1} day^{-1}

Surface Condition

NA

Conflict of Interest

The author did not declare any conflict of interest.

Appendix A- 13: Waste | Wastewater Treatment and Discharge - Industrial

Reference

Vijaya, S., Ma, A., & Choo, Y. M. (2010). Capturing biogas: a means to reduce green house gas emissions for the production of crude palm oil. ***American Journal of Geoscience***, *1*(1), 1–6. https://doi.org/10.3844/ajgsp.2010.1.6

Summary

NA

Field of Study/Sector

Waste

Method

NA

Location

NA

Emission Factor Value

0.225 CH_4 kg^{-1} COD

Surface Condition

NA

Conflict of Interest

NA

Appendix B: Data Survey

Appendix B- 1: List of Stakeholders identified.

Table B - 1 - 1 List of stakeholders identified. Last updated in December 2023.

No	Type of Entities	Sector	Institute	Person-in-charge	Phone number/Email
1	Government	Ministry	Ministry of Natural Resources, Environment and Climate Change (NRECC)	En. Mohamad Firdaus bin Nawawi	+60380917380 / firdaus@nrecc.gov.my
2	Government	Waste	Indah Water	Jabatan Komunikasi Korporat	comms@iwk.com.my
3	Government	Energy	Tenaga Nasional Berhad	En. Fizal Azuan bin Mhd Sidin	fizal@tnb.com.my
4	Government	Energy	Sabah Electricity	En. Fizal Azuan bin Mhd Sidin	fizal@tnb.com.my
5	Government	Waste	Malaysian Palm Oil Board (MPOB)	Dr. Mohamad Azri Sukiran	+60 387694485 / azri@mpob.gov.my
6	Government	Department	Malaysian Meteorological Department (METMalaysia)	Puan Natrah	+60 379678219 / syafiqa@met.gov.my
7	Government	Department	Malaysian Nuclear Agency and Department of Agriculture Malaysia	En. Ahmad Nazrul Abd Wahid	a_nazrul@nm.gov.my
8	Government	Department	Malaysian Agricultural Research and Development Institute (MARDI)	Dr. Mohd Saufi Bastami	msaufi@mardi.gov.my
9	Government	Department	Forest Research Institute Malaysia (FRIM)	Gs. Dr. Hamdan B. Omar	hamdanomar@frim.gov .my
10	Government	Department	Department of Environment (DOE)		
11	State Government	Energy	Sarawak Energy	Karen Lee Suan Peng	Karen.Lee@sarawakene rgy.com
12	State Government	AFOLU	Sarawak Tropical Peat Research Institute (TROPI), Environmental Research Division	Dr. Wong Guan Xhuan	kenwgux@gmail.com
13	State Government	Waste	Air Selangor	Sustainability team	sustainability@airselan gor.com
14	Industry	Energy	PETRONAS	Pn. Atiqah & En. Hasnul	
15	Industry	Energy	Shell	Ms. Roy Jihok	j.royjihok@shell.com
16	Industry	Energy	Petron	Petron Malaysia Team	+603 20828400 / corporate.affairs@petro n.com.my
17	Industry	Energy	Heng Yuan Refining Sdn Bhd (Formerly known as Shell Refining Company Berhad)	HengYuan Refining Company Berhad Corporate team	+606 641 2000 / HRCPD-Corporate-Affairs@hrc.com.my

Table B - 1 - 1 (continued)

No	Type of Entities	Sector	Institute	Person-in-charge	Phone number/Email
18	Industry	Energy	Uzma Malaysia	-	communications@uzmagroup.com
19	Industry	Energy	Hibiscus Petroleum Berhad	Hibiscus Petroleum Sustainability Department	+603-2092 1300 / info@hibiscuspetroleum.com
20	Industry	Waste	Sime Darby Plantation Sdn Bhd	Puan Nur Fadhilah Ikhsan	fadhilah.ikhsan@simedarbyplantation.com
21	Industry	Waste	IOI Corporation Berhad	Ms. Mastura	mastura@ioigroup.com
22	Industry	IPPU	Top Glove	Puan Nur Fatin Nazurah	f_nazurah@topglove.com.my
23	Industry	Energy	Malakof	-	info@malakoff.com.my

