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Enhancing oil palm productivity and lowering emissions through the application of local organic waste

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ABSTRACT

Oil palm plantations are a key component of Indonesia's agricultural economy but are also a major source of greenhouse gas (GHG) emissions. This study aimed to evaluate the use of local organic inputs – palm oil mill effluent (POME) and empty fruit bunches (EFB) – as sustainable alternatives to inorganic fertilizer in oil palm cultivation. A field experiment was conducted on mineral soils in South Kalimantan (2023–2024) using 18 randomized blocks with three treatments: NPK fertilizer, EFB, and POME. Emission intensities were estimated following IPCC guidelines, and productivity was assessed based on total fresh fruit bunch (FFB) yield. Results indicated that POME produced the highest yield and lowest emission intensity, while EFB provided the greatest absolute reduction in GHG emissions. These findings demonstrate the potential of integrating local organic waste into fertilization strategies to support low-emission, sustainable palm oil production within a circular economy framework.

Keywords: oil palm, POME, EFB, greenhouse gas emissions, sustainable agriculture.

INTRODUCTION

Oil palm plantations represent a vital sector of Indonesia's agricultural industry, both economically and socially (Hidayat et al., 2023; Murphy et al., 2021). However, the long-term sustainability of this sector is increasingly threatened by its adverse environmental impacts, particularly greenhouse gas (GHG) emissions. Key plantation management activities – such as land clearing, chemical fertilizer application, and waste treatment—contribute significantly to GHG emissions, thereby exacerbating global climate change (Khatun et al., 2017). Consequently, the adoption of more environmentally friendly oil palm plantation practices is essential to ensure a sustainable industry in the future (Purwadi et al., 2023).

GHG emissions from the palm oil industry, particularly methane (CH_4) and carbon dioxide (CO_2), originate from various sources, including the processing of fresh fruit bunches (FFB) in palm oil mills and the management of processing waste (Hong, 2022). One of the main waste products from palm oil processing is palm oil mill effluent (POME), which contains high levels of organic matter and can emit methane if not properly managed (Singh et al., 2010). In addition, the use of inorganic fertilizers in oil palm cultivation contributes to emissions of nitrous oxide (N_2O), a potent greenhouse gas (Fan et al., 2021; Inselsbacher et al., 2011). Therefore, it is essential to implement emission-reduction strategies that not only mitigate GHG emissions but also maintain productivity and support the long-term sustainability of plantations (Khatri-Chhetri et al., 2022).

One such strategy involves the use of organic matter as an alternative input in oil palm plantation management (Quezada et al., 2022). Organic residues, such as empty fruit bunches (EFB) and POME, can enhance soil quality and reduce reliance on chemical fertilizers (Adu et al., 2022; Suksaroj et al., 2023a). The application of organic materials is also considered effective in mitigating GHG emissions, as the decomposition of organic waste generally produces less methane compared to the excessive use of chemical fertilizers (Ayaz et al., 2023; Liem et al., 2022). Moreover, organic matter contributes to increased soil organic carbon, which improves soil fertility and water retention capacity (Dhaliwal et al., 2021; Gong et al., 2020).

The use of organic inputs thus offers dual benefits: reducing GHG emissions and enhancing the sustainability of oil palm production systems (Supriatna et al., 2023). Furthermore, the utilization of organic waste from FFB processing helps minimize environmental pollution by reducing the volume of unmanaged waste (Priambodo and Erdiansyah, 2024; Suksaroj et al., 2023b).

Empty EFB are a major solid by-product of palm oil processing and have considerable potential as a source of organic nutrients for the soil (Suksaroj et al., 2023). They contain essential nutrients such as nitrogen (0.32%), phosphorus (0.09%), potassium (1.16%), and magnesium (0.12%), among others (Hayawin et al., 2012). Other studies have reported nitrogen contents ranging from 0.26–0.38% in fresh EFB, and from 0.65–0.94% on a dry matter basis (Pardon et al., 2016).

POME, another significant by-product of palm oil production, mainly consists of water, organic matter, and nutrients (Anyaoha and Zhang, 2023). On average, it contains 457 mg/L nitrogen (N), 12 mg/L phosphorus (P), 375 mg/L potassium (K), and 56 mg/L magnesium (Mg) (Wahyuni, 2018). The nitrogen is mainly present as ammonia and total nitrogen, with concentrations ranging from 0.2 to 0.5 g/L (Maria and Anggraini, 2018).

