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CARBON FOOTPRINT ASSESSMENT OF SMALLHOLDER OIL PALM PLANTATIONS WITHOUT ISPO CERTIFICATION: A CASE STUDY IN MUSI RAWAS, INDONESIA

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Abstract
Oil palm is an important commodity for the Indonesian economy; however, its production activities have the potential to generate greenhouse gas (GHG) emissions. This study aimed to identify the main emission sources, quantify the total carbon footprint, and analyze the contribution of emissions across different production stages in non-ISPO-certified smallholder oil palm plantations. The study was conducted in the Rantau Jaya Farmer Group, Mandi Aur Village, Musi Rawas Regency, South Sumatra, using a cradle-to-gate life cycle approach. Data were collected through field surveys and interviews with farmers, and GHG emissions were estimated using the IPCC Tier 1 methodology with default emission factors and other literatures. The results showed that the main sources of emissions were biomass burning, chemical fertilizer application, and fossil fuel consumption. The total carbon footprint generated by the production system was 158.69 tons CO_2eq, equivalent to approximately 5 tons CO_2eq/ha, with Scope 1 emissions accounting for 99.98% of total emissions. Based on the life cycle assessment, the planting stage was the largest contributor to emissions (93.77%), primarily due to biomass burning and the use of al machinery, followed by the PM1 (4.10%), which was dominated by nitrogen-based fertilizer application. These findings highlight the need for more environmentally friendly cultivation practices to reduce GHG emissions and support the sustainable management of smallholder oil palm plantations.

Keywords: Carbon Footprint, GHG Emissions, IPCC, ISPO, Smallholder Oil Palm.

INTRODUCTION

Palm oil is one of Indonesia's strategic plantation commodities that contributes significantly to the national economy (Fatimah et al., 2024). Indonesia is currently the world's largest producer of crude palm oil (CPO), with a production share of more than 50% of the global market. Palm oil is highly sought after in industries such as food, cosmetics, and biodiesel (Abdullah et al., 2024). However, despite its economic contribution, the palm oil industry is often criticized for environmental issues, particularly greenhouse gas (GHG) emissions that contribute to global climate change. The largest sources of emissions from palm oil plantations come from fertilizer use and transportation.

Based on the total area of oil palm plantations in Indonesia, smallholder oil palm plantations account for 41% of the total national oil palm plantation area (Harisudin et al., 2024). Smallholder oil palm plantations are usually owned and managed independently by small-scale farmers, with an average area of 3-4 hectares per farmer (Prasetya et al., 2023). However, the majority of smallholder plantation land is not ISPO-certified, so environmentally unfriendly production processes remain common. Palm oil plantation production processes that are not environmentally friendly can contribute to global warming. Agricultural activities contribute 13% to greenhouse gas emissions, which are estimated to produce 62,758.43 tons of CO_2eq in 2030, studied by Farizal et al. (2024). The Indonesian government developed the Indonesian Sustainable Palm Oil (ISPO) certification scheme, which has been mandatory since 2011 to reduce the environmental impact of palm oil plantation practice. This certification aims to ensure sustainable and environmentally friendly palm oil production systems, including GHG emissions management (Indonesian Ministry of Agriculture, 2020). Based on ISPO data, only about 0.38%

(60,789.68 hectares) of smallholder oil palm plantation land has been ISPO certified (Direktorat Jenderal Perkebunan, 2024). This means that there are still many smallholder oil palm plantations that only focus on increasing production without considering the impact on the environment, including the potential GHG emissions produced, such as CO_2, CH_4, and N_2O.

LITERATURE REVIEW

The lack of carbon footprint research on oil palm plantation practice is one of the obstacles in GHG emission mitigation efforts (Harimurti et al., 2021). Carbon footprint analysis from the initial seedling stage to harvesting is essential to identify major emission sources and provide recommendations for better management. The Intergovernmental Panel on Climate Change (IPCC) method is an internationally recognized standard widely used to calculate GHG emissions (Al Hakim et al., 2014) from various sectors, including agriculture and plantations (IPCC, 2019).

The Rantau Jaya Farmer Group is one of the centers of smallholder oil palm cultivation located in Mandi Aur Village, Muara Kelingi Subdistrict, Musi Rawas Regency. The total area of oil palm plantations owned by the Rantau Jaya Farmer Group in 2025 is approximately 31.7 hectares. Oil palm plantation activities, including land clearing, seedling cultivation, planting, maintenance, harvesting, and transportation of Fresh Fruit Bunches (FFB), contribute to GHG emissions at each stage of production. Palm oil production activities in this farmer group are still carried out conventionally and have not yet obtained ISPO certification.

Although several studies have assessed the carbon footprint of oil palm production using a life cycle approach, previous studies have mainly focused on industrial-scale plantations and certified production systems (Arjuna & Santosa, 2018). Carbon footprint assessment at the smallholder level, particularly in non-ISPO-certified oil palm plantations, remains limited. Consequently, there is insufficient information regarding the emission hotspots and environmental performance of smallholder production systems that operate under conventional management practices.

