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Carbon Footprints

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# Carbon footprint estimation of palm oil production systems - impact of land use change and consequences of modeling choices

**Heinz Stichnothe**#, **Joerg Schweinle**#

**Keywords:** Peatland, by-product substitution, animal feed, smallholder, GHG, deforestation

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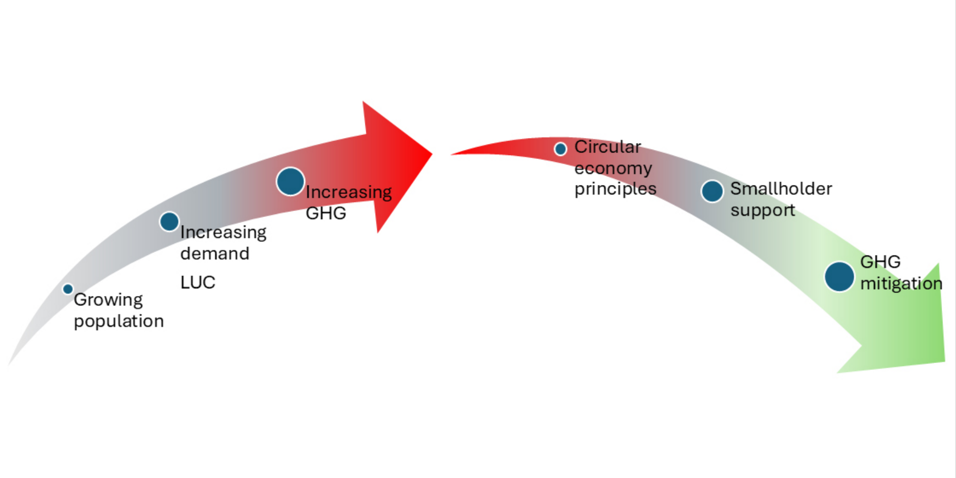

## Abstract

Anticipated growth in global palm oil demand is driving an expansion of Indonesian production, frequently necessitating land-use change (LUC). This study employs consequential life cycle assessment (LCA) integrated with Monte Carlo simulations to estimate the carbon footprint (CF) due to LUC and investigate the sensitivity of these results to modeling choices. Understanding the CF of palm oil, particularly from LUC and through rigorous LCA modeling, is paramount for providing sound advice on greenhouse gas (GHG) mitigation. Converting peatland to oil palm plantations represents the most detrimental scenario regarding climate impact. For example, a10% LUC from peatland alone leads to 5.4 t $CO_{2eq}$ $ha^{-1}$ $a^{-1}$, i.e., 54 t $ha^{-1}$ peatland converted and 1,350 t $CO_{2eq}$ $ha^{-1}$ over 25 years. Furthermore, the modeling choice for by-product substitution significantly influences CF results, potentially limiting the comparability of findings across different studies. Our analysis demonstrates that the CF of crude palm oil (CPO) varies from 0.26E3 to 1.4E3 kg $CO_{2eq}$ $t^{-1}$ without LUC and 0.85E3 to 1.9E3 kg $CO_{2eq}$ $t^{-1}$ when LUC is included, depending on by-product modeling. Transparency in these modeling choices is paramount for providing robust decision support to policymakers. Finally, a high-potential mitigation strategy involves supporting the smallholder sector, which managed approximately 40% of the 17 million hectares of oil palm plantations in 2021. Increasing smallholder yields from 11

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Thuenen Institute of Forestry, Hamburg 21031, Germany.
#The author contributed equally to this work.

**Correspondence to:** Dr. Heinz Stichnothe, Thuenen Institute of Forestry, Hamburg 21031, Germany. E-mail: heinz.stichnothe@thuenen.de

t to 20 t of fresh fruit bunches (FFB) ha$^{-1}$ would generate an additional 14 million tons of CPO without further LUC - effectively sparing 3 million ha of land.

## INTRODUCTION

Oil palms are recognized for their exceptional oil yield, the average oil yield per hectare is 3.7 to 4.6 ton of palm oil compared to 0.6 tons rapeseed oil and 0.36 tons soya oil[1,2]. Malaysia and Indonesia produce approximately 87% of the global palm oil[3]. In contrast to other biomass products, which are mainly consumed locally in the countries of production, more than half of the produced palm oil is exported[4]. Crude palm oil production in Indonesia grew from approx. 8 million tons in 2001 to 48 million tons in 2022. The expansion of oil palm plantations was associated with the deforestation of approx. 3 million ha over the past 20 years[5]. As of 2020 approx. 21% of the cleared forest in Indonesia is utilized for oil palms plantations, according to[6]. Palm oil residues are produced throughout the year and thus can be considered as major crop residues for power production, particularly in remote rural areas. Given the importance of palm oil for the national economy, the Indonesian policy on renewable energy is closely linked to its development, particularly to improve living standards and welfare in rural areas. In the long-term, renewable energy development, such as biogas from residues of the palm oil industry, may significantly contribute to a sustainable national energy supply. The management of residues is a paramount criterion for sustainable palm oil[7]. Residue management is also one of the key factors for greenhouse gas (GHG) emission reduction of the palm oil industry[8,9] and can generate additional income depending on access to the electricity-grid and attractive feed-in-tariffs.

The competition for palm oils between food, feedstock for chemicals, and biodiesel applications has put it in the limelight, resulting in a controversial worldwide debate[2,10-12]. By replacing tropical forests, new palm plantations provoke the killing of endangered species, uprooting of local communities, and release of huge amounts of GHG. Europe has banned biofuel feedstock and biofuels with a high risk of causing indirect land-use change in high carbon stock areas, however, with limited effect on deforestation[13,14], because larger markets in China and India as well as the domestic market tend to source palm oil and derived products from supply chains with comparatively higher rates of deforestation risk[15]. Zero-deforestation commitments are widespread in Indonesia, but that does not ensure the absence of deforestation risk[16]. While contributing to economic growth, the expansion of palm oil production has been a key driver of deforestation in the country. Most deforestation linked to palm oil has historically been driven by large-scale producers. Smallholders are however increasingly identified as important actors in relation to the deforestation of forests and peatlands in Indonesia[16].

Palm oil production is important for the Indonesian economy; it employs over 20 million people[17], the majority as plantation workers in rural areas. Plantation enterprises pay attention to economic factors and the social welfare of the community and surrounding areas and show concrete signs of improving the welfare of the community by strengthening the economy of the community[18].