A major challenge for the palm oil industry is achieving a balance between high productivity and environmentally sustainable management practices (Abubakar et al., 2023; Cheah et al., 2023). By applying organic materials to reduce GHG emissions, the industry has the potential to meet the growing global demand for sustainability while contributing to broader climate change mitigation efforts (Jamil and Asrol, 2024).

Although several previous studies have examined the use of organic inputs to enhance oil palm productivity or reduce greenhouse gas emissions, most were limited to laboratory-scale trials, simulations, or single-parameter analyses. This study presents a novel field-based evaluation that simultaneously addresses both productivity and emission outcomes using local organic inputs (POME and EFB) on mineral soils. It also introduces a practical low-emission management framework aligned with circular economy principles, offering both scientific relevance and operational applicability.

MATERIALS AND METHODS

Research procedure

This research was conducted on mineral soils within the oil palm plantation of PT. Citra Putra Kebun Asri (CPKA), located in Jorong District, Tanah Laut Regency, South Kalimantan. The study aims to assess the effects of organic and inorganic input applications on GHG emissions and oil palm productivity. Data were collected on the application of organic materials, namely EFB and POME, as well as inorganic fertilizers, based on experiments carried out across 18 experimental blocks. The treatment blocks were randomly assigned, with each treatment replicated in six blocks.

Productivity was assessed based on FFB yield (Tonnes/ha), bunches per tree, and average bunch weight (ABW) between 2023 and 2024. The study was conducted on 18 blocks planted in 2008, covering a total area of 363 hectares, with an average planting density of 131 oil palm trees per hectare. The EFB used in this study were applied in fresh form without prior composting and were distributed as mulch around the base of the oil palm trees, specifically outside the harvesting path (non-circular area). Nutrient composition data, including nitrogen (N), phosphorus (P), and potassium (K) contents, were obtained from the analysis reported by Hayawin et al. (2012). The palm oil mill effluent (POME) applied in this study was pre-treated in stabilization ponds through sequential sedimentation and biological processes involving anaerobic, facultative, and maturation stages to reduce organic load. The treated effluent had a BOD concentration ranging from 2,000 to 3,500 mg/L, which remained below the regulatory threshold of 5,000 mg/L for land application. The application was conducted using a flat-bed irrigation system, wherein the effluent was evenly distributed across shallow, leveled basins interconnected by drainage channels, allowing gravity-driven flow that followed the natural topography. Nutrient composition, including N, P, and K, was obtained from the analysis reported by Wahyuni (2018).

GHG emissions during the mature phase (MP) of oil palm cultivation were estimated based on two primary sources of field emissions: fertilization and pesticide application activities. These emissions were calculated annually for each experimental block using the following equation:

$$EMP = Efertilization\_MP + Epesticide\_MP \quad (1)$$

where: *EMP* represents total GHG emissions (kg CO_2-eq) from the mature phase per year, *Efertilization_MP* is the emission from fertilizer application, *Epesticide_MP* is the emission from pesticide application.

Each emission component was calculated using the standard equation recommended by the Intergovernmental Panel on Climate Change (IPCC, 2006; 2021):

$$GHG\ Emission\ (CO_2 - eq) = AD \times EF \quad (2)$$

where: *AD* (activity data) refers to the amount of input applied (e.g., kg of fertilizer or liters of pesticide), *EF* (emission factor) is the emission value per unit of activity (e.g., kg CO_2-eq/kg fertilizer), sourced from internationally recognized databases such as IPCC default values and the ISCC EU 205 methodology (ISCC, 2021). Emissions from nitrogen-based fertilizers were adjusted using the GWP (Global Warming Potential) of nitrous oxide (N_2O), while pesticide emissions were derived from input-specific energy and emission coefficients. All emission values were converted into carbon dioxide equivalents (CO_2-eq) using the most recent 100-year GWP values reported by the IPCC. The emission estimation accounted only for direct field emissions during the maintenance phase and excluded upstream emissions (e.g., from fertilizer manufacturing or transport).