Therefore, this study aims to quantify the carbon footprint of non-ISPO-certified smallholder oil palm production in the Rantau Jaya Farmer Group using a cradle-to-gate life cycle approach, covering all stages from land preparation to the transportation of FFB to the palm oil mill, and to identify the stages contributing the highest emissions. The novelty of this study lies in providing a comprehensive carbon footprint assessment of a non-ISPO-certified smallholder oil palm plantation in Indonesia, thereby generating baseline data that can support emission reduction strategies and sustainability improvements for smallholder palm oil production.

METHOD

Data Collection

The research area was located in Mandi Aur Village, Muara Kelingi Subdistrict, Musi Rawas Regency, South Sumatra (See Figure 1). This site was selected to represent smallholder oil palm plantations that have not yet obtained certification. A cradle-to-gate assessment approach was employed to estimate the carbon footprint associated with each member of the Rantau Jaya farmer group. The assessment covered all stages of the production chain, including seedling, planting, plant management (PM), harvesting, and transportation of FFB to the mill. The system boundary of the study is shown in Figure 2.

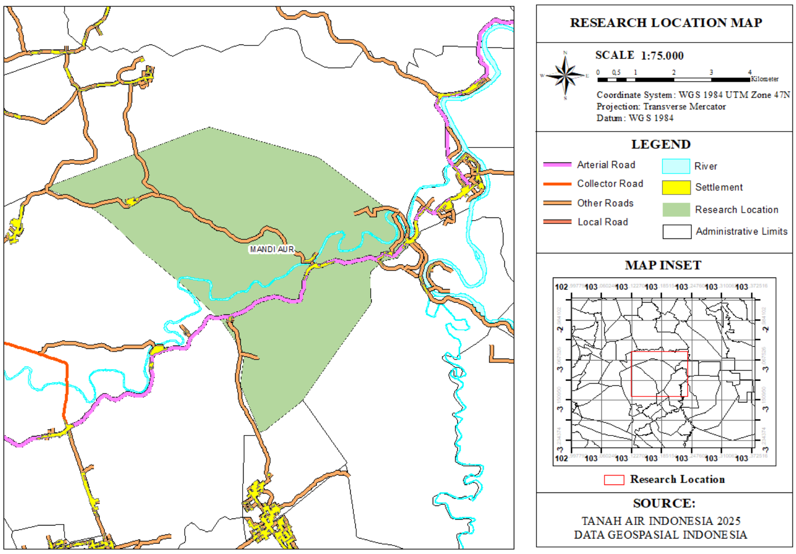

Figure 1. Location of the study

GHG emissions were quantified using the IPCC Tier 1 methodology. This approach applies default emission factors provided by the IPCC Guidelines for National Greenhouse Gas Inventories and requires activity data collected from field surveys and farmer interviews. Tier 1 was selected because site-specific emission factors and detailed monitoring data were not available for the study area. The carbon footprint was calculated by multiplying activity data from each production stage by the corresponding IPCC default emission factors and subsequently converting the resulting emissions into CO_2eq using the global warming potential (GWP) values recommended by the IPCC.