Oil palms are produced by nucleus estate and smallholder managed schemes, sometimes via joint-venture schemes but also by independent smallholders[19]. Oil palm cultivation has improved living standards and alleviated the poverty of many smallholder farmers[20]. However, there is a huge gap between the economic performance of professionally managed plantations with sufficient resources to buy seed, fertilizer, and plant protection agents compared to the agronomic performance of small holder's plantations. The average yield of Indonesian smallholders is reported at approx. 11 tons fresh fruit bunches (FFB) ha$^{-1}$, while private company plantations in favorable sites often reach yields of more than 30 tons FFB ha$^{-1}$[21]. Monzon reported that the oil FFB yield of independent farmers is low, representing 42% of the attainable yield[22]. Economic constraints and knowledge gaps among smallholders represent significant barriers to productivity. Moreover, independent smallholders do not have direct access to palm oil mills; frequently, they depend on middlemen and thus receive lower FFB prices. This leads to below average incomes of independent small holders, as confirmed by several publications[20-24].

Xin *et al.* modeled an increasing land requirement of 19 to 46 million ha oil palm plantations in Indonesia by 2050, with 20% to 50% associated with land use change from peatland and a smaller share from secondary forests[25]. Despite regulatory measures by the Indonesian government, extensive conversion of peatland and other land uses has occurred[26]. Dohong *et al.* show that over 40% of oil palm plantations located in central Kalimantan are situated in deep peat areas[27].

GHG emissions from palm oil production on carbon-rich peatland are responsible for a substantial portion of the country's total climate impact[5]. That is already confirmed in various papers[28-30]. However, all of them used an attributional approach and used different modeling choices for by-products. Lam *et al.*[28] provide spatially explicit calculation of GHG emissions of crude palm oil (CPO) at the level of administrative regions in Indonesia, considered kernels as by-products, and used economic allocation; the calculated carbon footprint (CF) was 0.7 to 26 t $CO_{2eq}$ $t^{-1}$. Schleicher *et al.*[29] examined CPO and neglected by-products. They calculated 4 to 30 t $CO_{2eq}$ $t^{-1}$. Wang *et al.*[30] investigated refined palm oil, defined kernel as by-product and used mass allocation in order to allocate GHG emissions, they calculated a CF for refined palm oil of 2.2 t $CO_{2eq}$ $t^{-1}$. The consequence of the modeling choice was not investigated in those papers.

Understanding the carbon footprint of palm oil, particularly from land-use change (LUC) and through robust life cycle assessment (LCA) modeling, is paramount for robust decision support for sustainable policy and mitigating climate change. Therefore, this study focusses on the carbon footprint of palm oil production, particularly the contribution of direct LUC from forest and/or peatland as well as the influences of modeling choices regarding by-product substitution.

## SYSTEM DESCRIPTION

Extensive research highlights the land-use efficiency of palm oil compared to other vegetable oils; however, a disadvantage is the poor GHG performance when LUC, particularly from peatland, occurs.

In Figure 1 the considered system boundary for the oil palm plantation is shown. The reported area for oil palm plantations in national statistics is the productive area, i.e. harvested area marked by dashed lines. The area required at the nursery stage, the End-of-Life and re-planting is not considered. However, land productivity can be addressed by varying the yield of FFB $ha^{-1}$. Usually, palm oil plantations operated 25-30 years; afterwards the palms are felled, and the trunks remain on the plantation. The harvest starts between year 3 to 5 and the FFBs are harvested manually and transported to the palm oil mill.

The plantation consists of the managed area and the lagoons, while the oil mill is defined as the mill and the combined heat and power (CHP)-plant. The palm oil mill effluent (POME) is stored in lagoons and is afterwards used to irrigate the plantation. It is assumed that fronds remain on the plantation and empty fruit bunches (EFB) from palm oil mills are returned to the plantation to recycle nutrients and to reduce costs for fertilizers.

It is well known that the residue management of the palm oil mill has a great influence on the environmental performance of palm oil production[31,32]. In this study we assume that all residues are utilized; the

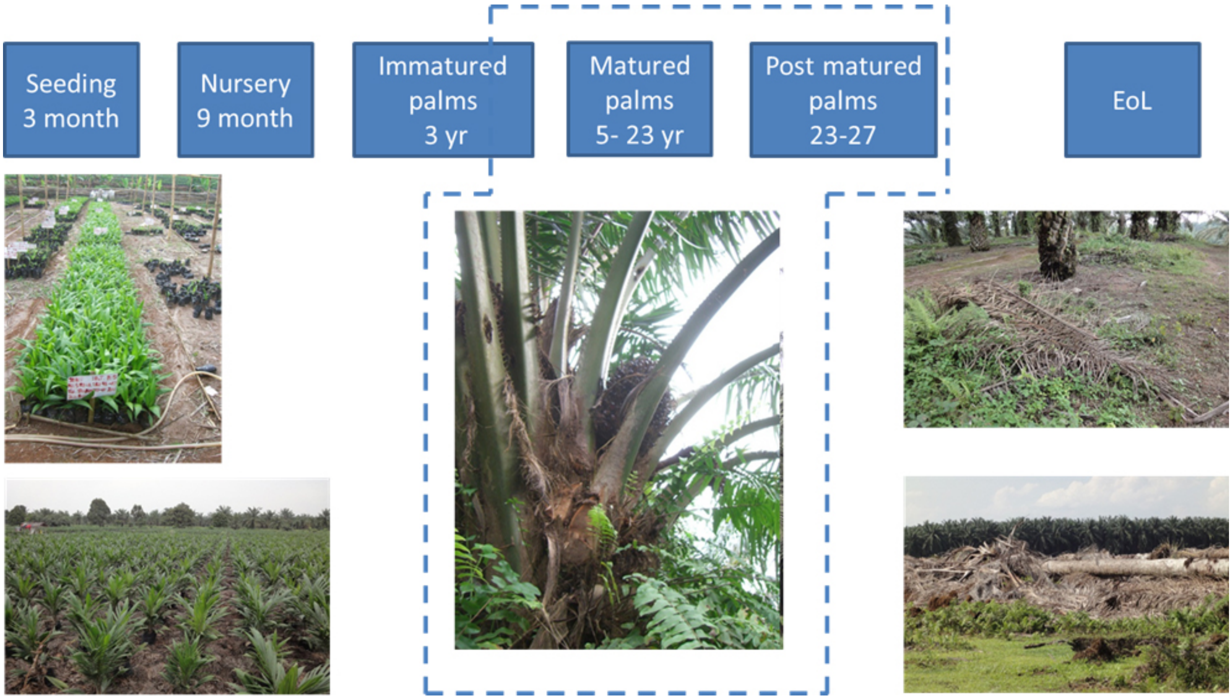

**Figure 1.** Life cycle of oil palms and the productive area usually considered, respectively reported by plantation operators (picture were self-taken).

mesocarp-fibers and shells are used as energy carriers for the CHP plant of the palm oil mill. Currently CHP plants fulfill two functions, they supply heat and electricity for all on-site operations and also serve as waste treatment. In this study, it is assumed that the CHP plant provides all heat needed in the oil mill. Palm kernel mills are modeled separately. The production system is shown in Figure 2 and relevant mass flows in Figure 3.