Appendix B- 2: Responses per Sector

Based on the data survey, most of the total stakeholders responded with complete answers (n=7) including the Department of Environment (DOE), Malaysian Meteorological Department (METMalaysia), Nuclear Agency Malaysia-Department of Agriculture, Malaysian Agricultural Research and Development Institute (MARDI), Sarawak Tropical Peat Research Institute (TROPI), Top Glove Corporation Berhad, and Malakoff Corporation Berhad. All these stakeholders responded well to the list of questions given in the email survey. Extra materials like related published reports, research articles, and slide presentations were given as well to support their answers. Few stakeholders provided the data on methane concentration and emissions factors but due to confidentiality status, the data is restricted to be published in this report.

Four stakeholders who responded but need further clarification are the Ministry of Natural Resources, Environment and Climate Change (NRECC), Petroliam Nasional Berhad (PETRONAS), Sarawak Energy and Indah Water Konsortium. Since the need for further clarification regarding the email survey, individual and group interviews have been made with the stakeholders via online meeting platforms. Many information has been obtained from these interviews since there is no boundary to ask the questions and extra information from the stakeholders was given to support this research that aim to find the gap of methane study in Malaysia.

Two stakeholder, HengYuan Refining Company Berhad and Petron responded to an email survey but refused to answer all those questions since no methane monitoring has been conducted by the stakeholder. Although the stakeholder has published the sustainability report, there is no detailed information related to the methane emissions.

Finally, four stakeholders responded but needed time to gather information and data to answer all the questions listed in the email survey. They are Sime Darby Plantation Sdn Bhd, Tenaga Nasional Berhad (TNB), Sabah Electricity Sdn Bhd and SWCorp. This is due to several reasons including;

i. Sarawak Energy needs to sign a confidentiality statement before the interview session can be conducted as they need approval to answer the questions listed in the email survey.
ii. Sabah Electricity Sdn Bhd is operated under TNB. An email survey should be addressed to TNB.
iii. TNB and Sime Darby need time to assign the email survey to the right person in charge.

All data survey responses from stakeholders were sorted into separate categories based on the sector of methane emissions, except NRECC, which is at the highest level of government in Malaysia. It controls government agencies and private sectors to limit the negative effects of methane emissions on the environment.

Ministry (NRECC)

All the answers by NRECC were obtained during the interview session on 17th August 2023. Additional material (Figure) was shared by NRECC to support their answer.

Q1, Ongoing Methane Monitoring Initiatives:

Do you have any ongoing methane monitoring initiatives within your company? If yes, we are interested to know more about the methodologies, technologies, and systems used, as well as the scope and geographical coverage of these initiatives.

Answer:

NRECC did not directly monitor and measure the methane concentration and emissions. However, a few agencies that are known as Sub-Working Groups (SWG) under the Technical Working Groups (TWG) oversee methane monitoring as shown in **Fig. 13**. For example, the DOE and METMalaysia are Sub-Working Groups in charge of continuous methane monitoring from the stationary monitoring station.

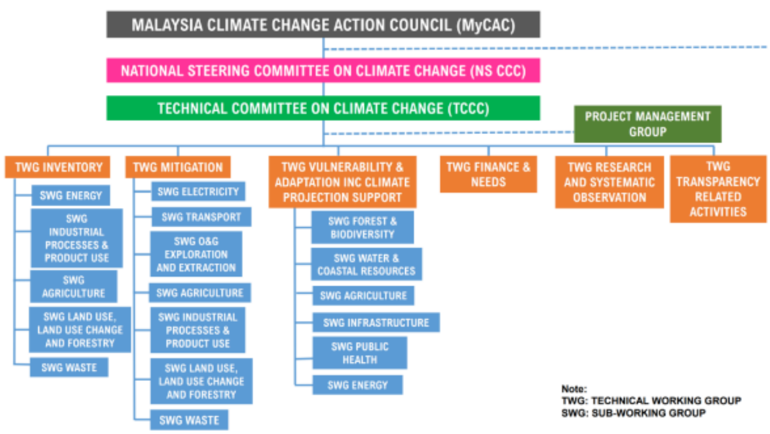


Fig. 13. Climate Change Institutional Arrangements and Thematic Working Groups (Malaysia 2022).