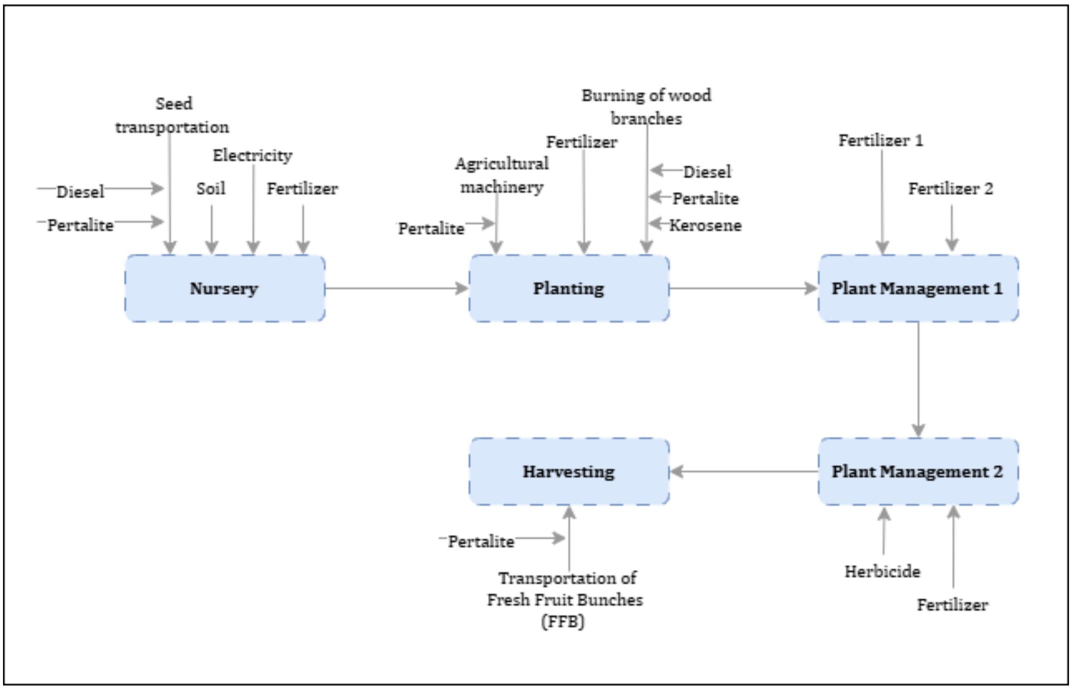

Figure 2. System boundary

Primary data were collected through field surveys and structured interviews with 16 oil palm farmers from the Rantau Jaya Farmer Group. Respondents were selected using a purposive sampling technique, whereby only farmers who actively managed oil palm plantations, had completed harvesting activities during the study period, and were willing to provide detailed operational information were included in the study. The sample size of 16 farmers reflects the total number of farmer group members who met these criteria and were available during the data collection period. The collected data included plantation area (ha), FFB productivity (kg or ton), fuel consumption for transportation and agricultural machinery (L), electricity consumption in nursery activities (kWh), quantities of fertilizers (kg) and herbicides (L) applied, and biomass burning data from the combustion of branches and wood during land preparation and plantation maintenance activities. These data were used as activity data for estimating GHG emissions and calculating the carbon footprint of oil palm production.

Emission sources were classified according to the GHG Protocol into Scope 1 and Scope 2 emissions. Scope 1 comprises direct GHG emissions generated from activities occurring within the plantation system and under the control of farmers (Chew et al., 2023), including fuel combustion from transportation and agricultural machinery, biomass burning of branches and wood, fertilizer application, herbicide application, and soil-related emissions associated with plantation management activities. In this study, emissions from fertilizer and herbicide use refer to emissions occurring during field application within the plantation boundary rather than emissions associated with their manufacturing and distribution processes. Scope 2 comprises indirect GHG emissions resulting from the consumption of purchased electricity used in nursery operations.

Table 1. Activity data

Farmer	Land Area (ha)	Fuel Usage (L)		Electricity Usage (kWh)	Fertilizer Usage (kg)	Herbicide Usage (L)
		Transportation	Agricultural machinery			
R1	2.5	16.32	80	2	1025	7.5
R2	2	13.44	20	0	450	0.1
R3	2	0.23	20	4.17	730	2
R4	2.5	6.21	25	0	650	10
R5	2	1.48	30	0	1265	2
R6	1	2.28	10	0	237	2
R7	1	24.51	40	2	298	2
R8	1.6	0.15	20	0	450	2.5
R9	5	7.66	100	3.33	1875	15
R10	1.6	0.61	10	0	650	2.5
R11	1	1.63	0	0	400	5
R12	1	10.21	0	0	220	5
R13	3.5	0.42	20	0	450	5
R14	2	6.65	20	2	550	5
R15	1	3.44	40	0	430	5
R16	2	6.65	20	1.67	810	40
Total	31.7	101.89	455	15.17	10490	110.6

Data Analysis

Carbon footprint calculations were performed in Microsoft Excel. Carbon footprint assessment includes CO_2eq parameters. In general, carbon footprints use equation (1). Other equations used are equation (2) for transportation diesel use, equation (3) for water pump diesel use, equation (4) for herbicide carbon footprint calculations, equation (5) for agricultural machinery use, equation (6) for N fertilizer use, equation (7) for dolomite, equation (8) for soil use in nurseries, and equation (9) for carbon footprint calculations from burning branches and wood.

$$\text{Carbon Footprint (CF)} = A \times EF \times GWP \quad (1)$$

where, A = activity data, and EF = emission factors (Farizal et al., 2024).

$$\text{CF (diesel transport)} = FC \times NCV \times EF \times GWP \quad (2)$$

where, FC = fuel consumption (L), NCV = the calorific factor (MJ/L), and EF = the emission factor (kg/MJ).

$$\text{CF (electricity pump)} = EC \times EF \times GWP \quad (3)$$

where, EC = electricity consumption in kWh and EF = the emission factor (kg/kWh) (Parameswari et al., 2019).

$$\text{CF (herbicide)} = Q \times \text{Active Ingredient} \times EF \times GWP \quad (4)$$

where, Q = herbicide consumption (L), and the active ingredient is a herbicide containing biologically active substances (gr/L) (Farizal et al., 2024).

$$\text{CF (diesel agricultural machinery)} = FC \times \rho \times NCV \times EF \times GWP \quad (5)$$

where, FC = fuel consumption (L), ρ = specific gravity of the fuel used (kg/L), NCV = net calorific value (kg/TJ), and EF = emission factor (kg/TJ).

$$N_2O = [N_2O\ Direct\text{–}N + N_2O\ (ADT)\text{–}N + N_2O\ (L)\text{–}N] \times 44/28$$
$$= [(FSN \times EF_1) + (FSN \times FracGASF \times EF_4) + (FSN \times FracLEACH\text{-}(H) \times EF_5)] \times 44/28 \quad (6)$$

where (Farizal et al., 2024) :