To assess the effects of organic and inorganic applications on GHG emissions and oil palm productivity components, a descriptive analysis was initially conducted to provide an overview of the existing data. Subsequently, the data were analyzed using ANOVA, followed by the least significant difference (LSD) test to identify statistically significant differences among treatments.

RESULTS

This study employs three fertilization treatments: inorganic fertilization using NPK fertilizer, and organic fertilization using EFB and POME. Table 1 presents the mean number of applications for each fertilizer type under each treatment over the two-year period (2023–2024), illustrating consistent application rates intended to evaluate their effects on oil palm productivity.

The fertilization rate of NPK 15:8:23 was 7 kg per tree per year, with an average planting density of 131 trees per hectare, resulting in a total application of 917 kg NPK per hectare annually. EFB were applied at a rate of 300 kg per tree per year, equivalent to 39,300 kg per hectare per year. Additionally, POME was applied at a rate of 600 m^3 per hectare per year using a flat-bed system.

Table 2 presents the estimated amounts of primary macronutrients – N, P, and K – based on the number of fertilization applications. The estimates are derived from the nutrient content of each fertilizer source, including inorganic fertilizers (NPK) and organic materials such as oil palm EFB and POME, using data from previously published studies.

The macro-element content from the application of inorganic fertilizer (NPK 15:8:23) at an average rate of 917 kg/ha/year corresponds to approximately 137.55 kg N, 73.36 kg P, and 210.91 kg K per hectare. For EFB, applied at 39,300 kg/ha/year with nutrient composition based on Hayawin et al. (2012), the estimated nutrient contents are 125.76 kg N (0.32%), 35.37 kg P (0.09%),

Table 1. Mean number of fertilizer applications for each treatment

Treatments	Year		
	2023	2024	Average
NPK 15.8.23 kg/ha/year	917	917	917
EFB kg/ha/year	39,300	39,300	39,300
POME m^3/ha/year	600	600	600

Table 2. Estimated quantities of macronutrients (N, P, K) for each treatment

Treatments	Amount	Macronutrient Content		
		N	P	K
NPK 15.8.23 kg/ha/year	917	137.55	73.36	210.91
EFB kg/ha/year	39,300	125.76	35.37	455.88
POME m^3/ha/year	600	274.20	7.20	225.00

and 455.88 kg K (1.16%) per hectare. According to Wahyuni (2018), POME contains 457 mg/L of N, 12 mg/L of P, and 375 mg/L of K, resulting in estimated contributions of 274.20 kg N, 7.20 kg P, and 225.00 kg K per hectare. In addition to its nutrient content, it is a colloidal suspension composed of 95–96% water, containing 0.6–0.7% oil and grease and 4–5% total solids (Azmi et al., 2023; Yovita et al., 2018). These findings indicate that EFB contains the highest potassium content, while POME contributes the greatest amount of nitrogen. Statistical analysis of the impact of different treatments on oil palm productivity components is presented in Table 3.

This study demonstrates that the application of POME as a fertilization treatment yields the highest oil palm productivity in both 2023 and 2024. In 2023, the POME application resulted in a yield of 23.19 tonnes/ha, surpassing the yields obtained from inorganic fertilizers (21.73 tonnes/ha) and empty fruit bunches (21.40 tonnes/ha). This positive trend continued in 2024, with POME achieving a significantly higher yield of 25.20 tonnes/ha. The differences among treatments were statistically significant at the 5% level, as indicated by differing letter annotations (e.g., "a" versus "b"). These findings suggest that POME serves not only as a nutrient source but also sustainably enhances soil fertility.

The calculation of GHG emissions in this study is limited to anthropogenic activities occurring during the mature (production) phase of oil palm plantations, with a particular focus on fertilization and maintenance practices, including pesticide applications. Data on these activities are used to estimate emissions by multiplying the frequency or quantity of each activity by the corresponding emission factors, as outlined in the guidelines provided by the Intergovernmental Panel on Climate Change (IPCC). The results of these calculations are presented below:

Three treatment types – namely inorganic fertilizers, EFB, and POME – showed significant differences in GHG emissions per hectare. The application of inorganic fertilizers resulted in the highest emissions, reaching 1,863.42 kg CO_2-eq per hectare. In contrast, POME application produced 1,610.84 kg CO_2-eq per hectare, while the EFB treatment recorded the lowest emissions at 767.82 kg CO_2-eq per hectare. These findings suggest that organic-based inputs such as EFB and POME generally lead to lower GHG emissions compared to inorganic fertilizers.