Q2, Ongoing Methane Emission Related Initiatives:

Do you have any ongoing methane emission initiative related to policy enforcement, a methane pledge action plan, or any start-off action plan on methane emission? For example, methane flux or eddy covariance.

Answer:

NRECC oversees reporting the emissions of methane in Malaysia by submitting the BUR4 Report. The input of methane emissions is obtained from the assigned SWG and TWG. Meetings and workshops were held to facilitate the communication between SWG and stakeholders with the frequency depending on the requirement of each SWG (3 to 4 times a year). Based on the status,

a. TROPI is working together with NRECC as a National Communication - Working Group of National Communication 4 (NC4) - Chapter 5 and provided published data on CH_4 emissions from the studies in tropical peatland.

b. Activity Data for Fugitive Emission reported by Malaysia is only taken from the National Energy Balance in which many assumptions were made until the most recent report in 2022, where industrial emissions (from NPM) were obtained.
c. Ongoing project in improving emission factor to country-specific factors:
    i. University Teknologi PETRONAS (UTP) to develop an emission factor for fugitive emissions.
    ii. Malaysian Palm Oil Board (MPOB) to develop emission factor based on individual mills (palm oil mill effluent).
d. To increase confidence in adopting the emission factor
    i. Previous project with TNB (complicated process to use the emission factor from published journal: presentation, publication, and submission through the EFDB database to be reviewed and accepted)
e. Rice paddies (emission factor of Thailand was used)

Q3, Methane Emission or Concentration Data:

Do you have any methane emission or concentration data that your company has collected? Regarding methane emission or concentration data, we kindly request your cooperation in indicating whether your company's data is publicly available or confidential. Understanding the availability of the data will assist us in evaluating the feasibility of incorporating it into our research.

Answer:

NRECC is obtaining the methane concentration and emissions from the assigned SWG and TWG. However, most of the data is confidential. NRECC needs to sign a non-disclosure agreement (NDA) which is solely used for reporting.

Q4, Challenges or Barriers in Reducing Methane Emissions:

What are the major challenges or barriers your company faces in reducing methane emissions? Your insights will help us better understand the complexities and develop effective strategies.

Answer:

Although NRECC is a ministry-level agency, there are still facing a challenge in a way to reduce methane emissions in Malaysia. The challenges are as follows:

a. Lack of involvement from stakeholders to develop Country Specific Emission Factor (CSEF) where the academician or industries contribution is needed to develop the CSEF.
b. Hard to emphasise the need for emission factor research especially methane emissions since there is low engagement with academicians.
c. Most of the data is confidential. Need to sign NDA and can be used solely for reporting. For example, data from SWG LULUCF belongs to the state government and data from SWG Waste belongs to the Department of Environment.
d. Different standards used in reporting for the Oil and Gas Sustainability Report make retrieving data hard to interpret. Hence, there is an issue of double counting.

e. No established acts or guidelines for mandatory reporting of greenhouse gas emissions. NRECC is working on a new act regarding climate change.

Energy Sector

There are two stakeholders (PETRONAS and Malakoff) from the Energy sector who responded with the full answer to the email survey and interview. An interview session with PETRONAS was held on 31st May 2023.

Q1, Ongoing Methane Monitoring Initiatives:

Do you have any ongoing methane monitoring initiatives within your company? If yes, we are interested to know more about the methodologies, technologies, and systems used, as well as the scope and geographical coverage of these initiatives.

Answer from PETRONAS:

PETRONAS is monitoring the methane concentration and emissions regularly from the monitoring station.

Answer from Malakoff:

Malakoff is not monitoring the methane concentration and emissions since they utilise methane gas in the production, by supplying electricity. The only source of emitting methane is when there is a need for maintenance and emergency situations.

Q2, Ongoing Methane Emission Related Initiatives:

Do you have any ongoing methane emission initiative related to policy enforcement, a methane pledge action plan, or any start-off action plan on methane emission? For example, methane flux or eddy covariance.

Answer from PETRONAS:

PETRONAS is one of the members of the Oil and Gas Methane Partnership (OGMP) 2.0. API Compendium acts as the guideline to develop an emission factor at the level 2. They are moving towards developing an industrial-specific emission factor, which is at level 4 based on OGMP 2.0. Meanwhile, the flow rate is used to develop specific activity data. There is an ongoing project related to methane regarding the emission factor of flaring. PETRONAS also pledged to reduce methane emissions by 50% by 2050.