$N_2ODirect\text{–}N$	=	N_2O-N emissions resulting from soil management (kg N_2O-N per year).
$N_2O(ADT)\text{–}N$	=	N_2O-N emissions resulting from N volatilization into the atmosphere during soil management (kg N_2O-N per year).
$N+N_2O\ (L)\text{–}N$	=	emissions generated from the destruction and runoff of N use for soil management (kg N_2O-N per year).
F_{SN}	=	the amount of N fertilizer used
EF_1	=	the emission factor for N_2O from N use (kg N_2O-N/kg N)
$Frac_{GASF}$	=	the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (10%).
EF_4	=	the emission factor for N_2O from atmospheric N deposition on soil and water surfaces [(kg N- N_2O/(kg NH_3-N + NO_x-N volatilization)].
$Frac_{LEACH\text{-}(H)}$	=	the fraction of all N use in soil management lost through destruction and runoff (kg N/kg N used) (30%).
EF_5	=	the emission factor for N_2O from N destruction and runoff (kg N_2O - N/kg N destruction and runoff).

$$CF\ (dolomite) = DC \times EF \times GWP \quad (7)$$

where, DC = dolomite consumption (kg or ton) and EF Dolomite is the Dolomite Emission Factor (in kg GHG/kg Dolomite) (Farizal et al., 2024).

$$CF\ (soil) = SW \times C_{in} \times C_{out} \times FC \quad (8)$$

where, SW = soil weight (kg or ton), Cin = the carbon mass in the soil of 1% (kg C), Cout = the amount of carbon released of 33.2%, and FC = conversion factor from C to CO_2 (44/12).

$$CF\ (wood\ burning) = WW \times LHV \times EF \times GWP \quad (9)$$

where, WW = weight of wood (kg or ton) LHV = calorific value of the wood (2.625 MJ/m3) and EF = emission factor (kg GHG/TJ).

The results of the calculations from the above equation were aggregated to obtain the CO_2eq/ha value for all activities in the oil palm plantation at the Rantau Jaya Farmer Group. The emission factors used in carbon footprint calculations can be found in the Table 2.

Table 2. Emission factors

Emission Source	Emission factors			Unit	Reference
	CO_2	N_2O	CH_4		
Pertalite (RON 90 Gasoline)	0.0693	0.000033	0.0000032	kg/MJ	(Ministry of Environment, 2012)
Diesel	0.0741	0.0000039	0.0000039	kg/MJ	(Ministry of Environment, 2012)
Electricity	0.774388897	0.0000088	0.000015943	kg/kWh	(Brander et al., 2011)
Fuel Agricultural machinery	69300	2	80	kg/TJ	(IPCC, 2019)
Wood	112000	4	300	kg/TJ	(IPCC, 2019)
Urea	0.20	-	-	ton/CO_2	(IPCC, 2019)

Emission Source	Emission factors			Unit	Reference
	CO_2	N_2O	CH_4		
NPK	-	0.01	-	kg N_2O	(Farizal et al., 2024)
Dolomite	0.77	-	-	ton CO_2	(IPCC, 2019)
Herbicide	4.702	-	-	kg CO_2	(Darmawan et al., 2021)

RESULTS AND DISCUSSION

Palm oil production on smallholder oil palm plantations managed by the Rantau Jaya Farmer Group consists of several stages of production. Based on interviews with 16 farmers, the production stages are seedling, planting, PM1, PM2, and harvesting (See Table 1). The production process for smallholder oil palm plantations begins with seedling cultivation at 0-8 months of age, where the seedlings are delivered to the nursery or picked up directly at the point of sale by the farmer. The seedlings are then fertilized and watered daily. During the seedling stage, the energy source input required for transportation fuel and electricity for water pumps. The planting stage is carried out when the seedlings are about 8 months old.

Before the seedlings reach 8 months old, the land is cleared. Once the land is ready, seedlings that have reached the planting age are planted and fertilized to accelerate their growth. The energy requirements in this phase are associated with fuel for grass- and wood-cutting equipment, fertilizers, and accelerants used for burning. In PM1, from 9 months to 2.5 years of age, fertilizer is applied twice to accelerate tree growth, serving as the energy source during this stage. Next, the PM2 from 2.5 to 3 years of age, involves spraying herbicides to reduce weeds in the plantation and applying fertilizer to supplement the trees' nutrient needs. The energy used in this stage is fertilizer and herbicides. The harvesting stage will be carried out at 3-3.1 years, with energy used to transport the fresh fruit bunches to the collection site before they are transported by a third party.

Table 3. Total GHG emission by source and production stage

Emission Source	Total Emissions (ton CO_2eq)				
	Nursery	Planting	PM1	PM2	Harvesting
Fuel Transportation	0.273	0	0	0	0.008
Electricity	0.011	0	0	0	0
Herbicide	0	0	0	0.205	0
Fertilizer	0.804	1.743	6.506	1.994	0
Fuel Agricultural machinery	0	0.996	0	0	0
Branches and wood	0	146.06	0	0	0

Transportation equipment at the nursery stage is used to transport seedlings and to purchase equipment for use during the production process. The nursery stage produces emissions from the use of fossil fuels for transportation. The amount of emissions produced varies greatly between farmers due to differences in distance traveled and the type of transportation used when transporting seedlings and purchasing equipment. In terms of emissions, diesel fuel produces higher emissions than Pertalite because diesel contains heavier hydrocarbons (Rokni et al., 2019). The use of fossil fuel-powered transportation equipment is a major source of carbon emissions in the agricultural sector (Mathur et al., 2022).

