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Improving Sustainability in the Palm Oil Supply Chain: Cradle-to-Gate Economic, Environmental, and Social Life Cycle Evidence from Indonesia

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Abstract: The palm oil supply chain plays a strategic role in Indonesia's economy; however, it faces persistent sustainability challenges related to economic volatility, environmental impacts, and social issues. These challenges necessitate an integrated sustainability assessment across all stages of the supply chain. This study aims to evaluate the sustainability performance of the palm oil agroindustry in North Sumatra, Indonesia, by simultaneously assessing economic, environmental, and social dimensions using a Life Cycle Thinking (LCT) approach. The study applies Life Cycle Costing (LCC) to assess lifecycle costs and financial feasibility, Life Cycle Assessment (LCA) using ReCiPe Midpoint (H) and USEtox methods to evaluate environmental impacts, and Social Life Cycle Assessment (SLCA) to analyze social performance. The assessment scope is cradle to gate, covering plantation activities through Crude Palm Oil (CPO) processing. Primary data were collected from 90 respondents, including workers and local communities, through surveys and interviews. Secondary data were used to compile life cycle inventories and cost structures. The results indicate that fertilization, pest and disease control, and fossil-based electricity consumption at the processing stage are the main contributors to environmental impacts, particularly global warming, eutrophication, and toxicity. Economically, the palm oil supply chain generates positive value added and is financially feasible. Social indicators generally meet minimum regulatory standards. Overall, the ecoefficiency assessment categorizes the system as affordable but not yet environmentally sustainable due to high environmental costs. The novelty of this study lies in the integrated application of LCC, LCA, and SLCA within a single cradle-to-gate framework for the palm oil agroindustry in Indonesia, enabling a comprehensive and simultaneous sustainability evaluation.

Keywords: Creating shared value; Eco efficiency; Life cycle thinking; Supply chain sustainability

Introduction

The palm oil industry is a strategic sector in the Indonesian economy, particularly through its derivative product, namely Crude Palm Oil (CPO), which serves as the primary raw material for various food, cosmetic, and energy industries. As one of the key global agricultural commodities, palm oil plays a crucial role in supporting economic development, industrial production, and employment generation in producing countries. Indonesia is listed as the world's largest CPO producer, contributing around 57% of total global palm oil production (Foreign Agricultural Service, 2025) and 56% of total world exports (Sulaiman et al., 2024). In addition to its role in international trade, the palm oil industry also provides more than 17 million jobs (Ministry of

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Agriculture, 2024), making it one of the important pillars for people's welfare. Given its substantial economic and social contributions, maintaining a sustainable palm oil supply chain has become an essential requirement to support long-term economic growth and social welfare in Indonesia.

Sustainability in the palm oil supply chain refers to the balance between economic viability, environmental protection, and social responsibility throughout all stages of production and distribution. Indonesia's palm oil supply chain still faces various sustainability challenges from economic, environmental, and social aspects. From an economic perspective, global price fluctuations create unstable income. This condition is also exacerbated by negative issues and campaigns related to the Indonesian palm oil industry, which are associated with nutrition, health, welfare, and environmental concerns, thereby becoming a challenge in international trade (Barus et al., 2024). From an environmental perspective, oil palm plantation land clearing contributes to 57% of deforestation in Indonesia (Wahyuni & Suranto, 2021). Apart from land clearing, fertilization, processing, and transportation activities contribute to increasing emissions and environmental pollution (Harimurti et al. 2021; Maulidah et al. 2023). From the social aspect, there are still agrarian conflicts (land grabs) in the Right to Use (HGU) areas and on land owned by farmers (Irawan et al., 2024). In addition to land conflicts, several social problems persist, such as child labor, unequal division of labor between men and women, and the lack of occupational health and safety facilities (Monitor, 2024).

To address these challenges, the Indonesian government has implemented the Indonesia Sustainable Palm Oil (ISPO) certification system as a policy instrument to promote sustainable practices in the palm oil sector. However, of the 16.8 million hectares of oil palm plantation land, 12.1 million hectares have not yet been certified (Aisyah et al., 2024). This condition indicates that sustainability issues remain prevalent across the palm oil supply chain and highlights the importance of comprehensive sustainability assessment at all stages of the supply chain.

One of the important regions for the palm oil supply chain in Indonesia is North Sumatra, which contributes 11.05% to total national production (Secretariat General of Agriculture, 2024). Despite its significant contribution, the palm oil agroindustry in North Sumatra is also inseparable from sustainability problems in its supply chain, such as river pollution in factory areas, conflicts over land with farmer groups, and ineffective corporate social responsibility (CSR) programs. These issues indicate the existence of gaps between expected sustainability standards and actual practices in the field. This condition emphasizes the need for improvement through sustainability assessments at all stages of the supply chain, covering economic, environmental, and social aspects.

An approach that can be used to assess the sustainability of the palm oil supply chain is Life Cycle Thinking (LCT). According to Mazzi (2020), LCT is an approach that considers the economic, environmental, and social impacts of a product or process throughout its entire life cycle, covering all stages from upstream to downstream. The LCT approach consists of Life Cycle Costing (LCC) to assess life cycle costs, Life Cycle Assessment (LCA) to assess environmental impacts, and Social Life Cycle Assessment (SLCA) to assess social impacts (Maciel et al., 2024).

