



## Research article

# Life cycle greenhouse gas assessment and geographic information system hotspot mapping of biofertilizer application on oil palm plantations

Kyle Sebastian Mulya<sup>a</sup>, Malvin Ma<sup>a</sup>, Jian Ping Tan<sup>a,c,\*</sup>, Kun Sang<sup>d</sup>, Siaw Ping Yeat<sup>e</sup>, Chia Ning Clara Yeat<sup>e</sup>, Kok Sin Woon<sup>a,b,\*\*</sup>

<sup>a</sup> School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900, Sepang, Selangor, Malaysia

<sup>b</sup> Carbon Neutrality and Climate Change Thrust, Society Hub, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, 511453, China

<sup>c</sup> Center of Excellence for Sustainable Technologies for Agricultural Advancement and a Zero-Waste Economy (STARGAZE), Xiamen University Malaysia, Selangor Darul Ehsan, 43900, Malaysia

<sup>d</sup> School of Humanities and Communication, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900, Sepang, Selangor, Malaysia

<sup>e</sup> IBG Manufacturing Sdn Bhd, No. 3, Jln TPP 3, Taman Perindustrian Putra, Puchong, 47130, Selangor Darul Ehsan, Malaysia

## ARTICLE INFO

## Keywords:

Life cycle assessment  
Carbon accounting  
Biofertilizer  
Oil palm  
Geographic information system  
Agricultural climate policy

## ABSTRACT

Oil palm plantations in Malaysia are a significant source of global greenhouse gas (GHG) emissions. While biofertilizers can sustainably substitute for chemical fertilizers, there is a lack of quantitative, site-specific assessments of their efficacy in mitigating GHG emissions, particularly at the national scale. This gap is bridged by establishing a GHG inventory of biofertilizer manufacture and application on oil palm crops, using a GHG quantification model based on Life Cycle Assessment, supported by primary on-site data, and validated with secondary data sources. The GHG performance of the biofertilizer is assessed by mapping GHG hotspots across all oil palm plantations in Malaysia using Geographic Information Systems (GIS). The emissions were quantified from the raw material extraction for biofertilizer production through their application in fields. The study demonstrated that biofertilizer application can reduce life cycle GHG emissions by 39% relative to chemical fertilizers while increasing yield by 19%. Soil organic carbon emissions are the most significant source, accounting for 66% of the life cycle GHG emissions. Its fluctuations are the most critical variable influencing overall GHG performance, whereas other variables, such as chemical fertilizer quantity and crop yield, have comparably negligible impacts on life cycle GHG emissions. The GIS analysis identified that biofertilizer adoption on oil palm plantations could reduce emissions in one state by 13%. Policy recommendations were provided based on these findings. The GHG-GIS methodology serves as a strategic tool for developing transparent, region-specific decarbonization policies and improving environmental performance for manufacturers and operators.

## 1. Introduction

Agriculture is a key sector for global population growth, with palm oil being the most produced vegetable oil worldwide, contributing to 36% of worldwide vegetable oil production (CME Group, 2020). However, oil palm cultivation is a significant contributor to greenhouse gas

(GHG) emissions and deforestation, only second to soya-based oils (iChemE, 2021). Recognizing this, countries that cultivate oil palm have begun launching initiatives for GHG reduction through methods such as the 6.5-million-hectare palm plantation expansion limit in Malaysia (Amirkadra, 2024; Ying and Ho, 2019).

With these restrictions in place, companies are seeking ways to

**Abbreviations:** FTSE, Financial Times Stock Exchange; GHG, Greenhouse Gas; GIS, Geographic Information System; GRI, Global Reporting Initiative; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; MSPO, Malaysian Sustainable Palm Oil; NDC RAP, Nationally Determined Contribution Roadmap and Action Plan; NDPE, No Deforestation, No Peat, and No Exploitation; RSPO, Roundtable on Sustainable Palm Oil; SOC, Soil Organic Carbon; TN%, Total Nitrogen; TOC%, Total Organic Carbon.

\* Corresponding author. School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900, Sepang, Selangor, Malaysia.

\*\* Corresponding author. School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900, Sepang, Selangor, Malaysia.

E-mail addresses: [jianping.tan@xmu.edu.my](mailto:jianping.tan@xmu.edu.my) (J.P. Tan), [koksinoon@hkust-gz.edu.cn](mailto:koksinoon@hkust-gz.edu.cn) (K.S. Woon).

<https://doi.org/10.1016/j.jenvman.2026.129559>

Received 17 October 2025; Received in revised form 27 February 2026; Accepted 1 April 2026

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**Table 1**  
Studies researching the GHG performance of various crops, and application of GIS for added analysis.

Author	Location(s)	LCA <sup>a</sup>	Crop	GHG <sup>b</sup>	Software	Fertilizer
X. Yang et al. (2024)	China	Yes	Rapeseed	CO <sub>2</sub> , N <sub>2</sub> O	Not stated	Yes <sup>c</sup>
Clarke et al. (2019)	Ireland	Yes	Energy crops	CO <sub>2</sub> , N <sub>2</sub> O, CH <sub>4</sub>	ArcGIS	Chemical fertilizer
Zhu et al. (2019)	China	No	Paddy	CO <sub>2</sub> , N <sub>2</sub> O, CH <sub>4</sub>	Not stated	Yes
Gangopadhyay et al. (2023)	India	No	Paddy	N <sub>2</sub> O, CH <sub>4</sub>	Not stated	Chemical fertilizer, vermicompost, and manure
Yu et al. (2024)	China	No	Energy crops	CO <sub>2</sub> , N <sub>2</sub> O, CH <sub>4</sub>	ArcGIS	Chemical fertilizer
Srisunthon and Chawchai (2020)	Thailand	No	Palm	CO <sub>2</sub>	ArcGIS	Not assessed
Zhao et al. (2022)	China	No	Not stated	CO <sub>2</sub>	Not stated	Not assessed
Ma et al. (2023)	China, USA, S. Korea, Italy	No	Paddy	CH <sub>4</sub>	ArcGIS	Manure
Wan Mohd Jaafar et al. (2020)	Malaysia	No	Palm	CO <sub>2</sub>	ArcGIS	Not assessed
Amirkadra (2024)	Cameroon	Yes	Palm	CO <sub>2</sub> , N <sub>2</sub> O	Not used	Chemical fertilizer
Manning et al. (2019) <sup>3</sup>	Malaysia	No	Palm	CO <sub>2</sub> , CH <sub>4</sub>	Not used	Not stated
Abubakar et al. (2023)	Malaysia	No	Palm	N/A <sup>d</sup>	ArcGIS	Not assessed
Rajakal et al. (2024)	Malaysia	No	N/A	CO <sub>2</sub>	Not used	Biofertilizer (manufacture only)
<b>This study</b>	<b>Malaysia</b>	<b>Yes</b>	<b>Palm</b>	<b>CO<sub>2</sub>, N<sub>2</sub>O</b>	<b>ArcGIS</b>	<b>Biofertilizer, Chemical fertilizer</b>

This study did not assess CH<sub>4</sub> as the palm plantation is not located in a peatland, where CH<sub>4</sub> emissions are significant.

<sup>a</sup> This column indicates whether LCA was used in their study.

<sup>b</sup> GHG refers to the inclusion of N<sub>2</sub>O and CO<sub>2</sub>, with the addition of CH<sub>4</sub> for relevant crops (e.g., paddy).

<sup>c</sup> Study included CH<sub>4</sub> emissions as it considers palm plantations built on peatland.