## METHOD - CARBON FOOTPRINT ANALYSIS

This CF study is conducted using OpenLCA[33] v.2.4 and the Ecoinvent database[34] version 3.11, consequential module, which provides extensive datasets on existing materials and processes. The ISO 14040 principles and framework are applied, which comprise four main stages: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Processing oil palm fruits generates multiple products, and market-based substitution is applied by using a simplified consequential approach, because the authors argue that the consequential approach is better suited for multi-output systems because mass and energy balances in product LCAs are maintained and indirect effects, e.g. indirect land use change (iLUC), can be identified[35-38]. However, different arguments can be used for identifying the most appropriate replacement of by-products[39,40] and consequently, multifunctionality modeling affects the results[41,42] Therefore, the consequences of modeling choices need to be investigated.

The products of the oil mill are palm oil, palm kernels and surplus electricity from the residues-fed CHP. Palm kernels are usually processed in separate mills. The average transport distance is 80 km[43] and the resulting products are palm kernel oil (PKO) and palm kernel meal (PKM). It is crucial to define the function in a specified system, e.g. replacement of ingredient X based on crude protein, gross energy, or….

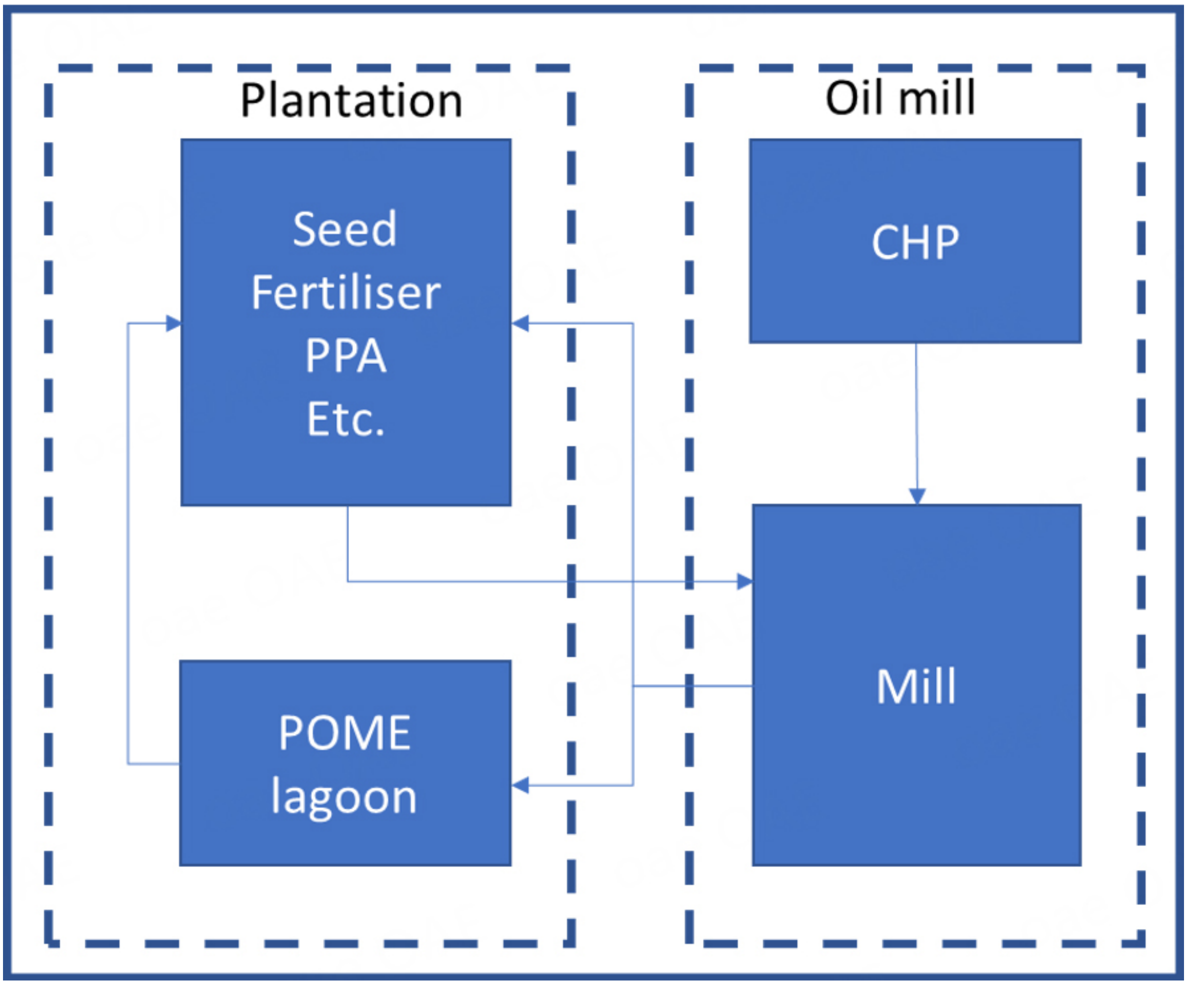

**Figure 2.** Life cycle stages of crude palm oil production. PPA: Plant protection agents; CHP: combined heat and power; POME: palm oil mill effluent.

