Estimation of carbon footprint resulting from tuna fishing activities using different fishing gear

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Abstract. Tuna fishing is a fishing activity with high fuel use intensity (FUI) that contributes significantly to greenhouse gas emissions. In order to support Indonesia's commitment to the Paris Agreement, efforts to reduce emissions are needed across all sectors, including fisheries. Mapping the carbon footprint (CFP) of tuna fishing activities is essential in identifying key emission points and formulating targeted strategies. This research aims to calculate and compare FUI and CFP from tuna fishing using handline, purse seine, troll line, and longline in several Indonesian fishing ports. Data were obtained through an inventory of previous studies and port statistics. Results showed that FUI ranged from 0.18-2.32 kg/kg, with the highest value for tuna longlines at Palabuhanratu Fishing Port and the lowest for purse seines at Kutaraja Fishing Port. Estimated CFP of tuna ranged from 0.06-1.72 kgCO_2eq/kg, with the highest value for tuna longlines at Nizam Zachman Fishing Port and the lowest for purse seines at Kutaraja Fishing Port. Based on each vessel's gear type, size, or location, no specific pattern was found for either FUI or CFP. This research confirms that FUI is influenced by fuel consumption and catch, while tuna CFP is primarily influenced by FUI and composition of the tuna catch.

1 Introduction

Indonesia agreed to commit to reducing greenhouse gas (GHG) emissions through the Paris Agreement, which was later renewed at the 2021 United Nations Climate Change Conference-COP26 in Glasgow, Scotland. In 2022, Indonesia joined the United Nations Framework Convention on Climate Change (UNFCCC). It submitted a plan to reduce emissions by 31.89% through its own efforts and 43.20% with international support through an Enhanced Nationally Determined Contribution, with a vision of achieving net zero emissions by 2060 or sooner.

Energy transition policy experts emphasise that failure to meet the Paris Agreement commitments could undermine international confidence and hamper green investment. In addition, uncontrolled GHG emissions will exacerbate the climate crisis and impact vital economic sectors. This underscores the importance of reducing GHG emissions in Indonesia.

GHG emissions come from various human activities and natural processes. The energy and transport sectors produce GHG emissions mainly through the combustion of fossil fuels. GHG gases can be defined as a combination of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other fluorinated gases. Among these gases, carbon dioxide (CO_2) is the most dominant in the atmosphere, accounting for about 76% of global GHG emissions. While other GHGs have a higher warming potential, carbon's much larger volume of emissions and

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long lifetime in the atmosphere make its impact on climate change more significant. Therefore, GHG emissions reduction is often focused on reducing carbon emissions, also known as the carbon footprint.

Carbon footprint measures the total carbon dioxide (CO_2) emissions released directly or indirectly caused by an activity. Direct emissions come from sources controlled or owned by the activity, such as emissions from burning fuel oil. Meanwhile, indirect emissions are produced due to the activity, but occur outside of direct control, such as from ship construction, provision of equipment and feed, fuel production, refrigeration, and so on.

One of the fishing activities that produce a high carbon footprint is tuna fishing. Tuna fisheries have a relatively high fuel use intensity (FUI) compared to other fisheries [1]. On the other hand, the number of tuna fishing vessels in Indonesia is relatively increasing annually [2].

Tuna fishing activities in Indonesia involve the use of a variety of fishing gear, such as handlines, purse seines, troll lines, and long lines. Handline is a passive fishing gear because fishermen wait for fish to eat the bait that is stretched manually without any active movement of the boat [3]. Meanwhile, purse seine is an active fishing gear operated by encircling schools of fish using a large net stretched by the fishing vessel, then the bottom of the net is pulled closed, forming a bowl-like shape. A troll line is an active fishing gear pulled horizontally by a boat while waiting for fish to eat the bait. Longline is a passive fishing gear operated through setting, immersing, and hauling the fishing line. Due to differences in the method and scale of operation, the carbon footprint generated from fishing using these gears will also be different.

To date, carbon footprint reduction efforts have been conducted through studies focusing on improving fuel efficiency mapping of various fishing activities. However, the unavailability of carbon footprint mapping of different types of tuna fishing gear means that efforts to reduce carbon emissions in the tuna capture fisheries sector cannot be accurately measured. In addition, the absence of data on the performance of tuna fishing gear in terms of the carbon footprint risks causing government policies to be less targeted, because they are not based on identifying efficiency targets and specific reduction strategies.

