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Research article

Toward carbon mitigation resiliency in the agriculture sector: An integrated LCA-GHG protocol-IPCC guidelines framework for biofertilizer application in paddy field

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ABSTRACT

The agriculture sector contributes 22 % of global greenhouse gas emissions, with fertilizers accounting for 10.6 % of that portion. To reduce this, biofertilizers can be employed due to their lower emissions throughout production and application. Past studies have quantified either the upstream or downstream emissions of biofertilizers, yet the direct and indirect emissions from a life cycle perspective remain unclear. Additionally, most studies did not consider local conditions such as soil organic carbon and soil nitrogen content, leading to inaccuracies in the calculated greenhouse gas (GHG) emissions. This study solves this gap by developing a new integrated methodology using the life cycle assessment, IPCC guidelines, and GHG protocol to quantify the life cycle greenhouse gases of a paddy biofertilizer product from Malaysia. Most GHG emissions are derived from Scope 3 emissions, contributing to 16.69 t CO_2eq/ha/yr or 87.33 % of the life cycle GHG emissions. Of this figure, methane alone contributes 84.48 % of all Scope 3 GHG emissions. Scope 1 emissions contribute to 2.08 t CO_2eq/ha/yr or 10.84 %, and Scope 2 emissions amount to 0.35 t CO_2eq/ha/yr or 1.83 % of the life cycle GHG emissions. Since the fertilizer ratios contain 70 % chemical fertilizer and 30 % biofertilizer, the upstream emissions of biofertilizers only contribute to 5.43 % of the total Scope 1 emissions, equal to 0.69 % of the life cycle GHG emissions. The sensitivity analysis revealed that fluctuations in total organic carbon content significantly impact on GHG emissions, potentially causing fluctuations of 100 t CO_2eq/yr. A scenario analysis suggests that a nationwide phase-out of chemical fertilizers could lead to a maximum reduction of 10.12 % in agricultural GHG emissions by 2030. This study contributes to the United Nations Sustainable Development Goal (UN SDG) 13 by providing a comprehensive assessment of biofertilizer life cycle GHG emissions, highlighting their potential to reduce GHG emissions and supporting the development of low-carbon national policies.

Abbreviations: BAU, Business-as-Usual; GHG, Greenhouse Gases; GDP, Gross Domestic Product; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; LED, Light Emitting Diode; MYR, Malaysian Ringgit; ROA, Rate of Organic Amendment Application; SOC, Soil Organic Carbon; TOC%, Total Organic Carbon; USD, United States Dollar.

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1. Introduction

Climate change is an increasingly urgent issue where temperature rises of 1.5 °C would cause irreversible damage to ecosystems and the environment worldwide (Masson-Delmotte et al., 2019; Woon et al., 2023). The agriculture sector alone contributes 22 % of global anthropogenic greenhouse gas (GHG) emissions (OECD, 2022). Rice is the third most GHG-intensive crop among these crops, contributing to 11 % of global agricultural GHG (Costa et al., 2022). Rice is one of the world's largest cereal crops and is especially prominent in Asia (OECD & FAO, 2021), serving as the primary food staple in countries such as Malaysia, where the government has implemented numerous policies to achieve self-sufficiency in paddy production (Firdaus et al., 2020).

Chemical fertilizers boost crop production to fulfill the increasing demand for rice (Naher et al., 2019). Chemical fertilizers contribute 10.6 % of agricultural emissions and 2.1 % of global GHG emissions (Menegat et al., 2022). Alternative sustainable fertilizers, such as biofertilizers, are needed to reduce GHG emissions while maintaining crop yields (Kumar et al., 2022; Pereira et al., 2023). Biofertilizers utilize microbes to accelerate the mineralization of nutrients in the soil, increasing nutrient availability while minimizing emissions (Daniel et al., 2022). Its benefits have been cited by studies like Rose et al. (2014), which found that 52 % of chemical fertilizers can be replaced with biofertilizers while retaining the yield of rice crops. Hu et al. (2024) utilized six biofertilizers with different bacteria and discovered that yield can increase by up to 26 %, while some bacterial strains may decrease GHG emissions by up to 14 %. In paddy fields, biofertilizers can contain oxygen-releasing components like azolla and blue-green algae that reduce GHG emissions by oxygenizing methane into carbon dioxide, which has a lower global warming impact (Qian et al., 2023). Certain microbes, such as cyanobacteria, have also been cited to reduce N_2O and CH_4 emissions by fixing nitrogen into the soil and promoting the propagation of methanotrophic bacteria (Malav et al., 2020; Pérez et al., 2023).

Despite the benefits of biofertilizers discovered through research, there is a need for incentives to push the implementation of biofertilizers into the industry. One incentive is the requirement that companies list their sustainability measures in financial instruments, such as stock indices. Thus, a global standardized methodology applicable to the industry is required. One widely applied framework is the GHG protocol, used by 92 % of Fortune 500 companies (Chan and Heung, 2022). The GHG protocol quantifies the emissions of an organization and is used for carbon accounting for regulatory compliance, such as the European Union's Emissions Trading System that fines companies exceeding the GHG limit and Singapore's Carbon Tax (Addy and Gan, 2022; EC, 2016). In Malaysia, the implementation of carbon regulations is in its infancy, with current regulations only enforcing GHG reporting for companies of certain sizes or issuing fines for non-compliance (MOF, 2024). It includes processes from material acquisition and manufacturing until the product's end-of-life before categorizing each emission under Scope 1, 2, or 3 (Bhatia et al., 2011). Scope 1 emissions are direct emissions from activities such as byproducts from chemical reactions or on-site fuel combustion; Scope 2 emissions are indirect emissions derived from off-site electricity; Scope 3 emissions stem from other indirect emissions such as employee commute or waste management (Barrow et al., 2013). Despite its widespread use, the GHG protocol does not outline specific procedures for quantifying product or process-based life cycle GHG emissions and requires other complementary methodologies. Integrating the GHG protocol into paddy cultivation helps farm operators identify emission hotspots within their direct control, such as methane emissions from paddy fields, and prioritize their resources towards the reduction of direct emissions. Scope 3 emissions should be de-prioritized as this responsibility is shouldered by their upstream supply chains. As upstream suppliers reduce their Scope 1 emissions to ensure compliance with financial and regulatory bodies, the Scope 3 emissions of farm operators will gradually decrease with time, with minimal investment. Thus, the identification of emissions within the farm operator's control will contribute to the decarbonization of the farm with efficient allocation of resources.

Life Cycle Assessment (LCA) and Intergovernmental Panel on Climate Change (IPCC) Guidelines can be utilized to overcome the limitations of the GHG protocol. LCA is a methodology that quantifies the emissions of a product through its life cycle and is divided into four phases (Mulya et al., 2022). The first phase, goal and scope definition, defines the study's system boundary, functional unit, geographical scope, and timeframe. The second phase is the life cycle inventory, where data for emissions quantification is compiled and verified. Next is the life cycle impact assessment, where data inputs are processed into emissions. Lastly, the life cycle interpretation phase analyzes the data through various analyses, such as hotspot, sensitivity, and scenario analysis. While LCA is a robust methodology, it does not categorize emissions into direct and indirect emissions, making it challenging to improve carbon reduction processes from an organization's perspective, as certain emission hotspots may be outside the organizational boundary. The lack of localized emission factors further contributes to inaccuracies when quantifying downstream field emissions, considering the high variation in geographic, climatic, and pedologic conditions. While the IPCC guidelines provide default emission factors for several variables, the guidelines also provide formulas that can be used to calculate emissions using readily available local data. This data is often collected to meet the compliance requirements of the relevant regulatory agencies. Thus, the IPCC is utilized as it provides models to quantify downstream emissions by considering field data such as fertilizer quantity and nitrogen composition, as well as soil variables such as the soil's C:N ratio, bulk density, and crop residue (IPCC, 2019). The acquired field data can be used to ensure regulatory compliance and monitor crop conditions and performance to maximize yields, such as ensuring that certain harmful substances do not exceed the stipulated environmental limit while simultaneously assessing areas of the cropland that require additional products to nurture crop growth. The integration of all three methodologies has been done by Sruthi et al. (2024), but the study lacked application in a case study to verify the practicality and potential uncertainties associated with the model, which this study aims to resolve.

Past studies have utilized direct sampling methodologies in the agricultural sector. Sapkota et al. (2017) observed the effects of tillage, residue management, and green gram integration on the rice-wheat systems, assessing the global warming potential, agronomic productivity, and economic profitability. Shang et al. (2021) and Xue et al. (2014) investigated the impacts of various tillage practices in double-cropping paddy systems on the resulting GHG emissions. Alam et al. (2019) studied the potential of conventional puddled paddy transplanting with non-puddled transplanting for conservation agriculture using LCA and several emission factors as secondary sources but still relied on the chamber method as the primary sampling method for accounting for field GHG. These studies utilized direct sampling methods such as gas chromatography and chamber methods. While these direct methodologies can provide more accurate readings over methodologies like the IPCC Guidelines, they require additional processes with equipment that are not commonly owned by corporations. Larger organizations may resist implementing such measures if they are required to sample thousands of hectares of croplands, hindering the widespread implementation of the carbon accounting model. Thus, the integrated methodology proposed in this study offers a less resource-intensive alternative for agricultural carbon accounting as the models used in this research utilize readily accessible data and pre-established models that are sufficiently robust for national and organizational-level implementation.

