



Measuring Greenhouse Gas Levels in Independent Smallholder Oil Palm Farms in Sarawak

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Abstract

Oil palm cultivation is recognized as a significant contributor to global greenhouse gas (GHG) emissions, primarily carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄), driven by agronomic inputs and palm oil mill effluents. Such debate that independent smallholder (ISH) farmers are part of the significant drivers of greenhouse gas (GHG) emissions in the Oil Palm Industry leading to environmental degradation in general is often heavily scrutinized and contested. While the Malaysian Sustainable Palm Oil (MSPO) certification mandates sustainable production across the sector, including independent smallholders, who account for approximately 14.5% of total acreage, the effectiveness of MSPO standards in promoting low-emission practices among ISH remains insufficiently explored. This scoping study measured soil GHG concentrations across 10 independent smallholder farms with varying fertilizer and pesticide application rates and associated with estimates generated by the MSPO GHG Calculator. Measured soil CO₂ concentration was 1648ppm to 4703ppm while for the emission of soil N₂O concentration was 303 ppm to 500 ppm. CH₄ was not detected. The soil concentrations of GHG were closely related to the calculated GHG which ranged from 4.07 Kg CO₂/yr to 18.36 Kg CO₂/yr determined by the farm age, type, application rate and frequencies of chemical fertilizers and pesticides. The findings were significant providing field validated data to draw conclusions of lower input agronomic practices of ISH farms compared to plantation scale keep GHG emission far below critical environmental thresholds.

Keywords: Oil Palm Cultivation, Greenhouse Gas Emission, Malaysian Sustainable Palm Oil (MSPO) Certification, Independent Smallholders, MSPO GHG Calculator, Critical Environmental Thresholds

1. Introduction

Sarawak has the largest number of independent smallholder (ISH) oil-palm farms according to the publicly report of 46,584 independent smallholders managing 256,738 hectares in 2023 (Bernama, 2025). The ISH sector is economically significant in Sarawak because they convert land-based production into household income, rural employment, and fresh-fruit-bunch (FFB) supply for the state's milling and downstream industries. As defined by Malaysian Palm Oil Board (MPOB, 2025), ISH own and manage their farms directly, generally on holdings below 40.46 hectares (100 acres) and therefore retain substantial control over production, marketing, and farm investment decisions. Their income circulates through rural economies via spending on labour, transport, fertiliser, machinery, local retail, and service providers. Economically, this group strengthens the resilience and inclusiveness of Sarawak's palm-oil value chain, providing a dispersed source of FFB, support mill utilisation, and create income opportunities in districts where formal employment may be limited. However, the sector's economic contribution depends on productivity, farm management, and continuing access to markets. Rising input and labour costs, variable FFB prices, ageing palms, logistics across Sarawak's dispersed rural areas, and sustainability requirements can constrain profitability. Increasingly, ISH face growing challenges in meeting greenhouse gas (GHG) primarily carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄), and sustainability-related market rules, thus pressure from buyers to demonstrate lower-emission practices. These requirements can increase compliance costs and risk excluding smallholders from premium or export-oriented supply chains. According to Martens et al. (2020), small-scale palm oil production by the ISH is generally less harmful. The Malaysian Sustainable Palm Oil (MSPO) 2.0 provides a standard specifically for ISH mandating MSPO Certification, however, many of them have limited time, technical knowledge, digital access, and funds to document fertiliser use, field practices, land history, and emissions related information (Kumaran 2019, Abidin et al. 2024, MSPO, 2025). This scoping study measured soil GHG concentrations across 10 independent smallholder farms with varying fertilizer and pesticide application rates and associated with estimates generated by the MSPO GHG Calculator.

