

Input and Output of Tuna Fishing Operations Using Longline Vessels Based at Cilacap Ocean Fishing Port

Kyssha Alya Larasati^{1*}, Vita Rumanti Kurniawati², Yopi Novita³

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Abstract—Tuna fishing not only generates significant economic profit, but also has negative environmental impacts due to the intensive use of materials, equipment, and energy. This study aims to identify and measure the input and output components of the tuna fishing process using longline vessels at the Cilacap Oceanic Fisheries Port through a life cycle inventory (LCI) approach. Data collection was carried out through field observations and structured interviews with 30 selected stakeholders, including the analysis of vessel specifications, fishing gear, and supplies. The results of the study show that supplies dominate operational inputs with a total mass of 62,026 kg/year. This indicates a high resource intensity, requiring 29.31 kg of material input to produce 1 kg of tuna. In addition, this activity produces outputs in the form of significant environmental impacts, including Sulfur Oxide (SO_x) emissions of 707.62 kg/year due to diesel fuel combustion and solid waste of 33,550 kg/year, predominantly consisting of single-use plastic packaging from leftover supplies. These findings indicate the need for improvements in logistics components from the upstream side and waste management strategies in the fisheries sector.

Keywords—Environmental impacts, emissions, Life Cycle Inventory (LCI), waste, provisions

*Corresponding Author: kysshaalya31@gmail.com

I. INTRODUCTION

National Fisheries Management Area of the Republic of Indonesia (WPPNRI) 573, located in the eastern Indian Ocean, is a highly potential tuna fishing area in Indonesia. Cilacap Ocean Fisheries Port (PPS Cilacap) serves as the primary landing site for catches from this area [14]. Tuna production data at the Cilacap PPS shows a significant increase over four years from 2,601.67 tons in 2018 to 8,846.92 tons in 2022 [19]. This increase is in line with the high intensity of fishing vessels engaged in fishing activities [18]. Tuna longline fishing areas originating from Cilacap are in the waters south of Central Java between 108-118°E and 8-22°S, where the majority (>70%) carry out fishing outside the Indonesian Exclusive Economic Zone (EEZ) [22].

Tuna fishing at PPS Cilacap uses longline gear, a process that involves a series of complex stages, from pre-catch to post-catch. All these stages require substantial materials and energy, such as fuel and other supplies. Although this sector provides significant economic benefits, the intensive use of energy and materials also produces emissions and negative environmental impacts [1]. Greenhouse gas (GHG) emissions, such as CO₂ and CH₄, contribute to climate

change, which could threaten the sustainability of the fisheries sector.

Life Cycle Assessment (LCA) is an approach to environmental sustainability that evaluates environmental impacts arising from a process [3]. LCA comprises four stages according to ISO 14040:2006 standards, which are interrelated: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. In general, LCA is carried out by calculating the environmental burden based on an inventory analysis of activities from raw material extraction, production processes, transportation, operations, and recycling processes [20]. Although LCA studies on tuna fisheries have been conducted abroad, such as Hospido's study in Spain, special reviews of tuna fisheries in Indonesia remain very limited [11]. This has become a significant obstacle in formulating sustainable policies. Therefore, LCA studies are critical to be carried out as input for the management of tuna fisheries in Indonesia.

This study uses input data on vessel components, supplies, and fishing gear as quantitative measures of environmental impact throughout the life cycle of the process. Meanwhile, the output produced includes waste and emissions. Life Cycle Inventory (LCI) plays a vital role in LCA, involving the collection of data and calculation of product input-output by inventorying, identifying, measuring, analyzing, and estimating the magnitude of resource use, costs, energy, materials, and final mass related to the product throughout its life cycle. This study examines the input-output of tuna fisheries at PPS Cilacap and analyzes them using the LCI approach. This study provides a comprehensive inventory of resource flows and emissions characterizing the entire fishing operation. These empirical findings are intended to function as a foundational dataset, enabling scholars to execute more holistic LCA evaluations and guiding