Several studies have quantified biofertilizer emissions. Pereira et al. (2023), Alengebawy et al. (2022), and de Souza et al. (2019) utilized the LCA methodology to quantify the emissions associated with biofertilizer production and application. These studies focus on microalgae and waste-derived biofertilizers, which have different life cycle GHG emissions compared to biofertilizers containing cultivated bacteria (Walling and Vaneeckhaute, 2020). Zhou et al. (2021) and Castro et al. (2020) quantified the emissions related to biofertilizer manufacturing without considering field emissions. Havukainen et al. (2018) utilized LCA and the GHG protocol to quantify and compare the manufacturing emissions of biofertilizers with chemical fertilizers. They did not disaggregate the results by the GHG Scopes. Styles et al. (2018) and Diacono et al. (2019) quantified nitrous oxide emissions from biofertilizer applications using the IPCC guidelines in addition to other processes contributing to GHGs. Only two studies utilized IPCC and GHG protocol to quantify biofertilizer GHG emissions (see Table 1).

This study improves on previous advancements on agricultural GHG modeling, accounting for all three primary emission sources (i.e., CO_2, N_2O, and CH_4). These primary emission sources include CO_2 equivalents for upstream processes such as energy consumption (i.e., fuel and electricity), downstream processes including fuel combustion for farm machinery and CO_2 generated from soil organic carbon (SOC) or carbon stock changes, N_2O emissions from fertilization, crop residue, nitrogen volatilization and runoff, and CH_4 emissions generated from flooded paddy fields. Among the assessed GHGs in past literature, studies integrating CO_2 from SOC are rare. For instance, Abdul Rahman et al. (2019) conducted an LCA of several fertilizers, evaluating their GHG emissions alongside N_2O and CH_4 released during paddy cultivation. They also

Table 1
Literature review of past articles quantifying biofertilizer emissions and the methodologies used.

Author	Study location	Biofertilizer type	Crop	Included methodologies			Objective(s)	GHG-related findings & research gap
				LCA	GHG protocol	IPCC		
Pereira et al. (2023)	Brazil	Microalgae	Corn	✓			- To assess the environmental performance of microalgae biomass biofertilizer and urea mix of various ratios.	15 % biofertilizer substitution produces the highest crop productivity and reduces GHG emissions by approximately 30 %. Emissions mainly stem from NaOH consumption for microalgae harvesting.
Alengebawy et al. (2022)	China	Bacteria (digestate)	Paddy	✓			- To evaluate four raw biogas digestate treatment techniques for biofertilizer production.	Heating is the largest contributor to digestate-sourced biofertilizers. Biofertilizer use resulted in avoided emissions compared to nitrogen fertilizers.
de Souza et al. (2019)	Brazil	Microalgae	Millet	✓			- To evaluate and compare the life cycle impacts of microalgae biomass fertilizer to urea fertilizer.	The focus of the study (i.e., nitrogen recovery) led to the selection of 1 kg of N from the microalgae biomass as the functional unit, which may cause uneven environmental impact comparison against urea fertilizers that are rich in N-content.
Styles et al. (2018)	Sweden	Bacteria (digestate)	Not Specified	✓		✓	- To assess the nutrient use efficiency of liquid from food waste digestate with digestate biofertilizer extracted from liquid digestate.	Production data is taken from a pilot scale plant, whereas field application data are formulated through scenarios and secondary data, excluding impacts from farm machinery and upgrading machinery.
Diacono et al. (2019)	Italy	Bacteria (digestate)	Zucchini, lettuce			✓	- To achieve a circular economy by producing biofertilizers from agricultural waste products, co-products, and byproducts. - To test the environmental sustainability of co-composting procedures. - To evaluate the agronomic performance of biofertilizers.	Quantification for upstream and downstream emissions is done separately with differing functional units, making quantifying the product's life cycle difficult.
Havukainen et al. (2018)	Finland	Bacteria (compost)	None	✓	✓		- To estimate the carbon footprint of phosphorous and nitrogen in organic (biofertilizers) fertilizers and compare it with chemical fertilizers.	The study is limited to upstream emissions. The emissions are not disaggregated by GHG Scopes, and organizational emissions (e.g., personal vehicles) are not considered.
Zhou et al. (2021)	China	Bacteria (waste)	None	✓			- To create a life cycle inventory of compound microbial fertilizer production. - To evaluate and identify key factors contributing to environmental impacts and economic costs.	The study only focuses on manufacturing. Processes contributing to climate change are discussed sparsely and undefinable by readers due to a lack of hotspot analysis and disaggregated data in figures or tables.
Castro et al. (2020)	Brazil	Microalgae	None	✓			- To assess the environmental impacts of microalgae-based phosphate fertilizer production compared to triple superphosphate fertilizers.	The study is limited to upstream emissions.
This study	**Malaysia**	**Bacteria (cultivated strains)**	**Paddy**	✓	✓	✓	- **To integrate LCA, IPCC, and the GHG protocol methodologies for comprehensive agricultural carbon accounting.** - **To quantify and compare biofertilizer life cycle GHG emissions with chemical fertilizer.**	**Quantifies the life cycle GHG emissions of biofertilizer with cultivated bacteria via bioreactor for industrial distribution, considering emissions from the manufacturer's indirect activities (e.g., personal vehicle emissions) that can be used beyond research (e.g., stock index compliance).**

included CO_2 emissions from straw burning, manure, and lime, which are not considered in this research as they were not used by the farm operator, but did not include CO_2 emissions from SOC fluctuation, which impacts GHG emissions in every farmland. Only one study by Pereira et al. (2021) accounted for both SOC-derived CO_2 and N_2O emissions. However, their study did not include key variables, including N_2O emissions from crop residue, volatilization, and runoff.

Additionally, no study has integrated all three methodologies to comprehensively account for the GHG emissions of the biofertilizer's life cycle, and the current method of using LCA or the GHG protocol to quantify downstream processes may not be geographically representative for modeling downstream emissions. Thus, this study provides a more holistic approach to GHG quantification by integrating the LCA, GHG protocol, and IPCC Guidelines into a single methodology. This integrated methodology was also developed to streamline GHG accounting processes for companies seeking to report and comply with

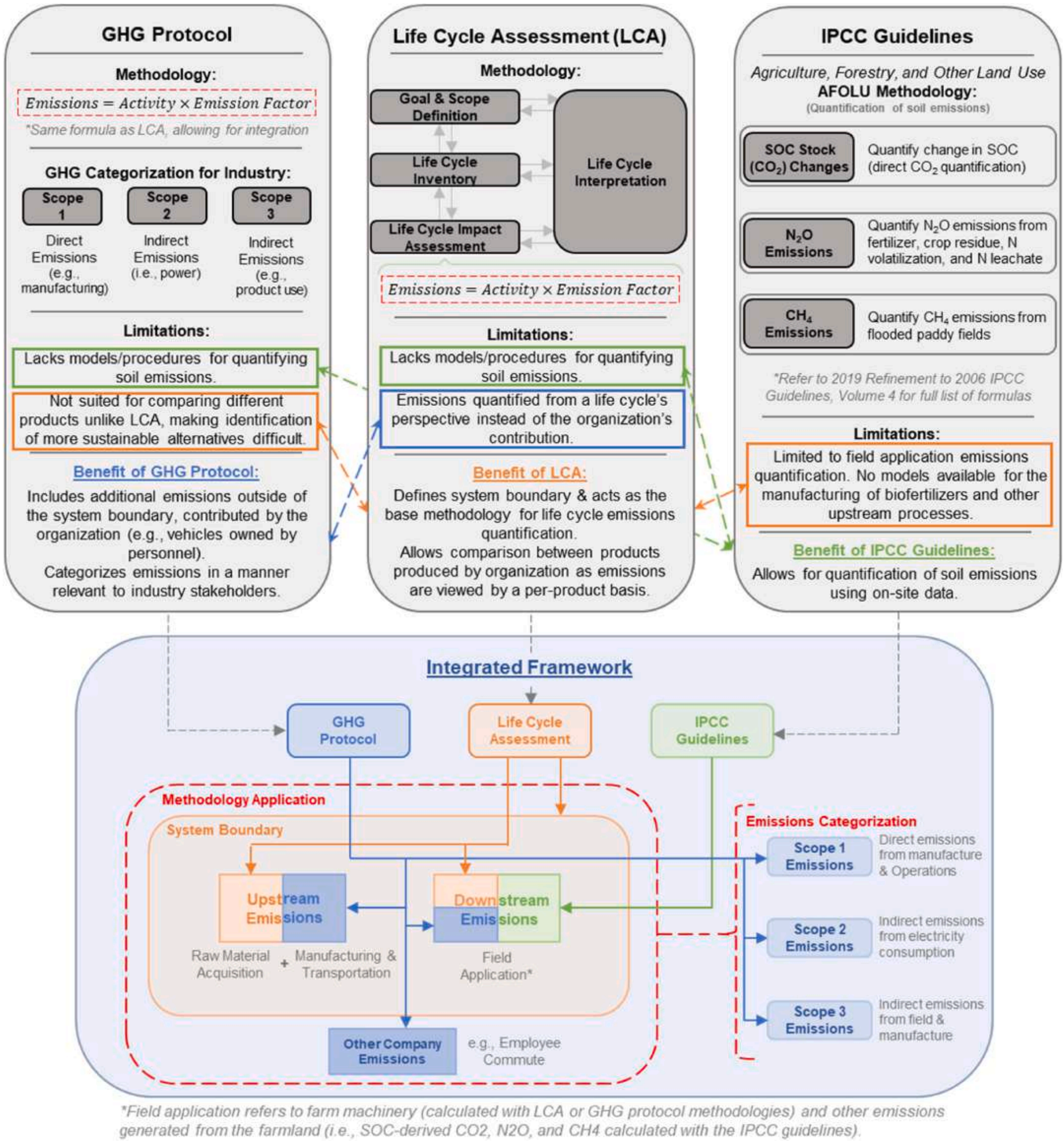

Fig. 1. Framework for IPCC, LCA, and GHG Scope integration for agricultural carbon accounting. The colored boxes and arrows inside the gray boxes show how the benefits of each methodology, assigned the font colors of blue for GHG protocol, orange for LCA, and green for IPCC Guidelines, solve the associated problems marked in their respective colored boxes. The boxes and arrows inside the integrated framework further clarify this integration.

regulatory or financial bodies. Detailed descriptions of the objectives, findings, research gaps, and methodologies of previous literature are included in Table 1.