Studies on the carbon footprint generated by tuna fishing activities using different fishing gears in Indonesian waters have been conducted by several researchers. For example, longline at Palabuhanratu Fishing Port [4], handline at Pondokdadap Fishing Port [5], and handline and purse seine at Kutaraja Fishing Port [6] have previously been assessed. Considering the results of existing research, this study is intended to compare the findings of the previous studies and provide comprehensive information on the performance of different tuna fishing gear in terms of the carbon footprint generated in various regions of Indonesian waters.

The benefits of this study are to provide information related to tuna fishing gear that has more efficient performance in terms of the carbon footprint, help businesses to compare the performance of fishing gear based on the carbon footprint, and provide a basis for further research on technological innovations in fishing gear that are more energy efficient and environmentally friendly.

2 Methods

The research was conducted in March-June 2025. The study was conducted by collecting data on fuel oil (BBM) consumption and the amount and composition of catch per trip per vessel for one year or more than one year from tuna fishing units. The data was obtained by reviewing research results. The data obtained were from handline fishing units at Pondokdadap Fishing Port, Malang, East Java; handline and purse seine at Kutaraja Fishing Port, Banda Aceh, Aceh; and troll line and longline at Palabuhanratu Fishing Port, Sukabumi, West Java. Data were also collected from the literature for Nizam Zachman Fishing Port, Jakarta, Special Capital Region of Jakarta, covering handline, purse seine, and longline fishing units (annual report of Nizam Zachman Fishing Port).

The research began by conducting a literature study on fuel consumption data and the amount and composition of catch per trip per vessel for one year or more than one year in handline, purse seine, troll line, and longline fishing units. Selected studies from the search were first reviewed to ensure data availability. Data validation was conducted by checking the credibility of the sources, as well as the completeness and clarity of the data. Field data were also collected as harbour statistics for handline, purse seine, and longline fishing units. Data processing was carried out so that the data can be analysed. Each data from each source had various data processing techniques. However, in general, what was done included grouping fishing vessels data based on the GT classification according to Indonesian Fisheries Statistics, namely motorboats <5 GT, 5-10 GT, 10-20 GT, 20-30 GT, 30-50 GT, 50-100 GT, 100-200 GT, and>200 GT. Furthermore, the units in the data were converted to consistent units, namely using kilograms. This unit was also chosen to adjust the carbon footprint, where the unit of fuel is kilograms.

Data analysis was carried out using the FUI calculation formula as follows.

$$FUI_{fish} = \frac{\sum FC\ (kg)}{\sum HT\ (kg)} \tag{1}$$

Description of formula (1):
$\sum FC$ = Fuel consumption per vessel per trip (kg)
$\sum HT$ = Total catch per vessel per trip (kg)

Based on FUI, data analysis was then carried out using a formula for calculating the estimated carbon footprint for the total catch, tuna, and non-tuna. The estimated carbon footprint is expressed in kilograms of carbon dioxide equivalent per kilogram of fish ($kgCO_2eq/kg$). The formula for calculating the carbon footprint per kilogram of fish caught was as follows.

$$CO_2\ emission = \frac{FUI \times NCV \times EF}{10^6} \tag{2}$$

Description of formula (2):
NCV = Net Calorific Value (MJ/kg)
EF = CO_2 Emission Factor (kg CO_2/TJ)
10^6 = conversion of MJ to TJ (1 TJ = 10^6 MJ)

Fishing vessels in Indonesian waters mostly use diesel fuel, which has an EF value of 74,100 kg CO_2/TJ and an NCV value of 43.00 MJ/kg.

Furthermore, numerical and descriptive comparative analyses were conducted to determine information on the performance of fishing gear in terms of the carbon footprint generated.

3 Result and discussion

Based on the results of data collection related to fuel oil (BBM) consumption as well as the number and composition of catches per trip per vessel for one year or more than one year from four types of tuna fishing gear, information from a total of eight tuna fishing units was obtained spread across four different fishing ports, namely Nizam Zachman, Kutaraja, Palabuhanratu, and Pondokdadap. The eight fishing units consisted of three units of handline, two units of purse seine, one unit of troll line, and two units of longline. A detailed summary of the data obtained is presented in Table 1.

Table 1. Details of data acquisition regarding the analysed tuna fishing gear.