Kyssha Alya Larasati is with Master Program of Marine Fisheries Technology, Faculty of Fisheries and Marine Sciences, IPB University Bogor Agricultural University, Bogor, 16680, Indonesia. E-mail: kysshaalya31@gmail.com

Vita Rumanti Kurniawati is with Department of Fisheries Resources Utilization, IPB University, Bogor, 16680, Indonesia. E-mail: vitarumanti@apps.ipb.ac.id

Yopi Novita is with Department of Fisheries Resources Utilization, IPB University, Bogor, 16680, Indonesia. E-mail: yopi_novita@apps.ipb.ac.id

policy-makers in designing ecologically sound fisheries governance frameworks.

II. METHOD

This research was conducted at the Cilacap Oceanic Fishery Port (PPS) located in Cilacap, Central Java, in March 2024. The study was conducted through direct field observations, using a list of questions as a guide for data collection. Furthermore, the obtained data were processed in spreadsheets to determine the quantities and costs of materials used throughout the entire life cycle of the tuna fishing process.

A. Life Cycle Inventory (LCI) Approach

Life cycle inventory analysis is defined by ISO 14040, which states that the tuna fishing process involves the systematic collection of data on inputs and outputs throughout the life cycle, from the use of materials to the landing of the fish [13]. This analysis identifies which processes or materials contribute most significantly to environmental impact, accounting for

variables such as vessel type, catch type, and fishing duration, thereby supporting sustainable policies, particularly in the tuna capture fisheries sector.

B. Description

The system boundaries are defined with this inventory analysis research on the tuna fishing process, which covers cradle-to-gate aspects, including all processes from catching tuna at sea through landing at the dock. This stage aims to conduct systematic research within predefined boundaries, avoid data bias, and ensure the analysis focuses only on the primary inputs that directly support tuna fishing activities. This study begins with the use of materials and energy in vessel construction, distribution of supplies, tuna fishing, maintenance of the vessel and fishing gear, including cleaning and inspection, up to the landing of the tuna. These boundaries are used to determine the environmental impact generated from a production process, which can be seen in Figure 1.

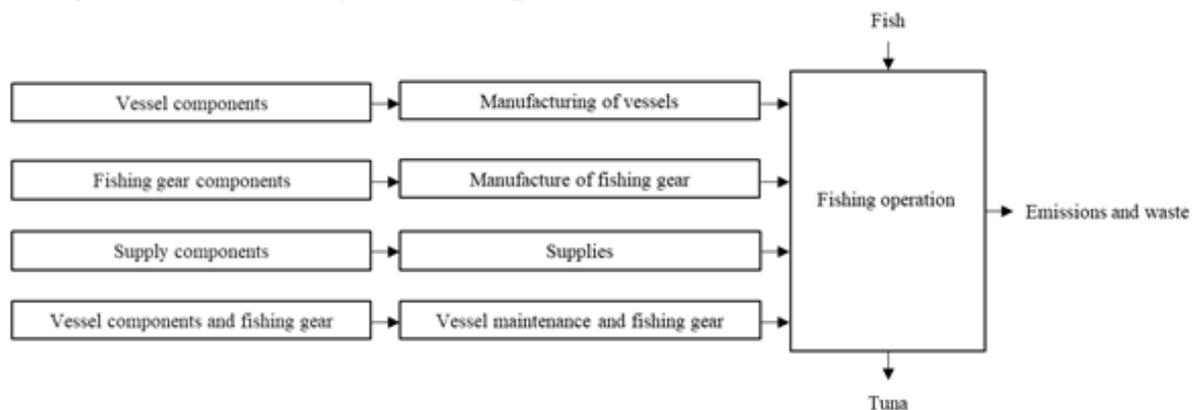


Figure 1. Scope of LCI in the tuna fishing process

C. Data processing

Data collection techniques used in determining respondents were purposive sampling with sampling based on specific considerations or criteria. The research sample consisted of 30 respondents selected based on specific criteria, namely having in-depth knowledge of fishing units, including fleets, fishing gear, and supplies. The respondents included 14 vessel owners who had complete records of their fleets and supplies, one vessel craftsman with 10 years of experience who understood

all components of a vessel, and 15 crew members with at least 10 years of experience who had an understanding of fish species, fishing gear specifications, vessels, and fuel consumption.