This study aims to use the integrated methodology to quantify and disaggregate the life cycle GHG emissions based on each GHG Scope, demonstrating the applicability of LCA, GHG protocol, and the IPCC guidelines for industry-wide application while determining emission hotspots at each life cycle stage. Results are compared with those of chemical fertilizers to assess the GHG improvement of biofertilizers. Recommendations for reducing GHG emissions are provided for plantation-scale applications. This integrated methodology contributes to the United Nations Sustainable Development Goal (UN SDG) 13 by providing methods for industry-wide quantification and supporting global decarbonization efforts.

2. Material and methods

2.1. Integrated LCA-GHG protocol-IPCC methodology framework

Fig. 1 shows an integrated framework combining LCA, GHG protocol, and the IPCC Guidelines. This integration is proposed to allow for a comprehensive quantification of agricultural GHG emissions applicable to industrial applications (i.e., carbon accounting of organizations involved in the agriculture sector).

The LCA methodology determines upstream GHG emissions associated with manufacturing biofertilizers and emissions from machinery used in field management, such as tillage and fertilizer application. Soil emissions have large uncertainties due to differences in soil sampling for various regions that also require long-term trials for data collection, which cannot be accurately accounted for using LCA (Goglio et al., 2018; Joensuu et al., 2021; Solinas et al., 2021). IPCC guidelines can simulate emissions from manufacturing and other upstream processes but report lower emissions than LCA, as the latter provides a systematic accounting of emissions (Cellura et al., 2018; O'Brien et al., 2012). For instance, the IPCC uses a sector-based approach and does not account for several aspects that are accounted for in LCA, such as emissions from the production of imported goods (O'Brien et al., 2012). Volume 4 of the IPCC guidelines, which is used in this study, allows for quantifying field emissions in detail by integrating on-site field data with its own emission factors and calculation models. Through this, the IPCC considers time-dependent variables that address the weaknesses of LCA in modeling agricultural downstream emissions.

The GHG protocol is used to quantify emissions at an organizational level. It is limited to comparing the performance of the same product over different timespans, whereas LCA allows for comparing various products to find more sustainable alternatives (Chew et al., 2023). However, the GHG protocol is more widely used in the industry and is better suited for industry-wide carbon accounting. Integrating these methodologies allows for the biofertilizer assessed in this study to be compared with chemical fertilizers, taking soil emissions which are not readily quantifiable through LCA while maintaining the GHG protocol standard for quantification of the organization's activities.

2.2. Research approach

2.2.1. Goal and scope definition

This study utilized LCA to quantify the GHG emissions from biofertilizer manufacturing and its application for paddy fields in Malaysia, considering all processes, including raw material extraction, manufacturing, transportation, and field application by farmers, were considered (see Fig. 2). As recommended by the GHG protocol, emission sources indirectly contributing to the biofertilizer's GHG emissions were included, such as company vehicles used during operational hours to conduct meetings with suppliers. This extends to the entire organization, including on-site water consumption unrelated to production and electricity consumption for office spaces, which are all integral to the operations of the biofertilizer manufacturer. A functional unit of 1 ha of land in the paddy field was selected to equally identify the impacts of biofertilizer and chemical fertilizer. The mass of harvested products was not considered a functional unit since the downstream focus of this study is the quantification of carbon dynamics from the soil as opposed to product growth optimization. Since the assessed paddy field is categorized as mineral soil, calculations in the IPCC guidelines for organic soils are assumed to be negligible. Similarly, variables from dung or excrement were excluded as no inputs were used. Raw material emissions were considered background data and assumed insignificant as they are low in quantity and not as carbon-intensive as electricity consumption (Järviö et al., 2021).

2.2.2. Life cycle inventory

Primary data from the manufacturing plant and plantation were provided by IBG Manufacturing Sdn. Bhd., which covers electricity,

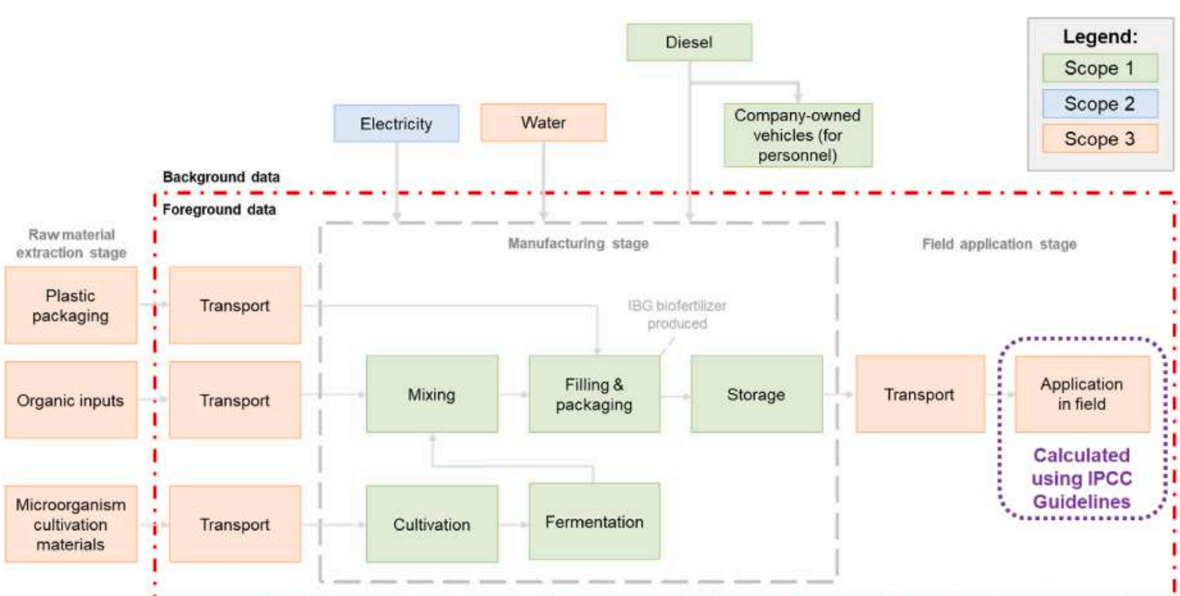

Fig. 2. The system boundary of the study integrated with the emission scopes and field emissions.

water, diesel consumption, and transportation. Farmland data, including fertilizer quantity and composition, management details, and soil information used to calculate field emissions, were obtained from a third-party farm operator. IBG's biofertilizer contains three cultivated bacteria grown in a bioreactor. *Bacillus subtilis* is included for its nitrogen-fixation properties, whereas *Bacillus amyloliquefaciens* and *Bacillus mycoides* are used for their phosphate and potassium solubilization properties, respectively. The biofertilizer also contains 4 % N, 73 % organic content, and approximately 10 % water content. Wastewater is negligible as all water inputs are used in the mixing stage, and any spillage or equipment washing (for maintenance) during the process consumes minuscule quantities of water compared to manufacturing. Further details related to the manufacturing process can be found in a previous study that investigated the upstream emissions in more detail (Mulya et al., 2024a). Emission factor values for various processes were taken from secondary sources, mainly from recent governmental reports. Tables 2 and 3 show primary input data for manufacturing biofertilizers and all emission factors used for calculation. The full list of IPCC emission factors and other details specific to the farm can be found in Appendix A. Chemical fertilizer manufacturing emissions were assumed to be from nitrogen fertilizer, as other non-nitrogen fertilizers produce negligible GHG emissions by comparison (Walling and Vaneeckhaute, 2020). The emissions were aggregated to a single value as provided by the Ecoinvent version 3.8 database and are differentiated from the biofertilizer manufacturing emissions (Symeonidis, 2021).

Two scenarios were assessed: 0:100 ratio, which used chemical fertilizers with no biofertilizers in the control plot, and 30:70 ratio, which used a mixture of 30 % biofertilizer with 70 % chemical fertilizer. 30:70 is the recommended ratio by the producer of the biofertilizer as it results in the highest yield based on their field trials. Field samples were taken from a paddy field in Selangor, Malaysia, from March 2017 to February 2020, at a soil depth of 30 cm. The field area allocated for biofertilizer and chemical fertilizer testing is 10 ha each. Soil samples were taken once for the 0:100 plot, in accordance with the farm operator's standard operating procedure, as the obtained values are consistent with previous testing done and historical trends, which are frequently taken for compliance purposes with regulatory bodies. This serves as the farm operator's *business-as-usual* control for the paddy field. Four samples were taken from the 30:70 plot to determine the effects of biofertilizer introduction into the field. The fertilizer combinations contain 810 kg/ha of chemical fertilizer for 0:100 and 567 kg/ha for 30:70, with an additional 3.3 L/ha of IBG biofertilizer every year. The soil samples were analyzed by a certified third-party laboratory and are noted in Table 3. The soil samples were then tested for the total organic carbon content (TOC%) using the Walkley-Black method. Bulk density and coarse fragment data were not collected by the farm operator during the sampling period. Bulk density data was taken as an average value between the values recorded by Azdawiyah (2019) and Mairghany et al. (2019). Coarse fragment data was not taken into consideration and assumed to be 0 %, as no secondary data that is both geographically relevant and similar in soil type is available. These substitutions may cause uncertainties and should be updated with local data in future studies through methods such as the excavation method for bulk density data and sieve analysis for the coarse fragment, which are cost-effective procedures that can be undertaken by corporations.