<sup>d</sup> Study only utilizes GIS for the study. Greenhouse gas mapping for crops was not performed.

maximize crop productivity within existing plantations. While these companies may convert other land types, such as crop lands or urban areas, to plantations, the location of oil palm cultivation sites is often located far from urban areas, within forest areas with suitable growing conditions (Shevade and Loboda, 2019). This restricts most companies to their own areas, thereby encouraging the use of crop productivity enhancers, such as chemical fertilizers, to maximize productivity. While chemical fertilizers are a conventional tool for boosting crop growth, their manufacture and application contribute to 2.1% of the world's total anthropogenic GHG emissions (Menegat et al., 2022). This has created a need for sustainable alternatives like biofertilizers, which have been shown to reduce life-cycle GHG emissions by half in various crops (Pereira et al., 2023; Rose et al., 2014). However, there is limited research on the GHG performance of biofertilizers for oil palm cultivation.

Despite ongoing decarbonization efforts, many oil palm organizations have few initiatives to reduce GHG emissions. While regulations in Malaysia require GHG reporting and certification from organizations such as MSPO, which include the No Deforestation, No Peat, No Exploitation (NDPE) policy, these measures primarily promote transparency rather than directly reduce emissions (Aziz, 2022; MOF, 2024; NST, 2023). There is a need for tools that help the palm oil industry assess its GHG performance and plan decarbonization strategies.

To support national GHG reduction goals, it is crucial to have robust and affordable GHG calculators. While some tools exist, they are often subscription-based, which limits their use. Additionally, there is an opportunity to enhance these tools by integrating macro-analysis elements like Geographical Information Systems (GIS) for nationwide GHG mapping and policy drafting (Phuang et al., 2025). A base GHG-accounting model by Mulya et al. (2025) has been developed that tailors local soil and crop elements. This method allows for the assessment of biofertilizers and other non-conventional products on soil properties and associated GHG emissions. Results can be extrapolated using GIS, while statistical analyses of soil nutrient dynamics, such as total nitrogen (TN%) and soil organic carbon (SOC), provide insight into treatment effects and their potential contributions to carbon-nitrogen cycling. Combining these tools can be valuable for various stakeholders, including oil palm operators, government bodies, and biofertilizer manufacturers, to facilitate self-reporting, policy-making, and the optimization of biofertilizer application. This methodological combination aims to provide a tool for a macro-level GHG performance map across all oil palm plantations in Malaysia. To address this gap and support national GHG reduction goals, this study introduces a comprehensive GHG

accounting model that integrates an LCA-based integrated GHG quantification methodology with GIS modeling to develop a holistic assessment tool. This addresses a limitation in existing research, as previous studies assessing biofertilizers on oil palm crops have mostly focused on their effects on soil nutrient availability, crop yield, and soil microbial diversity (Ajeng et al., 2020; Kassim et al., 2024; Zainuddin et al., 2022). Thus, while research confirms the general agronomic benefits of biofertilizers, a gap remains in the quantitative, site-specific assessment of their climate change mitigation potential.

Methodologically, past studies have established the importance of spatial mapping and life cycle impacts in oil palm plantations, but they have not integrated these methodologies into a comprehensive GHG accounting model (see Table 1). For instance, while remote sensing and GIS have been utilized to map regional soil characteristics and land-use patterns, these spatial datasets are independent of any GHG analysis, barring changes in carbon stock from land use transformations (Srisunthon and Chawchai, 2020; Wan Mohd Jaafar et al., 2020; Zhao et al., 2022). Contrarily, conventional LCA has quantified the carbon footprint of oil production at plantations, but often relies on static emission factors without inputs taken from fields, or complex soil samples requiring specialized equipment that hinders widespread adoption for corporate accounting and national GHG inventory building (Acobta et al., 2023; Manning et al., 2019; Rajakal et al., 2024). This methodological separation creates a research gap by failing to account for the effects of localized soil and geographic variability on the reduction potential of sustainable agricultural materials such as biofertilizers. The resulting GHG-GIS methodology proposed in this study serves as a tool for developing transparent, region-specific decarbonization policies and improving environmental performance for manufacturers and operators.

Given that palm oil is the world's most produced vegetable oil, there's an urgent need to assess the potential of biofertilizers as a sustainable alternative for GHG reduction (CME Group, 2020). Furthermore, existing research has predominantly focused on the agronomic benefits of biofertilizers, such as soil nutrient availability and crop yield. While these studies are valuable, they fail to provide a site-specific assessment of climate change mitigation potential at scale. Previous GHG assessments of oil palm plantations have often overlooked the impact of fertilizer substitution or lacked the spatial analysis necessary for land-use change policy. By combining LCA-based quantification with GIS modeling, this study aims to advance existing methodologies by translating micro-level field interactions into a macro-level analysis of national emissions hotspots, while accounting for GHG reductions from

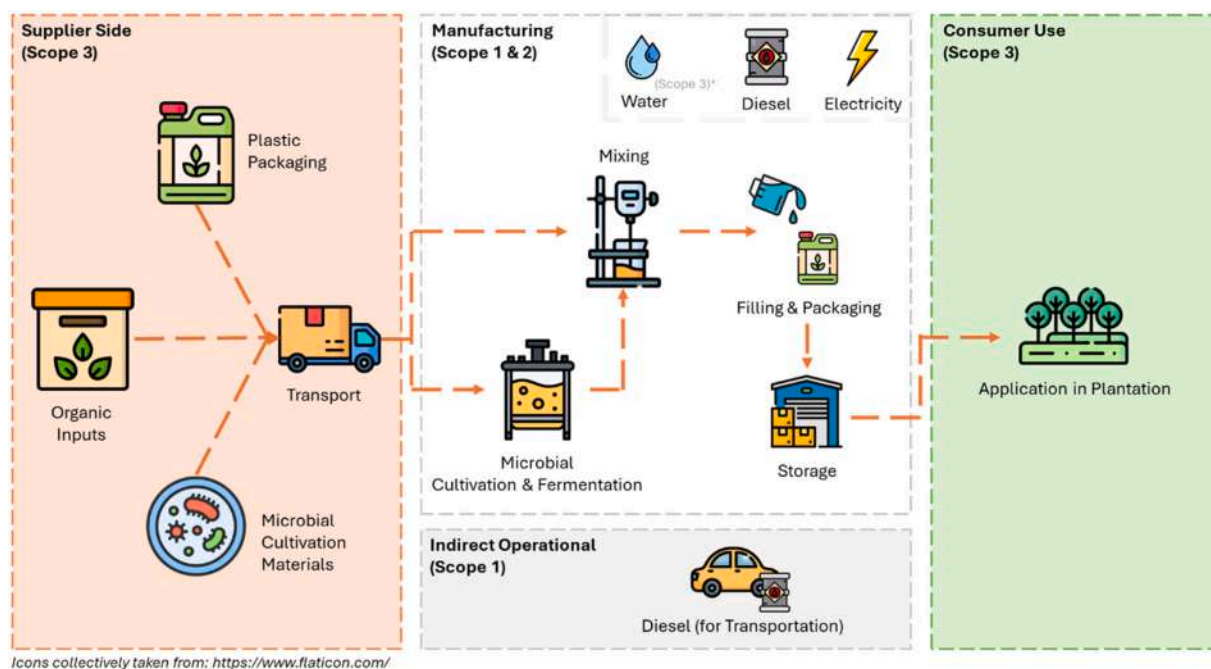


Fig. 1. The system boundary of the biofertilizer's life cycle. Indirect operational emissions refer to GHG emissions generated by business travel in company-owned vehicles. Water is classified as Scope 3 as it considers emissions from water treatment, as the water withdrawn was sourced from municipal sources.

manufacturing and from the application of biofertilizer products to oil palm crops. This system will track and visualize annual emissions and estimate the improvements resulting from new regulations and incentives. This approach is critical for national policy, as it provides the geospatial evidence needed to move from generic sustainability mandates to targeted, data-driven implementations. By developing an integrated methodology that benefits stakeholders, this research contributes to United Nations Sustainable Development Goals 2, 9, 12, and 13, which promote sustainable agriculture.