DISCUSSION

The results of the study indicate that the application of POME as a fertilizing agent significantly enhances palm oil productivity compared to other treatments in both 2023 and 2024. Specifically, POME application resulted in a yield of 23.19 Tonnes per hectare in 2023, which increased to 25.20 tonnes/ha in 2024, outperforming inorganic fertilizers and EFB applications (Figure 1).

These findings align with those of Priambodo and Erdiansyah (2024), who reported that POME improves FFB yields due to its high content of

Table 3. Effect of inorganic fertilizers, empty oil palm bunches, and POME on oil palm productivity

Treatment	Tonnes per Ha			Bunches per Tree			Average bunch weight		
	2023	2024	Δ Tonnes /Ha	2023	2024	Δ Bunches /Trees	2023	2024	Δ ABW kg
Inorganic fertilizer	21.73 b	22.95 ab	1.22	7.65 a	7.51 a	-0.13	21.60 a	23.28 a	1.68
EFB	21.40 b	23.00 ab	1.60	7.62 a	7.91 a	0.28	21.45 a	22.23 a	0.78
POME	23.19 ab	25.20 a	2.01	8.00 a	8.10 a	0.10	22.17 a	23.78 a	1.61

Note: Different letters show a statistically significant difference according to the Tukey test at a 95% confidence level (real level 5%).

Table 4. Effect of organic and inorganic fertilizer applications on greenhouse gas emissions

Treatment	Tonnes per ha			kg CO_2-eq/ha			kg CO_2-eq/tonnes FFB		
	2023	2024	Δ tonnes /Ha	2023	2024	Δ Kg CO_2-eq/Ha	2023	2024	Δ Kg CO_2-eq/tonnes EFB
Inorganic fertilizer	21.73 b	22.95 ab	1.22	1863.42 a	1863.42 a	-	86.32 a	81.73 a	-4.59
EFB	21.40 b	23.00 ab	1.60	767.82 b	767.82 b	-	36.17 b	33.76 b	-2.41
POME	23.19 ab	25.20 a	2.01	1610.84 c	1610.84 c	-	69.56 c	63.90 c	-5.66

Note: different letters show a statistically significant difference according to the Tukey test at a 95% confidence level (real level 5%).

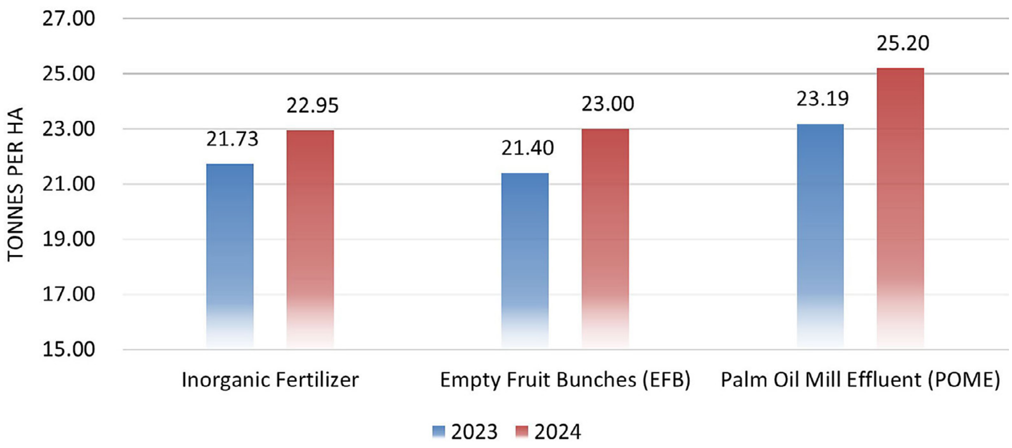

Figure 1. Fresh fruit bunch yields by fertilizer type (2023 vs 2024)

macronutrients (N, P, K) and organic matter. Conversely, Akra et al. (2024) emphasized that inorganic fertilizers remain important because of their precision and rapid plant uptake. Nevertheless, when applied in an integrated and well-measured manner, POME can be as effective as, or even superior to, chemical fertilizers (Pujono et al., 2021). With a yield increase of 2.02 tonnes per ha, POME has demonstrated its potential as the most effective treatment for improving palm oil productivity on mineral soils.