The data that has been collected and validated is then processed by classifying each type based on the specified criteria, such as types of supplies, fishing gear, and vessels. Next, the data is processed using the input-output-based LCI method to obtain the overall life cycle data from the beginning to the end of the process. The processed data can be seen in Table 1.

TABLE 1.
DATA PROCESSING RESULTS

Type of material needed	Amount (kg)	Life cycle	Discharge (%)	
			Discarded	Reused
Vessel construction				
Fishing gear construction				
Vessel maintenance				
Fishing gear maintenance				
Supplies				
Types of fish				

a. Calculation of material usage costs

The calculation of material usage is the sum of each type of material used during the process, using the following formula:

$$TC = F1.X1 + F2.X2 + F3.X3 + \dots + Fn.Xn \quad (1)$$

Explanation:

TC = Total cost of vessel production

Fn = Component of vessel manufacturing costs

Xn = Price

b. Calculation of material end of life

The calculation of the end of service life of materials aims to identify the amount and type of materials that will become waste after the service life of the components used in tuna fishing activities has ended. This analysis is carried out based on mass data on vessel materials, fishing gear, and supplies. From

this data, the amount of waste that will be produced can be estimated.

c. Calculation of pollutant emission levels

This calculation refers to the amount of fuel consumption based on data obtained to estimate CO, CO₂, NO_x, SO_x, and PM pollutant emissions on longline vessels using the formula [21].

$$E_{trip} = FC \times EF \quad (2)$$

Description:

E_{trip} = total overall emissions (tons)

FC = fuel consumption (tons)

EF = emission factor based on fuel consumption (kg/ton)

The determination of emission factors based on fuel type can be seen in Table 2.

TABLE 2.
 EMISSIONS FACTORS FOR VESSEL (KG/TON) BASED ON FUEL TYPE

Engine	CO	NO _x	SO _x	PM	CO ₂
MDO (<i>Marine Diesel Oil</i>) / Solar	7,40	10,90	19,00	0,30	2,67

Research uses quantitative descriptive analysis methods. Data is presented and processed using spreadsheets by inputting predetermined formulas. Next, the impact analysis resulting from the calculations is grouped according to the type of impact. In addition, a remediation analysis is conducted to reduce the resulting implications. This method is used to analyze the overall use of materials and energy during the tuna fishing process.

III. RESULTS AND DISCUSSION

Results of this study on mass and cost contributions throughout the entire life cycle of tuna fishing provide an overview of material use and expenditure for key components, namely vessels, fishing gear, and supplies. However, the explanation focuses solely on the repair and maintenance phase of the life cycle, omitting the harvesting phase. This is because the study focuses on consumable materials relevant to each stage of the main components. The tuna fishing process is divided into several stages, each of which plays an interrelated role in ensuring the success of the fishing operation. The following are the three main stages in the tuna fishing process:

Pre-fishing

Materials such as wood, nails, bolts, nuts, rings, hooks, glue, and paint. This is followed by the preparation of equipment by the vessel's crew, which takes 2-3 hours. Generally, these preparations are carried out in the afternoon or evening before the vessel departs for the fishing grounds. The fishing equipment to be used includes hooks, weights, floats, central lines, and branch lines. In addition, various supplies are provided, such as fuel oil (BBM), clean water, oil, rice, instant noodles, tea, coffee, cigarettes, cooking oil, granulated sugar,

mineral water, lighters, vegetables, chilies, onions, eggs, spices, bait, liquefied petroleum gas (LPG), freon, gloves, and kerosene. The amount and type of equipment and supplies carried are adjusted according to the duration of the operation and the number of crew members.