Various studies related to LCT have been conducted both internationally and domestically. Research by Munashinghe et al. (2019) assessed the palm oil supply chain in Brazil using LCA and found that land clearing is the largest source of emissions. Martinez et al. (2017) assessed the environmental impact of Malaysian palm oil in the cosmetics industry and identified the CPO processing stage as a critical point of energy consumption. Setiawan et al. (2024) analyzed the use of empty bunch pellets for co-firing in West Java, Indonesia, using LCA and found significant potential for emission reduction and cost efficiency. Haryati et al. (2022) used SLCA to assess social impacts in the Malaysian palm oil agroindustry and identified issues in occupational health and safety. Mulyasari et al. (2023) assessed social sustainability in smallholder plantations in Bengkulu, Indonesia, and identified problems related to low income, job insecurity, and limited access to training.

Although previous studies have provided important insights, most of them focus on single aspects of sustainability, either economic, environmental, or social dimensions separately. There remains limited research that integrates LCC, LCA, and SLCA simultaneously, particularly in the context of the palm oil agroindustry in Indonesia. Based on these research gaps, this study aims to assess the sustainability of the palm oil agroindustry in North Sumatra, Indonesia, through the integrated application of LCC, LCA, and SLCA approaches within a cradle-to-gate scope (from plantations to CPO processing). The urgency of this research lies in providing comprehensive sustainability evaluation and strategic recommendations to improve palm oil supply chain performance, support sustainable industrial practices, and strengthen national sustainability policies applicable to both large-scale and smallholder plantations.

Method

Research Design

The approach used in this study is a quantitative approach with a survey research design. The study was conducted on a sample of respondents drawn from the population to examine the phenomenon of sustainability in the palm oil supply chain. This research integrates Life Cycle Costing (LCC), Life Cycle Assessment (LCA), and Social Life Cycle Assessment (SLCA) approaches, in which the analytical stages were adapted and modified from previous studies to suit the characteristics of the palm oil agroindustry and the research objectives.

Sample and Population

The research was conducted in the palm oil agroindustry in North Sumatra, involving two stakeholder groups, namely workers (permanent and casual workers) and local communities. Sampling used the stratified random sampling equal allocation method, and a total of 90 respondents were obtained. The selection of stakeholders was adjusted to represent key actors within the palm oil supply chain who directly experience social impacts.

Data Collection and Measurement

Primary data were collected through questionnaires to assess aspects of social sustainability and were supported by unstructured interviews and non-participant observations. Secondary data were used for the assessment of environmental sustainability, including production inputs and outputs, and economic sustainability, including costs from plantations to CPO processing and revenues from CPO sales. The data collection procedure was designed by modifying standard life cycle assessment data requirements to accommodate data availability and field conditions in the study area.

Variables and Data Analysis

The research consists of three main analyses: economic sustainability, environmental sustainability, and social sustainability. The analytical procedures for each sustainability aspect were adapted from established life cycle approaches and modified to ensure their applicability to the palm oil supply chain context in North Sumatra.

Table 1. Variables and Data Analysis

Aspects	Method	Analysis Steps
Economic Sustainability	LCC (Life Cycle Cost)	Calculating lifecycle costs Value Added Analysis Feasible Analysis (Net Present Value, Net B/C Ratio, and Return on Investment) Interpretation of economic performance across supply chain stages based on modified lifecycle cost boundaries (plantation to CPO processing).
Environmental Sustainability	LCA (Life Cycle Assesment) ISO 14040/14044 compliant	Defining Goal & Scope Life Cycle Inventory Life Cycle Impact Assesment (Using SimaPro 9.0 software with the Recipe Midpoint H impact analysis method for the categories of impacts of abiotic resource depletion, global warming, acidification, and eutrophication and the USEtox analysis method to analyze the impact categories of human toxicity and ecotoxicity) Interpretation Ecoefficiency Index Analysis (EEI) Adjustment of system boundaries using a cradle-to-gate approach based on data availability and research scope.
Social Sustainability	SLCA (Social Life Cycle Assessment)	Worker Stakeholders (Consisting of indicators: Freedom of Association and Collective Bargaining, Child Labor, Fair Salary, Working Hours, Forced Labor, Equal Opportunities or Discrimination, Health and Safety, Social Benefits or Social Security, Employment Relationship, Sexual Harassment, and Smallholders Including Farmers) Local Community Stakeholder (Consisting of indicators: Access to Material Resources, Access to Immaterial Resources, Delocalization and Migration, Cultural Heritage, Safe and Healthy Living Conditions, Respect of Indigenous Rights, Community Engagement, Local Employment, and Secure Living Conditions) The average Likert scale score is converted to a PSIA (Poverty and Social Impact Analysis) score with the following criteria: –2 (1.0–1.5) no data or evidence of compliance

Aspects	Method	Analysis Steps
		–1 (1.51–2.5) is not standard but there is improvement 0 (2.51–3.5) meets the minimum standard +1 (3.51–4.5) goes beyond policy compliance +2 (4.51–5.0) ideal performance with documented positive impact Adaptation of SLCA indicators and scoring procedures based on stakeholder relevance and field conditions in the palm oil agroindustry.

Result and Discussions

Economic Sustainability

Life Cycle Cost (LCC)

Life cycle cost analysis is used to measure the overall cost used in the entire supply chain to produce 1 ton of CPO. Based on Table 2, the total life cycle cost for producing 1 ton of CPO is Rp. 6,671,372, with operational costs constituting the largest share (64.38%), followed by maintenance costs (26.94%), investment costs (5.24%), and replacement costs (3.45%).