There was no statistically significant difference in the number of bunches per tree among treatments in either 2023 or 2024, as indicated by the identical letter designation ("a") in Table 3. Nevertheless, the numerical data show that the treatment with POME resulted in the highest number of bunches, averaging 8.0 in 2023 and increasing slightly to 8.1 in 2024 (Figure 2).

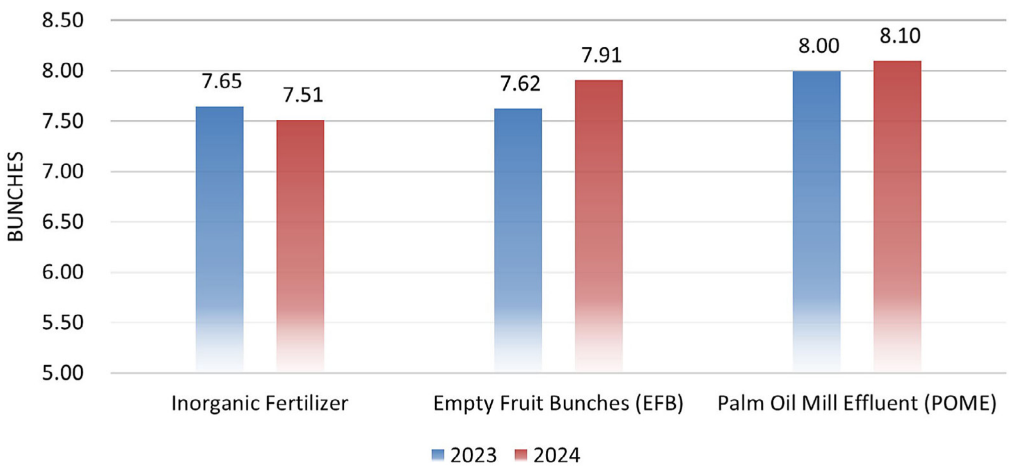

Figure 2. Bunches per tree by fertilizer type (2023 vs 2024)

This trend reflects the consistency of POME in promoting bunch formation, despite the lack of statistical significance. These findings are consistent with those of Ooi et al. (2007) and Hau et al. (2020), who reported that POME application enhances the availability of macro- and micronutrients essential for the development of fresh fruit bunches, thereby supporting oil palm productivity. Interestingly, the treatment with EFB exhibited the largest year-on-year increase (+0.28), despite having a lower absolute number of bunches compared to the POME treatment. This suggests that while EFB may offer long-term potential for yield improvement, its short-term effectiveness remains inferior to that of POME. These observations align with findings from Nasution et al. (2023) and TehBoon et al. (2010), which highlights that EFB improves soil structure and water retention but requires more time to decompose and exhibit agronomic benefits. Furthermore, Hatta et al. (2014) noted that the long-term application of EFB can eventually enhance oil palm productivity despite a delayed initial response. Overall, POME emerged as the numerically superior treatment during the observed period.

The average bunch weight (ABW) increased across all treatments from 2023 to 2024. However, the statistical analysis presented in Table 3 indicates that this increase was not statistically significant, as all treatments were assigned the same letter ("a") in the post-hoc test. This suggests that, despite numerical differences, the variations in ABW were not substantial enough to be attributed to the effects of different treatments (Figure 3).

The POME treatment recorded the highest ABW in 2024, reaching 23.78 kg, up from 22.17 kg in 2023. In contrast, the Inorganic Fertilizer treatment showed the greatest numerical increase (+1.68 kg), although its final ABW value remained lower than that of POME. Thus, while inorganic fertilizer demonstrated the largest absolute gain, POME remains the most effective treatment based on final bunch weight. These findings are consistent with those of Prayitno and Indradewa (2008) and Aziz et al. (2020), who reported that POME can enhance soil physical properties and improve bunch productivity. However, these results somewhat contradict the findings of Sudradjat (2019) and Han et al. (2022), who reported that inorganic fertilizers produce a faster response in oil palm growth and productivity compared to organic materials. These discrepancies may be attributed to differences in soil conditions and local climate, which can influence the effectiveness of each treatment.

