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Effect of Exhaust Emissions Produced by Fishing Vessels on Air Pollution: A Case Study of Purse Seine Vessels Operating in the Black Sea

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Abstract

In this study, exhaust emissions originating from purse seine fishing vessels were calculated. A bottom-up method based on ship activities was used for emission calculations. Necessary information for the calculations was obtained from the BAGIS (Fishing Vessels Monitoring System) system. Eighteen purse seiners in the Black Sea region with a length of 20 m or more engaged in fishing activities in the 2017-2018 fishing season were used as samples. These vessels were categorized into three different groups according to their length. The emissions produced by each length group were calculated separately under different conditions for vessels identified as "port", "operation", and "navigation". The total emissions in the Black Sea region and Türkiye were estimated. This study provides emission estimates using operational conditions and real data from Turkish-flagged purse seiners engaged in fishing in the Black Sea. In this respect, this research presents novelty and addresses an important gap in the existing literature. The annual emission amount of purse seine fishing vessels in the Black Sea is 260,000 tons, while the annual emission amount from purse seine vessels throughout Türkiye has been calculated as 440,000 tons. As a result, the effectiveness of the Emission Control Area (ECA)/Sulphur ECA region implementation in reducing emissions from maritime activities has been demonstrated. In addition, this study constitutes a source for the exhaust emission inventory of purse seiners in the Black Sea region.

Keywords: Ship emissions, Fishing vessels, Black Sea, Air pollution, Automatic identification system

1. Introduction

It is now well known that emissions due to fossil fuels have adverse environmental effects on a global scale, such as global warming, acidification, and eutrophication. Since the fishing industry is highly dependent on fossil fuel use, it produces significant amounts of greenhouse gasses (GHG) and other atmospheric pollutants [1]. Although emissions produced by ships are considered effective only in the sea, these emissions can affect hundreds of kilometres inland from the sea due to wind and other factors. Therefore, emissions produced by ships significantly contribute to air pollution and pose health risks to coastal residents. It is known that 70% of ship-borne emissions occur within the 200 nautical miles area [2], and fishing vessels contribute to air pollution because of their intense operations in the coastal area [3]. While GHG emissions from all maritime activities were 977 million tonnes in 2012, they increased by 9.6% and reached 1.076 billion tonnes in 2018 [4]. According to estimations based on data in 2015 [5], CO_2 emissions from global shipping were calculated as 932 million tons. This amount was 2.6% of the total CO_2 emissions estimated to be 36.062 billion tonnes worldwide.

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Of the total emissions from all maritime activities, 87% (812 million tonnes) is from international shipping, 9% from cabotage (78 million tonnes) and 4% from fishing (42 million tonnes). A study based on data from the Sea Around Us initiative revealed that CO_2 emissions from fishing significantly exceed previously documented levels [6]. In addition to CO_2 emissions, policies and academic studies have intensified in recent years to reduce other types of emissions such as CO, NO_x, SO_x, particulate matter (PM), volatile organic compounds, and NH_3 [7]. In this respect, a more inclusive approach would be to consider all exhaust emission types from fishing vessels. To comply with increasingly stringent environmental regulations, exhaust emissions from fishing vessels need to be reduced. Responding to climate change by reducing waste and toxic substances released into the environment would be wise for the fishing industry. Otherwise, ensuring sustainable fishing and a clean environment will not be possible for new generations. As stated in The Food and Agriculture Organization State of World Fisheries and Aquaculture Report 2008, “Fishing and aquaculture activities make a small but significant contribution to GHG emissions during production processes and the transport, processing, and storage of fish” [8].

There are three approaches used to calculate the fuel consumption of ships and therefore the emissions they cause: The bottom-up method based on the ship, the bottom-up method based on ship activities, and the top-down method based on fuel statistics [9]. In the literature, they are also referred to as the “full bottom-up” method, the “bottom-up” method, and the “top-down” methods, respectively. The difference between the two bottom-up methods is the ship position and the time spent in different ship operations. There are differences in the data obtained using different calculation methods in determining the GHG emissions from ships. Carbon dioxide equivalent (CO_2e) is a standard unit that expresses the total GHG emissions from various sources in terms of the equivalent amount of CO_2 that would have the same global warming potential [10]. Annual GHG emissions (all GHG emissions in CO_2e, excluding black carbon-BC) from ships in 2017 were calculated as 704 million tonnes CO_2e according to the top-down method. Additionally, they were determined to be 760 million tons CO_2e according to the voyage-based bottom-up method and 946 million tons CO_2e according to the vessel-based bottom-up method [4]. There may be incomplete information, errors, or inconsistencies in the fuel statistics. Therefore, fuel-based methods can cause problems in achieving clear results in emission calculations. On the other hand, activity-based methods can estimate fuel consumption more consistently because they use many common inputs and assumptions [11]. The emissions produced by global fisheries are estimated to be much higher than previously reported due to differences in fuel use intensity, unreported catches, and insufficient data [6]. An activity-based calculation method is a practical approach that significantly eliminates the aforementioned negativities so that emissions from fishing vessels can be revealed more clearly.

