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Life Cycle Carbon Footprint of Indonesian Refined Palm Oil and Its Embodied Emissions in Global Trade

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Abstract: Indonesia plays a dominant role in the global refined palm oil (RPO) supply chain. Given the increasing global emphasis on carbon neutrality and sustainable trade, understanding the carbon footprint of Indonesian RPO and its embodied carbon emissions (ECE) in global trade is essential for identifying mitigation opportunities and aligning with international sustainability standards. This study integrates life cycle assessment and trade data to quantify the carbon footprint of RPO products and analyze the spatiotemporal patterns of trade-related ECE. Results show that producing 1 ton of RPO emits 2196.84 kg CO_2e, with wastewater treatment (57.67%) and land use change (32.82%) as the main contributors. From 2010 to 2022, ECE induced by RPO exports rose from 35.79 Mt CO_2e to 54.94 Mt CO_2e (3.64% annual growth). Major ECE importers were India, China, and Pakistan, accounting for 20.36%, 14.29%, and 11.45% of Indonesia's total trade-related ECE, respectively. Comprehensive sensitivity and uncertainty analyses conducted on key parameters confirmed the robustness of the above results. Based on these robust findings, integrated mitigation strategies targeting both production optimization and sustainable trade mechanisms are proposed to accelerate Indonesia's RPO industry decarbonization.

Keywords: carbon footprint; life cycle assessment; refined palm oil industry; land use change; embodied carbon emissions

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1. Introduction

Refined palm oil (RPO) is widely consumed globally, accounting for over 30% of the world's total oil and fat demand [1,2]. As a crucial bio-based raw material with high economic value, RPO is considered a key driver of global low-carbon energy transition [3,4]. Its high yield characteristics and carbon reduction potential serve as key drivers for achieving the United Nations Sustainable Development Goals (SDGs), particularly "Zero Hunger" (SDG 2) and "Climate Action" (SDG 13) [5,6].

Indonesia is the world's largest producer and exporter of RPO [7,8]. As a pillar industry of the country, the RPO industry not only supports rural development, poverty alleviation, and employment but also holds a critical position in the global agricultural trade system [9,10]. However, the expansion of Indonesia's RPO production and trade can drive high levels of carbon emissions along RPO supply chains and impede carbon neutrality goals [11,12]. From a production perspective, the life cycle carbon emissions (i.e., carbon

footprint) of RPO, which include the total greenhouse gas emissions from raw material extraction through processing to final product delivery, primarily originate from land use changes (LUC), agricultural input use, product processing, and logistics [13–15]. Among these, emissions from deforestation of tropical rainforests and peatland conversion are particularly significant [16,17], posing a major challenge to the global carbon balance [18]. On the demand side, the continuous rise in import demand for RPO is a primary driver of industry expansion in Indonesia, indirectly exacerbating carbon emissions along the supply chain [19,20]. This trade-driven expansion results in the transformation of production-related carbon emissions into embodied carbon emissions (ECE), referring to the carbon dioxide released during RPO production that becomes "embedded" in traded products in importing countries [21,22]. This transfer results in RPO-consuming countries externalizing carbon emissions to Indonesia.

Given the global climate change context, a comprehensive assessment of the full life-cycle carbon footprint of Indonesian RPO is essential. Understanding the spatial distribution of ECE in the RPO trade is also crucial for fostering a sustainable supply chain that benefits all stakeholders along the supply chain [23]. Such insights can provide scientific and technical support for the transition of Indonesia's RPO industry toward a high-quality, low-carbon development model.

Previous studies examined the RPO-related carbon emissions from a production perspective. Jamaludin et al. assessed the contributions of wastewater treatment, diesel consumption, and water use to GHG emissions in RPO production based on the carbon footprint accounting and palm oil mill sustainability indices [24]. GHG emissions have also been traced to LUC in oil palm plantations [25]. For instance, the expansion of oil palm plantations on peatlands significantly increases GHG emissions [26,27]. However, these approaches overlook cumulative emissions from raw material inputs, processing stages, and waste management, potentially leading to an underestimation of carbon emissions throughout the entire RPO production process. Moreover, from the demand side, the redistribution of emissions through international trade has received little attention, and the mechanisms by which importing countries inherit Indonesia's RPO emissions remain unquantified.

By combining a full life cycle assessment (LCA) with a systematic analysis of ECE, this study addresses the above gaps. First, this study develops a comprehensive carbon emission accounting framework for RPO products using the LCA method, quantifying the carbon footprints across Indonesia's RPO production chain and identifying hotspots. Then, by integrating the carbon footprint results with Indonesian RPO export data (including trade flows and transportation modes), the spatial distribution patterns of ECE in global trade were characterized. The structure of the remainder of this paper is as follows: Section 2 introduces the data sources and methodological framework; Section 3 presents the results and analysis of the product carbon footprint and ECE, accompanied by sensitivity and uncertainty analyses; Section 4 discusses key policy implications and proposes decarbonization recommendations; and Section 5 concludes the study.

2. Material and Methods

2.1. Life Cycle Carbon Footprint Assessment

2.1.1. Functional Unit and System Boundary

This study defines the functional unit as the production of 1 ton of RPO in Indonesia, with all associated materials, energy, chemicals, transportation, and outputs accounted for accordingly. PAS 2050 [28] is one of the mainstream standards for carbon footprint accounting. It provides detailed methodological guidance for assessing GHG emissions across the entire product life cycle and is more suitable for product carbon footprint accounting

compared to other standards (e.g., ISO 14067 [29]). Following the PAS 2050 standard, a "cradle-to-gate" LCA approach is employed to establish the system boundary [28,30]. A "cradle-to-gate" LCA approach refers to an assessment that accounts for all environmental impacts from the extraction of raw materials (the "cradle") up to the point where the product leaves the production facility (the "gate"), excluding the use and disposal phases. The system boundary for RPO's carbon emission encompasses raw materials inputs, as well as key stages such as nursery, plantation, processing, refining, transportation, wastewater treatment, and LUC (Figure 1). Data on energy and material inputs and outputs, representing the "cradle-to-gate" perspective, are classified as foreground data. Within this boundary, all material and energy inputs are considered. The carbon footprint calculation model includes GHG emissions from carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs; including HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, and HFC-152a), perfluorocarbons (PFCs; including PFC-14 and PFC-116), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3), all of which are converted into carbon dioxide equivalents (CO_2e) based on their global warming potential (GWP) values for assessment according to the Intergovernmental Panel on Climate Change (IPCC)'s 5th assessment report (see Appendix A, Figure A1). The GWP values are used to compare the relative contribution of each gas to global warming over 100 years, with CO_2 as the baseline reference gas (GWP = 1).