Table 2
Life cycle inventory inputs for production of biofertilizer.

Process/variables	Quantity	Unit	Source
Ingredient transportation			
Land transport; lorry	295.52	tkm/ha	On-site data
Sea transport; sea freight	1660.32	tkm/ha	On-site data
Packaging input transportation			
Land transport; lorry	2.88	tkm/ha	On-site data
Sea transport; sea freight	380.22	tkm/ha	On-site data
Operational processes			
Electricity consumption	764.66	kWh/ha	On-site data
Water consumption	11.37	m^3/ha	On-site data
Diesel consumption			
Manufacturing operational machinery	6.30×10^{-5}	L/ha	On-site data
Transportation of diesel (for machinery)	1.91×10^{-2}	tkm/ha	On-site data
Personnel vehicles (Scope 1)	3.94×10^{-3}	L/ha	On-site data
Product transportation (to customers)			
Land transport; lorry	1210.21	tkm/ha	On-site data
Sea transport; sea freight	3403.38	tkm/ha	On-site data
Emission factors			
Chemical fertilizer	1.4865	kg CO_2eq/kg	Symeonidis (2021)
Land transport	1.065×10^{-4}	kg CO_2eq/t/km	CIDB (2021)
Sea transport	1.614×10^{-2}	kg CO_2eq/t/km	CIDB (2021)
Electricity generation	0.55	kg CO_2eq/kWh	TNB (2023)
Water processing	0.586	kg CO_2eq/m^3	Air Selangor (2022)
Diesel combustion	2697.49	kg CO_2eq/m^3	USEPA (2023)
Diesel combustion for paddy farm machinery	53.67	L/ha	Muazu et al. (2015)

On-site data refers to data provided by IBG Manufacturing Sdn Bhd, a biofertilizer manufacturing firm in Malaysia. Personnel vehicles are company-owned vehicles that do not directly contribute to production emissions but are used for the company's activities.

Table 3
Data inputs for IPCC field calculations.

Process/variables	Quantity	Unit	Source
Field parameters (IPCC)[a] – 30:70			
TOC_1	2.66	%	On-site data
SOC_1	87.78	t/ha	On-site data
TOC_2	2.64	%	On-site data
SOC_2	87.12	t/ha	On-site data
Organic fertilizer N-addition	0.171	kg N/ha	On-site data
Synthetic fertilizer N-addition	157.57	kg N/ha	On-site data
C:N ratio	3.73	N/A	On-site data
Application rate of organic amendment[b]	8.82	t/ha	On-site data
Cultivation period for rice	115	days	On-site data
Total field area	10	ha	On-site data
Bulk density	1.1	g/cm^{c}	Secondary data[c]
Number of growing seasons per year	2	N/A	On-site data
Field parameters (IPCC) – 0:100			
TOC_1	2.85	%	On-site data
SOC_1	94.05	t/ha	On-site data
TOC_2	2.77	%	On-site data
SOC_2	91.41	t/ha	On-site data
Organic fertilizer N-addition	0	kg N/ha	On-site data
Synthetic fertilizer N-addition	225.10	kg N/ha	On-site data
C:N ratio	7.1	N/A	On-site data
Application rate of organic amendment[b]	7.97	t/ha	On-site data
Cultivation period for rice	115	days	On-site data
Total field area	10	ha	On-site data
Bulk density	1.1	g/cm^{c}	Secondary data[c]
Number of growing seasons per year	2	N/A	On-site data

IPCC – Intergovernmental Panel on Climate Change (parameters for calculations), SOC_1 – Soil Organic Carbon at the start of assessment (year 2017), SOC_2 Soil Organic Carbon at the end of assessment (year 2020). The C:N ratio represents the ratio found within the soil samples. Units are written on a per-ha basis following this study's functional unit.

[a] Field parameters that can be displayed and averaged between all trials in accordance with confidentiality agreements with the field operator.

[b] The organic amendment used by the farm operator is leftover straw from the previous paddy harvest, considering no removal or burning was conducted.

[c] Taken as the rounded average from the findings by Azdawiyah (2019) and Mairghany et al. (2019).

2.2.3. Life cycle impact assessment

2.2.3.1. Upstream emissions quantification. The manufacturing GHG emissions were quantified using LCA methodology and GHG protocol by multiplying activity data (e.g., electricity in kWh, transportation in tkm, etc.) with the associated emission factor (see Eq (1)). Since this research focuses on GHG emissions for carbon accounting, only Excel was used as the software using data detailed in the previous section.

$$Emissions = Activity\ data \times Emission\ factor \qquad \text{Eq (1)}$$

2.2.3.2. Downstream emissions quantifications. Downstream emissions were divided into farm machinery and field application emissions. Farm machinery was calculated using Eq (1) through LCA and GHG protocol methodologies. Field application emissions were calculated with the IPCC guidelines and later combined with the upstream results to quantify the total life cycle GHG emissions of the biofertilizer. Tier 1 and Tier 2 calculations were used following the recommended methodological tiers and type of emission factors listed by the government's climate change report to the United Nations (NRECC, 2022).

Soil emissions from carbon, nitrous oxide, and methane were calculated using formulas provided by volume 4 of the IPCC guidelines (IPCC, 2019). A more detailed breakdown of the methodology can be found in Appendix A. Soil carbon emissions were calculated by subtracting the final and initial SOC of the studied period, where a positive value indicates carbon sequestration took place as more carbon is stored in the soil than was lost due to mineralization. A negative value indicates carbon released back into the atmosphere (Jian et al., 2020). The difference in SOC was multiplied by a conversion factor of 3.67 to convert it to carbon dioxide equivalents, as shown in Eq (2) (Bhatia et al., 2011; K. Chen et al., 2021; Turrell and Mcgregor, 2020).

$$SOC\ CE = 3.67 \times [(SOC_2 - SOC_1) \times A] \qquad \text{Eq (2)}$$

where *SOC CE* (SOC-derived carbon equivalents) is expressed in kg CO_2eq, SOC_2 and SOC_1 are the final and starting SOC values in units of tonnes C/ha, and *A* is the area in ha.

SOC is derived from three main sub-pool components (Hollesen et al., 2019; IPCC, 2019). The first is the active sub-pool, which contains readily decomposable organic material with a high turnover rate for several months or years. The second is the slow sub-pool generated from the decay of organic compounds with slower decomposition rates, such as lignin, which may take decades to decompose fully. The last is the passive sub-pool that contains mineral-protected carbon and other products from microbial decomposition with turnover rates that may take centuries to decompose fully. The summation of the three sub-pools represents the overall SOC value used for determining the change in carbon stock over an area in a certain period.

In this study, SOC was calculated using an alternative formula by multiplying the soil's total organic carbon with other physical properties, as shown in Eq (3) (USDA, 2023). This approach is less data-intensive and obtainable, considering resource constraints in collecting data from each sub-pool.

$$SOC = TOC\% \times BD \times SD \times (1 - \%CF) \qquad \text{Eq (3)}$$

where *SOC* (Soil Organic Carbon) is expressed in g C/ha, *TOC%* (total organic carbon) is expressed in % C, *BD* (bulk density) is expressed in g/cm^3, *SD* (sampling depth) is expressed in cm, and *%CF* (percent of coarse fragment in the soil sample) which is a dimensionless unit.

Nitrogen emissions were derived from direct nitrogen inputs from applying synthetic (chemical) fertilizer, organic components such as manure and wastewater, crop residue, and mineralized N from loss of soil C due to agriculture management changes. Indirect nitrogen emissions were derived from the atmospheric deposition of volatilized fertilizers alongside leachate from the nitrogen inputs. As shown in Eq (4), both nitrogen emissions were added and multiplied by a factor of 1.57 to convert into N_2O equivalents, which were then converted into carbon dioxide equivalents by multiplication with a factor of 273, in accordance with the IPCC guidelines (D. Chen et al., 2021; Shukla et al., 2019).

$$N_2O\ CE = 1.57 \times 273 \times (N_2O_{Direct} + N_2O_{Indirect}) \qquad \text{Eq (4)}$$

where $N_2O\ CE$ (nitrous oxide carbon equivalents) is expressed in kg CO_2eq, N_2O_{Direct} and $N_2O_{Indirect}$ are expressed in kg N_2O-N.

Methane emissions were calculated by multiplying the cultivation area and period of rice with emission factors based on the operations of the paddy field, as shown in Eq (5) (IPCC, 2019). The methane was multiplied by a factor of 27.9 to convert the emissions into carbon dioxide equivalents (D. Chen et al., 2021).

$$CH_4\ CE = 27.9 \times CH_4 \qquad \text{Eq (5)}$$

where $CH_4\ CE$ (methane carbon equivalents) is expressed in kg CO_2eq and CH_4 is expressed in kg CH_4.

The carbon equivalents from the SOC, nitrous oxide, and methane calculations were added together to show the net carbon emission (in kg CO_2eq) of the fertilizer as described in Eq (6).

$$Field\ emissions = SOC\ CE + N_2O\ CE + CH_4\ CE \qquad \text{Eq (6)}$$

2.2.4. Life cycle interpretation

All variables throughout the biofertilizer's life cycle were separated in a hotspot analysis to identify key contributors to GHG emissions. The life cycle GHG emissions of IBG biofertilizer were compared with the chemical fertilizer (0:100 ratio) to determine the improvement of fertilizer substitution with biofertilizer.