Capture

Longline fishing operations conducted by fishermen in PPS Cilacap vary in duration. In general, fishermen conduct one fishing operation for 2 months, with 4 trips in a year. Fishing is carried out in the morning, and some fishermen do it at night. The operation of this fishing gear is carried out in several stages, namely preparation, setting, drifting, and hauling [9].

After fishing

Boats that have finished tuna fishing will then return to port. The fish caught by the crew will be landed and transferred from the hold to barrels for weighing. Vessels that have completed their operations will undergo inspection and maintenance, and there is a break of about 2 months that can be used to repair or replace damaged components on the vessel. This is done so that the vessel is ready for the next fishing trip. This process is the final activity in the tuna fishing cycle by longline vessels.

Life cycle of longline fishing components

Regular maintenance is a vital process for ships to achieve optimal technical life. This process aims to prevent and repair potential failures or damage in order to maintain ship performance during fishing operations [7]. In addition, proper repairs are crucial for improving the ship's condition [15]. Vessel maintenance is generally carried out once a year through a docking process that includes cleaning the hull to protect the vessel's structure

from weather damage, as well as checking the engines, pumps, and navigation equipment to ensure they continue to function optimally. Repair stages, including repairs to ship components such as the hull, electrical systems, safety equipment, and steering systems, are also carried out periodically. Regular repairs to vital ship components are a priority in order to detect and prevent damage at an early stage, thereby maintaining the ship's functionality. End-of-life vessels at PPS Cilacap are generally disposed of in docking areas, harbor pools, or warehouses owned by each shipping company.

Fishing gear that has been damaged will be repaired, serviced, and maintained so that it can be used optimally again. In addition, periodic inspections and replacement of damaged components are also necessary. Fishing gear that has reached the end of its useful life, if not handled properly, can cause problems for the sustainability of fishery resources.

Fishing for tuna requires various types of supplies to support fishermen's activities on board. Supplies include all necessary items, both movable and immovable, that support the execution of tasks [5]. Managing the end of the supply's useful life is an important matter that needs to be considered. Based on observations and interviews with crew members and captains, the used supplies will generate 8,388 kg of waste. However, the current handling of this waste is still not optimal. Field observations show that around 54% of

supply waste, such as instant noodle packaging, tea, coffee, sugar, rice, drinking water, oil, eggshells, onion skins, chilies, vegetable scraps, and disposable gloves, is dumped directly into the sea. Only about 46% is reused, such as diesel fuel, freon, oil, LPG gas, and fresh water. The indiscriminate disposal of supplies into the sea can certainly have a negative impact on the aquatic environment and potentially endanger the safety of crew members during fishing operations.

Input components of each life cycle in the inputs and outputs of tuna fishing operations using longline vessels based at the Cilacap Ocean Fishing Port

The assessment focuses on the systematic compilation of all material flow and by products associated with tuna harvesting operations. Establishing this quantitative baseline is a prerequisite for any accurate environmental performance evaluation. Accordingly, the subsequent section delineates the granular inventory findings, beginning with a breakdown of primary input parameters such as vessels, fishing gear, and supplies during the manufacturing, repair, and maintenance phases. Tables 3 and 4 show the quantity and percentage of inputs and the annual costs of the three main components, respectively:

TABLE 3.
 NUMBER OF INPUTS AND PERCENTAGE OF EACH LIFE CYCLE PER YEAR

Life cycle	Component input (kg/year)					
	Vessel		Fishing gear		Supplies	
	Mass	Percentage	Mass	Percentage	Mass	Percentage
Manufacturing	354.27	86.93%	119.63	89.52%	62.026	100%
Repair	48.25	11.84%	14.00	10.48%	0	0
Maintenance	5.00	1.23%	0	0	0	0