Table 2. Life Cycle Cost 1 Ton CPO

Cost Component	LCC (Rp)
C (Investment) (Buildings, Machinery, Infrastructure, Means of Transport, Inventory, and Certification)	349.889
M (Maintenance) (Plant Maintenance and Fertilization)	1.797.538
O (Operational) (Salary, Harvesting, Transportation, Processing, Sales Costs, and Administration Costs)	4.293.877
R (Replacement) (Buildings, Machinery, Infrastructure, Means of Transport, and Inventory)	230.068
S (Salvage Value)	0
Total	6.671.372

Source: Primary Data Processed (2025)

This finding indicates that the economic sustainability of the palm oil supply chain is primarily influenced by operational efficiency, particularly labor, harvesting, transportation, and processing activities. This result is consistent with Chairat et al. (2026), who emphasized that operational cost structures and processing capacity variability significantly affect the financial viability of palm oil mills. However, unlike Chairat et al. (2026), which focused solely on mill-level boiler investment decisions, this study expands the scope by integrating upstream plantation activities into the life cycle cost analysis. This integration represents a novelty by capturing cost dynamics from plantations to processing stages (cradle to gate), providing a more comprehensive economic assessment of the palm oil supply chain.

Value Added (VA)

The calculation of added value is calculated from the difference between revenue and LCC (without labor salaries). The results of the added value calculation are as follows.

VA = Revenue (1 ton of CPO) - LCC (1 ton of CPO) - Salary (1 ton of CPO))
= IDR 9,386,200 – Rp. (6,671,372 – 97,866)
= IDR 9,386,200 – IDR 6,573,506
= IDR 2,812,694

The calculation of value added shows that the palm oil supply chain generates a value added of Rp. 2,812,694 per ton of CPO. A positive VA value indicates that after covering intermediate input costs, the business still produces an economic surplus.

This result confirms that the palm oil agroindustry in North Sumatra is capable of generating economic value, aligning with Amri et al. (2017), who stated that a positive value added reflects the ability of a business to create economic surplus beyond production costs. However, this study contributes novelty by linking value added analysis directly with life cycle cost components, enabling identification of cost-intensive stages that reduce value creation. Such integration is rarely addressed in previous palm oil studies, which tend to assess profitability without considering the full life cycle cost structure.

Feasibility Analysis

Net Present Value (NPV)

The Net Present Value (NPV) calculation was conducted over the economic life of oil palm plants, which is 25 years. The discount rate applied in this study was 4.75% (0.0475), referring to the benchmark interest rate set by Bank Indonesia in 2025. The results of the NPV calculation for 1 ton of CPO are presented in Table 3.

Table 3. NPV 1 Ton CPO

Year	Cash Flow (a) (Rp)	Cash Outflow (b) (Rp)	Discount Rate (4.75%)	NPV (Rp)	PV (-) (Rp)	PV (+) (Rp)
0	0	806,933,522,096	0.0475	-806,933,522,096		
1	0	764,612,880,046	0.0475	-729,940,696,941		
2	0	764,612,880,046	0.0475	-696,840,760,803		
3	0	325,196,857,451	0.0475	137,168,891,566		
4	482,855,478,647	330,341,571,178	0.0475	133,020,472,912		
5	490,494,399,973	378,300,406,616	0.0475	145,424,652,231		
6	561,704,148,499	408,204,460,521	0.0475	149,804,527,866		
7	606,105,980,592	424,757,769,712	0.0475	148,810,814,686		
8	630,684,496,188	426,987,457,942	0.0475	142,808,563,095		
9	633,995,159,107	369,473,176,129	0.0475	117,969,031,293		
10	548,597,390,226	371,239,126,681	0.0475	113,157,881,969		
11	551,219,490,899	188,936,891,183	0.0475	54,978,615,758		
12	280,535,346,317	222,624,713,042	0.0475	61,843,829,904		
13	330,555,354,123	348,858,649,091	0.0475	92,516,345,094	2,233,714,979,840	2,635,071,431,199
14	517,988,738,599	181,532,942,614	0.0475	45,958,980,749		
15	269,541,890,974	632,279,840,145	0.0475	152,816,498,434		
16	938,815,298,663	408,548,570,453	0.0475	94,265,021,949		
17	606,616,918,389	380,049,421,915	0.0475	83,713,003,183		
18	564,301,103,543	411,083,813,889	0.0475	86,442,872,806		
19	610,381,272,671	444,482,655,470	0.0475	89,227,680,092		
20	659,972,199,731	775,064,398,756	0.0475	148,534,910,887		
21	1,150,823,209,600	726,711,374,597	0.0475	132,953,164,126		
22	1,079,028,165,800	774,343,749,683	0.0475	135,243,526,058		
23	1,149,753,182,800	795,267,858,713	0.0475	132,599,561,175		
24	1,180,821,504,800	748,381,418,631	0.0475	119,123,548,164		
25	1,111,204,059,400	767,908,479,897	0.0475	116,689,037,201		
Total				401,356,451,359		

Source: Primary Data Processed (2025)

Based on Table 3, the results show that in years 0–2 there was no cash inflow because oil palm plants had not yet produced, while the largest cash outflow occurred in year 0 due to initial investment costs. Cash inflows began in year 3 when the oil palm plantations started producing.

Overall, during the 25-year economic life, the total Net Present Value obtained was IDR 401,356,451,359, indicating that the present value of benefits exceeds the present value of costs. According to Sofawan et al. (2023), an NPV value greater than zero (NPV > 0) indicates that a business is economically feasible. Therefore, the palm oil supply chain for producing 1 ton of CPO is economically viable and profitable over the project period.

This finding supports the economic feasibility of the palm oil supply chain and is consistent with Chairat et al. (2026), who reported positive NPV values for financially viable palm oil mill investments. However, while previous studies generally focus on isolated processing units, this research incorporates plantation-to-processing activities into the financial analysis. This integrated perspective strengthens the novelty of this study by demonstrating that economic feasibility is not only driven by mill efficiency but also by upstream cost management within the supply chain.