Answer from Malakoff:

Malakoff do not measure as they claim their methane release are only through the vents or flares during maintenance and emergency situations. They also do not plan on measuring methane regularly right now.

Q3, Methane Emission or Concentration Data:

Do you have any methane emission or concentration data that your company has collected? Regarding methane emission or concentration data, we kindly request your cooperation in indicating whether your company's data is publicly available or confidential. Understanding the availability of the data will assist us in evaluating the feasibility of incorporating it into our research.

Answer from PETRONAS:

Yes, PETRONAS does have methane concentrations and emissions data. However, the data is confidential except for the annual report published by PETRONAS.

Answer from Malakoff:

No further information since no methane monitoring is available.

Q4, Challenges or Barriers in Reducing Methane Emissions:

What are the major challenges or barriers your company faces in reducing methane emissions? Your insights will help us better understand the complexities and develop effective strategies.

Answer from PETRONAS:

PETRONAS is working hard to achieve the target of reducing 50% of the methane emissions by 2050 along with raising the production of oil and gas without compromising the impact on the environment.

Answer from Malakoff:

No further information since no methane monitoring is available.

Industrial Processes and Product Use (IPPU) Sector

TOP Glove is the only stakeholder under IPPU sector that has responded to the email surveys. Other stakeholders contacted under IPPU sector did not respond after the first email survey sent before 25th August 2023.

Q1, Ongoing Methane Monitoring Initiatives:

Do you have any ongoing methane monitoring initiatives within your company? If yes, we are interested to know more about the methodologies, technologies, and systems used, as well as the scope and geographical coverage of these initiatives.

Answer from Top Glove:

Top Glove is not monitoring the methane concentration and emissions since they utilise methane gas in their production, by supplying electricity.

Q2, Ongoing Methane Emission Related Initiatives:

Do you have any ongoing methane emission initiative related to policy enforcement, a methane pledge action plan, or any start-off action plan on methane emission? For example, methane flux or eddy covariance.

Answer from Top Glove:

No further information since no methane monitoring is available.

Q3, Methane Emission or Concentration Data:

Do you have any methane emission or concentration data that your company has collected? Regarding methane emission or concentration data, we kindly request your cooperation in indicating whether your company's data is publicly available or confidential. Understanding the availability of the data will assist us in evaluating the feasibility of incorporating it into our research.

Answer from Top Glove:

No further information since no methane monitoring is available.

Q4, Challenges or Barriers in Reducing Methane Emissions:

What are the major challenges or barriers your company faces in reducing methane emissions? Your insights will help us better understand the complexities and develop effective strategies.

Answer from Top Glove:

No further information since no methane monitoring is available.

Agricultural, Forestry and Other Land Use (AFOLU) Sector

There are three stakeholders (MARDI, TROPI and the Nuclear Agency Malaysia-Department of Agriculture) from the AFOLU sector who responded with the full answer to the email surveys.

Q1, Ongoing Methane Monitoring Initiatives:

Do you have any ongoing methane monitoring initiatives within your company? If yes, we are interested to know more about the methodologies, technologies, and systems used, as well as the scope and geographical coverage of these initiatives.

Answer from TROPI:

TROPI is conducting methane monitoring in Sarawak to estimate methane emissions from the AFOLU category.

Answer from MARDI:

There is no continuous monitoring of methane emissions from any sources or periodic methane release monitoring. The nature of the MARDI project focuses on agricultural activities and the effect of the treatment, if any. The current project of MARDI is about reducing or inhibiting the release of methane from the faecal slurry through several methods.

Answer from Nuclear Agency Malaysia- Department of Agriculture:

There is no continuous monitoring of methane emissions from the Nuclear Agency Malaysia-Agricultural Department. However, methane monitoring is only conducted based on research projects. For example, the current project is measuring methane emissions from the paddy field.

Q2, Ongoing Methane Emission Related Initiatives:

Do you have any ongoing methane emission initiative related to policy enforcement, a methane pledge action plan, or any start-off action plan on methane emission? For example, methane flux or eddy covariance.