## 2. Materials and methods

### 2.1. Research approach

This study utilized an agricultural GHG accounting model developed in a previous research by Mulya et al. (2025), utilizing the GHG protocol to quantify upstream emissions and identify direct and indirect emissions, the Intergovernmental Panel on Climate Change (IPCC) guidelines to estimate GHG emissions stemming from crop and soil interactions, and LCA to standardize both emissions under a common system boundary and functional unit, allowing for direct comparison and combination of all emission sources.

### 2.2. LCA methodology

#### 2.2.1. Goal and scope definition

This research uses LCA, based on ISO 14040:2006 and ISO 14044:2006, integrated with the GHG Protocol as developed in a previous research, to measure the GHG emissions associated with the production of biofertilizer and its use in a palm plantation located in Peninsular Malaysia (Mulya et al., 2025). This integrated methodology utilized the GHG Protocol and LCA to quantify upstream processes, including accounting for an expanded scope typically observed in organizational GHG accounting, while utilizing the IPCC guidelines to quantify downstream emissions from the application of fertilizers in the fields, providing a comprehensive GHG accounting tool that streamlines and unifies several methodologies into a single GHG accounting tool for corporate use or other quantification requirements.

The assessed scope includes the extraction of raw materials, manufacturing, transportation, and the application of the biofertilizer in palm plantations, as shown in Fig. 1, alongside a functional unit of 1 ha of palm plantation. Processes downstream of oil palm cultivation, including the refining of fresh fruit bunches into palm oil in mills and the associated transportation, are not included in this study, which focuses on quantifying GHG emissions from fertilizers.

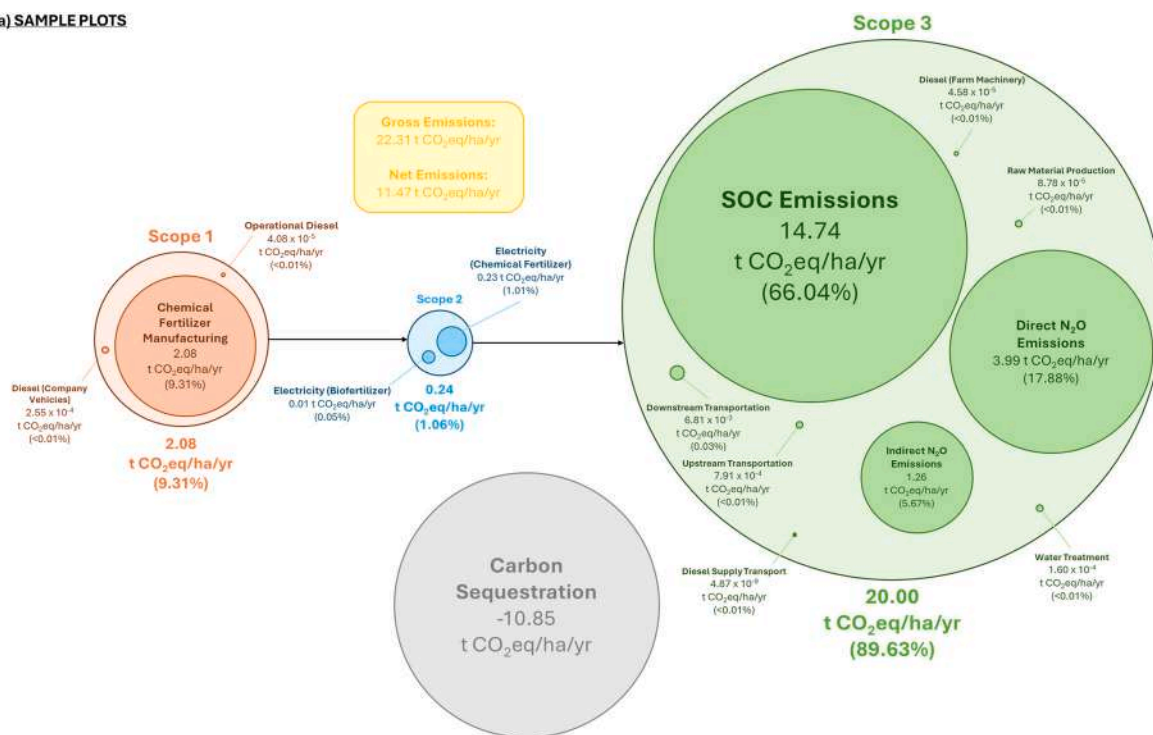
#### 2.2.2. Life cycle inventory

The primary data on biofertilizer manufacturing were obtained from the manufacturer's official internal records, including electricity bills issued by the national grid and signed supplier and procurement forms (full details provided in Table A2.2.1 in Appendix A). The biofertilizer uses cultivated microbes: *Bacillus subtilis*, *Bacillus amyloliquefaciens*, and *Bacillus mycoides*, for nitrogen fixation, phosphate solubilization, and potassium solubilization, respectively. Field data were obtained from a third-party oil palm plantation owner, where the collection was conducted in the presence of all relevant parties and analyzed by a certified third-party laboratory (see Table A2.2.2 in Appendix A). In the field study in Selangor, Malaysia, control plots used 100% chemical fertilizer, while sample plots used 55% less chemical fertilizer combined with 50 ml of biofertilizer per palm tree annually, containing a minimum of 1 million cfu/g of bacteria. In both plots, the chemical fertilizer composition consists of ammonium sulphate, muriate of potash, rock phosphate, and boron. Field sampling was conducted across 26 sites per plot, encompassing areas such as the weeding circle, ditch, and avenue, with a corresponding weighting factor applied based on land distribution. The palm trees were seven years old at the time of sampling and had not yet reached peak maturity or yield. Secondary data were used as substitutes when primary data were unavailable. All detailed downstream data, assumptions, soil sampling methodology, and validation methods are presented in Appendix A.

#### 2.2.3. Life cycle impact assessment

**2.2.3.1. Upstream emissions quantification.** GHG emissions associated with the acquisition, transport, and production of biofertilizers are assessed by multiplying activity data (e.g., electricity in kWh,