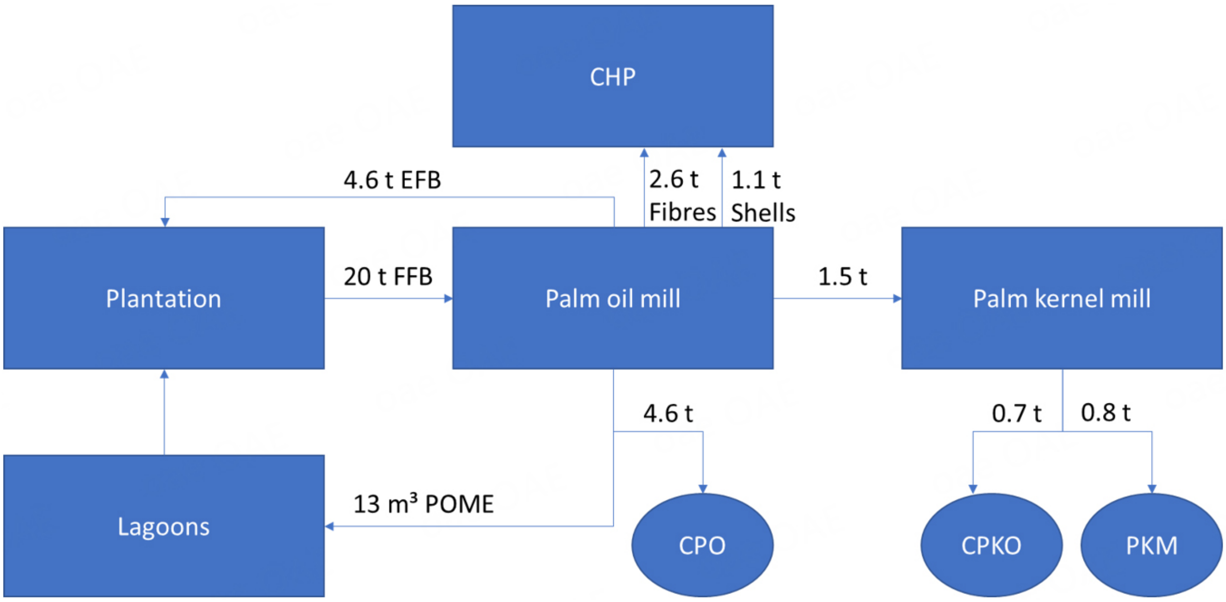

**Figure 3.** Relevant mass flows of FFB production and processing. CHP: Combined heat and power; POME: palm oil mill effluent; CPO: crude palm oil; CPKO: crude palm kernel oil; PKM: palm kernel meal; FFB: fresh fruit bunches.

## Goal and scope

The goal of this CF study is firstly to evaluate the importance of LUC and secondly to show consequences of modeling choices for by-product substitution. The functional unit is 1 ha of plantation area, using the average performance for a plantation lifetime of 25 years.

A state-of-the-art production system as described above is investigated, and Monte Carlo simulations with 1,000 runs are used to show system-inherent variability of FFB production. For the Monte Carlo simulations, triangle distribution of the two main parameters, yield and LUC, are used. The change in yield is associated with an increase or decrease of linked parameters, e.g. yield decrease also leads to higher land demand per product unit and higher fertilizer input and consequently higher GHG-emissions per product unit; the same applies to the application of pesticides and diesel consumed. Therefore, input parameters linked to the yield are not used for the Monte Carlo simulations. Waste management is discussed in detail[9,32] and more recently also in[30] and therefore not repeated here.

In 2020, approx. 21% of the cleared forest in Indonesia was used for oil palms, according to[6]. The situation concerning LUC is complex. To account for the complexity and regional variability across Indonesia, 20% LUC was chosen as the upper level and 1% as the lower level.

Various LUC scenarios are investigated:

- Palm oil production without LUC (baseline), assuming an FFB yield of 20 t FFB ha$^{-1}$.

- 1%, 5%, 10%, and 20% LUC, equally converted from forest and peatland, i.e., 10% LUC = 5% from forest and 5% from peatland. The equal conversion from forest and peatland is arbitrary; therefore, Monte Carlo simulations are used to calculate the uncertainty. In addition, two scenarios for 10% LUC from forest and 10% from peatland are calculated separately.

- Annual GHG emission factors from direct land use change in tropical regions are taken from[44].

LUC is of paramount importance with respect to the climate-relevant performances of oil palm plantation; therefore, 1 ha is used as a functional unit. Substitution is applied for by-products and surplus electricity. Moreover, the uncertainty due to substitution, is investigated by applying an approach used by[45] and in addition, three options with and without LUC. Substitutes are identified based on function and existing markets.

### *Identifying by-product substitutes*

By-products are PKO and PKM. The relevant market for PKO is the oleochemical sector, and the C-chain length, i.e., fatty acid composition, is the most relevant function. The situation for the PKM (or expeller) is more complicated. PKM is a source of protein (14%) and energy (12 MJ kg$^{-1}$ dry matter) with a high fiber (16.5%) content. It can be used as ingredient in various animal feeds.

In beef cattle, PKM can constitute up to 80% of the diet, and for dairy cattle. The fiber content is acceptable to most ruminants but is considered high for poultry. Biodegradation of PKM through solid-state fermentation can improve its nutritional quality, improving broiler health status and growth performance[46]. Hence, in monogastric animals such as the African catfish or layer chickens, palm kernel meal can be used to make up about 20% to 30% of the animal's diet. More recent studies have shown that PKM can also replace fishmeal in aquaculture[47].

Animal feed is usually a complex mix of different ingredients. Several studies have investigated the replacement potential of PKM with respect to mostly soybean meal but also fishmeal, corn, and wheat bran[48-54]. PKM can be integrated into all animal feed mixes to a certain degree, but what is substituted will most likely depend on the local market of animal feed.

### Inventory

Inventory data for oil palm production are taken from[31] and the nutrient composition of fronds and EFB are taken from[9].

The following assumptions are used for the CHP plant:

- For sake of simplicity the oil extraction rate (OER) is assumed to be 23%, although it can vary between 19% and 26%. However, the technical improvement of OER is not within the scope of this study

- 1 t FFB processed in the palm oil mill generates 130 kg mesocarp fibers and 54.6 kg shells, the ratio between the residues is assumed to be constant.

- The average low calorific value (LCV) of mesocarp fibers is 11 MJ kg$^{-1}$, while the LCV of shells is 13.4 MJ kg$^{-1}$. These values can vary, e.g.[55] reported 16.3 MJ kg$^{-1}$kernel nut shells and[56] 10 MJ kg$^{-1}$ for mesocarp fibers. The selected LCV values are at the lower end so that electricity surplus is not overestimated.

- Heat demand is 1,100 MJ t$^{-1}$ FFB and electricity demand is 22.5 kWh t$^{-1}$ FFB[57].

- CHP efficiency in typical palm oil mills is 0.72 according to[57] and can reach 88% in energy-optimized CHP plants. Just the lower CHP-efficiency is used, as it represents the current situation in palm oil mills better.

The life cycle stages and related mass flows for 1 ha plantation area are shown in Figure 3.