TABLE 4.
 TOTALS AND PERCENTAGES OF COSTS FOR EACH LIFE CYCLE PER YEAR

Life cycle	Component input (kg/year)					
	Vessel		Fishing gear		Supplies	
	Mass	Percentage	Mass	Percentage	Mass	Percentage
Manufacturing	22,851,000	86.27%	4,516,000	78.73%	735,819,400	100%
Repair	3,186,500	12.03%	1,220,000	21.27%	0	0
Maintenance	450,000	1.76%	0	0	0	0

Table 3 shows significant differences in mass contributions from vessel inputs, fishing gear, and supplies across phases or life cycles over 1 year. Supplies only contributed 62,026 kg of mass to the manufacturing phase, with a percentage of 100%, without any input in the repair or maintenance phases. This indicates that supplies are consumables, such as food and fuel, which are used entirely in the fishing cycle without replacement or maintenance requiring additional materials in the next phase. On the other hand, the mass contribution from the repair phase for vessel components and fishing gear reached 48.25 kg (11.84%)

and 14.00 kg (10.48%), respectively, which illustrates the use of materials for replacing damaged components. Meanwhile, in the maintenance phase, the smallest material input was 5.00 kg (1.23%) for vessels and 0 kg. This indicates that routine maintenance activities do not require significant new material input.

Total and percentage of costs for each life cycle per year, based on Table 4 show that the most significant component of vessel costs is allocated to the repair phase, amounting to Rp 3,186,500 or 12.3%. In comparison, the cost in the maintenance phase is Rp 450,000 or 1.76%. This indicates that replacing and

maintaining vessel components over one year requires more significant funds than routine maintenance, which is relatively less costly. Repair costs for fishing gear components were recorded at Rp 1,220,000 or 21.27%, while maintenance costs were not recorded or were zero. This condition shows that the main cost allocation for fishing gear is focused on replacing damaged components, while routine maintenance activities themselves do not require significant material expenditure over their lifecycles. The minimal material costs indicate that the economic burden on fishermen is associated with reduced fishing efficiency rather than with maintenance costs for boat construction [6]. Although the material input is small, this activity has crucial strategic value, namely that fishing gear maintenance remains the most effective mitigation measure recognized by 95% of fishermen to prevent greater losses due to gear loss at sea [17].

Supplies are not allocated to costs in either the repair or maintenance phases. This indicates that supplies are consumables that do not require additional costs after the initial phase or after use is complete. Overall, this data

shows that over a one-year period, the main costs outside the manufacturing phase focus on repairs to vessels and fishing gear. Meanwhile, maintenance costs are relatively small or even non-existent for fishing gear and supplies.

Output from tuna fishing operations using longline vessels based at Cilacap Ocean Fishing Port

Output in the tuna fishing process refers to the tuna catch obtained. Several factors that need to be taken into account in estimating output include the number of tuna caught, the vessel's exhaust emissions, and waste produced from the three components. Fuel combustion produces incomplete exhaust emissions such as CO, NO_x, SO_x, HC, PM, and CO₂ [23]. Data on exhaust emissions from longline vessels at the Cilacap PPS can be seen in Table 5. Furthermore, the vessels, fishing gear, and supplies used during fishing activities will produce waste at the end of their useful life. Information on the types and amounts of waste (kg) produced is shown in Table 6.

TABLE 5.
 LONGLINE VESSEL EXHAUST EMISSIONS IN 2024

Engine	CO	NO _x	SO _x	PM	CO ₂
MDO (Marine Diesel Oil)	275,38	405,62	707,05	11,16	99,36

TABLE 6.
 QUANTITY OF CONTRIBUTION OF COMPONENT TYPES TO WASTE

Component type	Type	Annual waste quantity (kg)
Vessel	Wood	237.52
Fishing gear	Plastic	113.88
Supplies	Plastic	33,550.00