Source	Type of fishing gear	Vessel size (GT)	Number of vessels (Unit)	Number of trips per year	Average trip length (days/trip)	Range of data taken
Statistics Nizam Zachman Fishing Port	Handline	30-50	2	1	85	2024
		50-100	16	1-3	113	
		100-200	2	1	236	
	Purse Seine	50-100	1	1	201	
		100-200	224	1-2	244	
		>200	9	1-2	287	
	Longline	30-50	5	1-3	121	
		50-100	47	1-5	178	
		100-200	21	1-5	148	
Kutaraja Fishing Port [6]	Handline	5-10	1	15	3	2023
		10-20	8		5	
		20-30	5		9	
	Purse Seine	20-30	6	12	6	
		30-50	7		11	
		50-100	4		9	
Palabuhanratu Fishing Port [7]	Troll Line	5-10	15	24	11	2023
Pondokdadap Fishing Port [5]	Handline	5-10	2	6	10	2022
		10-20	15	7	10	
		20-30	15	9	10	
Palabuhanratu Fishing Port [4]	Longline	20-30	128	12	-	2015-2021

Table 1 shows that these four types of fishing gear are used in various sizes, from small-scale 5-10 GT (Gross Tonnage), such as troll line vessels, to industrial-scale>200 GT purse seine vessels. The variation in vessel size indicates the diverse scale of operations in tuna fishing activities in Indonesia, from traditional to large industrial scales.

The number of vessels sampled also varied between locations, from 1 vessel to 224 boats, depending on the completeness of data from each source. Fishing activity, as reflected by the number of trips and trip length, also varied depending on the scale of operation and gear type. Large vessels tended to make few trips, with 1-5 trips per year and long fishing durations ranging from 85 to 287 days per trip. In contrast, small to medium-sized vessels usually made more trips, reaching up to 24 trips per year with a duration of fishing between 5 and 15 days per trip. This shows the capacity and cruising power difference between small, medium, and large vessels.

Data from Nizam Zachman Fishing Port shows that tuna are caught by handline, purse seine, and longline, with the most significant number of vessels being 224 purse seine vessels of 100-200 GT and 47 longline vessels of 50-100 GT. This reflects the character of that harbour as the base of the large-scale tuna fishing industry. Meanwhile, data from Pondokdadap Fishing Port [5] and from Palabuhanratu Fishing Port [7] reflect the condition of small and medium-scale fisheries, with smaller vessel sizes. The variation in gear from different locations provides a strong basis for comparing gear performance.

3.1 Fuel consumption

Fuel consumption is one of the main factors affecting the carbon footprint of tuna fishing activities. A common finding in fisheries life cycle assessment studies is that fuel inputs dominate GHG emissions, with 60-90% of life cycle GHG emissions resulting from direct fuel combustion during fishing [1]. In the fish supply chain, fuel combustion of tuna fishing vessels accounts for about 70-90% of total GHG emissions up to the point of landing. This exceeds the combative energy use and GHG emissions from processing, packaging, and product transport [8]. Fuel consumption per trip for each fishing gear is presented in Table 2.

Table 2. Fuel consumption of each tuna fishing gear.

Type of fishing gear	Name of fishing port	Vessel size (GT)	Average trip length (days/trip)	Average fuel consumption per day (kg)	Total fuel consumption per trip (kg)
Handline	Nizam Zachman Fishing Port	30-50	85	34.79	2,940.00
		50-100	113	93.79	10,225.39
		100-200	236	142.37	33,600.00
	Kutaraja Fishing Port	5-10	3	107.67	323.00
		10-20	5	123.90	632.65
		20-30	9	157.74	1,335.52
	Pondokdadap Fishing Port	5-10	10	100.84	617.01
		10-20	10	125.96	895.62
		20-30	10	141.25	1,259.03
Purse Seine	Nizam Zachman Fishing Port	100-200	243	133.36	29,008.91
		>200	287	152.12	42,702.54
	Kutaraja Fishing Port	20-30	6	241.53	1,380.95
		30-50	11	365.92	3,969.85
		50-100	9	573.81	4,644.42
Troll Line	Palabuhanratu Fishing Port	5-10	11	48.21	530.32
Longline	Nizam Zachman Fishing Port	30-50	121	112.61	9,711.77
		50-100	178	102.73	14,198.38
		100-200	148	291.90	22,486.61
	Palabuhanratu Fishing Port	20-30	-	-	-

In addition to generating GHG emissions, vessel fuel consumption has also been identified as a key driver of environmental toxicity, acidification, eutrophication, particulate matter emission, and abiotic resource depletion, further emphasising the impact of vessel fuel consumption as a life cycle ecological hotspot in capture fisheries [9].