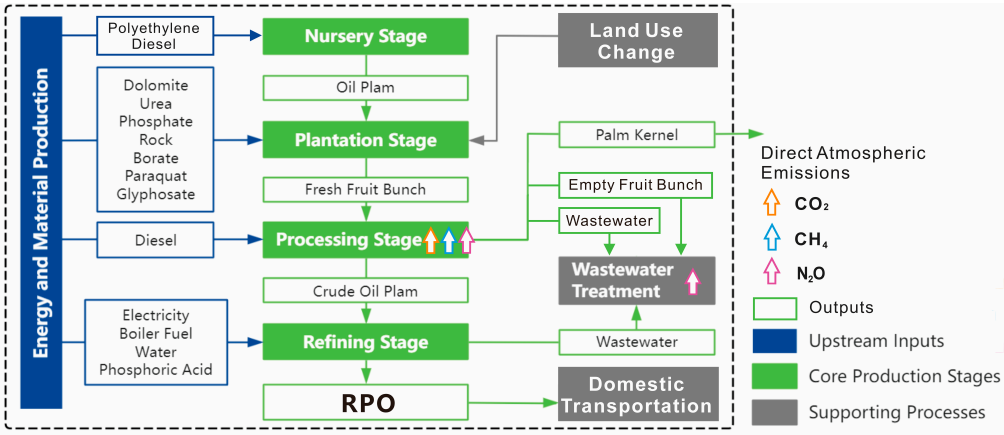


Figure 1. System boundaries for RPO production. Note: Within the system boundary, direct GHG emissions are solely attributed to the processing stage and wastewater treatment. Indirect emissions from upstream inputs (e.g., fertilizers, diesel, electricity), domestic transportation, and LUC are included in the LCA but are not shown separately in this diagram.

To accurately attribute emissions within the system boundary, an allocation principle is applied to account for the impact of by-products. In RPO production, the palm kernel is a key by-product, necessitating an allocation method that fairly distributes emissions between crude palm oil (CPO) and palm kernel. This study adopts a mass-based allocation approach, where emissions from the CPO production stage are allocated based on the production ratio of CPO to palm kernel [29,31]. According to process data, the production of 1.05 tons of CPO generates approximately 0.28 tons of palm kernel, resulting in an allocation ratio of 79% for CPO and 21% for palm kernel. This method ensures that resource consumption and GHG emissions are proportionally assigned to both products. However, in the refining stage, where CPO is further processed into RPO, palm kernel is no longer involved. As a result, all emissions from refining are fully attributed to RPO. Therefore, in the life cycle carbon footprint calculation, emissions from the fresh fruit bunch to the CPO stage are allocated according to the 79:21 ratio, while emissions from the refining stage are entirely assigned to RPO.

2.1.2. Life Cycle Inventory Analysis

To ensure a comprehensive assessment of carbon emissions, this study systematically quantifies material consumption, energy use, and direct GHG emissions across all production stages. Particular attention is given to the impact of LUC during oil palm cultivation, as it represents a significant source of emissions. The carbon emissions from LUC are estimated following the Intergovernmental Panel on Climate Change (IPCC) methodology, which accounts for changes in aboveground biomass, belowground biomass, deadwood, litter, and soil carbon content resulting from the conversion of different land covers into oil palm plantations. Given that oil palm is a perennial woody plant with an average lifespan of approximately 20 years, LUC-related carbon emissions are distributed evenly over its 20-year life cycle. Using land cover transition data from Indonesia's oil palm plantations between 1995 and 2015, the corresponding carbon emissions from LUC were determined. Based on these factors, the carbon footprint is estimated as:

$$C_{footprint} = \sum_{i=1}^{n} \left(C_{mat,i} + C_{eng,i} + C_{GHG,i} \right) + C_{LUC} \quad (1)$$

$$C_{mat,i} = \sum_{j=1}^{m} \left(M_j \cdot F_{mat,j} \right) \quad (2)$$

$$C_{eng,i} = \sum_{k=1}^{p} \left(E_k \cdot F_{eng,k} \right) \quad (3)$$

$$C_{GHG,i} = \sum_{l=1}^{q} \left(G_l \cdot GWP_l \right) \quad (4)$$

$$C_{LUC} = C_b + C_d + C_s + C_a \quad (5)$$

where $C_{footprint}$ represents the carbon footprint of Indonesian RPO products (kg CO_2e per ton of product). $C_{mat,i}$ denotes the carbon emissions from material consumption in stage i (kg CO_2e), while $C_{eng,i}$ represents the carbon emissions from energy consumption in stage i (kg CO_2e). $C_{GHG,i}$ corresponds to the direct GHG emissions in stage i (kg CO_2e). n denotes the total number of life cycle stages, excluding LUC-related emissions, while C_{LUC} represents the carbon emissions from LUC due to oil palm cultivation (kg CO_2e). For emissions from material and energy consumption: M_j represents the quantity of material j consumed in stage i (kg), with $F_{mat,j}$ as its carbon emission factor (kg CO_2e/kg); E_k denotes the amount of energy type k consumed in stage i (kWh), while $F_{eng,k}$ is the corresponding carbon emission factor (kg CO_2e/kWh). For direct GHG emissions: G_l denotes the mass of GHG l emitted in stage i (kg), while GWP_l represents its GWP (kg CO_2e/kg). Furthermore, for LUC-related emissions: C_b, C_d, C_s, and C_a represent the carbon emissions from belowground biomass, deadwood and litter, soil carbon, and aboveground biomass, respectively (kg CO_2e).

2.2. Embodied Carbon Emissions Quantification

ECE in Indonesia's RPO global trade entail two components: (1) product-related emissions, which capture emissions generated throughout the entire life cycle of the product, from raw material acquisition to manufacturing; and (2) transportation-related emissions, which account for logistic operations from production sites to final consumption markets.

The product-related emissions are estimated based on global trade data and the carbon footprint per unit of RPO. To quantify transportation-related emissions, this study incorporates transportation distances between Indonesia and major importing countries, export volumes, and maritime carbon emission factors. Given the multimodal nature of Indonesia's RPO export logistics, maritime shipping remains the dominant mode of trans-

port, particularly for bulk commodities. Due to the lack of detailed transport mode data for each export transaction and considering Indonesia's archipelagic geography and prevailing international trade practices, this study assumes that all RPO exports are transported via maritime shipping. This assumption aligns with industry realities, as approximately 95% of Indonesia's international trade, including palm oil, is conducted through maritime transport, according to a World Bank report [32]. The ECE in Indonesia's RPO global trade is derived by combining product-related and maritime transport-related emissions as follows:

$$ECE_{trade,i} = ECE_{prod,i} + ECE_{trans,i} \quad (6)$$

$$ECE_{prod,i} = E \times Q_i \quad (7)$$

$$ECE_{trans,i} = D_i \times Q_i \times F_{trans} \quad (8)$$

where $ECE_{trade,i}$ represents the trade-related ECE from Indonesia's RPO exports to country i (kg CO_2e); $ECE_{prod,i}$ denotes the product-related ECE from Indonesia's RPO exports to country i (kg CO_2e); $EC_{trans,i}$ represents the transportation-related ECE from exporting RPO to country i (kg CO_2e); E is the average ECE per unit of exported RPO (kg CO_2e/t); Q_i denotes the export volume of RPO to country i (t); D_i represents the transportation distance from Indonesia to country i (km); and F_{trans} is the carbon emission factor for maritime transport (kg CO_2e/t/km).