Overall, the results presented in Table 3 indicate that the POME treatment consistently outperformed the other treatments across all observed parameters. This treatment yielded the highest productivity, with a significant increase to 25.20 tonnes of FFB per hectare. It also demonstrated numerical superiority in both the number of bunches per tree (8.10 bunches/tree) and the average bunch weight (23.78 kg). These findings suggest that POME not only serves as a valuable source of organic matter but also supplies essential macronutrients that enhance oil palm growth and yield.

The results presented in Table 4 highlight significant differences among the three treatments. These findings confirm that organic-based inputs, such as EFB and POME, generally result in lower GHG emissions compared to inorganic fertilizers. From a climate change mitigation perspective, the application of EFB has the potential to reduce

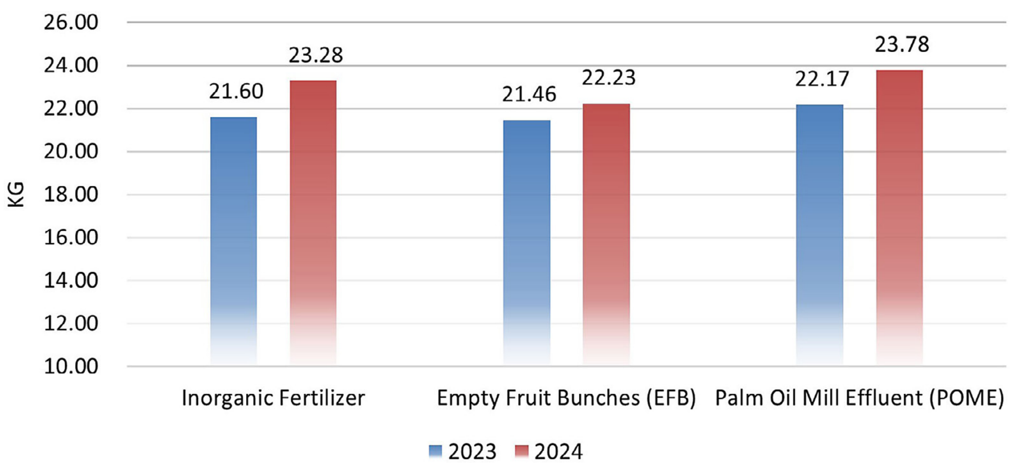

Figure 3. Average bunch weight by fertilizer type (2023 vs 2024)

GHG emissions (Dolah et al., 2021), particularly nitrous oxide (N_2O), which is often released in large quantities during the use of synthetic nitrogen fertilizers (Hansen, 2012; Menegat et al., 2022). A study by Wu et al. (2024) demonstrated that substituting 15% to 100% of synthetic fertilizers with organic alternatives can lead to a cumulative annual reduction in N_2O emissions ranging from 16.2% to 74.9%. This reduction is associated with lower levels of NO_3^- and NH_4^+, along with an increase in soil pH. Similarly, research by Andri et al. (2017) reported that EFB enhances the soil's capacity to retain water and nutrients, thereby decreasing reliance on chemical fertilizers and improving nutrient use efficiency. Rahman and Lim (2000) also found that EFB decomposition in the field facilitates the slow and sustained release of nutrients, making it suitable for long-term application in oil palm plantations. Beyond agronomic and environmental advantages, the use of EFB aligns with the principles of the circular economy in the agro-industrial sector, where production waste is reintegrated into the system as a valuable input (Samah and Halim, 2024).