The amount of fuel consumption is influenced by the size of the vessel, the distance to the fishing grounds, the type of fishing gear, the engine used, and the fuel used [5]. In addition, natural conditions, such as weather, wave height, wave period, and wind, also affect the amount of fuel consumption [10].

In general, the larger the vessel size and the longer the duration of fishing, the higher the fuel consumption per trip. Longline fishing gear's fuel consumption varied by port location and vessel size. Purse seine recorded the highest fuel consumption, especially at Nizam Zachman Fishing Port, with vessels >200 GT consuming up to 42,702 kg of fuel/trip over

287 days. Handline and longline also showed an increasing trend in consumption as vessel size and operating length increased.

There are limitations in determining fuel consumption data, especially at Nizam Zachman Fishing Port. The available data is the fuel data recorded when the vessel prepares to go to sea, so it only reflects the initial amount of fuel before the vessel sails. Based on interviews, vessels generally refuel at sea 4-5 times per trip, which is done when fishermen transship their catch. The port has not recorded this refuelling activity. Therefore, the actual fuel consumption during the trip cannot be known explicitly.

These limitations need to be addressed by the fishing port by starting to implement a comprehensive and continuous fuel consumption recording system, not only during departure. For example, vessels can be required to report their total fuel consumption after completing a trip to sea or to record each time they refill fuel at sea. This can assist the port in calculating the amount of fuel used each trip, so that the amount of tax from fuel purchases that needs to be paid by each boat owner can also be appropriate. In addition, the completeness of the data will also make future research more accurate.

3.2 Number and composition of catches

In addition to fuel consumption, FUI and carbon footprint are also strongly influenced by the amount and composition of the catch obtained in one trip during one year. The higher the catch, the lower the FUI because energy consumption is spread over more output. Therefore, the productivity of fishing gear is an essential factor in assessing energy efficiency prior to emission calculations. Knowledge of the proportion of tuna and non-tuna catch is also the basis for calculating FUI and estimating the carbon footprint of fishing activities [4].

Each fishing gear has varying catchability depending on the technical design, operational methods, and biological characteristics of the target species [11]. Differences in these characteristics impact variations in catch, both in terms of total numbers and the proportion of tuna to the overall catch. The number and proportion of tuna catches from each fishing gear sampled in this study are presented in Table 3. Data includes the average catch in one fishing trip that has previously been accumulated for one year from each fishing gear.

Table 3. Number and composition of catches for each tuna fishing gear.

Type of fishing gear	Name of fishing port	Vessel size (GT)	Average trip length (days/trip)	Catch (kg)			Percentage (%)	
				Total	Tuna	Non-tuna	Tuna	Non-tuna
Handline	Nizam Zachman Fishing Port	30-50	85	16,000	4,675	11,325	29	71
		50-100	113	31,440	15,653	15,787	50	50
		100-200	236	35,000	10,000	25,000	29	71
	Kutaraja Fishing Port	5-10	3	1,033	493	540	48	52
		10-20	5	1,800	718	1,082	40	60
		20-30	9	4,026	1,249	2,777	31	69
	Pondokdadap Fishing Port	5-10	10	1,706	853	853	50	50
		10-20	10	2,144	1,072	1,072	50	50
		20-30	10	2,857	1,428	1,428	50	50
Purse Seine	Nizam Zachman Fishing Port	100-200	243	70,442	16,042	54,400	23	77
		>200	287	75,455	16,245	59,209	22	78
	Kutaraja Fishing Port	20-30	6	7,090	707	6,383	10	90
		30-50	11	13,537	1,770	11,767	13	87

Type of fishing gear	Name of fishing port	Vessel size (GT)	Average trip length (days/trip)	Catch (kg)			Percentage (%)	
				Total	Tuna	Non-tuna	Tuna	Non-tuna
		50-100	9	17,228	1,892	15,337	11	89
Troll Line	Palabuhanratu Fishing Port	5-10	12	895	309	586	35	65
Longline	Nizam Zachman Fishing Port	30-50	121	8,500	4,009	4,491	47	53
		50-100	178	22,852	13,459	9,393	59	41
		100-200	148	34,857	28,615	6,241	82	18
	Palabuhanratu Fishing Port	20-30	-	-	-	-	18	82