Emissions calculations in Table 5 from the use of diesel fuel show that the use of MDO fuel produces various types of pollutants in certain amounts. Carbon monoxide (CO) emissions were recorded at 275.38, while nitrogen oxides (NO_x) reached 405.62. Sulfur oxide (SO_x) emissions were the highest at 707.05, followed by particulate matter (PM) at 11.16, and carbon dioxide (CO₂) emissions at 99.36. The significant sulfur oxide (SO_x) emissions of 707.05 kg per vessel per year are a strong indicator that the longline fleet in Cilacap continues to use Marine Diesel Oil (MDO) with high sulfur content. Regulatory gaps are a concern, as the capture fisheries sector is often not regulated in line with global maritime emission standards, such as the IMO 2020 Sulfur Cap, which has been implemented in commercial shipping [12]. Previous studies have confirmed that energy transition has a measurable ecological impact, but this does not yet reflect the current conditions, especially in the Cilacap PPS area. Research conducted by Zetterdahl et al. (2016) shows that fuel use can reduce PM emissions by up to 67% and SO₂ by up to 80%, although nanoparticle emissions remain a concern [25].

Previous research by Chu Van et al. (2019) has recommended the use of Liquefied Natural Gas (LNG) as an effective solution to eliminate SO_x and reduce

NO_x by reducing combustion temperature [2]. Therefore, the high SO_x load in Cilacap waters, which contributes to the risk of ocean acidification, urgently requires the adoption of low-sulfur fuels and the optimization of engine operations to meet global sustainability standards. In addition, these high sulfur emissions are consistent with the operational characteristics of fishing vessels that use high-sulfur diesel (HSD). Furthermore, SO_x is a dominant pollutant in the maritime sector that contributes significantly to the potential for environmental acidification [4]. This data confirms that fuel combustion in longline vessel engines is a significant source of greenhouse gas emissions that affect the environment, particularly air quality.

Life Cycle Inventory (LCI) analysis reveals a critical point in supply chain management, stemming from the supply waste ratio reaching 50%. This percentage was obtained from a total waste of 33.5 tons out of a total input of 62 tons. According to Table 6, the volume of supply waste was recorded at 33,550.00 kg/year, dominating the total operational residue and far exceeding the waste from ship maintenance, which was 237.52 kg/year, and fishing gear, which was 113.88 kg/year. The preponderance of packaging waste, particularly plastic bottles and food wrappers, parallels the patterns documented by Yuwono (2025). This

similarity underscores that waste from crew provisions and fishing gear remains the dominant source of pollution in this sector [24]. This occurred due to logistical management errors, which triggered global pollution [16]. If not properly managed, the accumulation of this plastic risks degrading marine ecosystems and threatening the sustainability of fishery resources through microplastic contamination in the food chain [10]. Results indicate that tuna fishing activities not only contribute to exhaust emissions that impact air pollution but also generate various types of solid waste that require attention in the sustainability of the fisheries sector.

Calculation of the total input of components per catch per year

Operational efficiency and environmental impact assessments of tuna fishing activities can be conducted

by calculating the total input components per kilogram of catch each year. The annual tuna catch per vessel at the Cilacap Fishing Port in 2023 was 992.13 kg. Furthermore, the life cycle of a fishing vessel requires an input of 5,560 kg at a cost of IDR 26,487,500.00. Within one year, supplies contribute an input of 62,026 kg at a cost of IDR 735,819,400.00. Meanwhile, the fishing gear used has an input of 134 kg, costing IDR 5,736,000. This analysis provides a detailed overview of the ratio of resource use to the amount of fish produced, as well as a basis for identifying stages that could be improved to maintain sustainability. Tables 7 and 8 show the analysis of mass and cost contributions for the LCI calculated per kilogram of catch. The calculations in the LCI analysis are carried out in detail for each component and life cycle.