The anchovy catch constitutes approximately 65% of the pelagic species living near the sea surface in Turkish territorial waters, with approximately 85% of the catch occurring in the Black Sea region [12]. Most of the fishing vessels engaged in anchovy fishing within the Black Sea region are purse seiners [13]. Additionally, these purse seiners operating in the Black Sea catch approximately 55.25% of the pelagic species residing near the sea surface within Turkish territorial waters. To evaluate the emission levels caused by pelagic fishing activities in Turkish territorial waters, it is essential to scrutinize the emission characteristics of purse seiners in the Black Sea. In this context, it is crucial to determine the volume of exhaust emissions originating from purse seine fishing in the Black Sea region.

This study determines the exhaust emissions produced by ships engaged in purse seine fishing in the Black Sea region. The bottom-up method based on ship activities introduced by Trozzi [14] was adopted for emission calculations. This method considers the ship’s technical characteristics, duration of different ship operations, fuel types, and emission types for the emission calculation. This approach is preferred because it allows for detailed data entry. The fact that all ship parameters are used with this method increases the sensitivity compared with other methods and provides a high level of accuracy in terms of emission estimations. The study will reveal exhaust emissions from ships engaged in purse seine fishing in the Black Sea region. The study’s estimates of exhaust emissions will be an important part of the puzzle necessary to determine the emissions from fishing activities worldwide. It will also be an important reference for estimating emissions from ships that are similar in size, main engine power, auxiliary engine power, and mode of operation.

2. Literature Review

In the literature, there are studies that reveal ships’ emissions by creating data sets with a remote monitoring system. Although many studies are widely conducted, it has been observed that studies focused on ships with high engine power and in port/strait areas where ship traffic is intense. When the literature is examined, a wide range of studies have been conducted on the calculation of emissions originating from ships, both regionally and internationally.

In particular, studies on the sensitivity of modelling focus on access to information and evaluation of ship data.

The Automatic Identification System (AIS) is a mandatory collision avoidance system on ships that allows ships to electronically share much information, including identity, position, speed, and course, with other ships and vessel traffic services stations [15,16]. Goldsworthy and Goldsworthy [17] calculated exhaust emissions separately for each ship according to the main engine, auxiliary engine, and boiler load factors based on AIS data for modelling exhaust emissions at ports and intense coastal navigation areas in Australia. They used Class-A AIS data because they believed that this approach would yield more accurate results in their studies. Class-A AIS contains much more detailed information and is installed on commercial vessels navigating international seas within the scope of SOLAS. Coello et al. [1] used the AIS-based method to calculate emissions from the British fishing fleet by limiting the operation between certain latitudes and longitudes. It is stated in the study that the methods in which ship movements are actively used will give more precise results. Nunes et al. [18] studied ship movements over two years to evaluate exhaust emissions from ships in four Portuguese ports and developed an AIS movement-based approach. Perez et al. [16] examined ship activities in Texas state waters based on the AIS system and estimated the ships' emissions by considering the ship traffic and the speed, condition of the ships (navigation, port and anchorage), and port arrival and departure times. Buber et al. [19] calculated the GHG emissions caused by domestic ship traffic in the Gulf of İzmir using the bottom-up method and examined these results by combining them with the geographic information system method. They found that the highest emission types in the region were CO_2, NO_x and SO_2, respectively. In addition, they reported that the highest emissions were during manoeuvres and that the emissions at the two piers where ships with more powerful machinery operated corresponded to more than half of the total emissions in the region. In terms of emission amounts per day, they stated that the highest emission was in the cruise condition.