2. Literature review

Oil palm production has been advocated to contribute to climate change with the strongest evidence linking high GHG emissions to land-use change, particularly when tropical forest or carbon-rich peatland is cleared and drained for plantations. Clearing releases carbon stored in vegetation, while peat drainage exposes organic soil to decomposition and can produce continuing CO₂ and N₂O emissions (Miettinen et al., 2017, Pärn et al., 2018, IPCC, 2022). Fertiliser uses



generate N₂O, while diesel used in field work, transport, and milling adds CO₂ emissions. A second major source is palm-oil-mill effluent (POME), a high-organic-content wastewater treated in open anaerobic ponds decomposition produces methane (CH₄), a powerful greenhouse gas. Measurements at a Sarawak mill found that CH₄ accounted for more than 85% of the treatment system's climate impact, demonstrating that mill operations can be an important emissions hotspot (Onodera et al., 2026). A plantation life-cycle assessment found fertilising to be the largest operational emissions contributor, accounting for approximately 0.07 t CO₂ equivalent (CO₂e) per tonne of FFB (Harimurti et al., 2021). However, oil palm itself is not inherently a high-emission crop. It has a high oil yield per hectare compared with many alternative vegetable-oil crops (Hasanudin et al., 2015). In addition, ISH may have lower environmental impacts than large agro-industrial oil-palm operations because their farms are generally smaller and less intensive (Martens et al., 2020). Initial GHG emissions from ISH farms may be significant primarily associated with historical land-use change and peat drainage where cultivation occurs on peat soils. For established farms, nitrogen (N) fertiliser application is typically the principal manageable emission source because of emissions from fertiliser production and soil N₂O release. Fuel use for farm operations and transport contributes additional emissions, whereas CH₄ is generally more significant at the palm-oil-mill stage through POME treatment than at the farm stage. However, direct, farm-level measurements for ISH holdings in Sarawak remain limited; therefore, emissions estimates should not be assumed to be identical to those of large estates.

The MSPO GHG Calculator was initiated as part of implementing the revised MSPO 2.0 standard (MS 2530:2022 providing Malaysian oil-palm plantations, mills, and processing facilities, a standard method to identify, calculate, report, and reduce their greenhouse-gas emissions. It is an online greenhouse-gas accounting tool under the Malaysian Sustainable Palm Oil certification scheme and estimates emissions in CO₂e from activities such as land-use change, peat management, fertiliser application, fuel and electricity use, transport, and palm-oil-mill effluent treatment, while also considering carbon sequestration by palms and conservation areas. The calculator supports MSPO certification requirements, improves consistency and transparency in emissions reporting, supports Malaysia's climate commitments, and helps producers meet increasingly strict international sustainability and market expectations (MSPO, 2026). For smallholders, its intended role is primarily to build awareness of farm emissions and support lower-emission practices, as it is not mandatory for ISH farms below that threshold. Consequently, farm-level GHG data for independent smallholders below this threshold remain limited. Soil GHG concentration is the amount of a gas present in soil air or in a chamber headspace at a particular time, commonly reported as ppm or ppb. In oil-palm farms, a high soil-gas concentration may indicate strong biological production of CO₂, N₂O, or CH₄, reflecting root respiration and microbial decomposition of organic matter but it does not automatically mean high emissions to the atmosphere (Ishikura et al., 2019). Emission depends on the concentration gradient between soil and air and on gas diffusion through the soil. Soil moisture, water-table depth, texture, compaction, temperature, rainfall, and root activity can alter this relationship. N₂O level commonly increases after nitrogen-fertiliser application, particularly when soil moisture is high; and CH₄ may be emitted in waterlogged conditions but can be negligible or even be absorbed by well-drained soils. Ishikura et al. (2014) showed that N₂O varies strongly by soil type, with peat soils having far higher emissions than sandy soils. Thus, concentration data are useful indicators of potential GHG production. Soil GHG concentration is expected to show a positive, but not necessarily linear, association with calculated farm-level GHG emissions. Higher soil CO₂ and N₂O concentrations may indicate greater biological activity and fertiliser-related N transformation, which can contribute to higher soil surface fluxes and CO₂e emissions (Kusa et al., 2008; Ishikura et al., 2019). However, concentration alone cannot quantify annual GHG emissions because surface flux is also affected by gas diffusion, soil moisture, temperature, water-table depth, and management practices. In addition, calculator-derived CO₂e includes upstream and operational sources that are not directly measured by soil-gas concentration.