A local sensitivity analysis was conducted to test the robustness of the models and identify input parameters that significantly impact the resulting emissions. The identification of sensitive parameters allows stakeholders to focus their resources on more stringent sampling procedures (e.g., increased supervision throughout farmlands or increased number of samples to reduce discrepancies) for parameters that may greatly impact the outcome of the analysis. In this study, the impacts of varying the input parameters (i.e., y-axis) by 10 % increments or decrements (i.e., x-axis), up to a maximum of 50 %, on the GHG emission output were assessed. The impact on the output was visualized through a heatmap, where input alterations that lead to increased GHG emissions were marked with more saturated colors, whereas changes leading to GHG reductions were marked with fainter or white colors as represented in the legend's color scale to the right of each figure. Input parameters with negligible impact have a pink color similar to the baseline value, set at 0 %. Gray boxes indicate that the selected input parameter has no impact on the final quantity of the GHG emissions. The assessed parameters include all soil sampling inputs and various field variables (e.g., yield and land area). As the nature of a local sensitivity analysis is theoretical, it does not account for any constraints, such as changes in dependent variables when one input parameter is altered, and each change in the parameter is to be treated as completely independent in this analysis. Thus, the sensitivity analysis results may not reflect the actual performance of the assessed emissions as the input parameters are adjusted manually during calculations.

A scenario analysis was conducted to quantify the GHG reductions observed by chemical fertilizers with biofertilizers on a national scale. By estimating the emissions of widespread biofertilizer implementation, this analysis provided context and information for formulating policies. As national data for the GDP and GHG emissions of paddy is limited, data for the country's agricultural sector was used instead with the assumption that the biofertilizer observed in this study achieves a similar level of GHG reduction when applied for non-paddy crops, thus serving as an example if biofertilizer were to be enforced as a national agricultural policy. The country's agricultural GHG emissions and GDP were projected to 2030 based on historical data from government and intergovernmental sources (ASEAN, 2023; NRECC, 2022). It should be noted that while the methodology presented in this research may be applicable in any country, the results only apply to tropical regions that are similar to the conditions in Malaysia. Further details on the scenario analysis and the regression analysis to create the business-as-usual (BAU) projections can be found in Appendix A.

Four scenarios were created based on various considerations. The first is to determine whether Malaysia's GHG reduction target of reducing the carbon intensity by GDP of the country by 45 % in 2030, relative to 2005 (MOE, 2023). The second scenario (i.e., the 2035 scenario) is the most realistic scenario based on past agriculture-related policy implementations from the Indian, European Union, and French governments (DGAL, 2015; EU, 2020; WFC and iFOAM, 2019). Policies made by these governments require 10–12 years to implement, which becomes the basis of the 2035 scenario as projections begin in 2025. The 2050 scenario is based on the country's net-zero carbon emissions target (MOE, 2023). BAU is also included as a reference to compare the emissions at each targeted year, calculated using a linear regression model from 34 years of historical data (i.e., 1990–2024).

Projections were modeled using a sigmoid growth curve model with three phases representing the slow transition to biofertilizers. The first phase considers the fact that the policy has just been introduced, and industry stakeholders are given time to develop manufacturing sites, supply chains, and sales networks, while downstream users such as farmers are given education on the purpose and application method of biofertilizers. The second phase is the policy enactment phase, in which downstream users are required to utilize biofertilizers. The last phase is the saturation phase, which simulates the remaining resistance towards the policy by a small number of downstream users, causing a slower decrease in GHG emissions. This model was used by the World Economic Forum to examine the impact of adopting climate-smart practices by 20 % of farmers on GHG emissions, soil health, and farmer profits (WEF, 2022). The model was adapted in this study to the formula shown in Eq (7).

$$\frac{\alpha}{1 + e^{\beta(x-t)}} + L \quad \text{Eq (7)}$$

where α represents the difference between the maximum reduction and the starting year of the projection, β is the steepness of the sigmoid growth curve, x is the year of the projection, t is the midpoint year (e.g., for the 2035 scenario, the midpoint year between 2025 and 2035 is 2030), and L is the starting year to act as the baseline. If L is not defined, the projections will assume the final-year projection as 0 t CO_2eq. The maximum reduction is the theoretical limit set by multiplying the projected BAU GHG emissions at a specified year with the reduction observed from the life cycle impact assessment. The values used to represent each variable can be found in more detail in Appendix A. Future research should test the robustness of the model and compare it with other sigmoid growth curve models.

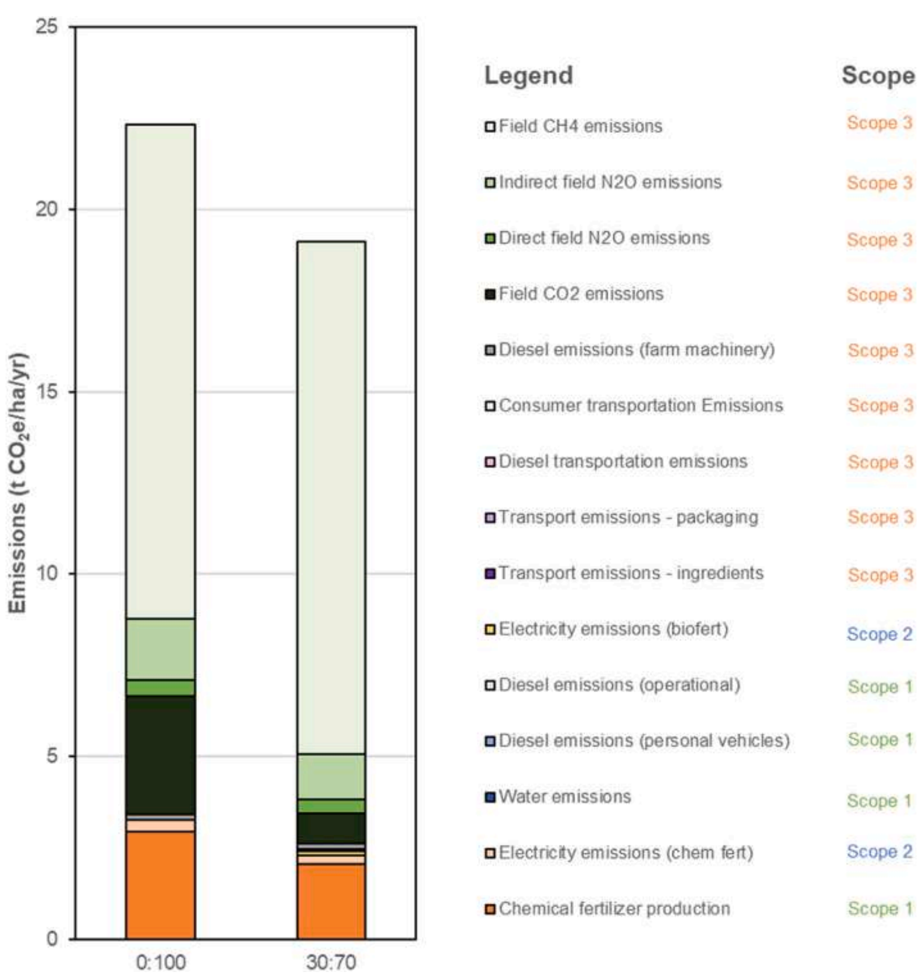

Fig. 3. GHG emission contributors of the biofertilizer (30:70 or "biofert") and chemical fertilizer (0:100 or "chem fert") scenarios. Diesel emissions (Scope 3) refer to diesel consumption for personal vehicles used by employees. Diesel emissions (operational) refer to diesel used for forklifts, generators, etc. in the biofertilizer's manufacturing.

3. Results and discussion

3.1. Life cycle hotspot and GHG Scope analysis

The life cycle GHG emissions of the 30:70 ratio are 19.11 t CO_2eq/ha/yr, which is 14.41 % smaller than the 0:100 ratio (22.32 t CO_2eq/ha/yr). As shown in Fig. 3, most GHG emissions are derived from methane emissions, representing 73.49 % and 60.63 % of the 30:70 and 0:100 life cycle GHG emissions, respectively. Chemical fertilizer manufacturing contributed the subsequent highest emissions (11.98 % and 14.65 % for 30:70 and 0:100, respectively). Chemical fertilizer emissions, mostly derived from nitrogen production, are high due to steam reforming to produce ammonia, which generates large quantities of CO_2 and CH_4 (Menegat et al., 2022). CO_2 emissions from SOC stock changes (4.23 % and 14.47 %). The last major contributor to GHG emissions is direct and indirect N_2O emissions at 8.52 % and 9.60 % for 30:70 and 0:100, respectively. The emissions generated during biofertilizer manufacturing are negligible, contributing to 1.03 % of the total emissions under the 30:70 scenario. Although the 0:100 plot represents the BAU case with consistent historical trends, it should be noted that there is potential uncertainty as only one sample was taken.

Although the GHG protocol intends to quantify the emissions from an organization's perspective, this research assumes that direct emissions are directly contributed by biofertilizer and chemical fertilizer manufacturing (i.e., aggregation of all upstream emissions). Direct emissions categorized under Scope 1 are derived from pollutants emitted by the producers throughout the fertilizer manufacturing process, most of which are from chemical fertilizers (see Table 4). The total Scope 1 emissions from biofertilizer manufacturing is 0.14 t CO_2eq/ha/yr, equal to 5.43 % of Scope 1 emission shares, or 0.69 % of the life cycle GHG emissions. As Scope 1 emissions are contributed mainly by on-site fuel combustion, utilizing electric vehicles and increasing equipment's fuel efficiency may reduce these emissions.

Scope 2 emissions, which are indirect emissions from purchased electricity, contribute to less than 2 % of both scenarios' life cycle GHG emissions. Notably, biofertilizers emit half as many electricity-related emissions as chemical fertilizers. As most Scope 2 emissions are generated from fossil-fuel sources, utilizing renewable energy sources, such as solar panels, can help reduce these emissions (Ng et al., 2024. Electricity consumption can be reduced by implementing more energy-efficient equipment like light-emitting diode (LED) bulbs throughout the manufacturing site (Mulya et al., 2024b).