Net B/C Ratio

The calculation of the Net B/C Ratio is done by dividing the overall PV (+) by PV (-).

Net B/C Ratio = PV (+) / PV (-) = (IDR 2.635.071.431.199)/(IDR 2.233.714.979.840) = 1.18

Based on the calculation results, a Net B/C Ratio value of 1.18 was obtained. According to Nisrina et al. (2022), a Net B/C Ratio greater than 1 indicates that a business is economically feasible. A value of 1.18 means that every IDR 1 of costs incurred in the supply chain to produce 1 ton of CPO generates a benefit of IDR 1.18. This result confirms that the palm oil production activity provides economic benefits and is financially feasible to implement.

This result reinforces the financial feasibility of the palm oil supply chain and aligns with Nisrina et al. (2022), who stated that a Net B/C Ratio greater than one indicates economic viability. The contribution of this study lies in embedding the Net B/C analysis within a life cycle framework, allowing benefits and costs to be evaluated across multiple stages rather than at a single operational point.

ROI (Return on Investment)

The ROI calculation is done by calculating a percentage of the division of profit after tax with investment costs. In the context of research, the investment cost is LCC (year 0).

ROI = (Profit After Tax) / (LCC (Year 0) x 100%

ROI = (Rp. 2,600,826) / (Rp.6,671,372) x 100%

ROI = 38.98%

Based on the results of the analysis, an ROI value of 38.98% was obtained. According to Yunita et al.(2023), a positive ROI value shows that the business or project is feasible to implement. The value of 38.98% shows that for every Rp. 1 investment cost incurred in the supply chain to produce 1 ton of CPO, a net profit of Rp. 0.3898 will be obtained.

This result reinforces the financial feasibility of the palm oil supply chain and aligns with Nisrina et al. (2022), who stated that a Net B/C Ratio greater than one indicates economic viability. The contribution of this study lies in embedding the Net B/C analysis within a life cycle framework, allowing benefits and costs to be evaluated across multiple stages rather than at a single operational point.

This ROI value is relatively high compared to conventional agribusiness investments, confirming strong profitability as also noted by Yunita et al. (2023). The novelty of this study is reflected in the use of life cycle-based investment costs as the denominator of ROI, providing a more realistic representation of capital efficiency across the palm oil supply chain rather than relying solely on initial capital expenditures.

Environmental Sustainability

Defining Goal & Scope

The study analyzed environmental sustainability in the palm oil supply chain in North Sumatra with the scope of cradle to gate and a functional unit of 1 ton of CPO. The production process includes the plantation, transportation, and processing stages. At the plantation stage, activities start from preparing land without burning using heavy equipment, seeding through the pre nursery and main nursery phases, weeding with herbicides, fertilization using urea and NPK, pest control using rodenticides, insecticides, and herbicides, to harvesting FFB (Fresh Fruit Bunches) using dodos and egrek. FFB is then transported via transportation in the garden using curtain vehicles to the product collection site, and continued transportation outside the garden using 7-10 ton trucks to the PKS (Palm Oil Mill). At the processing stage, FFB is processed through sterilization, threshing, digestion & pressing, clarification, and kernel recovery to produce CPO stored at a temperature of 50–55°C. The entire series of processes is the basis for the preparation of a life cycle inventory to calculate inputs and outputs in the production of 1 ton of CPO.

The environmental assessment was conducted using a cradle-to-gate approach with a functional unit of 1 ton of CPO. This scope selection is consistent with Life Cycle Thinking principles, which emphasize holistic assessment across supply chain stages (Maciel et al., 2024). Unlike many previous studies that focus only on processing stages, this research integrates plantation, transportation, and processing activities, thereby offering a more comprehensive environmental sustainability assessment of the palm oil supply chain in Indonesia.

Life Cycle Inventory

The life cycle inventory contains the inputs and outputs produced, in the supply chain to produce 1 ton of CPO. After having the life cycle inventory data, the amount of impact produced in the life cycle impact assessment will be analyzed so that the process can be determined which is the critical point or the process that produces the greatest environmental impact.

Table 4. Life Cyle Inventory 1 Ton CPO

Process	Material	Unit	Value
	Amcoxon Herbicide	kg	0.022995299
	Glyposat Herbicide	kg	0.155555383
	Metsulfuron Herbicide	kg	0.000490634
	Diesel	L	0.581992151
			Soil Emissions
	Paraquat	kg	0.005077362
	Glyphoshate	kg	0.04392152
	Metsulfuron Methyl	kg	0.000024532
			Air Emissions
	CO2	kg	1.542862124
	CH4	kg	0.000208214
	N2O	kg	0.000012493
	NOX	kg	0.016684681
	SO2	kg	0.000048422
Nursery			Input