TABLE 7.
 RESULTS OF MASS CONTRIBUTION ANALYSIS ON THE OVERALL LIFE CYCLE OF TUNA FISHING

Life cycle	Mass contribution to the overall tuna fishing life cycle (kg/year)		
	Vessel	Fishing gear	Supplies
Manufacturing	0.3568	0.1210	62.5190
Repair	0.0484	0.0141	0
Maintenance	0.0001	0	0

TABLE 8.
 RESULTS OF COST CONTRIBUTION ANALYSIS ON THE OVERALL LIFE CYCLE OF TUNA FISHING

Life cycle	Contribution of costs to the overall life cycle of tuna fishing (Rp/year)		
	Vessel	Fishing gear	Supplies
Manufacturing	23,032.26	4,551.82	741,656.23
Repair	3,211.78	1,229.68	0
Maintenance	453.57	0	0

Analysis of the contribution of mass throughout the entire tuna fishing life cycle, as shown in Table 7, indicates that the repair phase, vessel components, and fishing gear contribute 0.0484 kg and 0.0141 kg per year, respectively, while supplies do not contribute to mass in this phase. In the maintenance phase, mass contribution occurs only in vessels at 0.0001 kg, while fishing gear and supplies do not contribute additional mass. This data indicates that the use of materials for the replacement and maintenance of vessel components and fishing gear is relatively small, while supplies do not require additional materials during repair and maintenance.

The cost contribution analysis results shown in Table 8 indicate that during the repair phase, costs for vessels amounted to IDR 3,211.78 and for fishing gear to IDR 1,229.68 per year, while supplies incurred no costs during this phase. During the maintenance phase, costs are recorded only for vessels at Rp 453.57, with none recorded for fishing gear or supplies. This explains why the costs for replacing and maintaining vessel and fishing gear components are relatively limited. Overall, Tables 7 and 8 do not describe the manufacturing phase. Analysis of the repair and maintenance phase in this study shows that the mass input and costs allocated are relatively small, with supplies not requiring additional input at this

stage. The limited resource allocation in this maintenance phase confirms that, across the global fisheries life cycle, the burden of infrastructure and maintenance tends to be small compared to the impact of the operational phase. This shows that the main environmental burden is borne by the harvesting and processing stages, while the contributions from infrastructure maintenance and end-of-life treatment are marginal, accounting for less than 10% of the total environmental footprint [8].

Results of this study analyze the contribution of mass, cost, exhaust emissions, and waste throughout the entire life cycle of tuna fishing using longline vessels. Special emphasis is placed on three main components: vessels, fishing gear, and supplies. The quantitative data generated from the analysis are presented in several tables above. The manufacturing life cycle consistently accounts for the largest share of mass, materials, and costs, particularly supplies, which are the main source of consumables in tuna fishing operations. The repair and maintenance stage, which is the main focus of this study, has a smaller contribution in terms of both mass and cost, particularly for vessels and fishing gear. In addition, environmental aspects were also analyzed through exhaust emissions from vessels and waste,

which are important indicators in evaluating the impact of the fishing process.

IV. CONCLUSION

Based on a life cycle assessment (LCI) analysis aimed at quantifying the inputs and outputs of tuna fishing operations at the PPS Cilacap, this study concluded that the input component of supplies dominated operations, with a total mass of 62,026 kg and a total cost of IDR 735,819,400 per year. This contribution is directly proportional to the contribution per kilogram of tuna produced, as indicated by an input of 29.313 kg/kg of fish at a cost of IDR 347,740.74/kg of fish, where this high cost does not affect the selling price of tuna in the market. The LCA also shows the contribution of outputs in the tuna fishing process. The diesel fuel used by fishing vessels produces 707.62 kg of sulfur oxides (SOx) per year and 33,550.00 kg of solid waste per year, both of which come from supplies. Solid waste, which is dominated by supply residues, requires upstream mitigation strategies, including the implementation of bulk-provisioning policies and more efficient logistics management, both of which are highly recommended to reduce plastic waste. In addition, high SOx emissions require evaluating engine efficiency and the quality of the fuel used. Further studies using comprehensive Life Cycle Assessment (LCA) analysis are needed to convert this inventory data into specific environmental impact categories, such as Global Warming Potential (GWP) and Acidification, so that sustainability strategies can be formulated more precisely.

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