### Life cycle impact assessment

This study uses the CF as quantitative indicator. The CF is based on the Product Environmental Footprint methodology, version 3.1. The CF measures the potential contribution of a product to global warming. It considers all GHG emissions associated with the product throughout its life cycle—from raw material extraction to production, use, and end-of-life. The contribution of fossil-based emissions, biogenic-based emissions and emissions from land use change are separately shown for the oil palm plantation.

## RESULTS AND DISCUSSION

### Oil palm plantation

The CF of oil palm plantations is primarily driven by LUC and by biogenic methane emissions resulting from the treatment of POME. The CF varies significantly depending on the type of land converted. The same LUC from forest and peatland is arbitrarily assumed, although it varies between different regions of Indonesia. Therefore, two additional calculations are conducted to show the CF when 10% LUC comes either from forest or peatland. The CF is calculated for oil palm plantations having a yield of 20 t FFB ha$^{-1}$; corresponding CF results are shown in Table 1.

In the baseline scenario, 45% of CF originates from POME treatment, approx. 17.5% from N-fertilizer, 17.5% from diesel consumption, and 10% from potassium fertilizer. The CF nearly doubles if 10% of the area is converted from peatland or if 20% is converted from a mix of forest and peatland. Other environmental

**Table 1. Carbon footprint per ha and year due to LUC**

| | | Baseline no LUC | LUC 1% | LUC 5% | 10% from forest | LUC 10% | 10% from peatland | LUC 20% |
|---|---|---|---|---|---|---|---|---|
| Climate change | kg $CO_{2eq}$ | 6.3E + 03 | 6.5E + 03 | 7.7E + 03 | 6.6E + 03 | 9.2E + 03 | 1.2E + 04 | 1.2E + 04 |
| (biogenic) | kg $CO_{2eq}$ | 2.8E + 03 | 2.8E + 03 | 2.8E + 03 | 2.8E + 03 | 2.8E + 03 | 2.8E + 03 | 2.8E + 03 |
| (fossil) | kg $CO_{2eq}$ | 3.4E + 03 | 3.4E + 03 | 3.4E + 03 | 3.4E + 03 | 3.5E + 03 | 3.6E + 03 | 3.6E + 03 |
| (land use) | kg $CO_{2eq}$ | 3.0E + 00 | 2.9E + 02 | 1.5E + 03 | 3.9E + 02 | 2.9E + 03 | 5.4E + 03 | 5.8E + 03 |

LUC: Land-use change.

impacts are not considered in this study. In the LUC 20% scenario, CF originated from LUC (approx. 50%) and plantation activities, thereof 23% from storage of POME in lagoons. Biogenic methane emissions from POME treatment can be reduced by 2,600 kg $CO_{2eq}$ per 20 t FFB when co-composted with EFB. The high CF of peatland conversion is due to the drainage of organic matter, which triggers $CO_2$ release through oxidation. While $CH_4$ and $N_2O$ emissions occur, their contribution is small compared to the $CO_2$ released from peatlands.

Monte Carlo simulations were used to assess the variability of CF based on yield and LUC. Change in yield is associated with the increase or decrease of linked parameters, e.g., yield decrease also leads to higher area demand and higher nitrogen input and consequently higher GHG emissions per product unit; the same applies to the application of pesticides and diesel consumed. Therefore, input parameters linked to the yield are not used to avoid unrealistically high uncertainty due to the nature of Monte Carlo simulations. Typical yield ranges from 14 t to 25 t per productive area, besides four land use change scenarios (1%, 5%, 10%, and 20%) are defined. In the LUC scenarios, the contribution from forests and peatlands ranges from 0% to 100%. All Monte Carlo simulations are calculated with 1000 iterations. The CF results are shown in Table 2 and Figure 4.

In Figure 4 the upper and lower quartiles are shown, the median is indicated by a straight line, the average by crosses, and outliers are shown as circles; outliers are defined by 1.5 times the interquartile distance.

Land use change from peatland has a detrimental effect on climate change. The CF per ha doubles when 20% LUC occurs compared to no LUC. The uncertainty of CF increases with increasing LUC. The difference between the 5% percentile and 95% percentile increases from 2,382 kg $CO_{2e}$ in the baseline to 10,248 kg $CO_{2e}$ in the LUC 20% scenario. The fact that smallholders frequently achieve only 42% of attainable yields indicates a significant opportunity for improvement. Approx. 40% of 17 million ha of oil palm plantations are managed by smallholders[58]. The average yield from 2017 - 2021 was 17.5 t FFB $ha^{-1}$, according to FAOSTAT[59]. A yield increase of smallholders' plantation from 11 t FFB to 20 t FFB $ha^{-1}$ would generate an additional 14 million t CPO, 2.0 million t PKO and 2.2 million t PKM without significantly higher GHG emissions. The assumed yield increase for smallholders equals a plantation area of 3 million ha.