Inorganic fertilizers, particularly those containing synthetic nitrogen, often contribute to significant emissions of nitrous oxide (N_2O) through soil nitrification and denitrification processes. According to Priambodo and Erdiansyah (2024), the application of POME as a fertilizer can help mitigate environmental pollution caused by palm oil liquid waste. However, some studies caution that excessive use of POME may lead to increased methane (CH_4) emissions if not managed under anaerobic conditions. Additionally, the decomposition of certain organic materials can enhance methane emissions depending on soil aeration Lexmond and Zeeman (1994). Nevertheless, adopting a holistic and sustainable approach to POME utilization can effectively support environmentally friendly practices in oil palm plantations (Samah and Halim, 2024). By recycling POME as a fertilizer, the palm oil industry can significantly reduce the discharge of liquid waste into the environment, thereby minimizing the risk of water and soil contamination (Mariska et al., 2024).

As presented in Table 4, GHG emissions per hectare remained relatively constant; however, the increase in FFB yields significantly reduced GHG emissions per unit of yield (per tonne of FFB). In the treatment involving inorganic fertilizers, a production increase of 1.22 tonnes/ha/year corresponded with a reduction in emissions from 86.32 to 81.72 kg CO_2-eq per tonnes of FFB, representing a decrease of 4.59 kg CO_2-eq per tonne. The application of organic matter in the form of EFB increased production from 21.40 to 23.00 tonnes/ha/year (an increase of 1.60 tonnes/ha/year) and reduced GHG emissions from 36.17 to 33.76 kg CO_2-eq per tonne of FFB, equivalent to a decrease of 2.41 kg CO_2-eq per tonne. Meanwhile, treatment with POME resulted in the highest production increase – 2.01 tonnes/ha/year (from 23.19 to 25.20 tonnes/ha/year) – which contributed to a reduction in GHG emissions from 69.56 to 63.90 kg CO_2-eq per Tonne of FFB, equivalent to a decrease of 5.66 kg CO_2-eq per Tonne (Figure 4).

The analysis demonstrates that increased productivity directly reduces GHG emissions per Tonne of FFB. Treatments that effectively enhance crop yields – whether through inorganic fertilizers or organic amendments such as EFB and POME – contribute to lower GHG emission intensity. Notably, the application of POME

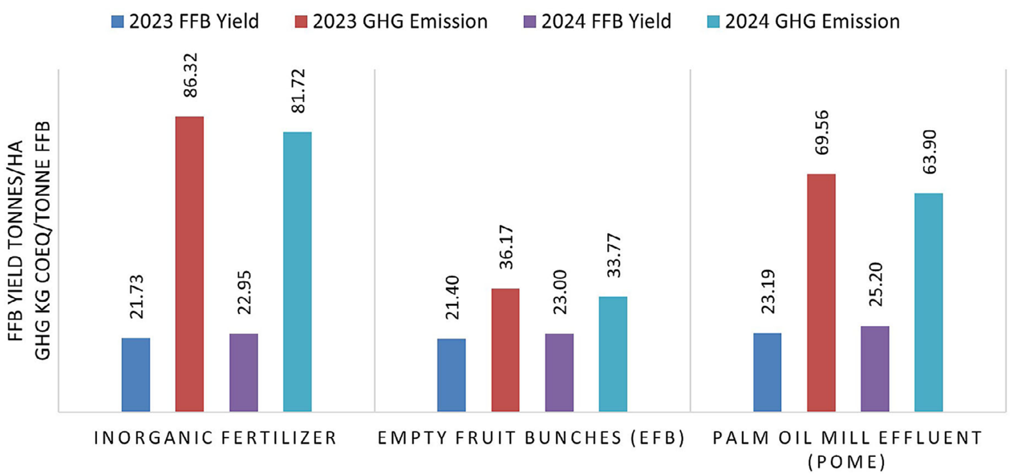

Figure 4. Impact of fertilizer types on fresh fruit bunch yield and GHG emission intensity (2023–2024)