In addition to estimating emissions, the importance of remote monitoring systems for fishing vessels in terms of sustainable fishing has been demonstrated by some studies. The ship remote monitoring system, established in Taiwan in 1990, has become a system in which 2,200 ships are under control after 20 years. The system has become an important data source for the control of illegal fishing, its contribution to the control of fish stocks on board and land, and scientific monitoring of fishing efforts [20]. Parker et al. [21] revealed that the global fishing vessel fleet grew by 28% between 1990 and 2011, resulting in approximately 179 million tons of CO_2 emissions in 2011. Dağtekin et al. [22] conducted an economic analysis of anchovy fishery in the Black Sea and stated that 0.17-0.59 tons of CO_2 emissions were emitted for each ton of fish caught. To prevent the increase in emissions produced by the fishing fleet, they made suggestions in their study, such as preventing excessive and unnecessary fishing, determining the fishing times, and arranging the distances of fishing activities from the coast. Winther et al. [23] created an emission inventory based on AIS data from ships in the Arctic. The study revealed that fishing vessels caused the highest emissions among other types of vessels in the Arctic, accounting for 45% BC, 38% NO_x, and 23% SO_2. Koričan et al. [3] conducted a comparison by analyzing the emission values of 163 purse seiners and 82 trawlers active in the Adriatic Sea. Emission calculations were performed using the bottom-up method. The study findings indicated that trawlers exhibit higher emission indices than purse seiners. This is primarily attributed to the relatively high energy demands and lower fish landing quantities associated with trawlers. However, the researchers noted that the disparity in emission indices between trawlers and purse seiners was relatively minor, especially when considering the income derived from fishing activities.

Different data sets can be used to calculate emissions from ships and to conduct impact analysis; Endresen et al. [24] used Automated Mutual-Assistance Vessel Rescue System data for the data set and Compherensive Ocean-Atmosphere Data Set data for calculating the effect. The use of an emission measuring device is one of the approaches that give the clearest results, but there are serious difficulties in their implementation. Liu et al. [25] used an emission measuring device system in their study and made instant gas measurements under different conditions, such as navigation, manoeuvring, and operation on offshore fishing vessels. As a result of the study, it has been determined that there are differences in terms of quantity in different types of exhaust emissions depending on the ship's activities. This method is very effective because it minimizes the assumptions. Winnes et al. [26] made an assessment by using the port of Gothenburg as an example of reducing GHG emissions from ships in ports. In the study, emission reduction measures were listed as "alternative fuel use", "changes in ship design" and "operation". It was stated that among the scenarios, the highest amount of emission reduction would occur in the "operation condition". In their extensive investigation, Xing et al. [27] investigated the strategies available for minimizing CO_2 emissions from ships. They categorized these strategies into technological measures, operational measures, eco-friendly fuels, and alternative power sources. The challenges in implementation were also highlighted, considering the impediments associated with adopting these measures. Based on their analysis, the researchers concluded that the diversification of ship power systems and marine fuels is an unavoidable necessity.

As a result of the literature review, although there are studies on the emission estimation of fishing vessels, no study has revealed the exhaust emissions produced by purse seiners in the Black Sea region. In this respect, the estimation of exhaust emissions produced by purse seine fishing vessels in the Black Sea region will fill an important knowledge gap. In addition, this study will contribute to the literature by comparing the emissions according to the size of the ships, as it reveals the exhaust emissions by considering the dimensions of the fishing ships. In this study, the activity-based bottom-up method, which considers the times in different ship activities (navigation, operation, port) and the technical characteristics of the ships, was applied by using BAGIS (Fishing Vessels Monitoring System) data. The BAGIS system is an AIS-like system developed for tracking the Turkish fishing fleet, which must be installed on vessels of 12 m and above in length. In this respect, detailed datasets obtained from the BAGIS devices of fishing vessels are a practical approach for estimating exhaust emissions to obtain clearer and more accurate results. This study differs from other studies in the literature with its mentioned aspects.

3. Methodology

3.1. Data Collection

This study aims to determine the exhaust emissions of Turkish fishing vessels with a length of 20 m or more engaged in purse seine fishing in the Black Sea region. In the study, as a sample, the data of 18 fishing boats engaged in purse seine fishing in the 2017-2018 fishing season (from 1 September 2017 to 15 April 2018) were examined. As a part of the research, the study analyzed data from 18 fishing vessels involved in purse seine fishing during the 2017-2018 fishing season (from September 1, 2017, to April 15, 2018). The data of 18 ships were evaluated in three categories. In this respect, they provide useful outputs for purse seiner exhaust emissions with similar characteristics. The number of purse seiners was limited due to the study's limitations and the detailed data that needed to be analyzed. Considering the data obtained, inferences were made about purse seiners in the Black Sea and Türkiye. Data showing the time spent by 18 purse seine fishing vessels under different operational conditions in the Black Sea region were obtained from the BAGIS system. BAGIS is a system that can only be accessed by engineers authorized by the Ministry of Agriculture and Forestry of the Republic of Türkiye and officials of the Coast Guard Command. The authorization to access certain data was obtained with the permission of the ministry officials. Information that can be accessed when querying ships in this system includes the ship's name, license number, mooring number, width, overall length, equipment ownership, fleet registration number, log length, vessel group, current ship speed, and position.