(a) SAMPLE PLOTS



(b) CONTROL PLOTS

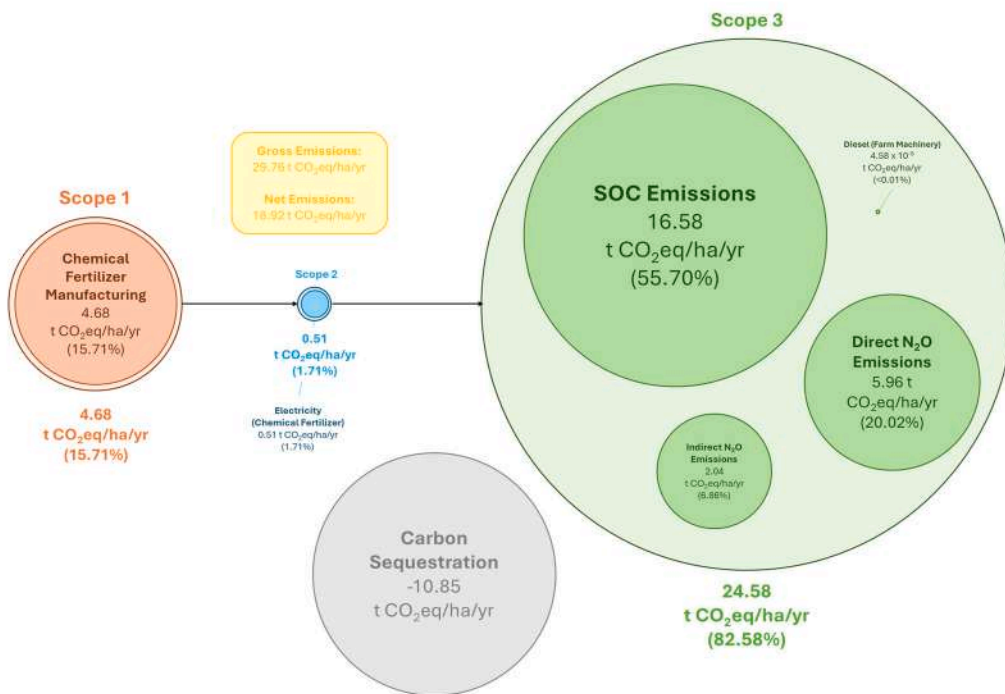


Fig. 2. Life cycle GHG performance of the (a) sample plots, and (b) control plots. Orange represents Scope 1 GHG sources, blue for Scope 2, and green for Scope 3. The bubble sizes represent the total emissions. This figure represents annual GHG emissions on a per-hectare basis and does not include land-use change emissions. There are fewer variables in the control, as the secondary source associated with the manufacturing of chemical fertilizers did not provide further breakdown to support the disaggregation.

transportation in tonne-kilometers) by the corresponding emission factors. Calculations are performed using Tier 1 and Tier 2 methodologies, following the suggested methodological tiers and types of emission factors outlined in Malaysia's climate change report submitted to the United Nations (NRECC, 2022).

2.2.3.2. *Downstream emissions quantifications.* Downstream emissions are calculated in accordance with the methodology developed in a previous study (Mulya et al., 2025). This methodology was based on Volume 4 of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which provides dedicated formulas

**Table 2**  
Monte Carlo simulation results for soil GHG emissions (n = 5000 iterations).

Emission Component	Plot	Mean	Median	SD	5th Percentile	95th Percentile	Probability ( $\Delta > 0$ )
CO <sub>2</sub> Flux ( $\Delta$ SOC)	Sample	14.79	14.75	1.68	12.23	17.65	0.81
	Control	16.61	16.59	0.85	15.30	18.08	
Direct N <sub>2</sub> O	Sample	4.00	3.996	0.25	3.59	4.43	1.00
	Control	5.99	5.98	0.25	5.60	6.40	
Indirect N <sub>2</sub> O	Sample	1.27	1.266	0.07	1.16	1.38	1.00
	Control	2.05	2.05	0.07	1.95	2.16	
Net soil emissions	Sample	20.05	20.00	1.97	17.06	23.41	0.983
	Control	24.65	24.63	1.04	23.02	26.43	

Mean, median, standard deviation (SD), 5th percentile, and 95th percentile are measured in t CO<sub>2</sub>eq/ha/yr.

for quantifying agricultural processes (see [Appendix B](#) for full details). This included accounting for SOC fluctuations and direct N<sub>2</sub>O emissions from crop residue, fertilizers, and mineralized soil carbon. Indirect N<sub>2</sub>O emissions from leachate and volatilization were also accounted for.

This study accounted for land-use change from virgin forests (i.e., deforestation) and carbon sequestration based on the quantity of biomass stored in the oil palm tree. The land use change was calculated based on the difference in the carbon stock from undisturbed forests with tree crop land use classification, in accordance with the findings by [Tiong et al. \(2018\)](#). Carbon sequestration was estimated using several secondary sources because data on the carbon content of aboveground and belowground biomass were unavailable. This includes the aboveground and belowground carbon biomass content in palm trees at the same age (i.e., seven years) and in the same state as the case study plantation to ensure consistency in carbon sequestration performance. Additionally, information on the average ratio of aboveground to belowground biomass for oil palm trees was obtained from averaged, verified DNDC model outputs.

#### 2.2.4. Life cycle interpretation

The information calculated from the life cycle impact assessment step was analyzed using a hotspot analysis to identify the areas of the biofertilizer's life cycle that contribute most to GHG emissions. This allows stakeholders from both the farm management and the biofertilizer manufacturing process to prioritize resources to the most polluting areas. The GHG emissions of the sample plots were also compared to identify areas in which biofertilizers outperform chemical fertilizers with respect to GHG and yield performance. A Monte Carlo uncertainty analysis (n = 5000) was also performed to propagate variability in key soil and fertilizer input parameters through the soil GHG emissions model and quantify the robustness of the comparative results between biofertilizer and chemical fertilizer treatments, with full details found in [Appendix A](#). A local sensitivity analysis was conducted to assess the model's robustness against variations in key input data, with the full details provided in [Appendix A \(Li et al., 2023\)](#). Additional statistical analysis of the impact of biofertilizers on TOC% and TN% was provided in [Appendix C](#). Lastly, a GIS analysis was conducted using QGIS version 3.34.15 to identify areas in Peninsular Malaysia that contribute most to GHG emissions, thereby helping to prioritize governmental efforts to decarbonize the oil palm sector. This study assumes a uniform GHG performance based on the GHG performance observed in the hotspot analysis. This assumption was necessary to ensure consistent, scalable assessment across a large area where detailed plantation data are unavailable. While this approach is necessary given the current systemic lack of detailed, regionally disaggregated plantation data, it introduces uncertainty by failing to account for the high degree of spatial heterogeneity in soil, climate, and farm management practices observed in localized studies. Detailed GIS modeling procedures, including data sources, projections, and function utilization, are provided in [Appendix D](#).