During the seedling stage, the amount of fuel used was 80.8 liters of diesel and 21.09 liters of Pertalite, with total emissions of 0.273 tons of CO_2eq. Previous research found emissions from diesel use during the seedling stage to be 0.332 kg CO_2eq/seedling (Al Hakim et al., 2014), whereas in this study, the emissions were 0.079 kg CO_2eq/seedling. This shows that vehicle mileage affects the total carbon emissions produced (Zinla et al., 2022) because the farther a vehicle travels, the more fuel it uses, resulting in higher emissions. Meanwhile, during the harvesting stage, only 3.36 liters of Pertalite fuel were used, resulting in total emissions of 0.008 tons of CO_2eq. Transportation equipment at the harvesting stage transports FFB from the plantation area to the FFB collection point, where they are then transported by a third party to the processing plant. Compared to the seedling stage, total emissions at the harvesting stage are much lower because the transportation distance and fuel consumption are smaller.

When clearing land, farmers use agricultural machinery powered by Pertalite fuel. Farmers use agricultural machinery to clear land that was previously rubber plantations. Agricultural machinery used by farmers emits because it runs on fossil fuels. The use of agricultural machinery during the production system generates 0.996 tons of CO_2eq from a total of 455 liters of fuel, or 2.19 kg of CO_2eq/liter. Research by Haavikko et al. (2022) found that the use of machines to cut wood produced 21.676 tons of CO_2eq from 14.2 ML of fuel, equivalent to 1.52 kg CO_2eq/liter. This is influenced by the size of the tree trunks and the number of trees felled. The more tree trunks are felled, and the larger their diameter, the more fuel is consumed, resulting in greater emissions (Kärhä et al., 2024). In addition, large-diameter wood can also store large amounts of carbon. When trees are felled, the carbon they store is released into the atmosphere as CO_2 in large quantities (Mildrexler et al., 2020).

At the seedling stage, only 6 farmers sowed seeds, while the rest purchased ready-to-plant seedlings. Seedlings were sown using 3 kg polybags filled with soil. The soil used can release 33.2% of stored carbon (Zhang et al., 2024). Based on calculations, farmers used 5850 kg of soil, releasing 0.071 tons of CO_2eq. Based on a study by Lazzerini et al. (2022), emissions from the seedling process in polybags totalled 1.15 kg CO_2eq/polybag, whereas in this study, they totalled 0.036 kg CO_2eq/polybag. This may be influenced by the type of soil used; in this study, red soil was used, whereas in the study by Lazzerini et al. (2022), peat soil was used. Peat soil has a higher carbon content than mineral soils such as red soil (Syahbian et al., 2023). When peat soil is used as a planting medium, its organic content can decompose quickly, releasing carbon as CO_2 and N_2O (Prananto et al., 2020).

Herbicides are applied during PM2 to control weeds in the plantation area. The use of chemicals, such as herbicides, can also increase carbon footprint emissions because their active ingredients, such as glyphosate, can increase carbon dioxide emissions (Cornish et al., 2024). The herbicides used by the Rantau Jaya Farmer Group include Supretox, Turmadan, Bablas, Roundup, and Gramoxone. Each type of herbicide has different active ingredients, so the emissions produced by each farmer also differ depending on the dosage used. The total herbicide use by farmers was 110.6 liters, producing emissions of 0.205 tons of CO_2eq. The active ingredient content of Bablas herbicide is higher than that of other herbicides used by farmers, because only 12 liters are used, resulting in emissions of 27.64 kg CO_2eq. However, Roundup herbicide produces the highest emissions of 114.46 kg CO_2eq with 50 liters used. A study by Gan et al. (2011) found that direct herbicide use in plantations can produce emissions of around 5 kg CO_2eq/ha. Meanwhile, in this study, herbicide use produced 6.48 kg CO_2eq/ha. This can be influenced by the herbicide's active ingredient content and the type of herbicide used. This is because the active ingredients in herbicides cause weeds to die and produce organic matter, which becomes a source of carbon for microbes that can emit CO_2 (Chávez-Ortiz et al., 2022). In addition, the active ingredients in herbicides readily evaporate into the atmosphere because they have high vapor pressures (Murschell & Farmer, 2019).