2.3. Data Sources and Assumptions

This study's analytical timeframe spans 2010–2022, constrained by the fact that official export statistics for Indonesian RPO are available only through 2022.

The GHG emissions in this study are converted into CO_2e based on GWP values. The GWP values for different GHGs are obtained from the Fifth Assessment Report (AR5) of the IPCC [33].

For the carbon footprint accounting in this study, foreground data refers to the specific input and output data of each production stage, collected from multiple authoritative sources following a "cradle-to-gate" approach. Table 1 summarizes the key data sources used in different life cycle stages of RPO production.

Table 1. Sources of foreground data for the carbon footprint assessment.

Life Cycle Stage	Data Description	Source
Nursery Stage	Resource consumption and emissions	[34]
Plantation Stage	Plantation management, agricultural input usage	[35]
Processing Stage	Energy and material consumption in CPO production	[35]
Refining Stage	Energy consumption and emissions in RPO refining	[36]
Wastewater Treatment	Carbon emissions from treatment technologies	[37]
LUC Stage	Land conversion data (1995–2015) and land cover types	[38]

Background data, including carbon emission factors, are primarily obtained from the Ecoinvent 3.6 database, with a preference for Indonesia-specific data where available (see Appendix A, Table A1 for details) [39]. All background data are categorized as "cradle-to-gate". Additionally, production data for Indonesian RPO are sourced from the Indonesian Palm Oil Statistics Yearbook [40], while export data are derived from the United Nations' UN Comtrade Database [41].

Furthermore, the following assumptions are made in the selection and processing of data:

(1) Standardized Production Processes: It is assumed that the technological level and operational practices of RPO production in Indonesia are representative of the indus-

try, reflecting the average production conditions in major producing regions. This assumption ensures the generalizability of the findings to Indonesia's RPO sector.

(2) By-product Allocation: It is assumed that the market demand and price of palm kernel remain stable, and thus, a mass-based allocation method is applied for distributing the carbon footprint between RPO and its by-products. Potential impacts of market price fluctuations and downstream applications on allocation results are not considered in this study in order to simplify the calculation and maintain consistency in the allocation approach.

(3) 100% maritime shipping: It is assumed that all RPO exports are transported exclusively by maritime shipping, without considering the use of other transport modes such as land or air. Although alternative modes may be used in certain cases, their likelihood is low, and the volume involved is limited. Therefore, this assumption is considered to have a minimal impact on the overall results.

To evaluate the robustness of the results sensitivity and uncertainty analyses were conducted. In the sensitivity analysis, each input/output emission parameter was independently increased by 10% while keeping all other parameters constant, enabling the assessment of its relative influence on the overall carbon footprint. For the uncertainty analysis, Monte Carlo simulations were conducted to capture the probabilistic variation in input parameters within the LCA model and to evaluate the associated uncertainty in the results. The Monte Carlo simulations were carried out using SimaPro 9.1 software.

3. Results and Analysis

3.1. Carbon Footprint of Indonesian Refined Palm Oil Production

3.1.1. Impact of LUC on the Carbon Footprint

Carbon emissions from LUC vary significantly based on the type of land cover (see Figure 2). Based on the functional unit (i.e., 1 ton of RPO), the highest level of emission (13,186.15 kg CO_2e) is linked to primary forest conversion to oil palm plantation, followed by secondary forest (4066.57 kg CO_2e) and plantation forest (2961.49 kg CO_2e), respectively. When these land cover types are converted into oil palm plantations, substantial amounts of carbon stored in vegetation and soil are released into the atmosphere, leading to significant carbon emissions. In contrast, the change in grassland and cropland to oil palm plantations reduces carbon emissions by −779.04 kg CO_2e and −1551.60 kg CO_2e, respectively. This suggests that oil palm plantations demonstrate significantly greater carbon sequestration potential compared to grasslands and croplands, mainly attributed to the higher aboveground biomass (including trunk and canopy) and extensive root systems that enable long-term organic carbon storage. Overall, the original land cover type directly influences the carbon footprint of palm oil products. The carbon emissions from LUC range from −1551.60 kg CO_2e to 13,186.15 kg CO_2e. Given the difficulty in determining the specific original land cover type for each unit of palm oil product, a weighted average approach is applied for the carbon footprint assessment. As a result, the estimated carbon emission from LUC is 721.09 kg CO_2e.

3.1.2. Lifecycle Carbon Footprint Analysis

This study conducted a comprehensive assessment of the carbon footprint throughout the Indonesian RPO production process. The results indicate that the carbon footprint of producing 1 ton of RPO is 2196.84 kg CO_2e. The absolute emissions and relative contributions of each life cycle stage as calculated by the LCA carbon footprint model are presented in Table 2. The analysis reveals significant variations in the contributions of different stages to the carbon footprint. Wastewater treatment and LUC are the primary sources of carbon emissions, accounting for 57.67% and 32.82% of the carbon footprint,

respectively. Within the wastewater treatment stage, CH_4 emissions constitute 57.61% of total stage emissions. This is mainly due to the use of open lagoon technology, where organic matter is anaerobically decomposed by microorganisms, leading to substantial CH_4 generation. Furthermore, CH_4 exhibits higher GWP compared to CO_2 (see Appendix A, Figure A1). Emissions from other stages remain relatively low, each contributing less than 5% of the carbon footprint. Therefore, wastewater treatment and LUC should be prioritized in future emission reduction strategies.

Table 2. Carbon emissions and their proportions at different stages of RPO production.

Stage	Carbon Emissions (kg CO_2e)	Proportions (%)	Input/Output	Carbon Emissions (kg CO_2e)	Proportions (%)
Nursery Stage	4.54	0.21	Polyethylene	4.53	0.21
			Diesel	0.01	0.00
Plantation Stage	97.59	4.44	Dolomite	3.72	0.17
			Urea	51.29	2.33
			Phosphate Rock	7.47	0.34
			Borate	19.05	0.87
			Paraquat	4.98	0.23
			Glyphosate	11.08	0.50
Processing Stage	58.06	2.64	Diesel	2.27	0.10
			CO_2	13.35	0.61
			CH_4	0.02	0.00
			N_2O	0.22	0.01
			Electricity	42.20	1.92
Refining Stage	33.80	1.54	Electricity	27.19	1.24
			Boiler Fuel	6.25	0.28
			Water	0.05	0.00
			Phosphoric Acid	0.30	0.01
Domestic Transportation	14.82	0.67	Land Transport	13.42	0.61
			Water Transport	1.40	0.06
Wastewater Treatment	1266.93	57.67	Electricity	1.32	0.06
			CH_4	1265.61	57.61
LUC	721.09	32.82	-	-	-
Total	2196.84	100.00			