### 3. Results and discussion

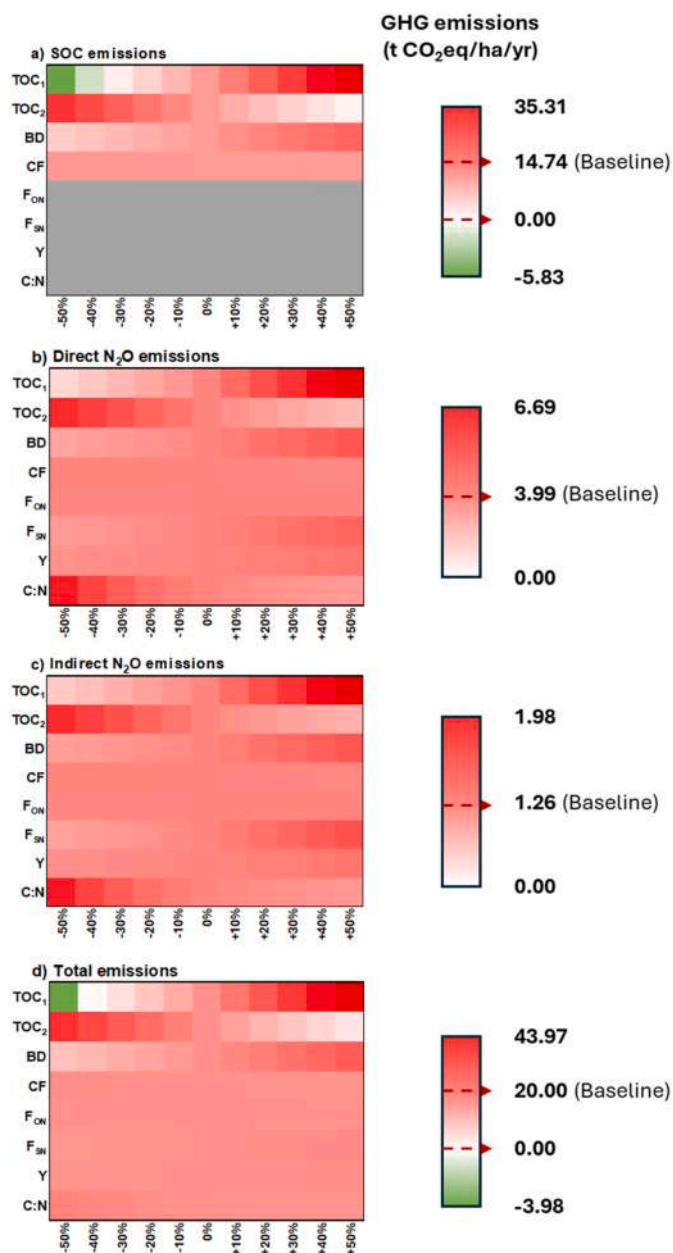
#### 3.1. Life cycle hotspot emissions

The application of biofertilizer to oil palm crops leads to a 39% reduction in annual GHG emissions, decreasing them from 18.92 to 11.47 t CO<sub>2</sub>eq/ha/yr (see [Fig. 2](#)). This value also considers carbon sequestration conducted by the oil palm crops at a rate of 10.85 t CO<sub>2</sub>eq/ha/yr (full details on the calculations can be found in [Appendix A](#)). While this study provided an estimate based on the region's average oil palm performance, future research should directly measure the carbon and biomass content of oil palm trees to provide a more accurate estimate of sequestered carbon. This reduction in biofertilizer substitution is primarily due to a decrease in Scope 3 emissions, which account for 90% of total life-cycle GHG emissions. The main contributor is improved SOC retention, which accounts for over 66% of emissions. Biofertilizer use reduced SOC emissions by 11% and also lowered direct and indirect N<sub>2</sub>O emissions by 34%. If GHG emissions from land-use change were considered, the conversion of virgin forests to oil palm plantations would result in an additional 708.31 t CO<sub>2</sub>eq/ha.

Several factors contribute to increased SOC. The use of biofertilizer increased crop yield by 19% in this case study. The increase in yield generates more root and decayed biomass that was left on the plantation, according to [Just et al. \(2024\)](#). Biofertilizers may also increase microbial activity, leading to a higher concentration of microbial necromass carbon and a faster humification rate of dead organic matter, as cited by previous literature ([Cui et al., 2025](#); [Tang et al., 2023](#)). Finally, the added nitrogen from nitrogen-fixing bacteria allows microbes to more efficiently convert carbon into biomass, promoting microbial growth and residue accumulation, which further contributes to higher SOC content, according to [Yang et al. \(2021\)](#).

Direct N<sub>2</sub>O emissions are influenced by several factors, including mineralized nitrogen, nitrogen from fertilizers, and crop residue. In this study, mineralized nitrogen is the largest contributor, accounting for 48% of these emissions, followed by chemical fertilizers (34%), crop residue (17%), and biofertilizers (0.21%). The significant impact of mineralized nitrogen is tied directly to fluctuations in SOC. As SOC is the largest source of life cycle GHG emissions, the associated nitrogen loss increases linearly with carbon loss. Emissions from chemical fertilizers and biofertilizers are directly proportional to the amount of nitrogen applied. The control plots, which used 2.25 times more chemical fertilizer, had a much higher N<sub>2</sub>O contribution from this source, contributing 51% of their total direct N<sub>2</sub>O emissions. By contrast, emissions from biofertilizers are negligible because of the small quantities used and their low nitrogen content. Similarly, crop residue emissions are low because of their inherently low nitrogen content (i.e., less than 0.01 kg N/kg dry matter), as indicated by the IPCC Guidelines ([Buendia et al., 2019](#)). The combined emissions of SOC, direct N<sub>2</sub>O, and indirect N<sub>2</sub>O account for 90% of the total life-cycle GHG emissions of the sample plots. The remaining Scope 3 emissions, which include those from farm machinery, logistics, raw material extraction, and other upstream processes (as shown in [Fig. 2](#)), account for 0.034%.

Scope 1 emissions account for 9.3% of the sample plots' GHG



**Fig. 3.** Local sensitivity analysis on the influence of variable field inputs on (a) SOC emissions; (b) direct  $N_2O$  emissions; (c) indirect  $N_2O$  emissions, and (d) total GHG emissions. Red indicates net emissions are generated; pink represents the baseline identified in the hotspot analysis; white represents net-zero GHG; green indicates that more GHG is absorbed than emitted; and gray indicates that the variable has no impact on that GHG type.  $TOC_1$  = initial total organic carbon;  $TOC_2$  = final total organic carbon; BD = bulk density; CF = coarse fraction;  $F_{ON}$  = nitrogen addition from organic inputs (i.e., biofertilizer);  $F_{SN}$  = nitrogen addition from synthetic fertilizer; Y = harvested fresh yield; C:N = C: N ratio.

emissions, primarily from chemical fertilizer manufacturing through processes like ammonia production (Walling and Vaneckhaute, 2020). The manufacturing of biofertilizer, which involves simple mixing and packaging, accounts for only 0.01% of the emissions generated by chemical fertilizer manufacturing. The raw materials for biofertilizer production contribute less than 0.01% to total life cycle GHG emissions, with their extraction accounting for 0.48% of upstream emissions. Scope 2 emissions, which are from electricity consumption, also show a significant difference. Chemical fertilizer production accounted for 1.0% of the total life cycle GHG emissions of the sample plots, whereas

biofertilizer manufacturing accounted for only 0.045%.