3. Conceptual Framework

The framework as indicated in Figure 1 proposes that farm characteristics, management practices, and environmental conditions influence biological processes in oil-palm soils, including respiration, nitrogen transformation, and organic-matter decomposition. These processes affect soil CO₂, N₂O, and CH₄ concentrations. In parallel, farm characteristics and management data are entered into the MSPO GHG Calculator to generate calculated CO₂e. The study then examined the association between measured soil GHG levels and calculated emissions, while identifying whether the calculator adequately represents conditions on independent smallholder farms in Sarawak.

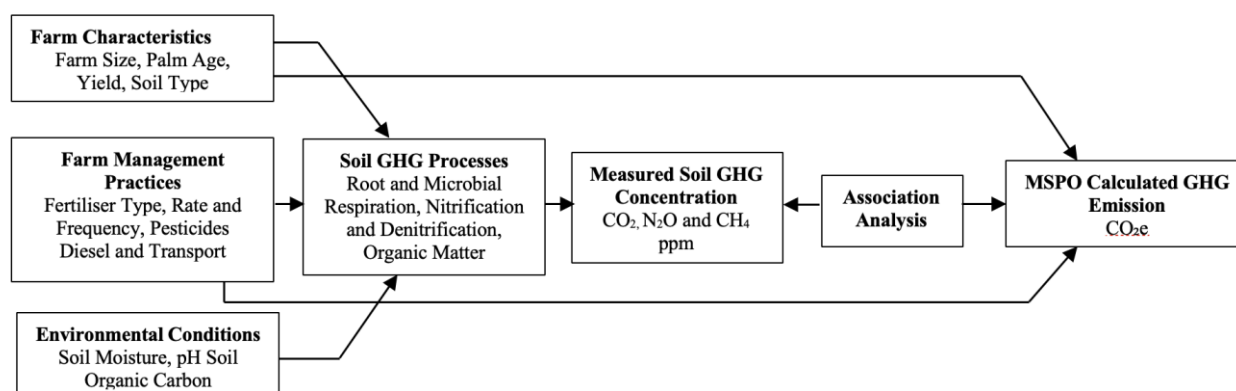


Figure 1: The conceptual framework of the study

4. Research Questions

The research questions formulated are as follow:

- N fertiliser types, high application rates and frequencies are associated with higher soil GHG concentration and Calculated CO₂e.
- Environmental conditions moderate the relationship between farm management and soil GHG level.
- Measured soil GHG level is positively associated with MSPO-calculated CO₂e.

5. Significance of Study

The information provides farm-level evidence on the relationship between N-fertiliser management and GHG emissions among ISH oil-palm farmers in Sarawak. While fertiliser use is recognised as an important source of agricultural N₂O emissions, data from large estates may not accurately reflect ISH practices, which often involve smaller farm areas, different fertiliser rates, irregular application schedules, and variable soil conditions. Measuring soil GHG concentration alongside calculated CO₂e emissions will help identify whether fertiliser application is a major emissions driver within ISH farms. The findings may support ISH farmers in promoting more efficient fertiliser practices, such as appropriate application rates, timing, placement, and nutrient management. The study can also contribute locally derived evidence for improving the applicability of GHG-estimation tools to Sarawak's independent smallholder context, where direct farm-level emissions data remain limited.