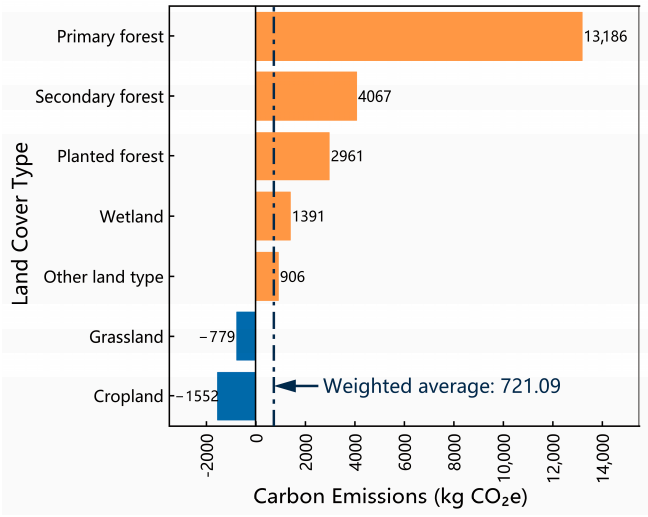


Figure 2. Carbon emissions from the conversion of different land cover types to oil palm plantations.

3.1.3. Spatiotemporal Dynamics of RPO Carbon Footprint

Based on the carbon footprint calculation for unit RPO, this study analyzes the spatiotemporal distribution characteristics of Indonesia's RPO carbon footprint from 2010 to 2022 by integrating RPO production data across different periods and regions in Indonesia (see Figure 3). In 2022, the regions with the highest carbon footprint are Kalimantan and Sumatra. Specifically, in Kalimantan, Kalimantan Tengah (18.37 million metric tons (Mt) CO_2e), Kalimantan Barat (11.28 Mt CO_2e), and Kalimantan Timur (9.01 Mt CO_2e) are the primary contributors, while in Sumatra, Riau (19.20 Mt CO_2e), Sumatera Utara (11.10 Mt CO_2e), and Sumatera Selatan (8.83 Mt CO_2e) exhibit the highest carbon footprints. These regions are the main production areas for RPO, therefore possessing high carbon emission reduction potential and being key to promoting the low-carbon transition of Indonesia's RPO industry. Furthermore, this study analyzes the spatiotemporal evolution of the RPO carbon footprint across Indonesian regions. Between 2010 and 2022, all regions experienced varying degrees of carbon footprint growth, with the most significant increases observed in Kalimantan Tengah (+14.59 Mt CO_2e), Kalimantan Barat (+8.14 Mt CO_2e), and Kalimantan Timur (+7.47 Mt CO_2e). The findings indicate that the regions with the fastest-growing carbon footprints are primarily located in Kalimantan, suggesting that this island is the core area for the expansion of Indonesia's RPO production and a critical focus for the carbon footprint management. Strengthening monitoring and mitigation efforts in these regions will not only effectively reduce the overall carbon footprint of Indonesia's RPO industry but also provide valuable insights for the sustainable development of the global RPO sector.

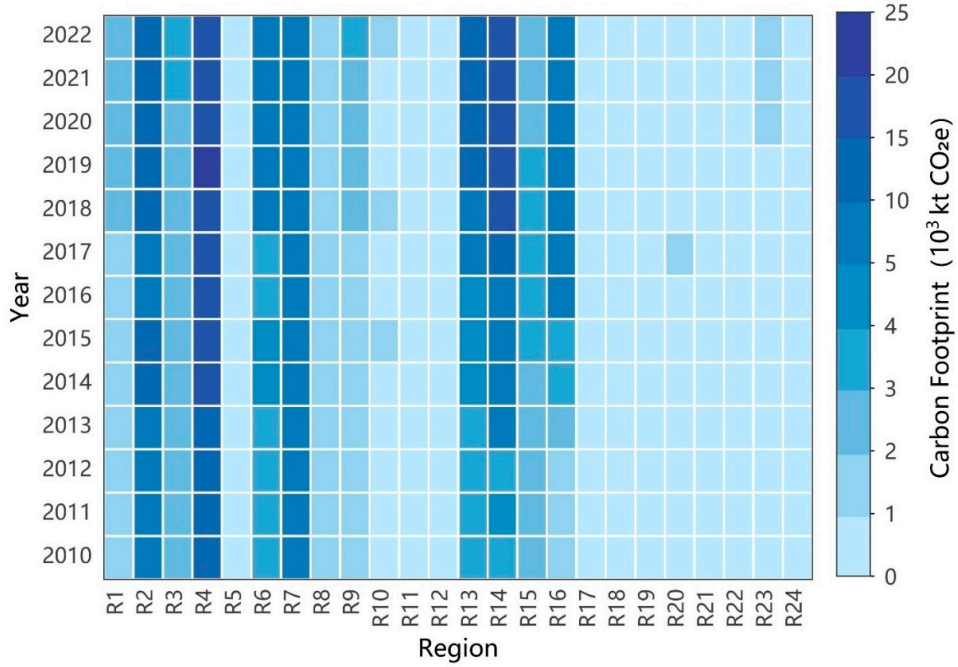


Figure 3. The carbon footprint of RPO in Indonesia by region, 2010–2022. Note: The horizontal axis represents regional codes (see Appendix A, Table A2 for details).

3.2. Embodied Carbon Emissions in Global Trade

The average ECE per unit of exported RPO product is 2196.84 kg CO_2e. By integrating Indonesia's RPO export data with this unit-based average ECE, the product-related ECE in Indonesia's RPO global trade from 2010 to 2022 was estimated (see Figure 4A). The results indicate that product-related ECE increased from 35.79 Mt CO_2e in 2010 to 54.94 Mt CO_2e in 2022, with an average annual growth rate of approximately 3.64%. In 2022, the total product-related ECE in Indonesia's RPO global trade reached 54.94 Mt CO_2e, with India, China, and

Pakistan being the largest contributors, accounting for 10.98 Mt CO_2e, 7.65 Mt CO_2e, and 6.16 Mt CO_2e, respectively. These three countries collectively contributed approximately 45% of the total product-related ECE. This finding highlights the significant influence of Asian markets, particularly India and China, on product-related ECE in Indonesia's RPO global trade. Other key markets, including the United States, Bangladesh, and Malaysia, also contributed to the increase in product-related ECE from Indonesia's RPO global trade.