### 3.2. Uncertainty analysis

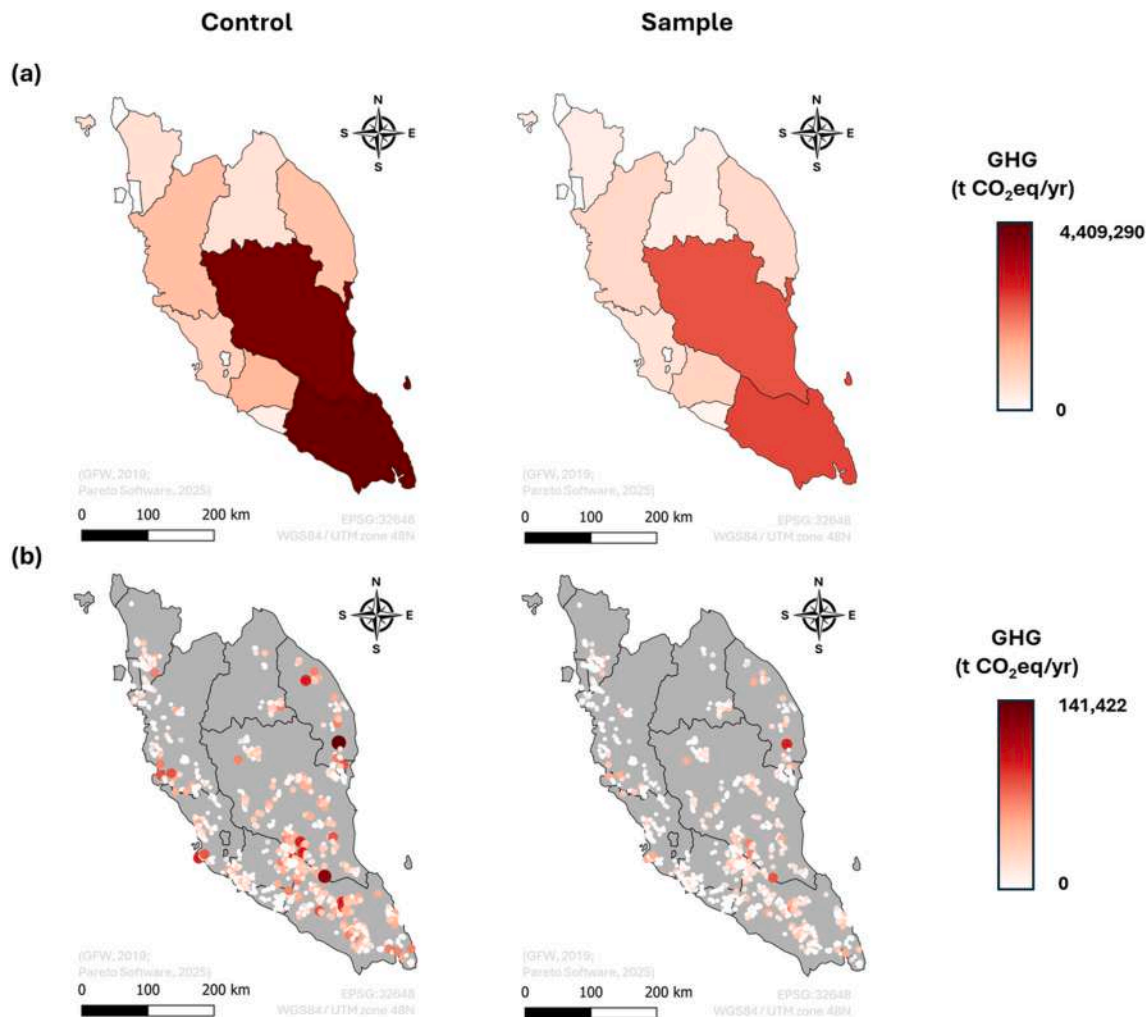
Monte Carlo simulations indicated that biofertilizer application consistently reduced net soil GHG emissions relative to chemical fertilizer, as shown in Table 2. Across 5000 iterations, the mean net soil emission for biofertilizer was 20.05 t  $CO_2eq/ha/yr$  compared with 24.65 t  $CO_2eq/ha/yr$  for the control, with median values and 5th–95th percentiles showing similar trends. Component-level analysis revealed that reductions were largest for direct field  $N_2O$  (mean  $\Delta = 1.99$  t  $CO_2eq/ha/yr$ ), followed by SOC-related emissions (mean  $\Delta = 1.83$  t  $CO_2eq/ha/yr$ ) and indirect  $N_2O$  (mean  $\Delta = 0.78$  t  $CO_2eq/ha/yr$ ). The probability of a positive reduction ( $\Delta > 0$ ) exceeded 98% for net emissions and was  $\geq 80\%$  for each individual component, with the 5th percentile of the net emission difference remaining above zero (0.81 t  $CO_2eq/ha/yr$ ), confirming the robustness of the mitigation effect. These results demonstrate that biofertilizer can reliably reduce soil GHG emissions, with the largest contribution arising from reductions in direct  $N_2O$  emissions.

### 3.3. Sensitivity analysis

The sensitivity analysis tests variables that have the greatest potential to alter the GHG output of the assessment. As field emissions under Scope 3 contribute 90% of the life cycle GHG emissions from the sample plots, only variables related to these emissions are assessed. As shown in Fig. 3(a), SOC emissions are influenced by only four variables: total organic carbon, bulk density, sampling depth, and coarse fraction. While sampling depth affects the final SOC output, the sampling procedure for this variable is commonly standardized (e.g., 30 cm), depending on the targeted soil layer, and is not assessed in this study. Among these variables, changes in the TOC% have the most significant impact in altering the GHG output of the crop between 2.64 and 4.11 t  $CO_2eq/ha/yr$  for each 10% change in the initial and final TOC% values, respectively, as this is the primary indicator of the concentration of the carbon stock within the soil. The GHG output of the sample plot can achieve net-zero GHG status for field emissions when the difference in carbon stock ( $\Delta TOC\%$ ) is zero, which occurs when  $TOC_1$  decreases by 36% or when  $TOC_2$  increases by 56%. When  $TOC_1$  decreases beyond 36%, the oil palm plantation sequesters more carbon than it emits, highlighted by the green cells in Fig. 3(a).

Variables affecting direct  $N_2O$  emissions are primarily driven by changes in TOC% and C:N ratio (see Fig. 3(b)), as mineralized nitrogen is calculated as a quotient of these two variables, and nitrogen inputs from chemical fertilizers ( $F_{SN}$ ). Given the significance of TOC% on SOC, slight variations in TOC% also have a considerable impact on direct  $N_2O$  emissions, with a 0.54 t  $CO_2eq/ha/yr$  increase per 10% change. This is followed by bulk density, which fluctuates by 0.19 t  $CO_2eq/ha/yr$ , and the C:N ratio, at 0.18 t  $CO_2eq/ha/yr$ , both of which are variables used to calculate SOC (i.e., carbon stock change). The impact of direct fertilization is smaller at 0.13 t  $CO_2eq/ha/yr$ , but it is the largest among the non-SOC variables contributing to direct  $N_2O$  emissions. However, as direct nitrogen fertilizer application can be easily influenced by farm management practices, this variable poses a higher risk for  $N_2O$ -related GHG emissions. Crop residue, estimated from the fresh yield quantity, contributes a smaller share at 0.07 t  $CO_2eq/ha/yr$  due to the low nitrogen content associated with the crop. Biofertilizer application has a negligible impact on the variation (i.e.,  $8.54 \times 10^{-4}$  t  $CO_2eq/ha/yr$ ) owing to its small dosage.

Indirect  $N_2O$  emissions are derived from leachate and the volatilization of  $N_2O$ . Leachate-related  $N_2O$  emissions are attributed to all four emission derivatives found from direct  $N_2O$  emissions (i.e., mineralized nitrogen, crop residue, chemical fertilizer, and organic amendments or biofertilizers). The most sensitive variable, as shown in Fig. 3(c), is the SOC-related variables and chemical fertilizer inputs. This follows a trend



**Fig. 4.** GHG performance of RSPO-certified oil palm plantations in Peninsular Malaysia, where the left column represents chemical fertilizer use and the right column represents biofertilizer application. The figures show the GHG performance by (a) state, and (b) individual plantations.

similar to that of direct N<sub>2</sub>O emissions, except for the more pronounced impact of chemical fertilizers, as indicated by the greater color contrast in Fig. 3(c). This can be traced to leachate generation, which accounts for 83% of indirect N<sub>2</sub>O emissions, estimated from the total nitrogen (kg N/yr). According to Nevison et al. (2000), higher nitrogen concentrations will increase the saturation of aquatic ecosystems with nitrogen runoff, thereby accelerating nitrification and denitrification by aquatic microbes. Nevertheless, the impacts of SOC-related emissions are greater when nitrogen inputs are derived from mineralized nitrogen. This is evidenced by a 10% change in TOC<sub>1</sub>, corresponding to a change of 0.14 tCO<sub>2</sub>eq/ha/yr, compared with chemical fertilizer inputs, which yield a change of 0.06 tCO<sub>2</sub>eq/ha/yr.