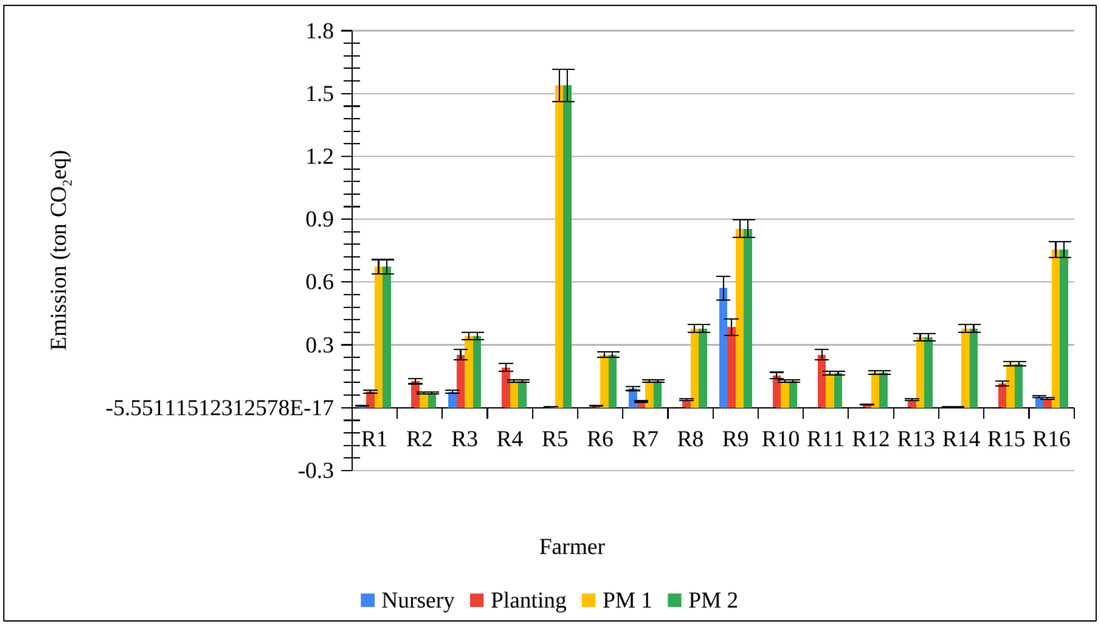

Figure 3. Fertilizer use by production stage

Fertilization using NPK fertilizer can increase carbon footprint emissions, because NPK fertilizer contains nitrogen that will react and produce the greenhouse gas N_2O (Atakora et al., 2019). During the production stage, the Rantau Jaya Farmer Group applies fertilizer four times. The first fertilization aims to provide nutrients to the roots and leaves (Ramadhan & Nasrul, 2022), the second fertilization aims to help seedlings adapt more quickly after being transferred from polybags to the field (Hastuti et al., 2024), the third fertilization aims to provide nutrients to the stems and fronds (Sihaan & Khoiri, 2023), and the fourth fertilization aims to produce maximum fruit yield (Aji et al., 2020). Even small amounts of NPK fertilizer can generate significant greenhouse gas because N_2O has a 100-year global warming potential of 265 times that of CO_2 (IPCC, 2014). The amount of emissions produced from the fertilization process depends on the type of fertilizer and the fertilizer dosage used by farmers. Using urea fertilizer will produce greater emissions because the nitrogen content in urea is around 46% (Mohammad et al., 2021). This means that the higher the urea dosage, the higher the N_2O emissions produced. This can be caused by nitrification and denitrification processes in the soil, where soil bacteria convert nitrogen into N_2O gas (Lazcano et al., 2021). However, N_2O emissions can be reduced by dividing the fertilizer dose into several small applications to reduce nitrogen loss (An et al., 2021). In addition, mixing organic fertilizers can increase crop yields and reduce the use of chemical fertilizers that emit high levels of greenhouse gas (Liu et al., 2021).

Based on the production system implemented by the Rantau Jaya Farmer Group, the most fertilizer was used in the PM1 because fertilization was applied twice at a fairly high dosage (See Figure 3). The amount of fertilizer used in the production system was 10.49 tons, resulting in emissions of 11.047 tons of CO_2eq. Agusta et al. (2022) reported that emissions from fertilizer use in smallholder plantations amounted to 604.9 kg CO_2eq or 3.37 CO_2eq/kg of fertilizer from the use of 179.1 kg of fertilizer, where emissions are generated from urea, NPK, dolomite, MgO, $CuSO_4$, and organic fertilizers. Meanwhile, in this study, the emissions produced amounted to 11.04 tons of CO_2eq from the use of 10,49 tons of fertilizer. So, the emissions produced in this study amounted to 1.05 CO_2eq/kg of fertilizer, from the use of urea, NPK, dolomite, and organic fertilizers.

Based on Figure 3, fertilizer-related emissions did not exhibit a clear linear relationship with plantation area. For example, farmer R5, who managed approximately 2 ha of oil palm plantation, generated the highest emissions, reaching approximately 1.54 tons CO_2eq/ha. In contrast, farmer R9, who managed a larger plantation area of 5 ha, produced lower emissions of approximately 0.53 tons CO_2eq/ha. These findings indicate that plantation area is not the primary factor determining the magnitude of fertilizer-related emissions. Instead, emissions are more strongly influenced by fertilizer application intensity, application frequency, fertilizer type, and plantation management practices adopted by individual farmers. Farmers with relatively small plantation areas tend to apply fertilizers at higher rates per unit area to enhance crop productivity, resulting in greater emissions. Conversely, farmers managing larger plantation areas may achieve more efficient fertilizer use, leading to lower emission intensity. Therefore, an increase in plantation area does not necessarily result in a proportional increase in emissions, and fertilizer-use efficiency plays a more important role in determining the level of carbon emissions generated.