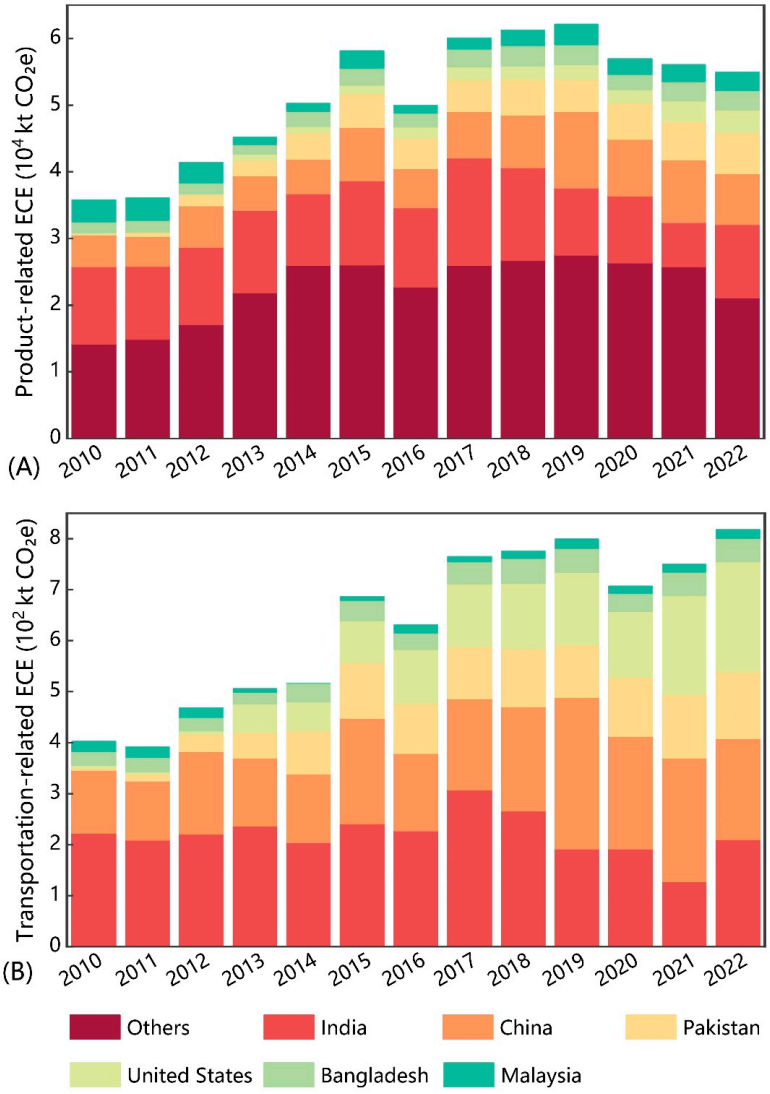


Figure 4. Product-related ECE (**A**) and transportation-related ECE (**B**) from 2010 to 2022.

The transportation stage is another major source of ECE in Indonesia's RPO exports. This study estimated the transportation-related ECE between Indonesia and its major export destinations from 2010 to 2022 by considering shipping distances, export volumes, and maritime transport emission factors (see Figure 4B). Given the uncertainty of shipping routes in maritime logistics, we estimated distances using the most likely direct sea paths between ports. In 2022, the highest transportation-related ECE were associated with exports to the United States (392.49 kt CO_2e), India (294.90 kt CO_2e), and China (285.12 kt CO_2e). While transportation contributes to the overall ECE in Indonesia's RPO exports, its impact is significantly lower compared to the product-related ECE. The potential margin of error introduced by using estimated distances is therefore considered negligible.

This study quantifies the overall ECE of Indonesia's RPO exports, accounting for both product- and transportation-related emissions (see Figure 5). In 2022, the majority of ECE

was concentrated in key export markets: India (11.19 Mt CO_2e), China (7.85 Mt CO_2e), Pakistan (6.29 Mt CO_2e), the United States (3.59 Mt CO_2e), Bangladesh (2.95 Mt CO_2e), and Malaysia (2.77 Mt CO_2e). Despite transportation emissions, product-related ECE remained the dominant source, with India, China, and Pakistan leading due to their high import volumes. These countries, through substantial imports of RPO, concentrate a significant amount of ECE from production and transportation processes within Indonesia, thereby significantly increasing Indonesia's environmental burden. Between 2010 and 2022, ECE contributions from Pakistan, the United States, and China surged by 6.09 Mt CO_2e, 3.50 Mt CO_2e, and 2.94 Mt CO_2e, respectively, intensifying environmental pressures on Indonesia's RPO supply chain. Pakistan saw the largest increase, emerging as a key driver of ECE transfers. In contrast, India and Malaysia reduced their contributions by 659.52 kt CO_2e and 524.05 kt CO_2e, respectively, due to declining import volumes. These trends highlight the critical influence of trade dynamics on ECE.

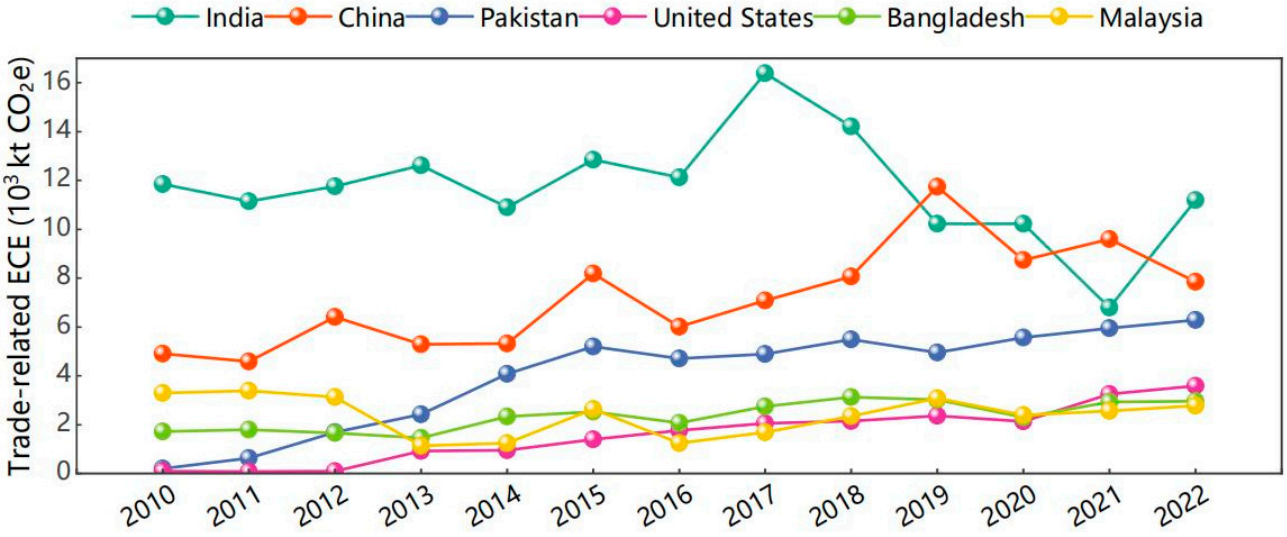


Figure 5. ECE in Indonesia's RPO global trade from 2010 to 2022, which is the sum of product-related ECE and transportation-related ECE.

3.3. Sensitivity Analysis

This study employs a sensitivity analysis to examine the influence of various inputs and outputs on the RPO carbon footprint.