Handlining at Nizam Zachman Fishing Port and Kutaraja Fishing Port showed moderate to high selectivity, with 29-50% of tuna. At the same time, at Pondokdadap Fishing Port, it was assumed to be 50% due to data limitations. Puse seiners, although focused on skipjack, produced large volumes of tuna but with low proportions (9-23%) and low selectivity. The troll liners produced 35% tuna with catch diversity due to the use of fishing aggregating devices (FADs). Longline showed the highest selectivity, reaching 82% on large vessels at Nizam Zachman Fishing Port, while at Palabuhanratu Fishing Port, it was only 18%.

In general, catches from each gear and location showed variations that reflected differences in operational strategies, vessel scale, and water conditions where operations took place. This variation not only shows the technical and ecological dynamics in the field but also becomes an essential component in calculating fuel use intensity and estimating carbon footprint in a more representative manner.

3.3 Fuel use intensity

Fuel use intensity (FUI) is one of the leading indicators in assessing the energy efficiency of tuna fishing activities. The FUI value is calculated as the ratio between the amount of fuel consumption and the total catch obtained, using formula (1), resulting in units of kg of fuel per kg of fish. This parameter is important because it directly represents how much energy consumption is required to produce one kilogram of caught fish. The smaller the FUI value, the more efficient fuel use and the lower the potential emissions. Table 4 presents the FUI values of each tuna fishing gear.

Table 4. Fuel use intensity of each tuna fishing gear.

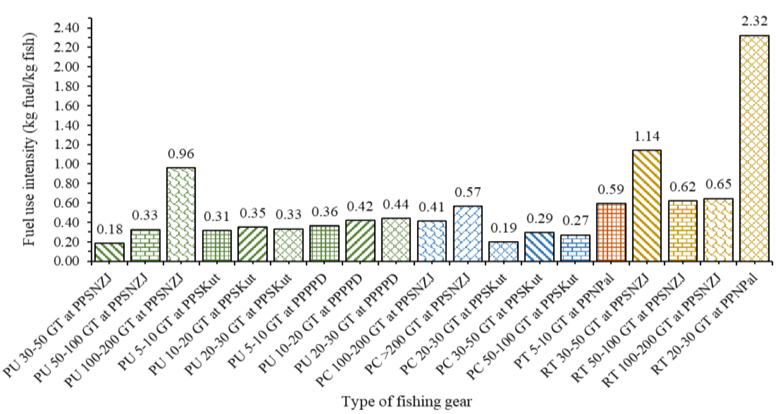
Type of fishing gear	Name of fishing port	Vessel size (GT)	Average trip length (days/trip)	Fuel use intensity (kg BBM/kg HT)
Handline	Nizam Zachman Fishing Port	30-50	85	0.18
		50-100	113	0.33
		100-200	236	0.96
	Kutaraja Fishing Port	5-10	3	0.31
		10-20	5	0.35
		20-30	9	0.33
	Pondokdadap Fishing Port	5-10	10	0.36
		10-20	10	0.42
		20-30	10	0.44
Purse Seine		100-200	243	0.41

Type of fishing gear	Name of fishing port	Vessel size (GT)	Average trip length (days/trip)	Fuel use intensity (kg BBM/kg HT)
	Nizam Zachman Fishing Port	>200	287	0.57
	Kutaraja Fishing Port	20-30	6	0.19
		30-50	11	0.29
		50-100	9	0.27
Troll Line	Palabuhanratu Fishing Port	5-10	12	0.59
Longline	Nizam Zachman Fishing Port	30-50	121	1.14
		50-100	178	0.62
		100-200	148	0.65
	Palabuhanratu Fishing Port	20-30	-	2.32

Fuel use efficiency in capture fisheries, interpreted through FUI values, is influenced by various operational and ecological factors. These factors include the type of fishing gear used, the relative abundance of target fish stocks, the distance travelled to the fishing grounds, the skill level of the captain and crew, and the use of FADs or fish aggregating aids [9].