Answer from TROPI:

There are ongoing methane monitoring initiatives for the methane fluxes from tropical peat swamp forests and oil palm plantations (on peat) located in Sri Aman, Betong, and Sibu. The eddy covariance method with open-path CH_4 analysers to measure methane flux above the canopy. Additionally, TROPI also uses the closed-chamber method to measure the methane flux from the soil. TROPI estimates the greenhouse gas emissions from tropical peatlands and contributes to the IPCC Guidelines for National Greenhouse Gas Inventories and Malaysia's Biennial Update Report to the UNFCCC.

Answer from MARDI:

MARDI, as an agency appointed as a Sub-Working Group by NRECC, makes projections of the release of greenhouse gas emissions from the country's agricultural sector using agricultural activity data. The NRECC uses this projection for reporting the country's greenhouse gas emissions and reports to the UNFCC through the BUR. The release of methane emissions is subjective according to the research approach. For example, a rice field study will measure the release of methane over a land area, however, emissions from the substrate will take the amount of available organic matter into account.

Answer from Nuclear Agency Malaysia-Department of Agriculture:

Nuclear Agency Malaysia in collaboration with the Department of Agriculture is taking the first step to measure methane emissions from agricultural production. This step is one way to reduce the impact of methane emissions on global warming. However, there is still no policy enforcement related to methane emissions from agricultural production.

Q3, Methane Emission or Concentration Data:

Do you have any methane emission or concentration data that your company has collected? Regarding methane emission or concentration data, we kindly request your cooperation in indicating whether your company's data is publicly available or confidential. Understanding the availability of the data will assist us in evaluating the feasibility of incorporating it into our research.

Answer from TROPI:

All unpublished data from TROPI are confidential. The published literature on methane emission from tropical peatlands shared by TROPI.

Answer from MARDI:

All unpublished data from MARDI is confidential. The published literature including research articles and reports on methane emission shared by MARDI can be used in this research to find the gap of methane study in Malaysia.

Answer from Nuclear Agency Malaysia-Department of Agriculture:

The research reports, methodology procedures, and slide presentations shared by the Nuclear Agency Malaysia-Department of Agriculture can be used in this research to find a gap in methane study in Malaysia. Acknowledgment to Nuclear Agency Malaysia-Department of Agriculture is required to utilise the shared information.

Q4, Challenges or Barriers in Reducing Methane Emissions:

What are the major challenges or barriers your company faces in reducing methane emissions? Your insights will help us better understand the complexities and develop effective strategies.

Answer from TROPI:

The major challenges faced by TROPI are the complexity of emission sources and the lack of methane flux measurement. TROPI is currently involved in the Working Group of National Communication 4 (NC4) - Chapter 5 in improving the methane emission factor, especially from the AFOLU sector.

Answer from MARDI:

The major challenges faced by MARDI are low research funds, lack of automation, and technology limitations due to excessive costs for advanced technologies. For example, the reduction of methane from the faecal waste sector involves extremely high costs. For example, the use of a biodigester.

Answer from Nuclear Agency Malaysia-Department of Agriculture:

The challenge faced by the Nuclear Agency Malaysia-Department of Agriculture is the lack of funds to continuously measure the emissions of methane from agricultural production. The methane monitoring is currently performed based on a research project.

Waste Sector

Q1, Ongoing Methane Monitoring Initiatives:

Do you have any ongoing methane monitoring initiatives within your company? If yes, we are interested to know more about the methodologies, technologies, and systems used, as well as the scope and geographical coverage of these initiatives.

Answer from Indah Water Konsortium Sdn Bhd (IWK):

IWK has limited anaerobic sources, with active anaerobic digesters installed in only 5 out of their 7000 plants. Within these digesters, online methane sensors are deployed to monitor the biogas production. Typically, the volume of biogas generated from these digesters ranges from 50% to 65%.

IWK is acutely aware of its most substantial emissions, particularly those falling under Scope 3. This primarily involves tracking the disposal of sludge and biosolids generated within their operations. They monitor the destination of these waste materials, whether they are sent to landfills or managed in other ways. Using emission factors recommended by the IPCC, they estimate the emissions associated with these activities. The activity data used for these calculations is specific to each plant and is sourced directly from IWK's own records.