Scope 3 emissions, which are miscellaneous indirect emissions, are attributed to the application of the fertilizers in the field (i.e., since the GHG protocol is from the perspective of the fertilizer manufacturer. Field emissions would fall under Scope 1 if the reporter is the field owner) and emissions generated by processes outsourced to other entities, including third-party transporters and emissions from farm machinery. Since these emissions are generated further from the supply chain, organizations can source materials from producers and third parties that have integrated low-carbon technologies and policies into their operations, including eco-labelled products or goods that have environmental product declarations (ISO 14024, 2018, ISO 14025, 2006).

Table 4
Scope emissions of the chemical fertilizer and biofertilizer scenarios. Chem fert = chemical fertilizer; biofert = biofertilizer.

GHG Scopes (t CO_2eq)	0:100		30:70	
	Value	Share	Value	Share
Scope 1 (chem fert)	2.95	13.22 %	2.07	10.81 %
Scope 1 (biofert)	0.00	0.00 %	0.01	0.03 %
Scope 2 (chem fert)	0.32	1.43 %	0.22	1.17 %
Scope 2 (biofert)	0.00	0.00 %	0.13	0.66 %
Scope 3	19.05	85.35 %	16.69	87.33 %

The high methane emissions are derived from organic amendment (i.e., 8.82 t/ha of leftover straw from the previous paddy harvest), continuously flooded water regimes, and other management practices with high scaling factors under the IPCC guidelines. SOC-derived GHG emissions are primarily quantified by the change of the carbon stock in the soil, where the 30:70 ratio decreases GHG emissions by 75 % compared to the 0:100 ratio. The change in TOC% content is the primary contributor to the decrease in emissions. An average TOC% reduction of 0.08 % was observed for the 0:100 plot, compared to the 30:70 plots with an average TOC% reduction of 0.02 %. Although no microbes within the biofertilizer directly affect the TOC%, the microbes may have secondary effects that stimulate the carbon retention property of the soil. For instance, a higher concentration of microbial necromass can be formed by increasing the concentration of microbes via biofertilizers, which has been cited for stabilizing carbon in soil (Ni et al., 2021). Although this research did not assess the change in SOC during the growth stages of the paddy crops, future research should take intermediary samples to identify the stage where the highest SOC fluctuations occur. This would allow for more specific strategies to be implemented by both farm operators and changes to the composition of the biofertilizer to enhance GHG reductions from SOC fluctuations.

Biofertilizers reduce N_2O emissions by 24.08 % (i.e., 2.14 t CO_2eq/ha/yr to 1.63 t CO_2eq/ha/yr), where indirect N_2O emissions were reduced by 26.50 % compared to direct N_2O emissions that saw a reduction of 14.79 %. The share of emissions from indirect N_2O is also 3.3 times larger than direct N_2O. Direct N_2O emissions are affected by the nitrogen content in fertilizers, crop residue, mineralized nitrogen within the soil, and nitrogen loss due to volatilization and leaching. There are no N_2O emissions from urine and dung, as none were used under the current management. Among the variables affecting direct N_2O emissions, nitrogen inputs from chemical fertilizers are the largest contributor, representing 51.76 % of the total, which could be reduced by reducing chemical fertilizer use. The second largest contributor is crop residue emissions, contributing to 47.89 % of direct N_2O emissions. Crop residue serves as a substrate for microbial propagation, accelerating nitrogen cycling in the soil and increasing the availability of nitrogen for nitrification or denitrification (H. Chen et al., 2013; M. Wang et al., 2018). As the current management practice of the sampled paddy field does not conduct any burning or residue removal, future studies should perform a trade-off analysis to determine the optimal quantity of organic amendments to use as fertilizer while minimizing emissions. Emissions from nitrogen mineralization are primarily affected by the change in carbon stock and can have varying intensities. In this study, emissions from mineralized nitrogen contribute less than 2 % of the direct N_2O emissions. Indirect N_2O emissions quantify nitrogen losses via volatilization and leaching (IPCC, 2019). 66.23 % of the indirect N_2O emissions are generated by volatilized nitrogen, and the remaining share is derived from leaching and runoff. Indirect N_2O emissions are mainly contributed by excess nitrogen inputs, which can be reduced using less nitrogen fertilizer.

The application of biofertilizers also increases methane emissions compared to chemical fertilizers by 3.74 %, which is consistent with previous studies (Hu et al., 2024; Yang et al., 2015). The increased methane generation observed in this study is primarily caused by the 9.6 % yield improvement observed when applying biofertilizer. The increase in yield is correlated with a higher quantity of biomass residue (i.e., straw) that is left in the fields as the farm management does not conduct any straw burning or removal. The increase in organic content has previously been cited to be the primary cause of higher methane emissions, whereas the impact of the biofertilizer itself remains negligible (Alam et al., 2023). The CO_2 and N_2O emissions from the 30:70 plots are lower than the 0:100 plots and show a similar trend with previous research with various types of cultivated bacteria biofertilizers (Hu et al., 2024). The interactions between microbes leading to these emission fluxes should be observed further in future research.

3.2. Sensitivity analysis

As most of the contributors to GHG emissions are derived from the field emissions, the sensitivity analysis observes differences in parameters affecting field emissions under the IPCC model for the 30:70 ratio, displayed in Fig. 4. SOC emissions represent CO_2 emissions from carbon stock fluxes within the soil, derived from the TOC%, bulk density, and coarse fragment. Sampling depth was not observed as this parameter is not affected directly by the fertilizers or other impacts related to the soil properties. While coarse fragments were not assessed in this study due to a lack of data, future studies should observe the impacts in relation to the other SOC components. It can be observed that slight variations in SOC heavily impact the overall emissions (see Fig. 4e). Direct and indirect N_2O emissions have negligible impacts on the overall field emissions, whereas variations in methane-related parameters subtly impact the overall emissions.

Slight changes in TOC% can significantly impact the overall emissions of the field but have the potential to achieve carbon sequestration. Changing the input values of the TOC% by 10 % leads to an emission variation of over 100 t CO_2eq/yr. Bulk density has a relatively negligible impact on CO_2 emissions from SOC, contributing 0.8 t CO_2eq/yr for every 10 % change in the input value. To offset the N_2O and methane emissions and achieve carbon sequestration in the field trial, the difference between the initial and final SOC needs to differ by an additional 16 % (approximately an additional 14 t SOC/ha difference between the initial and final SOC values). At this point, the total field emissions result in a negative value, indicating that more carbon is being absorbed from the atmosphere, resulting in a net quantity of carbon being sequestered than emitted. Several variables can affect SOC retention, including frequent irrigation and excessive nitrogen inputs from fertilizers (Howe et al., 2024; Yao et al., 2024). However, the net loss in SOC observed in this study could be caused by frequent extreme rainfalls and excessive flooding that occurred during the first year of the assessed period (H. Wang et al., 2023).

Under direct N_2O emissions, organic fertilizer N-addition (F_{ON}) has negligible impacts due to the low quantities of organic material in the biofertilizer compared with the nitrogen content supplied by the chemical fertilizer (F_{SN}) and leftover rice straw from the previous harvest (noted in Fig. 4 as application rate of organic amendment – ROA). While alterations to chemical fertilizer quantities have a straightforward and linear relationship with the N_2O emissions generated, the application of ROA contributes to crop residue N_2O emissions. Despite rice crop residues only containing 0.7 % N-content, the estimated aboveground and belowground crop residue, which are contributed by unremoved