Process	Material	Unit	Value
(Pre Nursery)	Seed	pcs	6
	Urea Fertilizer (46%)	kg	0.002199153
	NPK Fertilizer (12.12.17.2)	kg	0.00168849
	Matador Insecticide	kg	0.000385635
	Dithane Fungicide	kg	0.00042518
			Soil Emissions
	Lambda Cyhalothrin	kg	0.000105944
	Mancozeb	kg	0.000068029
	Water Emissions	kg	
	NO3	kg	0.00161319
			Air Emissions
	N2O	kg	0.000019081
	NH3	kg	0.000147442
Nursery			Input
(Main Nursery)	Seed	pcs	6
	Urea Fertilizer (46%)	kg	0.041002469
	NPK Fertilizer (12.12.17.2)	kg	1.428208737
	Matador Insecticide	kg	0.001279754
	Dithane Fungicide	kg	0.003601763
	Diesel	L	0.002449954
			Soil Emissions
	Lambda Cyhalothrin	kg	0.000351581
	Mancozeb	kg	0.000576282
			Water Emissions
	NO3	kg	0.252755645
			Air Emissions
	N2O	kg	0.002989635
	NH3	kg	0.023101322
	CO2	kg	0.006494831
	CH4	kg	0.000000876
	NOX	kg	0.000070236
	SO2	kg	0.000000204
Weeding			Input
	Herbicide Glyposat	kg	0.009814895
	Paraquat Herbicide	kg	0.053392174
	Herbicide Methyl Metsulfuron	kg	0.001377100
			Soil Emissions
	Glyphoshate	kg	0.002771265
	Paraquat	kg	0.011788992
	Metsulfuron Methyl	kg	0.000275420
Fertilization			Input
	Urea Fertilizer (46%)	kg	1.5982902
	NPK Fertilizer (12.12.17.2)	kg	3.707202919
			Water Emissions
	NO3	kg	1.567817705
			Air Emissions
	N2O	kg	0.018544080
	NH3	kg	0.143295167
Pest & Disease Control			Input
	Klerat Rodenticide	kg	0.000169146
	Racumin Rodenticide	kg	0.000263027
	Marshal Insecticide	kg	0.005623898
	Lamdador Insecticide	kg	0.050229563
	Cypermethrin Insecticide	kg	0.006379304
	Amitrin Herbicide	kg	3.695402134
	Klopp Herbicide	kg	0.25361568
			Soil Emissions
	Brodifacoum	kg	0.000000085
	Coumatetralyl	kg	0.000000039

Process	Material	Unit	Value
	Carbosulfan	kg	0.001124780
	Lambda Cyhalothrin	kg	0.002886756
	Cypermethrin	kg	0.000342973
	Ametryn	kg	1.565848362
	Ethylene Oxide	kg	0.105673200
Harvesting			Input
	Fresh Fruit Bunches (FFB)	kg	4460
Transportation			Input
	Diesel	L	2.424817563
			Air Emissions
	CO2	kg	6.428195238
	CH4	kg	0.000867503
	N2O	kg	0.000052050
	NOX	kg	0.069515213
	SO2	kg	0.000201745
CPO Processing			Input
	Diesel	L	1.139633582
	Electricity	MJ	135.37
	Calcium Carbonate (CaCO3)	kg	0.00826756
	POME	m3	0.935715447
	Empty Bunches (Used)	kg	779.762873
	Empty Bunches (Leftovers)	kg	334.184088
	CPO	Ton	1
			Air Emissions
	CO2	kg	38.36738947
	CH4	kg	73.431791333
	N2O	kg	0.286754411
	NOX	kg	0.032671271
	SO2	kg	0.000094818

Source: Primary Data Processed (2025)

The life cycle inventory results indicate substantial inputs of fertilizers, pesticides, diesel fuel, and electricity, along with emissions to air, water, and soil. The dominance of chemical inputs in plantation activities highlights the environmental trade-offs inherent in oil palm cultivation. This finding aligns with Alfiansyah et al. (2023), who emphasized the environmental risks associated with intensive pesticide use in Indonesian agriculture. However, this study advances existing knowledge by quantifying these inputs within a life cycle framework, enabling their direct linkage to downstream environmental impacts.

Life Cycle Impact Assessment

The life cycle impact assessment contains the amount of impact categories generated from the process to produce 1 ton of CPO.

Table 5. Life Cycle Impact Assessment 1 Ton CPO

Impact Categories	Unit	Value
Depletion of Abiotic Resources (Mineral Resources Scarcity)	kg CU eq	0.0759
Depletion of Abiotic Resources (Fossil Resources Scarcity)	kg oil eq	34.9
Global Warming	kg CO2 eq	2770
Acidification	kg SO2 eq	0.87
Eutrophication (Freshwater)	kg P eq	0.0615
Eutrophication (Marine)	kg mol eq	9.85
Human Toxicity (Cancer)	CTUh	0.00000004770
Human Toxicity (Non Cancer)	CTUh	0.00000004150
Ekotoxicity	CTUe	3100

Source: Primary Data Processed (2025)

After knowing the magnitude of the impact, it will then be further interpreted regarding the critical point in the production process of 1 ton of CPO.

The LCIA results show that global warming potential reached 2,770 kg CO_2-eq per ton of CPO, while eutrophication and ecotoxicity impacts were also significant. These results are consistent with Aziz et al.

(2017), who reported that emissions from palm oil processing and POME management contribute substantially to greenhouse gas emissions. However, this study extends prior findings by simultaneously evaluating multiple impact categories and linking them to specific supply chain stages, thereby enhancing the interpretability of environmental hotspots.

Interpretation (Interpretation)

Depletion of Abiotic Resources

The largest category of mineral resource scarcity impact came from the fertilization process (0.0424 kg Cu-eq or 55.82% of the total impact). This happens because NPK fertilizer production is highly dependent on mineral resources such as phosphate rocks and potassium salts. According to Anlauf (2023) and Yara International (2022), in the manufacture of NPK fertilizers, nitrogen is produced from natural gas, phosphorus comes from phosphate rock mining, and potassium comes from river and marine deposits that must be mined, resulting in a scarcity of mineral resources. In addition, according to Mnthambala et al. (2021) and Ridder et al. (2012), phosphate rocks are a non-renewable resource that requires the use of energy and large amounts of water in the extraction process, thereby increasing the risk of mineral scarcity. In the category of fossil resource scarcity, the largest comes from pest and disease control processes (16.4 kg oil-eq or 47.09% of the total impact). This happens because the production of herbicides such as Amitrin and Klopp depends on the petroleum fraction. According to Bauer et al. (2022) and Aghdam (2023), pesticides and herbicides are generally derived from petrochemicals. The large number of petroleum-based chemicals used makes the pest and disease control process a critical point in the scarcity of fossil resources.