6. Research Methodology

The study was conducted in February 2025 at 10 selected independent smallholder farms located in Kampung Stungkor and Kampung Kendaie Lundu, Sarawak. The GHG Inventory Data or activity data on farm characteristics and farm management practices were collected from the ISH farms owners and input into the MSPO GHG Calculator to generate the GHG emissions based on CO₂e. The field data collection used a systematic sampling design along diagonal transects on each farm. Ten sampling points as replicates from each farm were marked with the first palm selected randomly, and subsequently every 10th palm along the transect line. Soil samples were collected by using soil auger at two sampling points per palm. Sample were taken at 3 different depths at intervals of 20 cm. Each soil sample was placed in labelled plastic bag and taken to the laboratory in Universiti Teknologi MARA, Sarawak Branch, for further analysis. The soil CO₂, CH₄ and N₂O concentrations were measured using the static chamber method. The chamber was anchored into the soil at 10 cm depth to capture the GHG emission at 10 marked sampling points where soil samples were collected in each farm in the evening. After 12 hours, the concentration of the gas samples in the chamber were measured in the following morning. The concentration of the CO₂ and CH₄ gas samples (ppm) were measured using KP830 Portable Gas Detector and N₂O gas sample using S316 Pump Multi-4 Gas Detector. The soil samples were weighted immediately upon arrival at the laboratory to obtain the wet weight. The samples were then placed in open plastic container and air-dried. To determine dry weight, the soil sample were oven-dried at 105° C until a constant weight was achieved. Soil moisture content was calculated using the following formula:

$$\% \text{ Soil Moisture} = \frac{\text{Wet Weight of Soil} - \text{Dry Weight of Soil}}{\text{Wet Weight of Soil}} \times 100$$



Soil pH was measured using electric pH meter method as described by Kalra (1995). 10 g of air-dried soil, two mm-sieved soil was weighed in a 50 mL beaker and mixed with 50 mL of distilled water. The samples were continuously stirred for 10 minutes using a magnetic stirrer and left overnight. The pH of the mixture was measured using a calibrated pH meter. Measurement was repeated until a constant reading was obtained. The pH meter electrode was rinsed with distilled water before measuring each subsequent sample. The soil carbon content were determined using the Walkley-black method. This method estimates using soil organic carbon (OC) through oxidation with acidic dichromate followed by titration of excess dichromate with ferrous sulphate.

7. Findings

Table 1 indicates the emission factor and emission result (E_q) of type, quantity of fertilizers and pesticides their applications on environmental conditions and yield of the 10 ISH farms. Emission Result (E_q) stands for CO₂e standardizing the multiple GHG of CO₂, CH₄ and N₂O into a single unit based on their global warming potential in relation to the types of fertilizers, pesticides and their application frequency. This is generated from the calculator on the fundamental activity-based formula Emission Result (E_q) = Activity Data X Emission Factor (Muhammad, 2022). Five farms use pesticide Glyphosate once a year while 2 farms apply twice a year. All the farms practice manual weeding. The % carbon indicating the quantity of organic matter ranged from 26.39 to 36.18. The soil moisture ranged from 25.06 % to a high of 56.64%. The pH ranged from 4.58 to 5.64. There were 4 immature farms while the matured farms yielded between 9.00 MT/Ha to 32.81MT/Ha.

Table 1: Emission Factor and Emission Result (E_q) of type, quantity of fertilizers and pesticides their applications on Environmental Conditions and Yield

Environmental Conditions and Field									
Farm	Fertiliser					Environmental Condition			Yield/ Ha (MT)
	Type	Annual Data (Qty/kg)	% Active Ingredient	Emission		% Carbon	Soil Moisture (%)	pH	
				Factor	Result (Eq)				
1 12 yrs	Ammonium Nitrate	6	34	3.450	7	34.11	28.15	4.89	12.25
	Compound Fertilizer (COMPACT FERTILISER)				2				
	N-Fertilizer (N)	2	12	5.881					
	Phosphate (P ₂ O ₅)		6	1.011					
	Potash (K ₂ O)		24	0.576					
	Magnesium (MgO)		3	1.07					
	Glyphosate		2	41					
2 7 yrs	Compound Fertilizer (YARAMILA)				4	30.95	25.06	5.04	16.57
	N-Fertilizer (N)	4	13	5.881					
	Phosphate (P ₂ O ₅)		11	1.011					
	Potash (K ₂ O)		21	0.576					
	Magnesium (MgO)		2	1.07					
3 7 yrs	Compound Fertilizer (YARAMILA)				4	29.31	38.75	4.87	32.81
	N-Fertilizer (N)	4	13	5.881					
	Phosphate (P ₂ O ₅)		11	1.011					
	Potash (K ₂ O)		21	0.576					
	Magnesium (MgO)		2	1.07					
	Compound Fertilizer (GOLDEN FARM)								
	N-Fertilizer (N)	4	15	5.881					
	Phosphate (P ₂ O ₅)		15	1.011					
	Potash (K ₂ O)		15	0.576					
	Magnesium (MgO)		2	1.07					
Glyphosate	1		41	11.522		5			
4 (12 yrs)	Ammonium Fertilizer	2	15	3.450	1	36.18	56.64	5.02	9.0
	Compound Fertilizer (CAP BUNGA RAYA MERAH)				2				
	N-Fertilizer (N)	2	13	5.881					
	Phosphate (P ₂ O ₅)		6	1.011					
	Potash (K ₂ O)		22	0.576					
	Magnesium (MgO)		3	1.07					
	Glyphosate		1	41					
5	Compound Fertilizer (TWIN ARROW COMPACT)				3	26.83	45.90	4.58	16.0