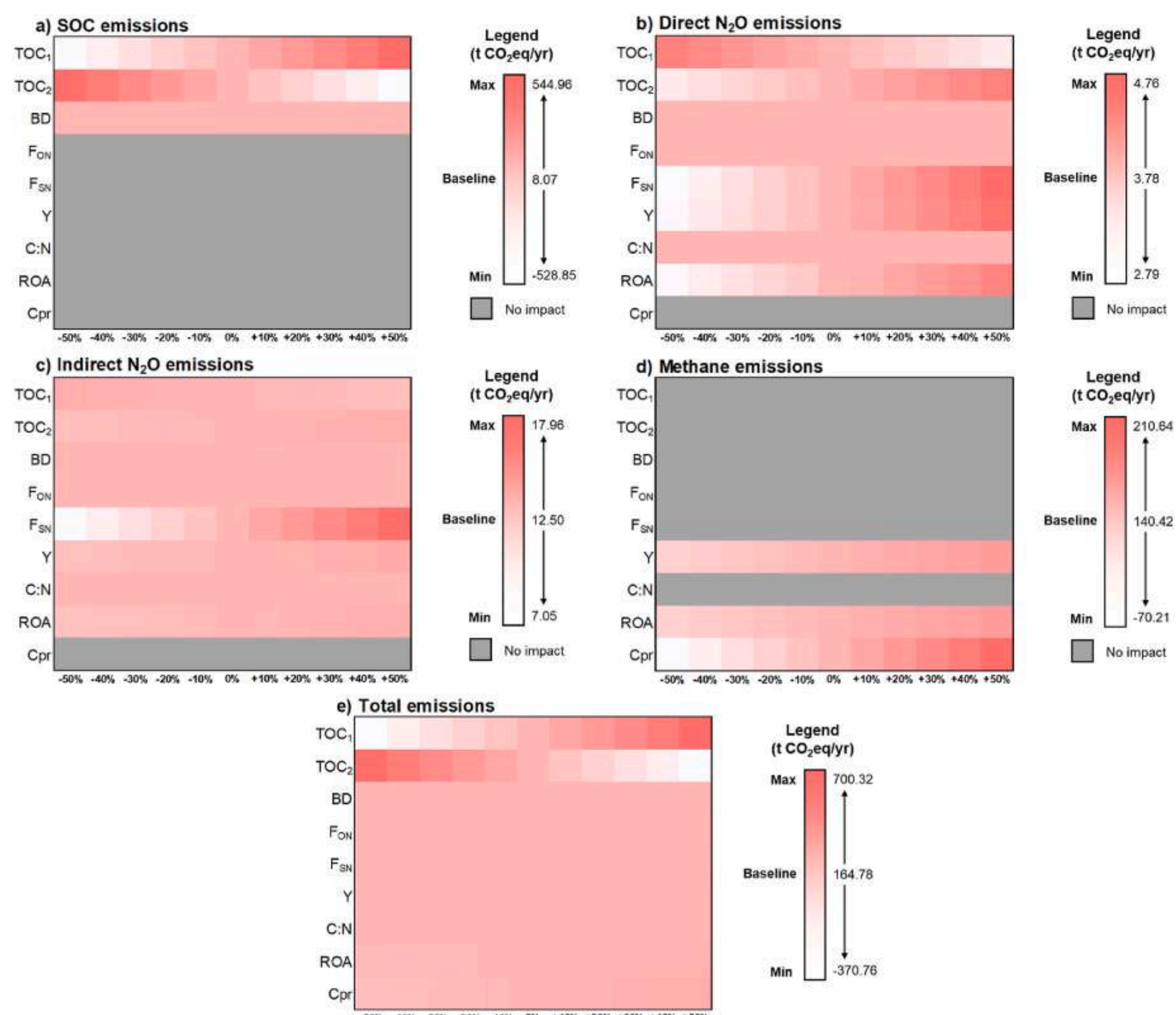

Fig. 4. Sensitivity analysis of field emissions that shows the relative impact of each variable affecting soil emissions on the resulting emissions when input values are altered on 10 % increments or decrements. More saturated colors indicate higher emissions, whereas white colors indicate lower emissions. Gray colors indicate that the variable has no impact on the emission of the assessed GHG type. TOC_1 = TOC% at the start of sampling; TOC_2 = TOC% at the end of sampling; BD = Bulk Density (set at 1.1 g/cm^3 for 0 %); F_{SN} = synthetic (chemical) fertilizer N-addition; Y = harvested fresh yield; C:N = C:N ratio; ROA = application rate of organic amendment (straw); Cpr = cultivation period of rice.

rice straw and a combination of decomposed rice straw and other subterranean processes such as root decomposition addition respectively, are significant in quantity as these variables are dependent on the crop yield which range several tonnes per hectare annually. It should be noted that the yield (Y) is directly correlated with the ROA and thus can be viewed as a near-identical variable for N2O emissions. Variation in the C:N ratio also has negligible impacts on N_2O emissions, as it is calculated by multiplying the change in SOC, which has a higher impact on determining the emissions. The change in SOC is calculated as a difference in carbon stock, similar to how SOC-derived CO_2 emissions are calculated. Therefore, it trumps the impacts of the C:N ratio in its impact on the emissions. Direct N_2O emissions are more sensitive than indirect N_2O due to parameter variation, as it quantifies the effect of nitrogen introduction into the soil on nitrification and denitrification (IPCC, 2019). Microbial activities drive both activities and depend on the nitrogen supply (Isobe and Ohte, 2014). Thus, chemical fertilizers that supply nitrogen and fresh yield are used to estimate the quantity of crop residues and have a greater impact on determining N_2O emissions.

Indirect N_2O emissions are less sensitive to parameters as they are determined mainly by emission factors and nitrogen inputs from fertilizers, as opposed to variations in soil conditions and differences in management practices. These emission factors are contributed by nitrogen inputs (e.g., "$Frac_{GASF}$" under the IPCC Guidelines), climate conditions, and other constants for volatilization and leaching. This is reflected in the IPCC guidelines formula, which relies heavily on constants for volatilization and leaching compared to variables derived from soil sampling, such as the C:N ratio and TOC%.

Methane emissions are only affected by the application ROA and cultivation period (Cpr), the latter of which is more sensitive to changes. Similar to N_2O emissions, the yield primarily influences the quantity of rice straw generated, which indirectly impacts methane generation. The cultivation period used in the case study is 115 days. However, the IPCC guidelines have an error range of up to 78 days for rice crops grown in Southeast Asia, resulting in a reduction of methane emissions by 32.71 %. ROA has a smaller impact, reducing methane emissions by 19.88 % when the inputs are decreased by 50 % (i.e., 4.41 t straw/ha). The increase in yield from biofertilizer application is also suspected of causing an increase in methane emissions, as the leftover straw was not removed or burned, providing methanogenic bacteria present in the paddy fields with more organic material. Methane emissions can be reduced further by adopting management practices with lower IPCC scaling factors. For instance, switching from a continuous flooding water regime to multiple drainage periods can reduce methane emissions by 45 % (6.32 t CO_2eq/ha/yr) for the 30:70 ratio. Rainfed and deep-water regimes are not considered, as these management schemes significantly differ from the irrigated system in the case study. Under the best-case scenario that also uses a non-flooded pre-season where rice fields were not flooded for over a year and a cultivation period of 78 days (i.e., lowest range under the IPCC guidelines' Tier 1 values), an additional 4.63 t CO_2eq/ha/yr can be reduced, resulting in a total reduction of 78 % compared to the current scenario's methane emissions. Changing management practices may impact crop yield and incur additional operational costs, which should be investigated further in a trade-off analysis for future research.

Overall, changes in carbon stock still have the largest impact on the field's emissions, followed by parameters affecting methane emissions. While TOC% changes of 10 % can impact the life cycle GHG emissions by approximately 100 t CO_2eq/yr, changes to parameters affecting methane emissions when ROA and cultivation period are altered by the same magnitude can vary the life cycle GHG emissions by approximately 19 t CO_2eq/yr, of which, 73.27 % of this share is derived from changes in the Cpr. N_2O is the least sensitive, where the highest variation of 1.28 t CO_2eq/yr is caused by changing synthetic fertilizer inputs, and altering all parameters by a 10 % increment or decrement can lead to a maximum GHG emission of 1.63 t CO_2eq/yr. While the findings of the hotspot analysis show methane as the largest contributor to GHG emissions, other case studies with better methane control procedures but poor TOC % retention practices can potentially lead to higher SOC-derived CO_2 emissions than methane emissions. Nitrous oxide emissions are smaller in quantity and do not heavily affect the total field emissions, even when parameters are set to be as polluting as possible. Soil carbon retention can be increased to reduce TOC% losses by management strategies such as deep ploughing, subsoil water management (e.g., via subsoil artificial drainage), and straw burial within the soil (Button et al., 2022). The inclusion of microbes with direct impacts on carbon retention can be integrated into the biofertilizer. For instance, *Bacillus mucilaginosus* fixes atmospheric carbon dioxide into biotic calcium carbonate through its carbonic anhydrase secretion in the presence of calcium (Zheng, 2021). Although this bacterium thrives in more basic conditions, it can be cultured and survive in environments with a pH of 7, which is within the pH of paddy fields during flooding periods (Ding et al., 2019; Zheng, 2021). For nitrogen improvements, management practices in handling crop residue, such as removing straw from paddy fields after harvesting, can reduce nitrogen emissions, as most emissions in this study stem from nitrogen inputs from chemical fertilizers and nitrogen inputs from crop residues. Alternatively, shallow incorporation of the crop residue (straw) in depths between 0 and 15 cm has been cited to produce lower N_2O emissions compared to deep incorporation (>15 cm), which decreases the frequency of anaerobic microsite formation that is conducive to N_2O generation (Abalos et al., 2022). From the microbial perspective, *Bacillus subtilis*, which is currently utilized in IBG's biofertilizer, can be co-inoculated with *Azospirillum* sp., which has been shown to increase the nitrogen-fixing capabilities compared to a single-species inoculum, believed to be due to biofilm formation synergies that protects the bacteria from oxygen (favorable for nitrogen-fixing conditions) and co-supplement nutrients that can stimulate nitrogen fixation (Ribeiro et al., 2022).

3.3. Scenario analysis

Fig. 5 shows the carbon intensity projection of the agriculture sector in Malaysia. Based on the 2030 projection, the introduction of biofertilizers can help reduce emissions by 10.12 % compared to 2024 levels. Still, achieving the 45 % carbon intensity reduction national target is insufficient as the sole measure for reducing GHG emissions in the agricultural sector. Relative to 2005, the sector's carbon intensity increased by 1.04 %, which is an improvement compared to the BAU scenario which would have increased the sector's carbon intensity by 18.05 %. The 2035 projection does not have specific targets set by the Malaysian government, but it represents the most feasible case, where the carbon intensity is expected to decrease by 6.69 % to 0.5493 t CO_2eq/thousand USD, compared to the most recent carbon intensity in 2024 (0.5887 t CO_2eq/thousand USD). When extending the policy implementation to 2050, the carbon intensity remains nearly unchanged until 2024, ending at 0.6049 t CO_2eq/thousand USD. However, this still represents a 14.41 % decrease in emissions compared to the BAU scenario at that year.

Despite biofertilizers being unable to achieve Malaysia's national GHG emission targets as a sole product, they show great potential in GHG reduction and should be paired with other GHG reduction products and practices to make achieving the GHG reduction targets more feasible. Several recommendations for other improvements have been discussed in the sensitivity analysis, predominantly farm management practices that reduce SOC losses and limit nitrogen inputs. While this study uses national agricultural data instead of paddy data for projections, future research should utilize data specific to the crop to reduce the uncertainty of the simulation.