Some farmers burn branches and wood from land clearing during planting. Burning branches and wood speeds up the land-clearing process. The branches are collected into piles and left to dry first. Once dry, the branches are burned with fuel to speed up the burning. A total of 457.84 tons of wood branches were burned, consisting of previously planted rubber trees. Calculations show that the burning of wood branches produced 146.06 tons of CO_2eq emissions. A study by Vásquez et al. (2020) estimates that emissions from burning peatlands in Indonesia will reach 872 tons of CO_2eq. The depth of the burned peat is a determining factor in the amount of emissions produced because peat stores large amounts of carbon. Therefore, the emissions estimated in this study are lower because the effect of peat burning depth was not considered. As the depth of burned peat increases, the amount of carbon released and the resulting greenhouse gas emissions also increase (Azmi et al., 2021).

Electricity is used during the seedling stage to power water pumps for watering the seedlings. Seedlings are watered twice a day, in the morning and in the afternoon. Only six farmers use pumps to water their seedlings, while the others have purchased seedlings that are ready to plant and do not need watering. The source of electrical energy used by farmers comes from a Gas Engine Power Plant (PLTMG) located in Musi Rawas Regency. The total electricity used by farmers for irrigation is 15.17 kWh, resulting in emissions of 0.011 ton CO_2eq. Based on research by Fani & Anggraini (2025), electricity-related emissions are 0.774 kg CO_2eq/kWh, whereas in this study they are 0.777 kg CO_2eq/kWh. Electricity use contributes about 25% of total global greenhouse gas emissions, especially electricity generated from burning fossil fuels such as coal and gas (Tranberg et al., 2019). If electricity consumption, especially from fossil fuels or gas, continues to increase, then emissions will also increase.

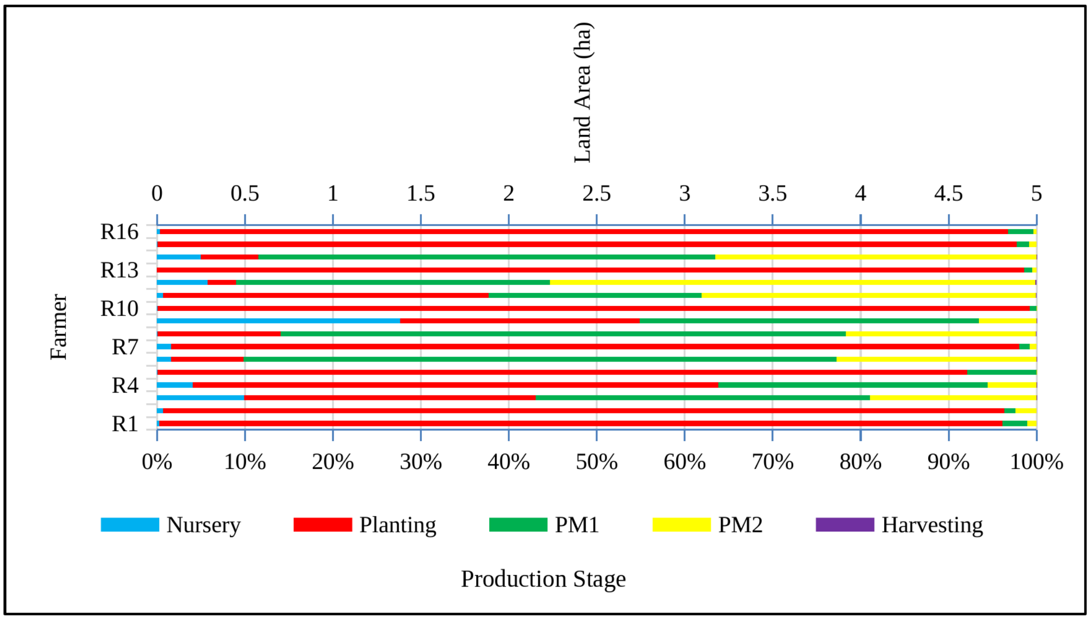

Figure 4. Percentage of emissions generated by each farmer

The results show that the planting stage produces the largest emissions (148.79 tons of CO_2eq or 93.77%) because during this stage, wood branches are burned during land clearing. Burning branches and wood during land clearing can cause biomass to decompose and release CO_2 into the atmosphere (Saharjo & Ary, 2024). This means that each branch and piece of wood stores a certain amount of carbon, which when burned can be released quickly (Proto et al., 2021). If burning is not carried out, the release of stored carbon can take decades (Garmston et al., 2019). Therefore, the planting stage produces the highest emissions because the burning of branches and wood accelerates the release of large amounts of carbon.