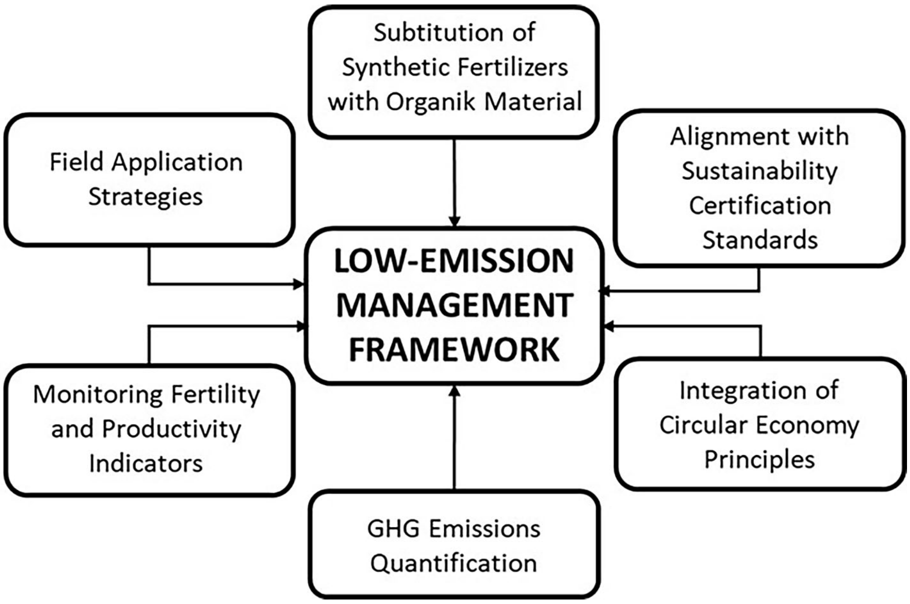

Figure 5. Low-emission management framework

resulted in the most substantial reduction in emissions per tonne of FFB as yields improved, underscoring agronomic efficiency as a key factor in reducing product-specific emissions. These findings align with those of Kheong et al. (2010) and Xu et al. (2020), who identified improved production efficiency in the palm oil sector as a highly effective GHG mitigation strategy. Conversely, some studies caution that intensification without adequate environmental management may lead to sustainability trade-offs (Henriksson et al., 2018). However, in this context, waste-based treatments such as POME and EFB not only enhance efficiency but also promote waste valorization. This evidence suggests that treatment choices influence both productivity and GHG emission intensity. The positive impact of both organic and inorganic fertilization on yields further emphasizes the critical role of agronomic efficiency in advancing sustainable agricultural practices.

Based on the findings of this study, an environmentally friendly oil palm management model can be developed by integrating local organic inputs – such as EFB and POME – into the cultivation system. The optimal utilization of plantation waste not only reduces GHG emissions but also enhances soil quality and decreases reliance on energy-intensive chemical fertilizers. This approach aligns with circular economy principles and contributes to climate change mitigation in the agricultural sector. A diagram is presented below illustrating the low-emission management framework, which comprises six key components to support sustainable and environmentally friendly oil palm cultivation.

Based on Figure 5, a low-emission management framework is proposed, comprising six main components: (1) substitution of synthetic fertilizers with locally available organic materials (EFB and POME) as nutrient sources; (2) field application strategies tailored to each material's characteristics – for example, flat-bed irrigation for POME and surface mulching for EFB – using agronomically appropriate application rates; (3) continuous monitoring of soil fertility and crop productivity indicators, including number of bunches, average bunch weight, and FFB yield (tonnes/ha); (4) GHG emissions quantification using IPCC-based CO_2 equivalent calculations per hectare and per tonne of FFB; (5) integration of circular economy principles through waste recycling and nutrient recovery; and (6) alignment with sustainability certification standards (e.g., ISPO, RSPO) and global market requirements. This framework offers a practical and scalable model for sustainable oil palm cultivation, supporting input diversification, waste valorization, and carbon footprint monitoring as essential components of future industry practices.

CONCLUSIONS

This study demonstrates that the application of organic materials, such as POME and EFB, can enhance palm oil productivity while simultaneously reducing GHG emissions. Among the treatments, POME significantly increased productivity to 25.20 tonnes per hectare and reduced GHG emissions per tonne of FFB by 5.66 kg CO_2-equivalent. EFB, on the other hand, achieved the greatest absolute reduction in GHG emissions, reaching 767.82 kg CO_2-equivalent per hectare. The application of POME also contributes substantial amounts of macronutrients, particularly nitrogen, whereas EFB offers potential long-term benefits for soil quality improvement. The agronomic efficiency of these organic treatments directly influences the reduction in GHG emission intensity per unit of yield, thereby promoting a sustainable palm oil management model aligned with the principles of a circular economy.

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