A typical representation of fishing vessels on the BAGIS system screen is presented in Figure 1. The meanings of icon colours are as follows (Figure 1): light green colour indicates fishing vessels with location information via GSM; dark green colour indicates fishing vessels with location information via satellite; blue colour indicates AIS track information received from the Ministry of Transport; red colour indicates fishing vessel violating a rule defined by the ministry, orange colour indicates the ship that needs to be introduced to the system because any information is missing [28]. Using Microsoft Excel, a raw data set was structured. The data taken from the BAGIS system were used to form the raw data. While using the speed data in the raw dataset, the study of Campbell et al. [29] is taken as a reference. In addition, the opinions of the captains of the fishing vessels examined in this study were considered. Thus, a ship is assumed to be stopped at a speed range of 0-1 knots (confirmed to be in port condition by mapping), manoeuvring or operating at a speed range of 1-6 knots, and navigating at speeds of 6 knots and above. The purse seine fishing vessels considered in the study were classified into three different size groups: length group A represents 20-30 m range; length group B represents 30-40 m range; and length group C, 40 m and above. The numbers of main and auxiliary engines of purse seine fishing vessels examined in this study differ. Hence, in the computation of both main engine and auxiliary engine powers, the cumulative main engine power in vessels equipped with multiple main engines and the cumulative auxiliary engine power in vessels featuring more than one auxiliary engine were considered.

Figure 1. The display of fishing vessels on the BAGIS system [28]

3.2. Stages of the Study

First, a literature review was conducted to reveal the exhaust emissions produced by purse seine fishing vessels in the Black Sea region. As a result of the literature review, the most appropriate method is to use the activity-based bottom-up method for the most precise calculation of emissions. Ship navigation information and technical data of 18 purse seine fishing vessels of groups A, B, and C in the study were obtained from the BAGIS system. A dataset was created in Excel for easier analysis of the data. This dataset contains the following information: ship length, main engine power, auxiliary engine power, total operating time (days), total stay in port (hours), total operation/manoeuvre time (hours), total navigation time (hours), average navigation speed (knots), total distance navigated (Nm), and type of ship activity (port, operation, navigation). In the next step, numerical values of NO_x, SO_x, CO_2, hydrocarbons (HC), and PM emissions from the vessels were calculated using the bottom-up method. Then, emission estimates of purse seiners in the Black Sea and Türkiye were made according to the emissions calculated for the sample ships. In the last stage of the study, the emissions from purse seine fishing vessels were compared with those reported in the literature, and recommendations were made to reduce