Each input/output emission parameter was systematically varied by +10% independently while holding all other parameters constant to quantify its contribution to the carbon footprint (see Table 3). The results indicate significant variations in the contributions of different inputs and outputs to the carbon footprint. Notably, CH_4 emissions from the wastewater treatment stage have the most substantial impact. When CH_4 emissions increase by 10%, the carbon footprint rises by 5.76%. This is primarily due to the significantly higher GWP of CH_4 compared to CO_2, amplifying its effect on the lifecycle carbon footprint. Additionally, carbon emissions from LUC also play a considerable role, with a 10% increase resulting in a 3.28% change in the carbon footprint. This finding highlights the critical importance of LUC in the carbon footprint assessment of RPO. In contrast, variations in other input and output emissions exhibit relatively minor effects, each contributing less than 1%, suggesting lower sensitivity to the overall carbon footprint changes. Therefore, wastewater treatment and LUC should be prioritized in future carbon reduction strategies to effectively mitigate the carbon footprint of RPO products.

Table 3. Sensitivity analysis of the carbon footprint.

Life Cycle Stages	Input/Output	Carbon Footprint Change (%)
Nursery Stage	Polyethylene	0.02
	Diesel	0.00
Plantation Stage	Dolomite	0.02
	Urea	0.23
	Phosphate Rock	0.03
	Borate	0.09
	Paraquat	0.02
	Glyphosate	0.05
Processing Stage	Diesel	0.01
	CO_2	0.06
	CH_4	0.00
	N_2O	0.00
	Electricity	0.19
Refining Stage	Electricity	0.12
	Boiler Fuel	0.03
	Water	0.00
	Phosphoric Acid	0.00
Transportation	Land Transport	0.06
	Water Transport	0.01
Wastewater Treatment	Electricity	0.01
	CH_4	5.76
LUC	LUC	3.28

3.4. Uncertainty Analysis

In the LCA model, several key input parameters including activity data (e.g., material and energy inputs, LUC, and transportation distances) and carbon emission factors, contain inherent uncertainties stemming from differences in data quality, measurement approaches, and spatial or temporal resolution. These uncertainties may influence the robustness and reliability of the final carbon footprint results. To quantify this uncertainty, a Monte Carlo simulation was applied to estimate the probability distribution of input parameters in the LCA model and to assess the uncertainty of the results. The simulation was conducted using SimaPro 9.1 software. This probabilistic method evaluates uncertainty by generating multiple input parameter values and computing the corresponding carbon footprint distribution [42]. Multiple input values were generated through random sampling from lognormal distributions assigned to each parameter. A lognormal distribution was assumed for all inputs, following the default method used in the Ecoinvent database and SimaPro, which reflects the typical non-negative nature of environmental data in LCA. The uncertainties of input parameters were defined using the pedigree matrix approach embedded in the Ecoinvent database, which assigns default uncertainty factors based on key data quality indicators, including reliability, completeness, temporal, geographical, and technological correlation. The geometric standard deviation for each parameter was derived from these uncertainty factors and used to construct the input distributions. Based on these distributions, the model was run over 500 iterations to simulate the carbon footprint distribution under different scenarios, with a 95% confidence interval (CL) set to characterize the uncertainty of the results.

Figure 6 presents the results of the uncertainty analysis conducted using Monte Carlo simulation. The results indicate an average carbon footprint of 1501.86 kg CO_2e per ton of

RPO, with a median of 1377.21 kg CO_2e, a standard deviation (SD) of 640.61 kg CO_2e, and a coefficient of variation (CV) of 42.65%, reflecting high dispersion. The 2.5th and 97.5th percentiles are 637.56 kg CO_2e and 3083.96 kg CO_2e, respectively, with most values falling within this range. A standard error of 28.65 suggests high accuracy in the mean estimation. The primary sources of uncertainty are related to variations in data quality across different lifecycle stages, with the wastewater treatment and LUC stages contributing the most. Future research should prioritize improving the accuracy of inventory data for these stages by incorporating site-specific measurements and updated emission factors. By defining the uncertainty range, this study provides a stronger foundation for policymakers and industry stakeholders to interpret and apply carbon footprint data effectively.

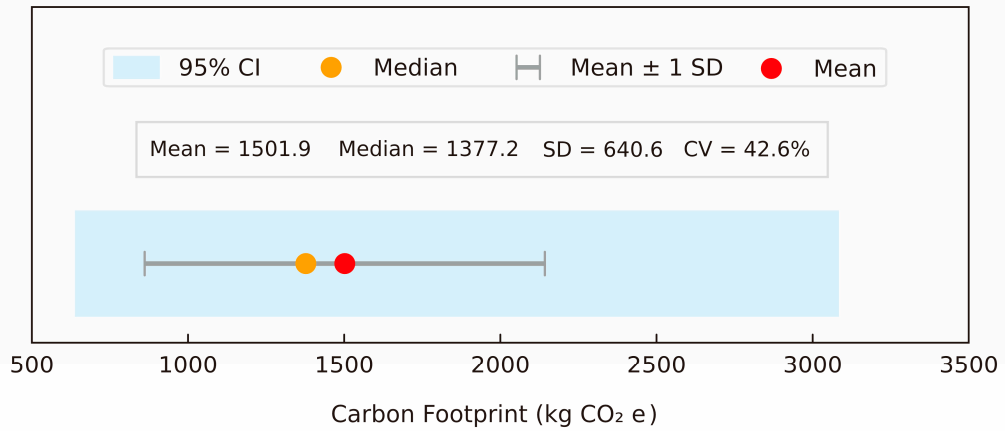


Figure 6. Uncertainty analysis of RPO carbon footprint.

4. Discussion and Recommendations

4.1. Production-Based Decarbonization Pathways

The major sources of carbon emissions in Indonesia's RPO production process are wastewater treatment and LUC, contributing 57.67% and 32.82% of the carbon footprint, respectively. To reduce the carbon emissions in Indonesia's RPO industry, it is essential to focus on improving wastewater treatment technologies and optimizing LUC management.

In wastewater treatment, traditional open lagoon systems contribute significantly to CH_4 emissions (see Table 2), thus increasing the overall carbon footprint. To mitigate this, covered biogas technology can be adapted to capture CH_4 from wastewater treatment for reuse [37,43]. The captured biogas can be purified and used for electricity generation or as an industrial fuel, thereby promoting resource utilization. As illustrated in Figure 7, adopting covered biogas technology significantly reduces the carbon footprint to 782.03 kg CO_2e, with wastewater treatment achieving net negative emissions (−147.88 kg CO_2e). The contribution of biogas recovery for electricity generation is −212.74 kg CO_2e, while composting further reduces emissions by 44.42 kg CO_2e. Therefore, promoting such high-efficiency, low-emission technologies is crucial for reducing the carbon footprint of RPO production, ensuring the industry's sustainable development, and providing a replicable model for similar industries.