When considering all GHG emissions (see Fig. 3(d)), changes in variables affecting SOC have the greatest impact. 10% variations in TOC<sub>1</sub> and TOC<sub>2</sub> lead to fluctuations of 4.80 and 3.08 tCO<sub>2</sub>eq/ha/yr, respectively. This is followed by bulk density, which causes fluctuations of 1.72 tCO<sub>2</sub>eq/ha/yr, and a C:N ratio of 0.22 t CO<sub>2</sub>eq/ha/yr. This disparity further shows the significance of SOC-related input variables in determining the total GHG performance of the oil palm plantation. By extension, C:N ratio relies on SOC fluctuations to estimate the mineralized nitrogen content. Although chemical fertilizers are significant contributors to direct and indirect N<sub>2</sub>O emissions, their impact on the total GHG emissions only represents 4.0% (i.e., 0.19 tCO<sub>2</sub>eq/ha/yr) of the impact from altering TOC<sub>1</sub>. This is also supported by the hotspot analysis, which shows that the combined emissions from direct and

indirect N<sub>2</sub>O account for 19% of the emissions attributable to SOC fluctuations.

### 3.4. GIS analysis

Fig. 4(a) illustrates the change in GHG emissions at the state level, where the most significant reductions from biofertilizer addition are observed in the states of Johor and Pahang, with decreases of 1,734,742 and 1,651,491 tCO<sub>2</sub>eq/yr, respectively. This represents a 13% and 12% reduction in GHG emissions for each state, the highest among all states in Peninsular Malaysia. It should be noted that the results presented assume a uniform GHG performance based on the interpolation of one plantation. The actual GHG reduction value will require the participation of numerous plantation owners and relevant stakeholders to build a more robust and comprehensive national GHG inventory. These findings highlight that targeted policies for Johor and Pahang have the largest impact on reducing national GHG emissions. Unlike traditional LCA, which provides a static emission value, the GIS-integrated methodology enables the government to allocate resources and ensure sufficient resources can be allocated for incentives such as tax breaks, green financing, and other benefits to encourage biofertilizer use. Following a successful transition, this implementation may be replicated in other states until sufficient resources are available to support a comprehensive GHG reduction policy. If positive incentives prove insufficient, regulatory requirements could be developed to drive decarbonization, either

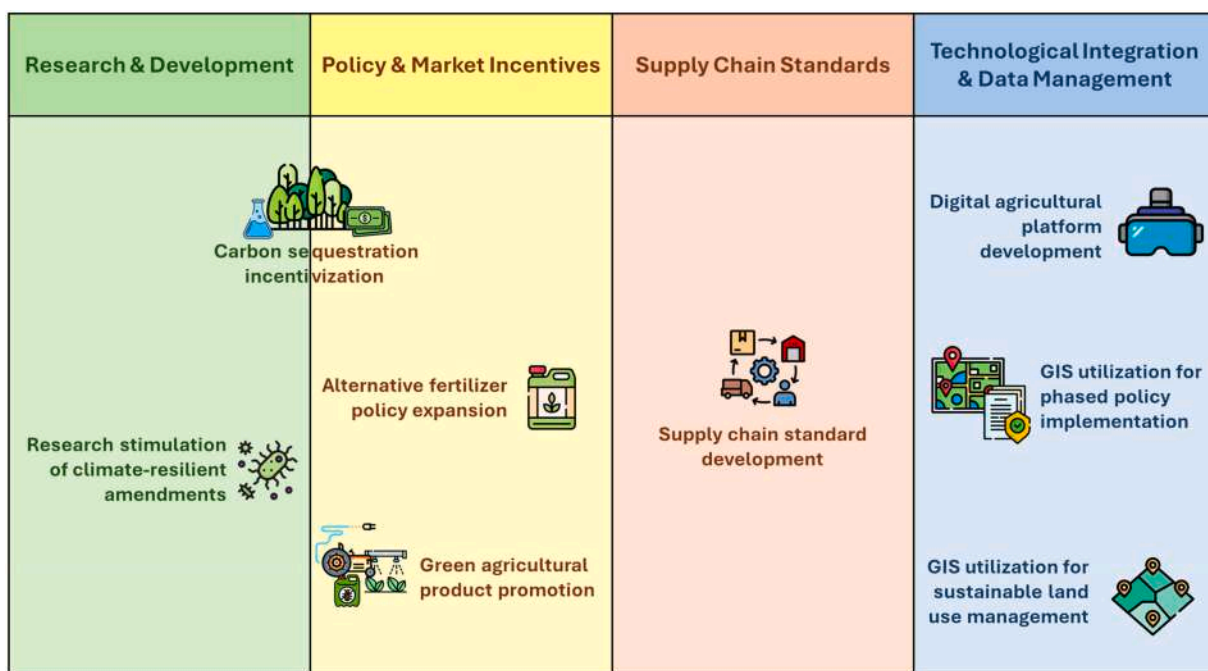


Fig. 5. Summary of various policy recommendations on climate change for oil palm plantations and their greater supply chain.

by targeting the highest-polluting states or by implementing pilot programs in smaller states.

Fig. 4(b) highlights the GHG emissions from individual RSPO-certified oil palm plantations in Peninsular Malaysia. While policy-making at the level of individual entities may not be practical, this approach allows the government to track progress and identify areas with unusually high emissions for further investigation. A government-run GIS platform could enable plantations to upload their data, allowing the platform to estimate each organization's GHG emissions. This would increase transparency, thereby encouraging a market-driven approach in which government bodies, investors, and other stakeholders can advocate for more sustainable, low-carbon operations. Government agencies such as the Department of the Environment could use GIS-based tracking to identify non-compliant entities and investigate areas with high GHG emissions. The government could also use GIS to prepare plantations for carbon taxation by creating a transparent GHG reporting platform. This level of transparency would enable investors to benchmark organizations' sustainability performance directly, leading to more informed decisions. This is particularly relevant in Malaysia, where green financing initiatives and ESG-focused stock indices already exist to encourage sustainable practices (FTSE Russell, 2023; SC, 2024).

While this study focuses on oil palm in Peninsular Malaysia, the modular nature of the LCA-GIS framework enables its application in other regions. A current limitation is the use of uniform emission factors due to data gaps in climate and soil variability. However, the current GIS projection serves as a viable simplified model for national scaling. By mandating the use of this GHG quantification tool, authorities can require plantation owners to report site-specific performance within their boundaries. Since the methodology relies on output-related indicators (e.g., TOC% and TN%) that inherently reflect local variability, it offers a cost-effective path to national GHG mapping through owner participation. As quantitative models for soil-climate interactions mature to enable nationwide simulation with less intensive data requirements, the system can transition to a centralized estimation approach that requires only management data (e.g., fertilization rates and residue management practices) as inputs. While remote sensing and meteorological data can bridge gaps in geographical and climatic variability, high-resolution soil mapping, including TOC%, TN%, and bulk

density, may require continued stakeholder participation to remain economically feasible.

### 3.5. Malaysian oil palm GHG policy implications

The Malaysian government has implemented numerous policies that tie agricultural performance with climate change considerations (Phuang et al., 2021). The full details of Malaysia's existing agricultural climate policies are provided in Appendix E. To further improve GHG-reducing initiatives and align the country with its GHG targets, several policy recommendations are provided for further consideration based on the results observed in this study and are summarized in Fig. 5. The list of policy recommendations is shown in Table 3.