Global Warming

The largest category of global warming impacts comes from the CPO processing process (2660 kg CO_2-eq or 96% of the total impact). The high emissions come from very large electricity consumption at the main stages such as sterilization, threshing, digestion & pressing, and clarification (Aziz & Hanafiah, 2017). In addition, Indonesia's electricity is still dominated by fossil-based power plants, especially coal (60% of total power plants) (Pahlevi et al., 2024). Coal-based power plants produce more CO_2 than other power plants (Pratama et al., 2024) and (Voumik et al., 2022). Therefore, large amounts of electricity consumption are a critical point in global warming.

Acidification

The largest category of acidification impact came from the fertilization process (0.298 kg SO_2-eq or 34.29% of the total impact). This happens because NPK fertilizer contains nitrogen that releases ammonia (NH_3) into the air after application. According to Liu et al. (2020), 10–20% of nitrogen will be released as ammonia after application. The ammonia gas released will react with H_2SO_4 and HNO_3 to form ammonium sulfate/nitrate particles that trigger acid rain resulting in acidification (Chatain et al., 2022). Acidification is able to lower soil pH and interfere with nutrient absorption by plants (Hafif, 2021). Therefore, fertilization is a critical point in soil acidification.

Eutrophication

The largest category of freshwater eutrophication impact comes from the CPO processing process (0.0605 kg P-eq or 98.37% of the total impact). This happens because of the use of electricity with coal-based plants. Coal mining as a power generation material produces phosphorus-containing tailings (United Nations, 2022). In addition, the combustion process at the power plant will produce fly ash and bottom ash that contain phosphorus which allows it to dissolve into the water. (Kinasti & Notodisuryo, 2017). Phosphorus entering the waters will trigger eutrophication, which is an explosion of algae that can kill aquatic organisms (Pratiwi et al., 2025). The largest marine eutrophication impact category came from the fertilization process (7.5 kg mol-eq or 76.29% of the total impact). This happens because not all nitrogen and phosphorus in NPK fertilizer can be absorbed by plants, so it is possible to wash during rain and enter river flows to the sea (Zulapriansyah et al., 2022). According to Syafrizal et al. (2021), nitrogen and phosphorus dissolved in the waters will trigger excess algae growth and disrupt marine ecosystems. Therefore, the CPO processing and fertilization process is a critical point in eutrophication.

Human Toxicity

In the category of carcinogenic impacts, the greatest comes from the process of pest and disease control (0.0000000453 CTUh or 94.88% of the total impact). This is due to the use of Klopp herbicides (the active ingredient ethylhene oxide) which is a carcinogenic substance that causes breast cancer, blood cancer, and lymphatic cancer (Pawestri & Arsyi, 2024). In addition, insecticides such as Marshal (active ingredient carbosulfan) and Cypermethrin (active ingredient cypermethrin) are also used which are also carcinogenic (Alfiansyah et al., 2023) and (Benu et al., 2019). In the category of non-carcinogenic impacts, the largest comes from the pest & disease control process (0.0000000377 CTUh or 90.76% of the total impact). This occurs due to the use of the herbicide Amitrin (the active ingredient ametryn) which is toxic and can cause irritation to nerve disorders (Susanti et al., 2022). In addition, Klerat rodenticide (active ingredient brodifacoum) which can cause prolonged bleeding (Nosal et al., 2021), and rodenticide Racumin (active ingredient coumatetralyl) which can interfere with blood clotting (Isackson & Irizarry, 2025) are also used. In addition to herbicides and rodenticides, Lamdador insecticides (the active ingredient of lambda cyhalothrin) are also used which can cause tremors and seizures (Silwal et al., 2023). The wide variety of harmful chemicals makes the pest and disease control process a critical point of human toxicity.

Ecotoxicity

The largest ecotoxicity impact category came from the pest and disease control process (2870 CTUe or 92.45% of the total impact). This happens due to the use of Amitrin Herbicides (the active ingredient ametryn) which are toxic to aquatic organisms such as algae (Warne et al., 2018). In addition, Klerat Rodenticide (active ingredient brodifacoum) is also used to easily pollute water and is anticoagulant for aquatic organisms (Warne et al., 2018). In addition to herbicides and rodenticides, Marshal insecticides (active ingredient carbosulfan) are also used which can contaminate and cause hypoxia in aquatic organisms (David, 2020). The large number of chemicals that are easily soluble in water makes the pest and disease control process a critical point in the category of ecotoxicity impacts.

Ecoefficiency Index (EEI)

The calculation of the ecoefficiency index is carried out to compare the profits generated with the environmental costs of the resulting environmental impact.

Table 6. Ecoefficiency Index 1 Ton CPO

Impact Categories	Environmental Costs (a)	Profit After Tax (b)	EEI (c=b/a)	Category
Mineral Resources Scarcity	5.458	2,600,826	476.52	Sustainable & Affordable
Fossil Resources Scarcity	462.774	2,600,826	5.62	Sustainable & Affordable
Global Warming	7.063.500	2,600,826	0.37	Affordable not Sustainable Yet
Acidification	147.900	2.600,826	17.59	Sustainable & Affordable
Freshwater Eutrophication	17.042	2,600,826	152.62	Sustainable & Affordable
Marine Eutrophication	4.012	2,600,826	648.32	Sustainable & Affordable
Human Toxicity (Cancer)	746	2,600,826	3,486.23	Sustainable & Affordable
Human Toxicity (Non Cancer)	152	2,600,826	17,067.13	Sustainable & Affordable
Ecotoxicity	152.303	2,600,826	17.08	Sustainable & Affordable
Total	7.853.887	2,600,826	0.33	Affordable not Sustainable Yet

Source: Primary Data Processed (2025)

Social Sustainability

Worker

All indicators were analyzed with the standards of Law no. 13 of 2003 concerning labor and the ILO (International Labour Organization) Convention. The Freedom of Association and Collective Bargaining indicators obtained a score of 4.46 (+1), indicating compliance that exceeds the standards according to the Law (Articles 104 & 106–109) and the ILO (87 & 98), free workers to join unions, collective bargaining is carried out regularly, and clear and tiered conflict resolution mechanisms ranging from internal, bipartite, to industrial relations courts.