Based on Table 2, FUI values varied significantly between gear types, ports, and vessel sizes. The overall FUI value ranged from 0.18 to 2.32 kg fuel/kg fish. The lowest FUI value was recorded for purse seine gear at Kutaraja Fishing Port, with a range of 0.18-0.29 kg fuel/kg fish, indicating high fuel efficiency. The highest FUI value was found in longline gear at Palabuhanratu Fishing Port at 2.32 kg fuel/kg fish, indicating high fuel consumption for every kilogram of fish produced. This is in line with the results of Tyedmers and Parker's research [1] that tuna caught using purse seines tend to have low FUI or are not too wasteful in terms of energy. In addition, vessels catching tuna by longline have historically consumed more fuel per landing unit than vessels catching tuna by purse seine [1].

Showing more detail, the FUI values of each fishing gear are compared in a graph, as seen in Figure 1.



PU = Handline PPSNZJ = Nizam Zachman Fishing Port
PC = Purse Seine PPSKut = Kutaraja Fishing Port
PT = Troll Line PPPPD = Pondokdadap Fishing Port
RT = Longline PPNPal = Palabuhanratu Fishing Port

Fig. 1. Comparison of fuel use intensity in tuna fishing gear.

Fuel use intensity is based on the type of fishing gear in each fishing port, and it can be seen that the handline does not show a consistent pattern between vessel sizes. The FUI value of handline in three fishing ports tends to fluctuate and does not form a particular trend. However, the FUI value at Pondokdadap Fishing Port is slightly higher than for the other two ports, although the difference is insignificant. There is an anomaly in the 100-200 GT handline at Nizam Zachman Fishing Port because it has a significantly different FUI from the other handline vessel sizes.

Furthermore, a slightly more evident pattern can be seen if the comparison is made based on the GT size of the vessel, namely in purse seine and longline fishing gear. In purse seines, the larger the vessel size, the higher the FUI tends to be, except for the 30-50 GT purse seine vessels at Kutaraja Fishing Port, which is higher but not significant, with a difference of 0.10 from the 20-30 GT vessel size and a difference of 0.02 from the 50-100 GT vessel size. Meanwhile, longline displays the opposite pattern, where the larger the vessel size, the lower the FUI tends to be, except for the 100-200 GT longline vessel at Nizam Zachman Fishing Port, which is higher but not significant, with a difference of 0.03 higher than the 50-100 GT vessel size. Handline has no trend, but it is known that the average FUI is moderate. The anomaly with the handline at Nizam Zachman Fishing Port is that the larger vessel size, the higher the FUI. The troll line was not compared because there were no other GT sizes, only 5-10 GT vessels.

Based on the location of the fishing port, at Nizam Zachman Fishing Port, the larger the vessel size for the same gear type, the higher the FUI, whether for handline, purse seine, or longline gear. While at Kutaraja Fishing Port, FUI tends to be equally low, both in handline and purse seine gear, but it appears that purse seine has a lower average FUI compared to handline, even though this may be due to various factors, such as operational support (e.g. the use of FADs), a more organised fishing plan, and a system of mass fishing in a short time. The use of FADs in the waters around Aceh, including Kutaraja, has been shown to increase fishing efficiency [12]. Research demonstrated that production factors such as vessel engine power, number of crew members, and number of lights affect the efficiency of purse seine at Kutaraja Fishing Port [13].

3.4 Carbon footprint

The estimated carbon footprint was calculated by multiplying the FUI values in Table 4 by the emission factor and net calorific value of diesel fuel, according to formula (2). The carbon footprint value is expressed in kilograms of carbon dioxide equivalent per kilogram of fish (kgCO_2eq/kg). The tuna carbon footprint column shows how much GHG emissions each kilogram of tuna catch has to "bear". The higher the carbon footprint value, the greater the activity's environmental impact. The estimated carbon footprint resulting from tuna fishing activities with different fishing gear is presented in Table 5.

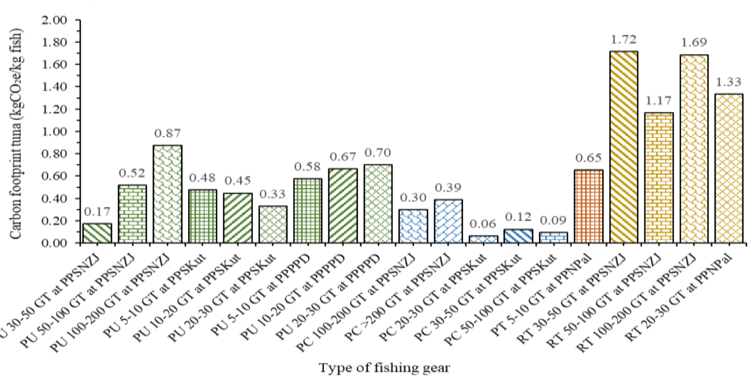
Table 5. Estimated carbon footprint resulting from tuna fishing activities with different fishing gear.