Beyond the regulatory framework and policy implications, the transition to widespread biofertilizer use entails socioeconomic trade-offs that may affect its practical feasibility. While biofertilizers can reduce GHG intensities, their adoption is heavily influenced by the trade-off between potential additional costs and yield gains, especially given the variety of microbes used in biofertilizer products. For instance, the initial price premium of high-quality bio-inoculants compared to subsidized synthetic nitrogen is a variable contributing to hesitancy of its application, alongside its uncommon and non-standardized use, with minimal disseminated technical knowledge on its application among the farmers, which necessitates further investment in education (Mulugeta et al., 2024; Samanta et al., 2025). However, the long-term economic viability is supported by the potential to reduce chemical input costs and enhance soil nutrient-use efficiency, thereby safeguarding yields against climate-driven soil degradation (Mahmud et al., 2021).

Furthermore, scaling up the use of biofertilizers in oil palm cultivation faces significant logistical challenges. The efficacy of these products is dependent on the survival of live microbial consortia, which are often sensitive to the high temperatures and prolonged storage conditions typical of tropical plantation logistics (Seenivasagan and Babalola, 2021). Without specialized stabilized delivery systems or cold-chain infrastructure, the risk of bio-efficacy loss remains a deterrent for large-scale estates (Packebush et al., 2022).

**Table 3**  
Summary of policy recommendations to streamline and decarbonize oil palm and agricultural GHG emissions.

Policy	Description
Carbon sequestration incentivization	Develop incentives targeting farm management and biofertilizer suppliers that focus on carbon retention, as TOC% fluctuations have the greatest impact on GHG emissions and can contribute to carbon sequestration.
Alternative fertilizer policy expansion	Expand the Nationally Determined Contribution Roadmap and Action Plan (NDC RAP) policy of increasing the share of organic fertilizer use by 1% annually to include other green products, such as biofertilizers. This offers greater flexibility in using sustainable fertilizers that may be better suited to the farm or plantation's soil and crop conditions.
Green agricultural product promotion	Explore the GHG performance of other green products, such as biopesticides. As biofertilizer application reduced GHG life cycle emissions from oil palm plantations by 39%, substituting other traditionally polluting agricultural products with sustainable alternatives may further help align the sector with national decarbonization targets.
GIS utilization for phased policy implementation	Use GIS mapping to enable a phased transition period from a geographical perspective. Incentives or regulations should be implemented first in high-polluting regions (e.g., Johor and Pahang), as these states have the greatest potential to reduce national GHG emissions. GIS imaging also provides an additional layer of transparency for stakeholders and investors.
GIS utilization for sustainable land use management	Utilize GIS to track progress toward the mandated 6.5-million-hectare oil palm plantation limit. GIS can conduct scenario analysis of land-use change emission trade-offs to identify suitable non-forest land categories (e.g., urban areas) for plantation expansion that reduce GHG emissions or improve climate resilience, while meeting yield productivity benchmarks, as in <a href="#">Fu et al. (2017)</a> .
Digital agricultural platform development	Incentivize a unified digital agriculture platform that integrates IoT sensors and low-altitude monitoring technologies (e.g., drones) to collect real-time, site-specific data ( <a href="#">Shahab et al., 2024</a> ; <a href="#">Singh et al., 2025</a> ). This data can be used to create a digital twin for predictive modeling, to optimize fertilizer use, and to accurately account for GHG emissions ( <a href="#">Wang, 2024</a> ).
Supply chain standard development	Require the use of environmental assessment forms during supplier assessments or procurement processes, in addition to the existing MSPO supply chain traceability requirement. This measure is critical because the hotspot analysis indicates that biofertilizer manufacturing accounts for only 0.01% of emissions from chemical fertilizer manufacturing, highlighting the potential for Scope 3 emissions reduction through substitution.
Research stimulation of climate-resilient amendments	Stimulate research on combinations of microbes that enhance crop climate resilience, such as those that improve soil structure and water retention. Although these microbes may have minimal impact on GHG reduction, they are essential for maintaining crop productivity amid increasing physical climate risks (e.g., drought or flooding).

#### 4. Conclusions

This study developed an integrated GIS-GHG accounting methodology that provides a platform for greater transparency and supports the implementation of national decarbonization policies, while identifying the GHG performance of biofertilizer application on oil palm

plantations. The findings of this research were then used to compare the performance of biofertilizer application with chemical fertilizers to inform policymaking recommendations. The inclusion of biofertilizers in oil palm plantation fertilization has been shown to reduce GHG emissions by 39%, increase yield by 19%, and reduce chemical fertilizer use by 55%.

The hotspot analysis revealed that Scope 3 emissions account for nearly 90% of life cycle GHG emissions from the perspective of fertilizer manufacturers. Among the benefits of biofertilizers, improved carbon retention resulted in an 11% reduction in life cycle GHG emissions. The manufacturing processes (Scope 1 and 2) for biofertilizers account for only 0.045% of emissions, compared with approximately 10% for chemical fertilizers.

The GIS analysis revealed that geographically targeted policies could maximize the impact of decarbonization efforts by prioritizing high-potential regions such as Johor and Pahang. This proposed platform offers a transparent, market-driven mechanism for stakeholders, including plantation operators and investors, to benchmark sustainability performance.

Future research could enhance this model by moving toward site-specific GHG performance factors by utilizing regionalized soil and climate datasets and integrating long-term field data to observe spatial fluctuations in carbon sequestration. Future iterations should incorporate the sigmoid growth curve modeling and disaggregated GHG scope reporting established by [Mulya et al. \(2025\)](#) to provide temporal projections of biofertilizer adoption. Additionally, adopting the patent-based prospective framework proposed by [Spreafico et al. \(2025\)](#) would allow the model to anticipate technological maturity and industrial scale-up scenarios for emerging microbial formulations currently in the research and development phase.

While this study substitutes half of the chemical fertilizers, the studied biofertilizer product observed the highest yield using a 30% fertilizer substitution ([Ajeng et al., 2020](#)). Future studies should conduct a trade-off analysis of fertilizer compositions to identify the optimal balance between GHG emissions and economic performance, thereby advancing the understanding and adoption of biofertilizers. Additionally, an alternative plot should be tested that follows the chemical fertilizer reduction of the sample plot, without the biofertilizer, to ascertain the impact of the biofertilizer on N<sub>2</sub>O reduction.

Finally, the assessment scope should be expanded to include all MSPO-certified plantations and leverage digital agricultural platforms, such as IoT sensors and drone-assisted monitoring, to provide high-resolution data on microbial interactions and their effects on GHG performance. Alternatively, as mapping soil variability on a national scale can be costly and time-consuming, the government can involve the participation of individual plantation owners to quantify and determine their plantations' emission factors, allowing individuals to upload their emission factors into a collective GIS platform managed by the government, as an alternate solution to manage variability.

#### CRedit authorship contribution statement

**Kyle Sebastian Mulya:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Malvin Ma:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Jian Ping Tan:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Conceptualization. **Kun Sang:** Writing – review & editing, Visualization, Validation, Methodology. **Siaw Ping Yeat:** Writing – review & editing, Resources, Funding acquisition. **Chia Ning Clara Yeat:** Writing – review & editing, Resources, Funding acquisition. **Kok Sin Woon:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

## Declaration of competing interest

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

## Acknowledgements

This work is supported by IBG Manufacturing Sdn Bhd (EENG/0049), Guangdong Provincial Project (2024QN11L096), Guangdong Provincial Key Lab of Integrated Communication, Sensing and Computation for Ubiquitous Internet of Things through the research grant (No. 2023B1212010007), the Hong Kong University of Science and Technology (Guangzhou) for the start-up grant (G0101000268), and Xiamen University Malaysia for the Xiamen University Malaysia Research Fund (XMUMRF/2023-C11/IENG/0057, IENG/0069, and XMUMRF/2024-C14/IENG/0075).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.129559>.

## Data availability

The authors do not have permission to share data.

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