Table 7. Worker's SLCA

Indicator	Score	Score Conversion PSIA
Freedom of Association and Collective Bargaining	4.46	+1
Child Labor	4,41	+1
Fair Salary	4,27	+1
Working Hours	4,29	+1
Forced Labor	4,21	+1
Equality of Opportunity or Discrimination	4,28	+1
Health and Safety	4,47	+1
Social Benefits or Social Security	4,35	+1
Employment Relationship	4,46	+1
Sexual Harrasment	4,36	+1
Smallholders Including Farmers	4,40	+1
Average	4,36	+1

Source: Primary Data Processed (2025)

The Child Labor indicator obtained a score of 4.41 (+1), indicating compliance exceeding standards according to the Law (Article 69) and ILO (138), the admission of minors is prohibited, with strict selection for vendor workers and strict sanctions for vendors who are proven to employ child laborers.

The Fair Salary indicator received a score of 4.27 (+1), indicating compliance exceeding the standard set by Government Regulation No. 36 of 2021, the basic salary is provided in accordance with the Regional Minimum Wage and is adjusted regularly, and workers are allowed to request negotiations for wage evaluations.

The Working Hours indicator obtained a score of 4.29 (+1), indicating compliance exceeding the standards according to the Law (Articles 77–79). Working hours of 5 days x 8 hours or 6 days x 7 hours, with flexibility for garden workers, overtime is only done with written consent and a set maximum limit.

The Forced Labor indicator obtained a score of 4.21 (+1), showed compliance exceeding the standards according to the Law (Articles 87 & 88) and the ILO (29), there was no forced overtime, assignment was transferred based on competence and voluntary consent, and all leave rights were given in full.

The Equality of Opportunities or Discrimination indicators obtained a score of 4.28 (+1), showed compliance exceeding standards according to the Law (Article 5 & 6) and ILO (100 & 111), promotion was carried out objectively, prevention and handling of discrimination was carried out through socialization, anonymous reporting systems, and counseling services.

The Health and Safety (K3) indicator obtained a score of 4.47 (+1), showing compliance exceeding standards according to the Law (Article 87 & 90), Government Regulation No. 50 of 2012, and ILO (155), health facilities are fully available, regular inspections are carried out, and the implementation of K3 is strengthened through training, PPE, and extra fooding for workers related to chemicals.

The Social Benefits or Social Security indicator obtained a score of 4.35 (+1) which indicates that the implementation exceeded the standards according to the Law (Articles 86, 93, and 94) of the BPJS Law No. 24 of 2011, and ILO (102), there are health and employment insurance, death assistance, holiday allowances, service period awards, old age compensation, retirement programs, and home assistance, monitoring of allowance receipts is carried out regularly every year.

The Employment Relationship indikcator obtained a score of 4.46 (+1) which indicates compliance exceeding the standards according to the Law (Articles 104–106 and 160–161), communication is carried out through meetings with workers and unions, the rights of lay off workers are fulfilled with compensation of 3× salary, and relations with retirees are maintained and evaluated periodically.

The Sexual Harrasment indicator obtained a score of 4.36 (+1) which indicates compliance exceeding standards in accordance with Law No. 12 of 2022 and the ILO (190), all forms of harassment are prohibited and subject to severe sanctions, there is anti-harassment socialization, psychological assistance, and a reporting mechanism through a whistleblower system that guarantees the confidentiality of victims.

The indicator of Smallholders Including Small Farmers obtained a score of 4.40 (+1) indicating compliance exceeding the standard according to Law No. 19 of 2013 Articles 4-6, there are facilities and infrastructure for smallholders and the purchase of 10-20% FFB from local farmers at market prices. Based on all these indicators, the social condition of workers in the CPO supply chain received a score of 4.36 (+1), so it is sustainable because at the level of practice that exceeds the minimum standards of regulations and international guidelines.

Based on these findings, the social sustainability performance of workers in the CPO supply chain demonstrates a high level of compliance that not only meets but exceeds national regulations and international labor standards across all assessed indicators. The specificity of this study lies in its quantitative SLCA-based evaluation, which systematically measures labor conditions using a standardized scoring approach, rather than relying on qualitative or descriptive assessments as commonly found in previous palm oil sustainability studies. This provides a clearer and more measurable representation of social performance at the supply chain level.

The novelty of this finding is reflected in the integration of comprehensive labor protection indicators ranging from occupational safety, social security, wage fairness, to protection against forced labor and sexual harassment within a single SLCA framework. Previous studies tend to focus on isolated labor issues such as workplace safety or wage compliance, without capturing the cumulative social impact across the entire production system. Moreover, the strong performance in occupational health and safety is particularly relevant in agricultural sectors that involve chemical exposure. This result aligns with Susanti et al. (2022) and Silwal et al. (2023), who emphasize that improper handling of synthetic pesticides poses serious risks to worker health, thereby reinforcing the importance of strict K3 implementation and adequate personal protective equipment as observed in this study.