Q2, Ongoing Methane Emission Related Initiatives:

Do you have any ongoing methane emission initiative related to policy enforcement, a methane pledge action plan, or any start-off action plan on methane emission? For example, methane flux or eddy covariance.

Answer from Indah Water Konsortium Sdn Bhd (IWK):

IWK does not have any monitoring plans as the company is gradually transitioning to aerobic processes that do not emit methane. This shift presents an opportunity for IWK to embrace a circular economy approach, where waste is viewed as a resource rather than a problem. Furthermore, the company ensures that downstream methane emissions are not released into the ambient air; instead, they are either flared or converted into electricity.

In addition, local environmental regulations do not mandate monitoring of gaseous emissions, further reducing the need for such monitoring within IWK's operations.

Q3, Methane Emission or Concentration Data:

Do you have any methane emission or concentration data that your company has collected? Regarding methane emission or concentration data, we kindly request your cooperation in indicating whether your company's data is publicly available or confidential. Understanding the availability of the data will assist us in evaluating the feasibility of incorporating it into our research.

Answer from Indah Water Konsortium Sdn Bhd (IWK):

Site specific data needs NDA.

Q4, Challenges or Barriers in Reducing Methane Emissions:

What are the major challenges or barriers your company faces in reducing methane emissions? Your insights will help us better understand the complexities and develop effective strategies.

Answer from Indah Water Konsortium Sdn Bhd (IWK):

IWK, which relies on government subsidies, faces significant financial constraints when dealing with methane emissions. Installing methane sensors in all 7,000 plants is prohibitively expensive.

Moreover, IWK's facilities handle waste from the food industry, which typically contains a high organic load, leading to increased methane emissions.

Due to the absence of a Malaysian National Data Inventory, IWK adopts default emission factors and methane correction values from the IPCC guidelines. This is done out of necessity, as local data is lacking, potentially affecting the accuracy of emission calculations and mitigation strategies.

Appendix C: Drone Services

Table C - 1 - 1 Drone services available. Last updated in December 2023.

No	Companies	Websites	Country	Phone Number /Email	Notes
1	IKM Testing Malaysia	https://www.ikm.com/ikm-testing-malaysia/	Based in Malaysia	-	IKM Testing UK with Burmi Armada drone-based methane emissions survey
2	Alam Sekitar Malaysia Sdn Bhd	https://enviromalaysia.com.my/products/scentroid-dr1000-flying-lab/	Malaysia	asma@enviromalaysia.com.my	-

About the Institutions

School of Industrial Technology, Universiti Sains Malaysia (USM)
School of Industrial Technology, Universiti Sains Malaysia (USM), is committed to advancing education, research, and innovation in environmental, food, bioprocess, and bioresource technologies. The school champions interdisciplinary research that supports national sustainability goals of Malaysia.

Universiti Kebangsaan Malaysia (UKM)
UKM is committed to excellence in education, research, and innovation across a wide range of disciplines - from the sciences and engineering to medicine, social sciences, and humanities. The university fosters a vibrant research ecosystem, contributing significantly to national development through high-impact research, interdisciplinary collaboration, and community engagement.

Environmental Defense Fund (EDF)
EDF is a global nonprofit environmental organization. Guided by science, economics, and climate justice, it develops practical, lasting solutions to urgent environmental problems worldwide. EDF works across more than 30 countries to reduce pollution, curb greenhouse-gas emissions (especially methane), protect ecosystems, and safeguard human health and environmental equity.

About the Authors

This report was prepared by a multidisciplinary team of researchers with expertise in atmospheric science, climate modelling, environmental engineering, and methane emissions research. The authors represent Universiti Sains Malaysia (USM) and Universiti Kebangsaan Malaysia (UKM).

For Correspondence

Yusri Yusup
School of Industrial Technology
Universiti Sains Malaysia (USM)
11800 Penang, Malaysia
Email: yusriy@usm.my
Website: https://indtech.usm.my/yusri

Version Information

Version 1.0 — December 2025
First edition of *Methane in Malaysia: A Report on Sources, Data, and Research Needs*.
Future revisions may incorporate updated methane measurements, new datasets, and advancements in monitoring technology.

Copyright