Given the substantial variation in carbon emissions across different types of LUC, assessing the carbon reduction potential of RPO requires a detailed evaluation of the original land cover type. When primary forests are converted into oil palm plantations, the contribution of LUC to the RPO carbon footprint is particularly high, indicating that such conversion releases large amounts of carbon and significantly reduces carbon storage capacity. Consequently, rather than contributing to carbon mitigation, the conversion of primary forests exacerbates GHG emissions. In contrast, when grassland or cropland is converted, the resulting carbon emissions are lower or even negative, suggesting that oil

palm plantations can effectively sequester carbon, thus offering some potential for carbon reduction. Therefore, when evaluating the carbon reduction potential of RPO, it is essential to comprehensively consider the impact of original land cover on carbon emissions. In particular, the substantial carbon emissions associated with the conversion of primary forests to oil palm plantations cannot be overlooked.

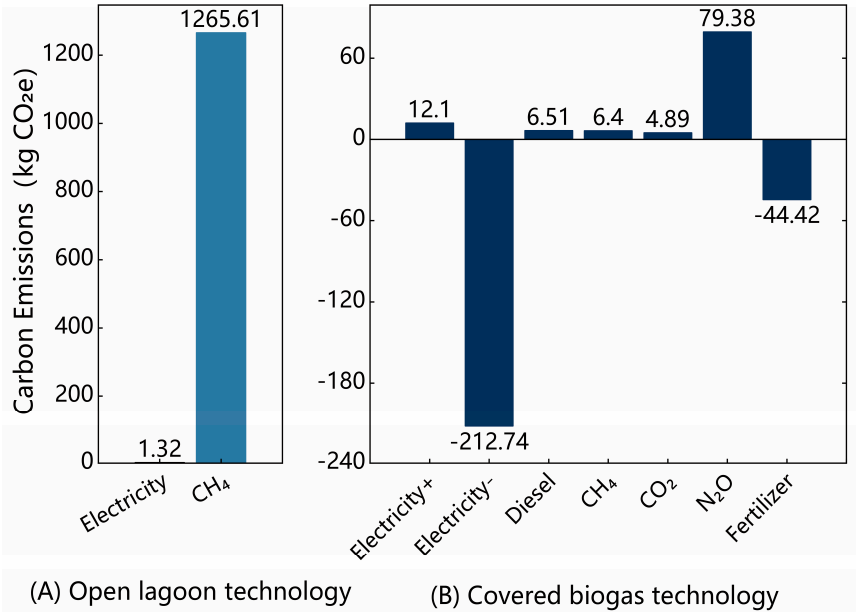


Figure 7. Carbon emissions based on different wastewater treatment technologies. Note: Electricity^{+} represents electricity input, and Electricity^{-} represents electricity output.

In terms of LUC, converting land for oil palm plantations often involves the transformation of forests and other natural land covers, significantly affecting carbon stocks in biomass, litter, deadwood, and soil organic carbon. The carbon emissions associated with LUC depend on the original land cover type, making it a critical factor in assessing the carbon footprint and reduction potential of RPO. Given the substantial variation in emissions across different types of LUC, a detailed evaluation of the original land cover type is necessary to accurately estimate its contribution to the RPO carbon footprint. According to LUC emission results (see Figure 2), the conversion of primary and secondary forests leads to the highest emissions, particularly in primary forests, which store substantial carbon in their biomass. Clearing these forests substantially reduces carbon storage capacity and contributes to increased GHG emissions. In contrast, converting croplands or grasslands to oil palm plantations results in significantly lower emissions and, in some cases, net negative emissions. This suggests that oil palm plantations established on non-forest land can function as a carbon sink, offering some potential for carbon reduction. Therefore, when evaluating the carbon reduction potential of RPO, it is essential to comprehensively consider the impact of original land cover on carbon emissions. To mitigate LUC-related emissions, a stringent land classification and management policy should be implemented to strictly prohibit the conversion of forests and other high-carbon-stock lands into oil palm plantations. Instead, oil palm plantation development should be actively directed toward low-carbon-impact areas, such as existing croplands or grasslands. To support this transition, tax incentives and subsidies should be introduced to encourage companies to adopt sustainable land use practices. In addition, a real-time LUC monitoring system based on satellite imagery should be established to improve transparency and oversight. Strengthening traceability and certification mechanisms across the RPO supply chain is also essential, ensuring that all plantations can provide verifiable proof of legal and sustainable

land origin. Strict penalties should be enforced against illegal land clearing to enhance compliance and uphold environmental standards.

4.2. Trade-Based Decarbonization Pathways

As the world's largest RPO producer and exporter, Indonesia's carbon emissions are closely tied to its export-driven development model. To achieve a low-carbon transition in the RPO industry, Indonesia should adopt a series of trade-focused strategies aimed at incentivizing sustainability and aligning with global green trade practices.

To begin, Indonesia could implement a differentiated export tariff system, whereby higher export tariffs are levied on RPO products with higher carbon footprints, while offering tax incentives for those produced with lower emissions [44,45]. This would encourage producers to adopt more sustainable production methods and facilitate the development of cleaner technologies within the industry. While this may have a short-term impact on export revenues, the long-term benefits of reducing emissions and improving sector competitiveness would be substantial. Furthermore, Indonesia could collaborate with major importing countries to explore the establishment of a carbon border adjustment mechanism (CBAM), drawing on existing frameworks such as the European Union's CBAM. Such a system would ensure that low-carbon RPO products are more competitive in the international market by accounting for the carbon content of imported goods. This would help level the playing field, while also supporting Indonesia's transition to a more sustainable model. In addition, Indonesia could pursue green trade agreements with key importing countries, drawing inspiration from ASEAN's sustainable trade initiatives. Such agreements could facilitate preferential market access for certified low-carbon RPO products, promote mutual recognition of sustainability standards, and strengthen the alignment between Indonesia's palm oil trade and global climate objectives. Finally, promoting the trade of clean technologies will be essential for supporting the low-carbon transformation of Indonesia's RPO industry. By lowering barriers to the import of low-carbon production technologies and equipment, Indonesia can accelerate the adoption of more sustainable practices and facilitate the transfer of green technologies from developed countries. This would not only reduce emissions in the RPO sector but also support the broader economic diversification of Indonesia.

5. Conclusions

This study evaluated the life cycle carbon footprint of RPO production in Indonesia and its export-related ECE within the context of global trade.

The results show that the average carbon footprint of Indonesian RPO production is 2196.84 kg CO_2e per ton, with wastewater treatment (57.67%) and LUC (32.82%) identified as the dominant emission sources. CH_4 emissions from wastewater treatment alone account for 57.61%, making it a critical focus for carbon footprint management. The spatiotemporal analysis revealed a rising emission trend, with Kalimantan and Sumatra emerging as emission hotspots and priority regions for targeted mitigation efforts. In terms of international trade, Indonesia's export-related ECE is largely driven by demand from India (11.19 Mt CO_2e), China (7.85 Mt CO_2e), and Pakistan (6.29 Mt CO_2e). These importing countries effectively externalize their carbon emissions to Indonesia, exacerbating the environmental burden on producers.

Based on these findings, comprehensive decarbonization pathways are proposed. On the production side, transitioning to covered anaerobic biogas systems for wastewater treatment and strengthening forest protection policies can significantly reduce emissions. On the trade side, measures such as carbon border adjustments, differentiated export

tariffs, and green trade agreements with major importing countries could accelerate the low-carbon transformation of Indonesia's RPO industry.