Local Communities

The Access to Material Resources Indicator obtained a score of 3.52 (+1) indicating compliance exceeding the standard according to the Village Law No. 6 of 2014 Article 54 & 61, the community can access resources such as water and land, aspirations related to material needs, including access to roads and public facilities, accommodated through dialogue and field review.

The Access to Non-Material Resources indicator obtained a score of 3.51 (+1) indicating compliance exceeding standards in accordance with Law No. 36 of 2009 Articles 4–6, health services are available to the community through public hospitals, educational scholarships are available, and technology facilities are available.

The Delocalization and Migration indicator obtained a score of 3.53 (+1) indicating compliance exceeding standards in accordance with Law No. 32 of 2009 Articles 66–67, community complaints are handled directly by the plantation unit by identifying the needs of residents as the basis for settlements, applying waste treatment technology and layered filtration systems to prevent pollution that can interfere with the comfort of settlements.

The Cultural Heritage Indicator obtained a score of 3.64 (+1) according to showing compliance exceeding standards according to Law No. 11 of 2010 Articles 14-15, the company's operations are adjusted so as not to interfere with local cultural practices, accompanied by support for traditional activities and assistance with religious facilities such as the construction of mosques and churches.

The Safe and Healthy Living Conditions indicator obtained a score of 3.54 (+1) indicating compliance exceeding standards in accordance with Law No. 32 of 2009 Articles 69–71, there are efforts to maintain environmental quality through waste treatment and filtration technology, the use of empty bunches, and community waste treatment programs.

The indicator of Respect for the Rights of Indigenous Peoples obtained a score of 3.53 (+1) indicating compliance exceeding standards in accordance with the ILO (169), respect for customary rights through providing space for indigenous peoples to manage customary lands around operations, providing support for plantation facilities and purchasing part of community garden products.

The Community Engagement indicator obtained a score of 3.53 (+1) indicating compliance exceeding standards in accordance with Law No. 32 of 2009 Article 70, there was a deliberation with the community to convey aspirations and evaluation of activities, there were social programs such as plasma partnerships, local bazaars, and business credit facilities that were monitored through routine reports.

The Local Employment indicator obtained a score of 3.54 (+1) indicating compliance exceeding the standards according to the ILO Convention (122), there is a special quota for local workers on plantations with the opportunity to be appointed as permanent workers.

The Secure Living Conditions indicator obtained a score of 3.59 (+1) indicating compliance exceeding standards in accordance with the 1945 Constitution Article 28H and Law No. 39 of 1999, there is prevention of agrarian conflicts through asset management by prioritizing consensus deliberation, non-litigation. Based on all these indicators, the social condition of the local community in the CPO supply chain received a score of 4.36 (+1), so it is sustainable because of all aspects of the community and is at a level of practice that exceeds the minimum standards of international regulations and guidelines.

Table 8. Local Community's SLCA

Indicator	Score	Score Conversion PSIA
Access to Material Resources	3.52	+1
Access to NonMaterial Resources	3.51	+1
Delocalization and Migration	3.53	+1
Cultural Heritage	3.64	+1
Safe and Healthy Living Conditions	3.54	+1
Respect for the Rights of Indigenous Peoples	3.53	+1
Community Engagement	3.53	+1
Local Employment	3.54	+1
Secure Living Conditions	3.59	+1
Average	3.55	+1

Source: Primary Data Processed (2025)

The results for local community indicators indicate that the CPO supply chain contributes positively to community welfare, access to resources, cultural preservation, and social security, with all indicators exceeding minimum regulatory standards. The specificity of this study lies in its ability to quantify community-level social impacts using SLCA indicators, enabling a structured assessment of material and non-material access, community engagement, and indigenous rights protection within the operational area of palm oil plantations.

The novelty of this finding is demonstrated through the integration of social, environmental, and governance-related community aspects into a single sustainability evaluation, which is rarely conducted in previous studies that often emphasize economic benefits or environmental impacts in isolation. The results strengthen the argument that sustainable palm oil development must be accompanied by inclusive community engagement and conflict prevention mechanisms. These findings are consistent with Maulidah et al. (2023), who highlighted that social factors such as workplace safety, community involvement, and social harmony play a crucial role in achieving overall sustainability in the palm oil agro-industry. Additionally, the emphasis on environmental quality and safe living conditions supports previous environmental studies indicating that unmanaged waste and nutrient runoff can degrade surrounding ecosystems and community health (Pratiwi et al., 2025), thereby underscoring the importance of integrated environmental management for sustaining community well-being.

Conclusion

The results of the sustainability assessment using LCC, LCA, and SLCA show that the palm oil supply chain is in the affordable category but not sustainable yet, especially due to the high level of CPO processing that relies on fossil-based electricity. Economically, value-added and feasibility indicators show positive results so that the supply chain is viable and profitable and socially all indicators of workers and local communities have met minimum standards. Recommendations for improvement include reducing chemical inputs and increasing the use of organic matter, the use of biopesticides and biological agents, and optimizing methane capture technology to reduce dependence on fossil energy. In addition, strengthening CSR programs based on Creating Shared Value (CSV) can improve people's welfare. At the policy level, governments are advised to increase oversight of chemical inputs, provide renewable energy incentives, and expand access to organic fertilizers and biopesticides.

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Author Contributions

Conceptualization, M.S.H.F.; formal analysis, M.S.H.F.; writing—original draft preparation, M.S.H.F..; review, S.M. and F.D.R.; supervision, S.M. and F.D.R.

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Conflicts of Interest

The authors declare no conflict of interest.

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