3.4. Policy implications towards agricultural GHG reduction

Currently, the government has dedicated policies for paddy cultivation involving changes in management practices to increase land and water usage efficiency and restructuring financial supports to provide

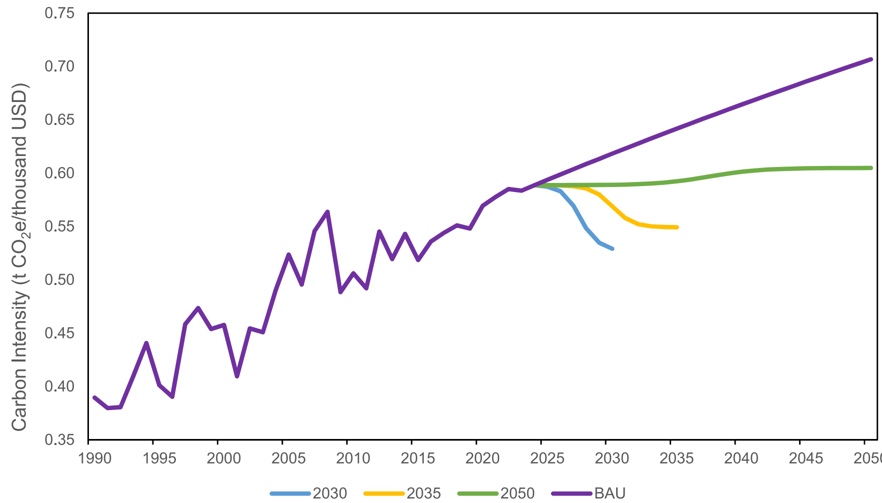

Fig. 5. Carbon intensity projections for several targets. BAU = Business-as-Usual.

farmers with the means to create their own business decisions (KPKM, 2021). Most current agricultural policies aim toward smart farming and integration with the Internet of Things and AI (EPU, 2021). The country's national climate change policy creates various agricultural-related policies but does not have quantifiable goals (NRES, 2024). These include promoting more efficient production and low-carbon farming methods in the agricultural and food industry, reducing methane emissions and intensity within the sector, promoting research, and developing methodologies and monitoring tools to acquire data and assist in risk assessment and decision-making. Despite the broad policies for the agricultural sector, several government initiatives have been launched to assist with developing the sector's low-carbon transition. The Ministry of Agriculture and Food Security of Malaysia has allocated 156 million MYR (approximately 37 million USD) for biofertilizer subsidies, and the outlook for biofertilizer development is accelerating (Halim et al., 2023). To mitigate the increasing emissions observed in the BAU scenario of Fig. 5, the country urgently needs to set more stringent and quantifiable goals for the agricultural sector.

Based on the findings of this research, indirect Scope 3 emissions, primarily from field emissions, are the main contributors to the biofertilizer's life cycle GHG emissions. To counteract this, several national policies aimed at reducing the agriculture sector's GHG emissions are outlined below.

- Enforce drainage periods throughout the cultivation season to reduce methane generation, which has been proven in a meta-analysis of 61 studies across the globe to not have any adverse impacts on crop yield (i.e., 0.11 % increase) at the cost of increased nutrient losses (Z. Wang et al., 2020).
- Limit the quantity of organic amendments (i.e., straw) introduced to the field by encouraging removal and conversion into value-added products such as compost, mushroom production, silica extraction, or animal feedstock (Singh and Patel, 2022).
- Nitrous oxide emissions can be reduced further by introducing nitrification-inhibiting microorganisms that can be included as an independent soil amendment or part of biofertilizers to prevent bacteria from generating nitrous oxides (Papadopoulou et al., 2020).
- Promote carbon-retention biofertilizers or soil amendments to reduce SOC release, which has the largest potential for GHG emissions, as discovered in the sensitivity analysis.
- Methane emissions can be reduced by including microbes in the biofertilizer that compete with methanogenic microbes for organic sources. For instance, *Methylobacterium oryzae* consumes methanol, a common organic material for methanogenesis, and produces CO_2 instead. One study by Rani et al. (2021) discovered that this bacterium, alongside *Paenibacillus polymyxa,* increases crop yield by up to 14 % while reducing methane emissions by 12 % at most.
- Encourage the use of sustainable fertilizers, including organic and biofertilizers, to offset the nitrous oxide emissions generated from chemical fertilizers. This can be in the form of incentives for manufacturing and utilizing sustainable fertilizers or increased taxation for certain chemical fertilizer supply chain materials.
- In accordance with reporting frameworks such as the Global Reporting Initiative (GRI), the country can enforce the creation of supply chain environmental assessments for the suppliers of all companies as part of a broader national decarbonization framework (GRI, 2016). The policy should be implemented over a wide timeframe with adequate transition time and can be implemented in a stepwise approach. For instance, the first few years will focus on mandating all companies to report their Scope 1 emissions, and subsequent years should focus on implementing increasingly stringent criteria for supplier evaluations, eventually requiring entities to report and reduce their Scope 3 emissions by encouraging companies to switch to suppliers with lower emissions.
- Beyond the subsidies provided for the research and deployment of biofertilizers by the Ministry of Agriculture and Food Security, the country can offer tax reliefs for companies that report lower GHG emissions for farm operators and alternative fertilizer manufacturers. Tax reliefs can be provided to farm operators reporting Scope 1 emissions improvement when substituting with alternative fertilizers, alongside manufacturers that can prove the use of their fertilizers reduces GHG emissions via Scope 3 reporting. The government must set a benchmark for the expected GHG emissions from chemical fertilizer use serving as the basis for comparison. This policy can be extended to cover other low-carbon alternatives outside of fertilizer.

A step-wise implementation of these policies must be considered to avoid the abrupt enforcement of fertilizer shift as seen in Sri Lanka in 2021, which saw a significant decrease in yields from a policy banning the import and use of chemical fertilizers and agrochemicals, leading to inflation of rice prices by approximately 30 % (Beillard and Gal-appattige, 2021; Ghoshal and Jayasinghe, 2022). This research recommends implementing a 10-year transition period for any phase-outs of chemical fertilizers, as observed in the 2035 scenario under the scenario analysis section.

4. Conclusions

This study was conducted to develop a carbon accounting methodology that provides a comprehensive assessment of upstream and downstream biofertilizer emissions for both corporate and academic use, extendable to other agricultural products. This is done through the LCA-GHG protocol-IPCC methodology that utilizes LCA and the GHG protocol to calculate upstream emissions while utilizing the IPCC guideline's formulas and emission factors that consider local farm conditions through direct sampling in the calculations.

The results show that the partial substitution of chemical fertilizers with biofertilizers leads to a total GHG reduction of 14.41 %, most of which is contributed by methane under scope 3 GHG emissions, followed by SOC-derived CO_2 emissions. Biofertilizer manufacturing and application result in significantly smaller GHG and field N_2O emissions compared to chemical fertilizers. The sensitivity analysis revealed that emissions from SOC flux have the largest impact on downstream GHG emissions, and factors affecting the large methane emissions were primarily caused by the continuous flooding regime used in the farm management. Based on the scenario analysis, enforcing the partial substitution of chemical fertilizers with biofertilizers can reduce nationwide emissions significantly, most likely reducing agricultural GHG emissions by 6.69 % by 2035. Other scenarios, including Malaysia's 2030 and 2050 GHG reduction targets, are assessed, but biofertilizers alone are insufficient in achieving these targets and must be supplemented by other low-carbon initiatives. Thus, several policy recommendations that can reduce GHG emissions are discussed, including recommendations for farm management changes that minimize methane emissions, biofertilizers through the introduction of various microbes, gradual reduction of Scope 3 emissions by introducing a mandate for supplier environmental assessment, and fiscal incentives for farm management adopting and reporting low-carbon agriculture products.

Future research should focus on the following developments to advance low-carbon technology, contributing to the decarbonization of the agriculture sector. For biofertilizers, research should be conducted on the role of other GHG-reducing microbes, such as cyanobacteria and blue-green algae for N_2O, and bacterial strains that compete with methanogenic bacteria, such as *Paenibacillus polymyxa* and *Methylobacterium oryzae*. Studies should also investigate the extent of their GHG reduction abilities and assess their compatibility with other bacterial strains to create a biofertilizer that can reduce all types of greenhouse gases. The GHG emissions of other bio-based products, such as biopesticides, should be investigated as additional green alternatives other than biofertilizers are needed to achieve the country's carbon neutrality targets in the agriculture sector. Furthermore, the integrated methodology can be refined by separating SOC-related emissions sources by their fractions, such as water-soluble organic carbon, readily oxidizable organic carbon, and particulate organic carbon, to provide a more in-depth hotspot analysis and create emission mitigation strategies more tailored to the farmland. Additionally, the integrated methodology can be expanded to include land use transformation to account for cropland expansion.

As this research utilizes various GHG accounting models, there will be a certain degree of uncertainty associated with the models. Secondary data such as the bulk density and coarse fragment also increases the uncertainty, which should be addressed in future research. This study did not quantify the uncertainties of the integrated methodology as each model is well established internationally, but future studies should conduct a more rigorous uncertainty assessment and test the accuracy of the integrated model by directly comparing the results with direct sampling methods.

CRediT authorship contribution statement

Kyle Sebastian Mulya: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jian Ping Tan:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Conceptualization. **Siaw Ping Yeat:** Writing – review & editing, Resources, Funding acquisition. **Chia Ning Clara Yeat:** Writing – review & editing, Resources, Funding acquisition. **Aitazaz Ahsan Farooque:** Writing – review & editing. **Sheng Zhou:** Writing – review & editing. **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.

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Appendix A. Supplementary data

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Data availability

The authors do not have permission to share data.

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