	N-Fertilizer (N)	3	12	5.881						
	Phosphate (P ₂ O ₅)		6	1.011						
	Potash (K ₂ O)		24	0.576						
	Magnesium (MgO)		3	1.07						
6 (1 yr)	Compound Fertilizer (YARAMILA)				2	29.79	36.63	5.17	-	
	N-Fertilizer (N)	2	13	5.881						
	Phosphate (P ₂ O ₅)		11	1.011						
	Potash (K ₂ O)		21	0.576						
	Magnesium (MgO)		2	1.07						
7 (4.5 yrs)	N-Fertilizer (N)	3	12	5.881	3	32.87	47.16	5.64	-	
	Compound Fertilizer (AGROBRIDGE)									
	N-Fertilizer (N)		12	5.881						
	Phosphate (P ₂ O ₅)		12	1.011						
	Potash (K ₂ O)		17	0.576						
	Magnesium (MgO)	2	1.07							
	Glyphosate	1	41	11.522	5					
8 (0.5 yrs)	Ammonium Nitrate	2	15	3.450	1	26.39	38.39	5.44	-	
	Compound Fertilizer (YARAMILA)									
	N-Fertilizer (N)	2	13	5.881	2					
	Phosphate (P ₂ O ₅)		11	1.011						
	Potash (K ₂ O)		21	0.576						
	Magnesium (MgO)		2	1.07						
	N-Fertilizer (N)		13	5.881						
	Glyphosate	1	41	11.522	5					
9 (0.25 yrs)	N-Fertilizer	1	13	5.881	1	32.61	54.06	4.95	-	
	Compound Fertilizer (COMPACT FERTILISER)									
	N-Fertilizer (N)	1	12	5.881	1					
	Phosphate (P ₂ O ₅)		6	1.011						
	Potash (K ₂ O)		24	0.576						
	Magnesium (MgO)		3	1.07						
	Glyphosate		1	41						11.522
10 (7 yrs)	Compound Fertilizer (CAP BUNGA RAYA MERAH)				4	33.63	55.23	5.57	17.28	
	N-Fertilizer (N)	4	13	5.881						
	Phosphate (P ₂ O ₅)		6	1.011						
	Potash (K ₂ O)		22	0.576						
	Magnesium (MgO)		3	1.07						
	Glyphosate	2	41	11.522	9					

Table 2 shows the calculated GHG emission generated by the MSPO GHG Calculator based on the fertilizer and pesticide types and the frequencies of application. The total emission ranged from 2.04 kgCO₂/yr to 18.36 kgCO₂/yr.