This study is subject to several limitations. First, uncertainties and potential inaccuracies in the primary input data for carbon footprint calculation, such as emission factors and activity data, may introduce biases. Second, estimations of international transportation distances lack precise tracking of actual logistics routes, which could result in over- or underestimation of transport-related emissions. Third, the omission of downstream re-export flows of Indonesian RPO in importing countries leads to incomplete identification of ECE transfer pathways. Collectively, these limitations may contribute to uncertainties or biases in the estimated carbon footprint and ECE exports associated with RPO. Future research should prioritize the integration of multi-source data validation and field measurements to improve the accuracy of input data. Additionally, incorporating input-output analysis can facilitate more comprehensive supply chain tracing, thereby enhancing the precision and reliability of ECE for exported RPO.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RPO	Refined palm oil
ECE	Embodied carbon emissions
LCA	Life cycle assessment
SDGs	United Nations Sustainable Development Goals
GHG	Greenhouse gas
LUC	Land use change
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
HFCs	Hydrofluorocarbons
PFCs	Perfluorocarbons
SF_6	Sulfur hexafluoride
NF_3	Nitrogen trifluoride
CPO	Crude palm oil
IPCC	Intergovernmental Panel on Climate Change
AR5	the Fifth Assessment Report
CO_2e	Carbon dioxide equivalents
GWP	Global warming potential
CBAM	carbon border adjustment mechanism

Appendix A

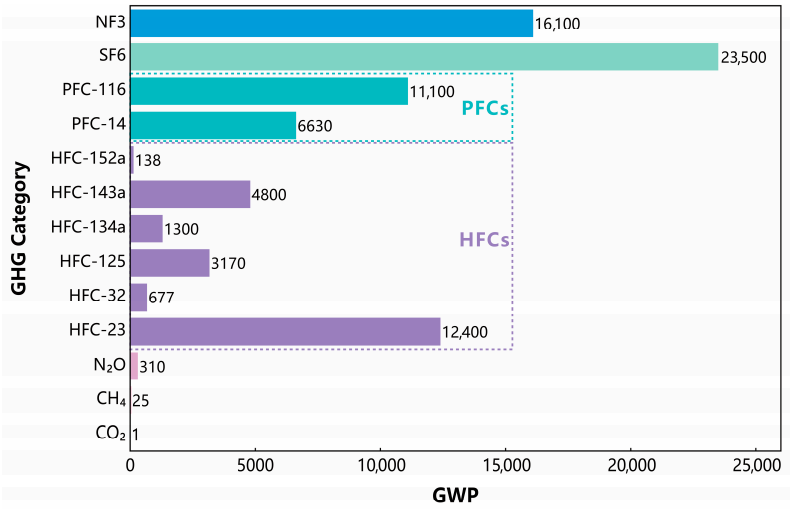


Figure A1. GWP values of different greenhouse gases. The GWP values are used to compare the relative contribution of each gas to global warming over 100 years, with CO_2 as the baseline reference gas (GWP = 1).

Table A1. Carbon emission factors of key inputs and outputs used in the LCA model.

Item	Unit	Emission Factor (kg CO_2e/unit)
Dolomite	kg	0.0463
Urea	kg	0.599
Phosphate Rock	kg	0.083
Borate	kg	2.217
Paraquat	kg	2.64
Glyphosate	kg	4.5
Diesel	L	0.564
CO_2	-	1
CH_4	-	25
N_2O	-	310
Electricity	kWh	0.537
Boiler Fuel	kg	0.564
Water	L	0.000464
Phosphoric Acid	kg	0.505
Wastewater	L	0.493
Land Transport	t·km	0.22
Water Transport	t·km	0.009

Table A2. Regional codes of Indonesia used in this study.

Code	Region Name	Code	Region Name	Code	Region Name
R1	Aceh	R9	Bengkulu	R17	Gorontalo
R2	Sumatera Utara	R10	Lampung	R18	Sulawesi Tengah
R3	Sumatera Barat	R11	Jawa Barat	R19	Sulawesi Selatan
R4	Riau	R12	Banten	R20	Sulawesi Barat
R5	Kepulauan Riau	R13	Kalimantan Barat	R21	Sulawesi Tenggara
R6	Jambi	R14	Kalimantan Tengah	R22	Maluku
R7	Sumatera Selatan	R15	Kalimantan Selatan	R23	Papua
R8	Bangka Belitung	R16	Kalimantan Timur	R24	Papua Barat

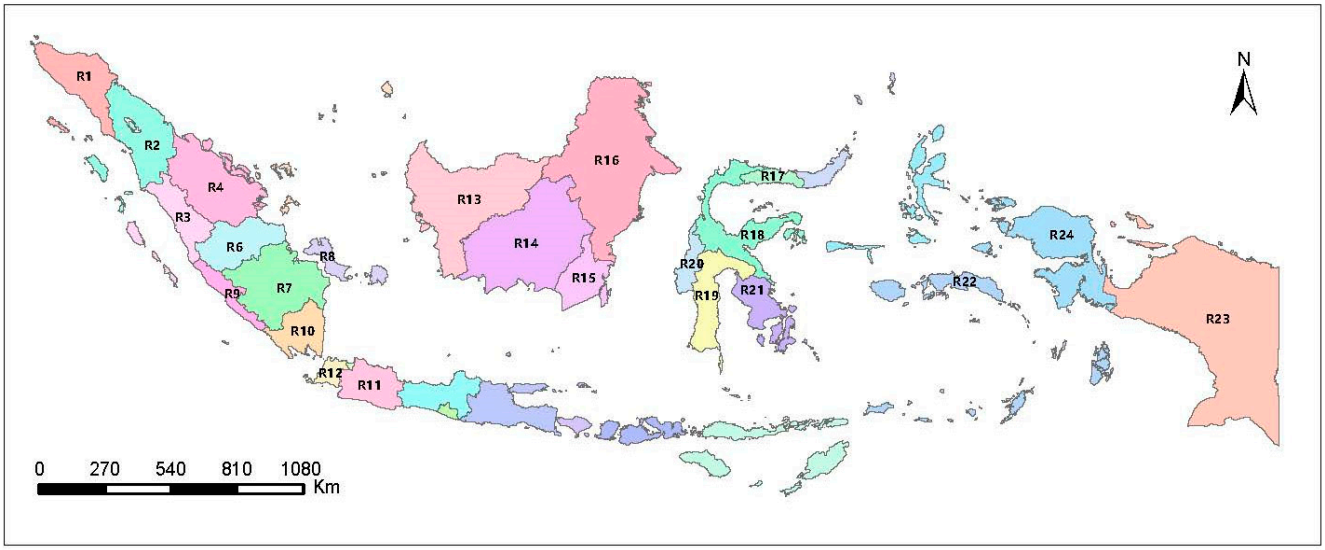


Figure A2. Regional distribution of RPO production in Indonesia.

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