Type of fishing gear	Name of fishing port	Vessel size (GT)	***Carbon footprint* (kgCO_2eq/kg)**		
			Total	**Tuna**	**Non-tuna**
Handline	Nizam Zachman Fishing Port	30-50	0.59	0.17	0.41
		50-100	1.04	0.52	0.52
		100-200	3.06	0.87	2.18
	Kutaraja Fishing Port	5-10	1.00	0.48	0.52
		10-20	1.12	0.45	0.67
		20-30	1.06	0.33	0.73

Type of fishing gear	Name of fishing port	Vessel size (GT)	*Carbon footprint* (kgCO₂eq/kg)		
			Total	Tuna	Non-tuna
	Pondokdadap Fishing Port	5-10	1.15	0.58	0.58
		10-20	1.33	0.67	0.67
		20-30	1.40	0.70	0.70
Purse Seine	Nizam Zachman Fishing Port	100-200	1.31	0.30	1.01
		>200	1.80	0.39	1.42
	Kutaraja Fishing Port	20-30	0.62	0.06	0.56
		30-50	0.93	0.12	0.81
		50-100	0.86	0.09	0.76
Troll Line	Palabuhanratu Fishing Port	5-10	1.89	0.65	1.24
Longline	Nizam Zachman Fishing Port	30-50	3.64	1.72	1.92
		50-100	1.98	1.17	0.81
		100-200	2.06	1.69	0.37
	Palabuhanratu Fishing Port	20-30	7.40	1.33	6.07

Table 5 shows the variation in carbon footprint values between gear types, vessel sizes, and ports. The fishing gear's overall tuna carbon footprint value ranged from 0.06 to 1.72 kgCO_2eq/kg. The highest overall tuna carbon footprint was for longline at Nizam Zachman Fishing Port, with a tuna carbon footprint of 1.72 kgCO_2eq/kg for vessels of 30-50 GT, reflecting a very high level of emissions. The lowest average tuna carbon footprint was for purse seine gear at Kutaraja Fishing Port, with a tuna carbon footprint as low as 0.06 kgCO_2eq/kg for vessels 20-30 GT, reflecting very low emission levels.

This finding aligns with the results of Tyedmers and Parker [1], who also showed that longline gear produces a much higher carbon footprint than purse seine gear. In their study, longline fishing produced emissions of 3.83 kgCO_2eq/kg, while purse seine only produced 1.53 kgCO_2eq/kg. This difference indicates that, in general, active fishing gear, such as purse seine, tends to be more environmentally friendly in terms of the carbon footprint produced than passive fishing gear, such as longline. Although the carbon footprint values in this study are lower in absolute terms, the comparison pattern between gear types still shows a similar trend. For more detail, the carbon footprint values of each fishing gear are compared in a graph, as seen in Figure 2.



PU	= Handline	PPSNZJ	= Nizam Zachman Fishing Port
PC	= Purse Seine	PPSKut	= Kutaraja Fishing Port
PT	= Troll Line	PPPPD	= Pondokdadap Fishing Port
RT	= Longline	PPNPal	= Palabuhanratu Fishing Port

Fig. 2. Comparison of tuna carbon footprint in tuna fishing gear.

The tuna carbon footprint based on the type of fishing gear at each fishing port does not appear to have a clear pattern. For handliners at Nizam Zachman Fishing Port and at Pondokdadap Fishing Port, the larger vessel size was associated with a higher tuna carbon footprint value. Meanwhile, for handline gear at Kutaraja Fishing Port, the larger vessel size was associated with a lower tuna carbon footprint value. The purse seiners at Nizam Zachman Fishing Port had a higher average tuna carbon footprint than that at Kutaraja Fishing Port. Troll liners had a medium tuna carbon footprint. Meanwhile, longliners at Nizam Zachman Fishing Port fluctuated and had the highest average tuna carbon footprint compared to other gears. This was the same as for the longliners at Palabuhanratu Fishing Port, with a high tuna carbon footprint value compared to other fishing gears.