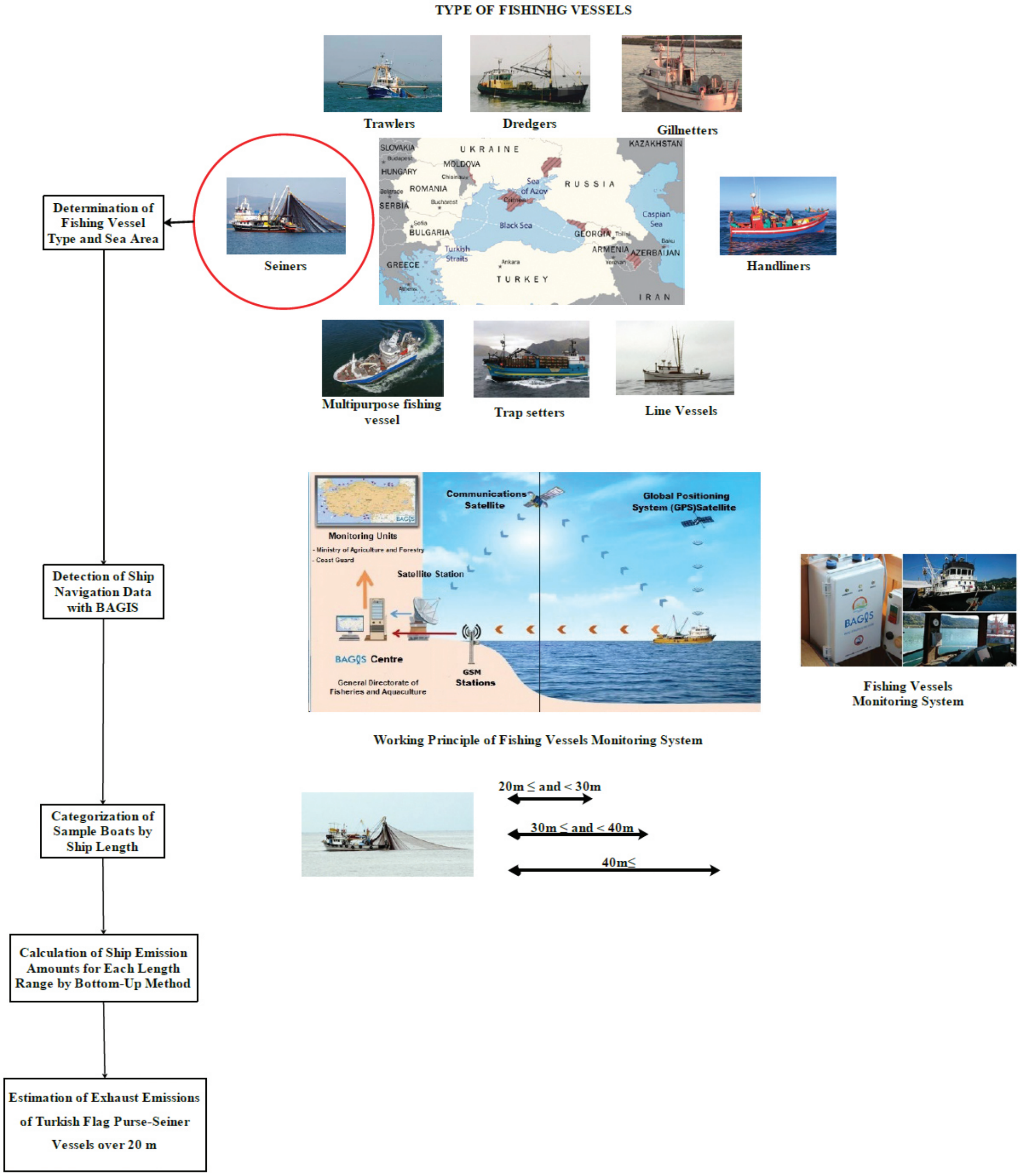

Figure 2. *Flow chart of the research*

emissions and create awareness. The research flowchart is shown in Figure 2.

3.3. Research Method

In this study, the approach introduced by Trozzi [14] within the framework of the EMEP/EEA air pollution emission inventory guidebook was used within the scope of the bottom-up method. In the literature, there have been many studies using the approach presented in Trozzi's [14] study [30,31]. The bottom-up method derives emission estimates using data sources that describe maritime activities; these data are AIS data, including a ship's identity, position, speed, draft, and other information [32]. AIS data serves as an essential input to enhance bottom-up inventory, offering the potential for positive outcomes in research through this approach. Instead of AIS data, this study utilized BAGIS data, which, similar to AIS, encompasses navigational details such as ship identity, location, time, speed, and route. To apply the "full bottom-up" method based on ship activities, data such as main engine power, auxiliary engine power, speed, position, and type of ship activity should be considered. Using a ship's full parameters in this method increases its sensitivity compared with other methods. The formulation is expressed as:

$$E_{trip,i,j,m} = \sum_{p}[T_{P} \times \sum(P_{e} \times LF_{e} \times EF_{e,i,j,m,p})] \quad (1)$$

EF: Emission factor (g/kWh)

LF: Load Factor

P: Power according to engine type (kW)

T: Time (hours)

p: Different phases of the trip (navigation, port, operation)

j: Engine type (low speed, medium speed, high speed)

i: Emission type (NO_x, SO_x, etc.)

m: Fuel type (MDO-Marine Diesel Oil, HFO-Heavy Fuel Oil)

trip: The navigation, manoeuvre, or port condition the ship is in

$E_{trip,i,j,m}$: Sum of emissions under all conditions

e: Engine type (main, auxiliary)

In this study, while calculating the main engine and auxiliary engine emission factors, the EMEP/EEA 2016 air pollution inventory was used as a reference, and similar studies were used [14,32]. Emission factors in this study are those used for vessels with high-speed diesel engines. All the emission factors used are shown in Table 1. The uncertainty ratios in the emission factors used can be calculated as ±20% for NO_x, ±20% for SO_x, and ±10% for PM ±25% [33].