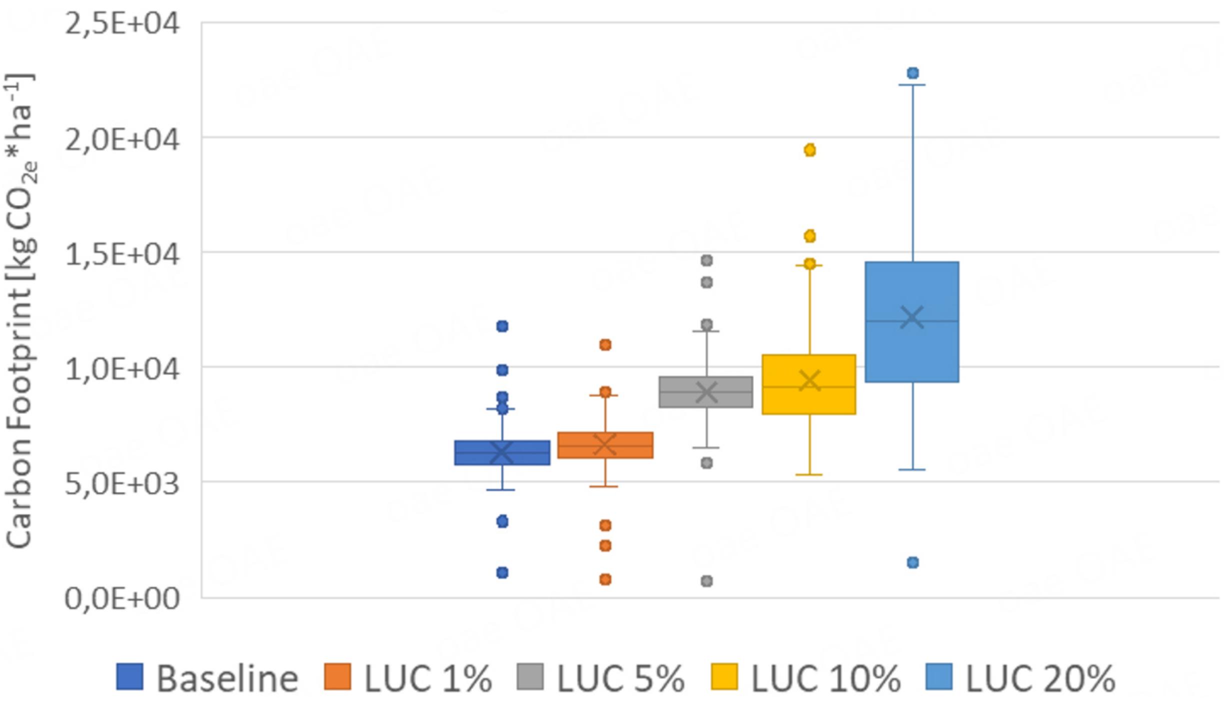

**Figure 4.** Climate change range due to LUC and yield variability. LUC: Land-use change.

**Table 2. Overview of Monte Carlo simulation carbon footprint results expressed in kg CO$_{2eq}$ ha$^{-1}$ a$^{-1}$**

| | Baseline | LUC 1% | LUC 5% | LUC 10% | LUC 20% |
|---|---|---|---|---|---|
| Mean | 6,216 | 6,642 | 8,914 | 9,431 | 12,384 |
| Standard deviation | 778 | 840 | 999 | 5,247 | 3,516 |
| Minimum | 1,045 | 762 | 713 | 5,318 | 4,841 |
| Maximum | 11,758 | 11,046 | 14,637 | 164,584 | 58,108 |
| Median | 6,262 | 6,602 | 8,892 | 9,142 | 12,367 |
| 5% Percentile | 5,223 | 5,432 | 7,410 | 6,466 | 7,302 |
| 95% Percentile | 7,605 | 8,042 | 10,527 | 12,389 | 17,549 |
| D percentile | 2,382 | 2,610 | 3,117 | 5,924 | 10,248 |

LUC: Land-use change.

## Palm oil mill

Palm oil mills are inherently energy self-sufficient, utilizing residues (mesocarp fibers and shells) to heat and power. Processing 1 t of FFB generates 130 kg of fibers and 54.6 kg of shells. The total energy is calculated based on the energy content and the conversion efficiency of the CHP-plant:

$$\text{Total energy} = \text{Shells}^{*}\ \text{LCV}_{\text{shells}} + \text{fibers}^{*}\text{LCV}_{\text{fibres}} = 43{,}233 * \text{CHP}_{\text{efficiency}}$$

The total energy content of these residues (31,123-38,045 MJ ha$^{-}$1) comfortably exceeds the mill's heat demand (22,000 MJ) and electricity demand (1,623 MJ) for processing 20 t FFB. At 72% efficiency, the system can export a surplus of 2,083 kWh to the national grid. Providing there is grid access, the CHP unit allows the mill to transition from a net GHG-emitter to a climate-beneficial system by displacing fossil-based electricity.

The mass and energy flows of the palm oil mill are shown in Figure 5.

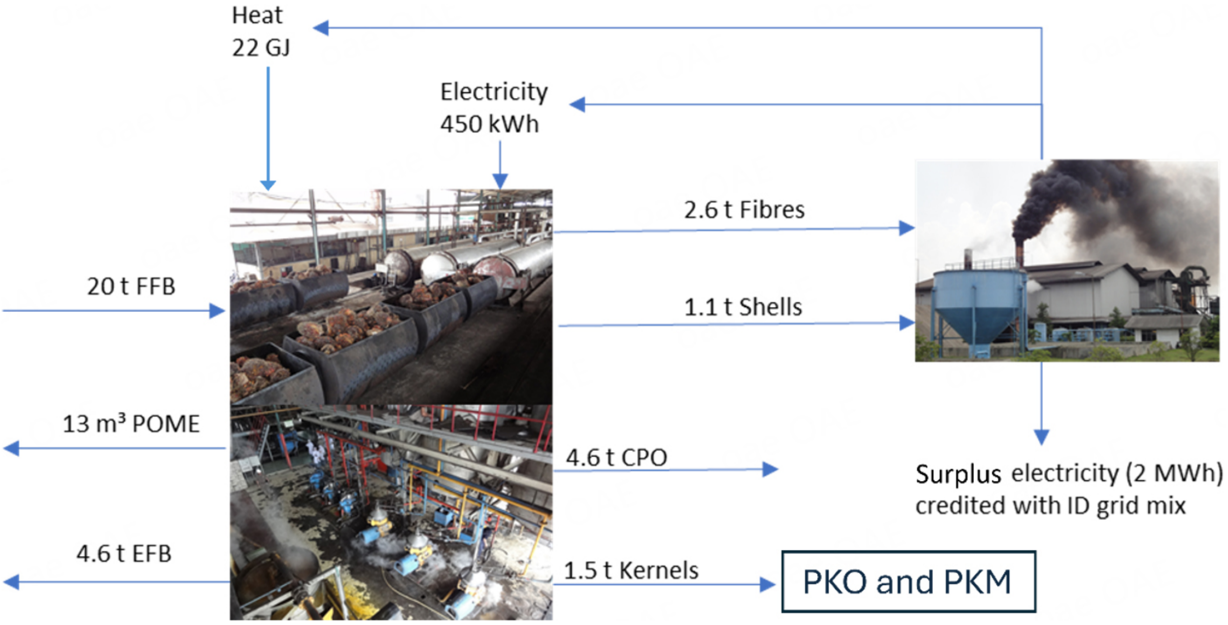

**Figure 5.** Mass and energy flows of a typical palm oil mill per 20 t FFB (pictures were self-taken). CPO: Crude palm oil; PKO: palm kernel oil; PKM: palm kernel meal; FFB: fresh fruit bunches; EFB: empty fruit bunches.