Furthermore, based on GT size, there was no clear pattern. Handline and longline gear had a tuna carbon footprint that fluctuated significantly. Purse seiners displayed a trend where the larger the vessel size, the higher the tuna carbon footprint value, but there was an anomaly for purse seiners 30-50 GT with a difference that was not significant, only 0.03 higher than purse seiners of size 50-100 GT.

Based on the location of the fishing port at Nizam Zachman Fishing Port for handline and purse seine gear with larger vessel sizes, the tuna carbon footprint was also higher. Meanwhile, longline gear with the smallest size had the largest tuna carbon footprint value. Furthermore, at Kutaraja Fishing Port, the larger vessel size was associated with a lower tuna carbon footprint value, while the purse seine gear showed no trend. At Pondokdadap Fishing Port, the average tuna carbon footprint value was medium, with a trend that the larger the vessel size, the higher the carbon footprint value produced. Fishing ports with their respective gear types that produced the lowest to highest average tuna carbon footprint values are Kutaraja, Pondokdadap, Palabuhanratu, and Nizam Zachman.

The results of this study provide a quantitative overview of the FUI and carbon footprint of different gears in several fishing ports. Findings show significant variations among gear types, vessel sizes, and operational locations, reflecting the field's strategic technical and energy efficiency differences. With this data, efforts to reduce the carbon footprint of the capture fisheries sector can be more measurable because it is based on the value of the fuel consumption and the proportion of catch from each unit.

In addition, this information can serve as the basis for more targeted policy development. The government can prioritize energy efficiency interventions in fishing units with the highest carbon footprint values, and encourage using fishing gear proven more efficient and environmentally friendly. This mapping can also support the development of a gear-based emissions reporting and monitoring system as part of the national commitment to reduce GHG emissions, in accordance with the Paris Agreement targets.

Data limitations mean that measuring the carbon footprint of capture fisheries is still challenging, especially regarding the availability of accurate and detailed fuel consumption data. Currently, most fishing ports only record the amount of fuel when the vessel leaves for sea, with no information on the actual consumption during the trip and refuelling at sea. However, research shows [14] that even for years the data at fishing ports has increased in completeness, it still does not meet the data needs to calculate FUI and carbon footprint more accurately.

Based on this explanation, the government needs to encourage improving the fuel consumption recording system, such as through digital daily logbook filling, fuel flowmeter installation, and port data with the vessel monitoring system (VMS). With the availability of more accurate data, future carbon footprint estimation studies can be more representative and support evidence-based policy making. Investing in a good data collection system is an important foundation for Indonesia's more efficient, low-emission, and sustainable fisheries transformation.

Furthermore, the FUI value of global tuna capture fisheries showed an increasing trend from 2009 to 2023 [9]. However, these findings may be influenced by the limited sample size of the latest study, which was smaller than the sample size of their monitoring in the fisheries sector.

The results of this study, on a national scale, also show that some tuna fishing units produce a high carbon footprint, such as the longliners at Nizam Zachman Fishing Port. This indicates that the issue of energy efficiency in fisheries is a local and globally relevant challenge. Therefore, efforts to improve fuel efficiency must be considered in managing sustainable capture fisheries locally and internationally.

4 Conclusion

The fuel use intensity (FUI) value in tuna fishing units at the research sites ranged from 0.18 to 2.32 kg of fuel/kg of fish. The highest FUI value was recorded for longline gear at Palabuhanratu Fishing Port, while the lowest was for purse seine gear at Kutaraja Fishing Port. Based on these FUI values, the estimated carbon footprint of tuna ranged from 0.06-1.72 kgCO_2eq/kg, with the highest value also found in the 30-50 GT longline gear at Nizam Zachman Fishing Port, and the lowest value found in the 20-30 GT purse seiners, which tend to produce a lower carbon footprint than passive gears such as longlines.

The results of comparisons between gear types, vessel GT sizes, and fishing port locations show no consistent pattern regarding fishing gear performance in terms of the FUI value and the resulting carbon footprint. Nevertheless, it can be confirmed that the FUI value is strongly influenced by fuel consumption and the amount of catch, while the tuna carbon footprint is mainly influenced by the FUI value and the composition of tuna caught by each gear.

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