In addition to the harvesting stage, emissions from the seedling stage totaled 1.16 tons of CO_2eq. The largest emissions during the seedling stage were from the use of 0.676 tons of fertilizer by all farmers, resulting in 0.80 tons of CO_2eq. In PM1, emissions were generated only from the use of 5625 tons of fertilizer, resulting in 6.50 tons of CO_2eq. In PM2, the total emissions generated were 2.20 tons of CO_2eq. The largest emissions in PM2 also came from the use of 2.69 tons of fertilizer by all farmers, producing 1.99 tons of CO_2eq. Meanwhile, emissions generated during the harvesting stage were only from the use of fuel to transport FFB. The emissions generated during the harvesting stage amounted to 0.0086 tons of CO_2eq, corresponding to the use of 3.36 liters of fuel. These results indicate that the main emission sources in non-ISPO-certified smallholder oil palm production systems are the burning of wood branches during the planting stage and the intensive use of fertilizers during PM1 and PM2. Both activities contributed the largest share of total greenhouse gas (GHG) emissions generated throughout the oil palm production cycle.

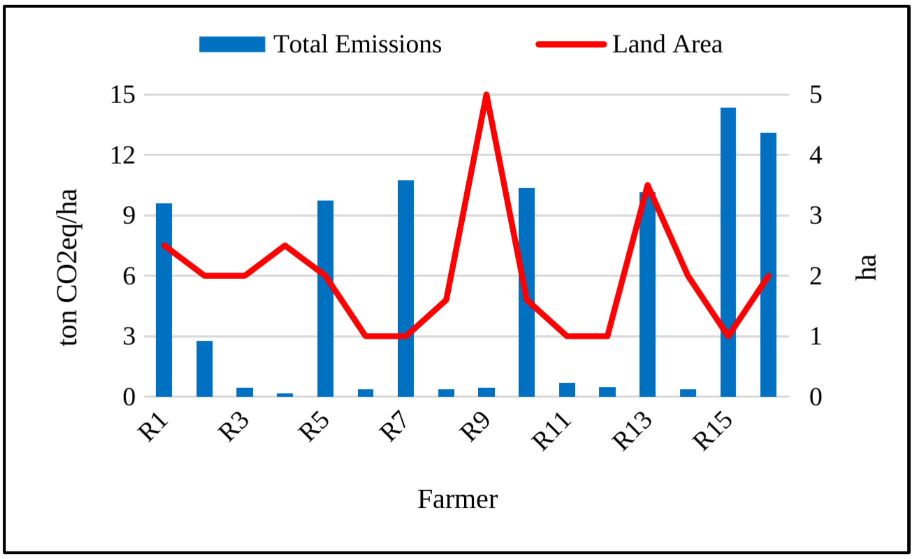

Figure 5. Emission intensity per farmer (t CO_2eq/ha)

Based on calculations of total emissions generated by each farmer from seedling cultivation to FFB transportation, the total emissions amounted to 158.69 tons of CO_2eq. Emissions generated from Scope 1 amounted to 158.66 tons of CO_2eq, while emissions from Scope 2 amounted to only 0.011 tons of CO_2eq. This is because there is more activity data in Scope 1, so the energy used is also very large. The largest emissions come from R15, amounting to 14.34 tons of CO_2eq/ha with a land area of 1 hectares. The burning of wood branches during planting is the main source of emissions from R15. The smallest emissions are generated by the R4 production process, totaling 0.16 tons of CO_2eq/ha. The source of emissions from the R4 production system does not come from burning branches and wood, but from the use of 260 kg of chemical fertilizers per hectare during the production system. The land area is not the determining factor; rather, the amount of energy and inputs used drives total emissions (Bai et al., 2023). Therefore, burning branches and wood during planting and using fertilizer for tree maintenance produce the highest emissions (Agusta et al., 2022). A study from Safitri et al., (2024) states that carbon emissions can be reduced by minimizing tree felling and burning during land clearing.

FUTURE RESEARCH

This study was limited to 16 smallholder farmers and employed the IPCC Tier 1 approach using default emission factors. Therefore, future research should incorporate a larger sample size and apply higher-tier methodologies (Tier 2 or Tier 3) with site-specific emission factors to improve the accuracy of emission estimates. Additionally, the inclusion of carbon sequestration and life cycle stages beyond the farm gate would enable a more comprehensive assessment of the environmental performance of smallholder oil palm plantations.

CONCLUSION

Based on the study results, the main emission sources in non-ISPO-certified smallholder oil palm production systems were biomass burning (wood branches and residues), chemical fertilizer application, and fossil fuel consumption. The total carbon footprint generated across all production stages, from seedling cultivation to harvesting, amounted to 158.69 tons CO_2eq, equivalent to 5 tons CO_2eq/ha. Emissions were overwhelmingly dominated by Scope 1 emissions, which accounted for 99.98% of the total carbon footprint, while Scope 2 emissions contributed only 0.02%. According to the cradle-to-gate life cycle assessment, the planting stage was the largest contributor to GHG emissions, generating 148.79 tons CO_2eq or 93.77% of the total carbon footprint. This was followed by PM1, which contributed 6.51 tons CO_2eq or 4.10% of total emissions, primarily due to the intensive application of nitrogen-based fertilizers.

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