The palm oil mill is divided into FFB processing (left side of Figure 5) and a CHP (right side); lagoons are associated to the plantation because the treated POME is used for irrigation. Environmental performance can be improved by treating POME instead of storing it in lagoons, as already demonstrated by[32,60-62]. The oil mill is modeled using the Indonesian electricity mix and global heat mix based on natural gas due to data limitations. The residues are used as biogenic feedstock for the CHP-plant. The CHP is considered a waste treatment unit; hence it received the residues without upstream emissions. The generated energy in the CHP is credited by the same heat and electricity mix used in the palm oil mill. The treatment of 20 t FFB (yield per ha equals 4.6 t CPO) in the mill results in 2.0 t $CO_{2eq}$ while the CHP credit would be 3.1 t $CO_{2eq}$, provided access to the electricity grid exists. The CHP covers the entire heat demand of the oil mill. The combined system (oil mill + CHP) is climate-friendly and saves fossil resources but produces harmful dust and other air emissions[31]. The mill generates three products, CPO and kernels, which are further processed in specialized mills, as well as surplus electricity. Feed-in tariffs for electricity vary between different regions in Indonesia, as do prices for palm oil products. Hence, a simplified economic approach is applied, where the revenues from CPO, PKO, and PKM are used for the palm kernel mill operations. Recent revenue figures are taken from Malaysia[63] due to a lack of data from Indonesia.

## Consequences of modeling choices

The CF results are highly sensitive to how PKO and PKM are handled. The most important application of PKO is in the oleochemical sector; 70% are used for oleochemicals, 28% for food, and just 2% for biofuels, according to[64]. Table 3 shows that based on fatty acid composition, PKO serves as a direct substitute for coconut oil. The average price of PKO and coconut oil is almost the same. Therefore, 1 t PKO substitutes 1 kg coconut oil.

The consequences of modeling choices will be demonstrated using publications from[45,66], although they aggregated CPO and PKO hence do not use substitution for PKO despite both oils ending-up in different markets[64].

**Table 3. Fatty acid composition of selected plant oils (modified from[65])**

| Plant-oil | Principal fatty acids | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Lauric** | **Myristic** | **Palmitic** | **Stearic** | **Oleic** | **Linoleic** | **a-Linoleic** |
| Palm oil | | 1 | 43 | 4 | 40 | 10 | |
| Palm kernel oil | 48 | 16 | 8 | 2 | 15 | 2.5 | |
| Soybean oil | | | 11 | 4 | 23 | 54 | 8 |
| Rapeseed-oil | | | 4 | 2 | 60 | 20 | 10 |
| Coconut-oil | 49 | 17 | 9 | 2 | 6 | 2 | |

**Table 4. Composition of feed ingredients[67]**

| | PKM, < 5% oil | Grass, de-hydrated | SBM, <5% oil | Barley | Wheat | Corn gluten | Fish-meal |
|---|---|---|---|---|---|---|---|
| Dry matter % | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Crude protein g/kg | 183 | 162 | 495 | 113 | 126 | 216 | 678 |
| Crude fibre | 207 | 260 | 72 | 54 | 21 | 90 | 0 |
| Crude fat g/kg | 32 | 34 | 19 | 19 | 16 | 28 | 103 |
| Starch g/kg | 6 | 12 | 68 | 599 | 691 | 205 | 0 |
| Gross energy MJ/kg | 18.9 | 18.7 | 19.5 | 18.3 | 18.2 | 18.7 | 20.2 |
| Phosphorous g/kg | 6.1 | 3.1 | 7.1 | 3.9 | 3.6 | 9.8 | 29.9 |
| Phytate P g/kg | 4 | 0.2 | 4.3 | 2.1 | 2.3 | 6.4 | 0 |

PKM: Palm kernel meal.

**Table 5. Comparison of 0.122 kg PKM with other animal feed ingredients and mixtures**

| | Palm kernel meal, < 5% oil | Soybean meal, < 5% oil | Barley | Sum of barley + soybean meal | Just soybean meal, < 5% oil |
|---|---|---|---|---|---|
| Mass (kg) | 0.122 | 0.035 | 0.066 | | 0.045 |
| Crude protein g | 22.3 | 17.3 | 7.5 | 24.8 | 22.3 |
| Crude fiber g | 25.3 | 2.5 | 3.6 | 6.12 | 3.24 |
| Crude fat g | 3.9 | 0.67 | 1.3 | 1.96 | 0.86 |
| Starch g/kg | 0.73 | 2.4 | 39.5 | 41.9 | 3.06 |
| Gross energy MJ | 2.3 | 0.68 | 1.2 | 1.88 | 0.88 |
| Phosphorous g | 0.74 | 0.25 | 0.26 | 0.51 | 0.32 |
| Phytate P g | 0.49 | 0.15 | 0.14 | 0.29 | 0.19 |

PKM is used for animal feed, but identifying a single substitute is difficult because PKM provides protein, energy, and fiber. The composition of relevant animal feed ingredients is shown in Table 4.

Schmidt and Weidema[45] used the Feeding Component Table of[68] in order to calculate the substituted products for 0.122 g PKM, which is generated when 1.0 kg palm oil is produced. PKM replaced 0.035 kg of soybean meal (SBM) and 0.066 kg barley and generated additional 0.007 kg of soybean oil (SBO).

Alternatively, just SBM can be substituted by PKM based on the protein content, 0.122 kg PKM would substitute 0.045 kg of SBM and 0.011 kg of SBO. Using the feed composition figures from Table 4 results in the figures shown in Table 5.

**Table 6. Influence of modeling choices for by-product substitution**

| Approach | [45] | Based on protein content | Based on cereal unit |
|---|---|---|---|
| Upstream emissions | Integrated | 0.75 kg $CO_2$*$kg^{-1}$ PKO<br>0.15 kg $CO_2$*$kg^{-1}$ PKM | 0.75 kg $CO_2$*$kg^{-1}$ PKO<br>0.15 kg $CO_2$*$kg^{-1}$ PKM |
| By-product substitutes | 0.028 kg SBM,<br>0.007 kg SBO<br>0,066 kg barley | 0.045 kg SBM<br>0.011 kg SBO<br>0.14 kg PKO | 0.091 kg SBM<br>0.023 SBO<br>0.14 kg PKO |
| Total credit | 0.132 kg $CO_{2eq}$ | 0.324 kg $CO_{2eq}$ | 0.463 kg $CO_{2eq}$ |

PKO: palm kernel oil; PKM: palm kernel meal; SBM: soybean meal; SBO: soybean oil.

Neither soybean meal (SBM) alone nor a mixture of SBM plus barley provides the same function as PKM, e.g. the fiber content is substantially lower, while the starch content is higher, as shown in Table 5.