Table 2: The Greenhouse Gas measured in term of kg CO₂/year from fertilizers and pesticides using Malaysian Sustainable Palm Oil GHG Calculator

Farm No.	Farm Age	Fertilizer Kg CO ₂ / yr	Pesticide Kg CO ₂ / yr	Total Emission Kg CO ₂ /yr
1	13	8.91	9.45	18.36
2	7	4.07	0.0	4.07
3	7	8.64	4.72	13.36
4	6	3.00	4.72	7.73
5	10	2.81	0.0	2.81
6	1	2.04	0.0	2.04
7	5	4.25	4.72	8.97
8	0.5	3.07	4.72	7.80
9	0.25	1.70	4.72	6.43
10	7	3.94	4.72	8.66



Table 5 shows the soil GHG emission converted to equivalent Kg CO₂/yr using the conversion factor of soil CO₂ to Kg CO₂/yr is 1 while the soil N₂O is 298 ranging from 9.23 Kg CO₂/yr to 15.28 Kg CO₂/yr. In this study, CH₄ was not detected. The estimated GHG emissions from fertilizers and pesticides calculated by MSPO GHG Calculator ranged from 2.04 Kg CO₂/yr to 18.36 Kg CO₂/yr. Except for Farm 1, the soil GHG showed higher emission as compared to the estimated GHG. Farm 1 indicated 28% less. Farm 7 indicated the lowest difference of only 3% while Farms 2, 5, 6 and 9 indicated more than 50% differences.

Table 3: Greenhouse Gas (GHG) Emission based on Soil GHG Concentration (ppm) and Malaysian Sustainable Palm Oil (MSPO) GHG Calculator from Independent Smallholder Oil Palm Farms in Lundu, Sarawak

Farm No	Soil GHG Concentration (ppm)		CO ₂ equivalent			MSPO GHG Calculator (Kg CO ₂ /yr)
	CO ₂	N ₂ O	Captured CO ₂ (Factor = 1) C	Captured N ₂ O (Factor = 298) N	Kg CO ₂ /yr Total=C + N	
1	3665±1546.4	467.2± 33.02	0.3665	13.9225	14.29	18.36 (-28%)
2	3908±1653.9	499.8± 0.45	0.3908	14.8940	15.28	4.07 (73%)
3	4703± 601.0	497.4± 5.27	0.4703	14.8225	15.29	13.36 (13%)
4	3915±1487.8	462.8± 50.50	0.3915	13.7914	14.18	7.73 (45%)
5	3860±1001.9	500.0± 0.00	0.3860	14.9000	15.28	2.81 (82%)
6	1976± 603.1	418.0± 69.70	0.1976	12.4564	12.65	2.04 (84%)
7	1993±1723.0	303.0±187.38	0.1973	9.0294	9.23	8.97 (3%)
8	2583± 742.2	500.0± 0.00	0.2583	14.9000	15.16	7.8 (49%)
9	2256±1560.3	498.0± 4.47	0.2256	14.8404	15.07	6.43 (57%)
10	1648± 657.4	369.0± 25.99	0.1648	10.9962	11.17	8.66 (22%)

8. Discussion

The relatively high FFB yield of Farm 3 with 32.81 MT/Ha/yr above the reported potential yield of 26.6 MT/Ha/yr based on MPOB (2023) is indicated to be associated with the types of fertilisers and pesticides used and their application regimes. However, this relationship should be interpreted alongside other factors, including palm age, soil properties, rainfall, harvesting frequency, and labour availability. By comparison, the national average FFB yield for ISH was reported as 10.60 MT/Ha/yr while estates and organised smallholders in Sabah and Sarawak as an average of 15.29 MT/Ha/yr (MPOB, 2023). Chen et al. (2024) stated that conventional oil palm management involving high fertiliser rates and pesticide application can achieve high yields but also result in substantial soil GHG emissions. Therefore, fertiliser management is a key determinant of GHG emissions, which can be estimated in CO₂e using farm activity data and relevant emission factors. In general, ISH with limited financial capital are applying fertiliser at lower than recommended rates or delay application, as fertiliser is a major production cost and inadequate application is associated with lower FFB productivity (Abdullah, 2013). Lower N input may reduce fertiliser-related soil N₂O emissions and calculator-derived CO₂e per Ha because N fertiliser is an important emissions source in oil-palm cultivation (Ishikura et al., 2014). However, it should not be concluded that these farms are below a universal “GHG threshold” or do not contribute to climate change as any positive GHG emission contributes to atmospheric warming. In addition, prolonged under fertilisation may reduce FFB yield and potentially increase emission intensity when expressed per tonne of FFB produced. Therefore, both total emissions (CO₂e /Ha/yr and emissions intensity (CO₂e /MT of FFB) should be assessed, rather than interpreting low fertiliser use as automatically climate-friendly.

It can be argued that oil-palm productivity and soil GHG emissions should not be examined separately because both are strongly mediated by soil conditions, particularly soil pH, moisture, and soil organic carbon (SOC). Soil pH affects nutrient availability and microbial activity, thereby influencing palm nutrient uptake and the microbial processes that produce N₂O. Soil moisture regulates water availability for palm growth and controls soil aeration; excessively wet conditions may promote N₂O and CH₄ formation, whereas low moisture or a deep water table can accelerate peat oxidation and CO₂ emissions. SOC is equally important because it supports soil fertility, structure, water retention, and nutrient cycling, but readily decomposable organic carbon can also stimulate microbial respiration and increase CO₂ and N₂O production. Accordingly to Hasimah et al. (2021), productive farms may not necessarily have low emissions; management that improves nutrient availability and yield can also increase GHG emissions if it creates favourable conditions for microbial decomposition and N loss. Similarly, Ishikura et al. (2014) showed that soil type and N fertiliser management substantially affected CO₂ and N₂O fluxes in oil-palm plantations. Therefore, assessing pH, soil moisture, and SOC together with fertiliser practices is essential for identifying management strategies that improve FFB yield



without increasing the GHG footprint of ISH farms. A positive association between measured soil GHG levels and MSPO-calculated CO₂e is theoretically expected because both measures respond to the same underlying farm-management activities as shown in the conceptual framework. The MSPO GHG Calculator estimates emissions from activity data such as fertiliser use, land-use change, peat management, energy use, and transport, while soil measurements capture the biological response of the soil to these management practices. Higher N fertiliser inputs stimulate nitrification and denitrification in the soil, leading to higher measured N₂O concentration. Similarly, peat drainage, low water tables, and loss of soil organic carbon can increase both calculator-derived land-use emissions and measured soil CO₂. Similarly, they increase the MSPO GHG calculator's emissions through fertiliser-related emission factors. Therefore, farms with higher calculated CO₂e are expected to have higher measured soil GHG levels, particularly where fertiliser is the major sources of emissions. This relationship is supported by evidence that fertiliser management and soil conditions affect measured GHG emissions in oil-palm systems. Ishikura et al. (2014) found that soil type and nitrogen fertiliser management significantly influenced CO₂ and N₂O level, while Chen et al. (2024) showed that high fertiliser and herbicide inputs under conventional oil-palm management were associated with high yields but also substantial soil GHG emissions, particularly N₂O. Hasimah et al. (2021) reported that variation in peat type, soil moisture, water-table depth, and management was associated with differences in both soil CO₂ efflux and FFB yield.

9. Conclusion

This study concludes that reducing the GHG footprint of ISH oil-palm farms in Sarawak requires an integrated approach to nutrient management, soil-condition monitoring, and emissions accounting. Fertiliser type, application rate, and application frequency are expected to be important drivers of soil GHG concentrations and calculated CO₂e; therefore, fertiliser use should be matched to palm nutrient requirements and applied at appropriate rates, timing, and placement to minimise avoidable N losses. Environmental conditions, including soil pH, moisture, soil organic carbon, temperature, and water-table depth, must also be considered because they influence how farm-management practices affect soil GHG levels. Finally, a positive relationship between measured soil GHG levels and MSPO calculated CO₂e would demonstrate the value of combining field measurements with calculator-based estimates. Together, these findings can provide evidence for more accurate GHG assessment, improved fertiliser practices, and context-specific MSPO guidance for independent smallholders in Sarawak, helping to maintain FFB productivity while reducing emissions.

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