The cereal unit (CU) is a key figure, which reflects the energy supply capacity of a product in relation to the calculated energy supply capacity of feed barley, depending on the structure of use of the agricultural product in feeding, according to BMELH[69]. The CU of PKM is 0.41 CU $dt^{-1}$ and of soybean meal 0.95 CU $dt^{-1}$. Hence, 0.122 g PKM would replace 0.91 g SBM.

Depending on whether PKM is assumed to replace SBM, barley, or a "cereal unit", credits can deviate by up to 100%. This illustrates the importance of modeling choices and illustrates also the uncertainty related to product substitutions. Therefore, the assumptions for product substitution need to be transparently described.

To show the consequences of the modeling choices for by-product substitution, the same amount of PKM is used for the following analysis. Based on the economic revenue the kernels account for 10% of the upstream emissions, i.e. are 0.35 t $CO_{2eq}$ per t kernel. The kernels are transported to kernel mills and processed to PKO and PKM. Treating the kernels causes another 0.062 t $CO_{2eq}$ $t^{-1}$ and generates 0.53 kg PKM and 0.47 kg PKO. Using market-based substitution ratios of 78.5% for PKO and 21.4% for PKM results in 0.75 t $CO_{2eq}$ $t^{-1}$ PKO and 0.15 t $CO_{2eq}$ $t^{-1}$ PKM.

For simplicity, it is assumed that the same amounts of PKM and SBO are produced as reported by[45]. The system is credited for by-products using data from[34], consequential module, market-datasets. Results are shown in Table 6 and compared with[45].

The credits vary substantially. The most important assumption by [66] is that PKO equals CPO, which is an oversimplification. For each ton CPO, approx. 0.14 t PKO is produced. Globally 15% of CPO is used as biofuel and 77% as food, while 70% of PKO is used for oleochemicals, 28% for food, and just 2% for biofuels, according to[64]. The choice of the most appropriate substitution for PKM (and PKO) is context-specific and limits the comparability of results from different studies and other data sources, respectively.

In addition to the comparison above, different approaches used by[28-30] are applied to reveal the consequence of modeling choice for by-products for this analysis. Six scenarios are defined, i.e., baseline without LUC, and 5 % LUC, each with three approaches. Coconut is used as a replacement for PKO and soybean for protein feed from Ecoinvent 3.11, consequential. Results are expressed per ha and subsequently converted per t CPO, or t (CPO + PKO) in Table 7. The scenarios are defined below:

(1) Baseline, CPO as product PKO and PKM as distinguished products

**Table 7. Influence of by-product substitution choices on the CF of CPO per ha and per t**

| Substitution scenario | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| All products [kg $CO_{2eq}$*$ha^{-1}$] | 6.2E + 3 | 6.2E + 3 | 6.2E + 3 | 8.9E + 3 | 8.9E + 3 | 8.9E + 3 |
| PKO (credit)[kg $CO_{2eq}$*$ha^{-1}$] | -1.4E + 3 | - | - | -1.4E + 3 | - | - |
| PKM (credit) [kg $CO_{2eq}$*$ha^{-1}$] | -3.6E + 3 | 3.4E + 3 | - | -3.6E + 3 | 3.4E + 3 | - |
| CPO [kg $CO_{2eq}$*$ha^{-1}$] | 1.2E + 3 | 2.8E + 3 | 6.2E + 3 | 3.9E-3 | 5.5E + 3 | 8.9E + 3 |
| CPO [kg $CO_{2eq}$*$t^{-1}$] | 0.26E + 3 |  | 1.4E + 3 | 0.85E + 3 |  | 1.9E + 3 |
| (CPO + PKO) [kg$CO_{2eq}$*$t^{-1}$] |  | 0.54E + 3 |  |  | 1.0E + 3 |  |

CF: Carbon footprint; CPO: crude palm oil; PKO: palm kernel oil; PKM: palm kernel meal.

(2) Baseline CPO + PKO as combined product and PKM as by-product (similar to[45])

(3) Baseline, CPO and kernels as negligible by-product (similar to[29])

(4) With 5% LUC and as 1

(5) With 5% LUC and as 2

(6) With 5%LUC and as 3

The CF of CPO ranges from 0.26E3 to 1.4E3 kg $CO_{2eq}$ $t^{-1}$ without LUC and 0.85E3 to 1.9E3 kg $CO_{2eq}$ $t^{-1}$ depending on the modeling choice for by-products. These variations demonstrate that a direct comparison of results from different studies is often impossible because substitution can introduce remarkable uncertainties. Therefore, it is highly recommended to check the underlying assumptions and relationships used in the CF models, as also suggested by[70-72].

## Limitations of this study

This study aims to estimate the carbon footprint variability due to LUC in Indonesia. Regional variables, such as peatland depth in Kalimantan or local feed-in tariffs, may lead to different localized results. In this study it is assumed that access to the electricity grid exists.

Due to data limitations, revenue figures from Malaysia (2023-2024) were used as a proxy for the Indonesian system. Given the similarity of palm oil production systems in both countries and the global market price fluctuations, it is assumed to be a reasonable approach. Although Indonesian average data over the same data collection period as for the palm oil system would be the preferred option.

Substituting single ingredients for PKM is not fully representative of real-world animal feed markets; economically optimized feed mixtures would provide a more realistic baseline.

## CONCLUSION

While the expansion of Indonesian oil palm production stimulated by global economic growth improves local living standards, it simultaneously triggers substantial GHG emissions through LUC. Peatland conversion is the most carbon-intensive development pathway. A critical determinant of the environmental performance of palm oil mills is access to the national electricity grid. Under conditions where surplus electricity from CHP units can displace marginal fossil-based electricity, the mill transitions from a net GHG emitter to a climate-beneficial system.

The CF of palm oil products is highly sensitive to yield, LUC intensity, and specific modeling choices regarding by-product substitution. Substituting PKM by single ingredients in animal feed is not fully convincing, future research should prioritize economically optimized feed mixtures to better reflect market dynamics. To move toward a more sustainable economy, it is essential to demonstrate the consequences of these modeling choices to stakeholders in policy and industry. Significant potential exists through the application of circular economy principles, such as improved residue management through co-composting EFB with POME to reduce methane emissions. Additionally, providing smallholders with essential agricultural inputs and tailored technical training represents a vital opportunity to maximize yields and enhance rural incomes while minimizing the environmental footprint.

## DECLARATIONS

### Authors' contributions

The authors contributed equally to the article.

### Availability of data and materials

Inventory data not shown in this paper are available in[8,27,28]. Other data are available from the corresponding authors upon reasonable request.

### AI and AI-assisted tools statement

Not applicable.

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### Conflicts of interest

All authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Copyright

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