Diesel engines can be classified as slow, medium, or fast, depending on their rated speed. Low-speed diesel engines have engines with a maximum operating speed of 0-300 rpm. Medium-speed diesel engines have a maximum operating speed in the 300-900 rpm range. High-speed diesel engines have an operating speed of 900 rpm and above. Approximately 18% of existing engines are slow, 55% are medium, and 27% are fast diesel engines [33]. All ships in this study have high-speed diesel engines. Load factors are 0.8% for "navigation condition" for main engines, 0.2% for "port conditions", and 0.2% for "operation conditions". For auxiliary engines, it is 0.3%, 0.4%, and 0.5% for navigation, port, and operational conditions, respectively [33]. The emission factors in Table 1 and daily ship movement data from BAGIS were transferred to a Microsoft Excel table, and daily NO_x, SO_x, CO_2, HC, and PM emissions were calculated according to the ship's operation, port, and navigation conditions.

Table 1. *Main engine and auxiliary engine emission factors [33]*

Main engine (g/kWh)					
Emission factor	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**
Navigation	11.20	1.00	697	0.45	0.30
Port	9.30	1.00	725	0.50	0.90
Operation	9.30	1.00	747	0.97	0.90
Auxiliary engine (g/kWh)					
Emission factor	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**
Navigation	13.20	1.00	697	0.46	0.30
Port	13.20	1.00	725	0.50	0.30
Operation	11.80	1.00	747	0.97	0.30

4. Results

Trozzi [14] stated that to calculate the emissions produced by ships in detail, the voyage of a ship should be evaluated separately as navigation, port, and manoeuvre. In the study, it was emphasized that the most sensitive method for calculating emissions would be the sum of the emissions under these three conditions. In this study, the emission factor values in the manoeuvre condition stated by [14] were assumed to be equivalent to the values in the "operation conditions" of the vessels. The information on each purse seine fishing vessel's technical characteristics and activities used in the emission calculation is given in Table 2.

The average "port", "operation", and "navigation" times of the ships within the scope of the study were 2,839, 566.8, and 854 h in group A, respectively; 2,097.5, 531.3, and 890.5 h in group B; and 1,429.8, 539, and 706.5 h in group C. The ships with the longest average operating time were group ships with a rate of 40.76% (Table 2).

The average "main engine" powers of the ships in groups A, B, and C were calculated as 825.2, 1,077.6, and 1,675 kW, respectively. The average "auxiliary engine" powers were 109.4, 142.0, and 201.7 kW, respectively. In terms of total

Table 2. *Information on technical specifications and activities of each purse seine fishing vessel*

Vessel	Length (m)	Main engine (kW)	Auxiliary engine (kW)	Duration of all conditions (Day)	Duration of port (Hour)	Duration of operation (Hour)	Duration of navigation (Hour)	Average ship speed (Knot)	Total distance (Nm)
A1	27.9	797.8	126.8	220	3,370	754	1,162	7.38	8,571.9
A2	24.5	850	102.1	130	2,056	488	571	7.27	4,149.3
A3	26.5	708.3	104.4	170	2,951	459	668	10.52	7,027.1
A4	22	895	90	197	3,110	612	1,006	7.50	7,549.2
A5	27	1,137	136	163	2,544	578	790	8.15	6,440.1
A6	29.8	563	97	185	3,003	510	927	7.99	7,406.8
B1	39	1,744.7	79.8	102	1,274	436	743	8.07	5,996.8
B2	33	1171	120	202	2,839	844	1,180	7.25	8,555.5
B3	31.44	1,159.4	119.3	108	1,988	260	344	7.55	2,596.3
B4	33.8	768	134	175	2,744	665	791	7.50	5,935.8
B5	36.3	862	101	138	1,976	411	925	7.40	6,841.5
B6	38	760	298	154	1,764	572	1,360	7.77	10,572.8
C1	44	1,823	160.3	186	2,800	621	1,048	7.91	8,288.7
C2	40	1,749.2	203.5	99	1,035	511	828	7.70	6,374.4
C3	42	1,647.8	223.7	102	1,164	526	751	8.59	6,454.6
C4	42.2	1,897	224	97	1,210	534	584	7.88	4,603.1
C5	42.7	1,315	149	92	1,175	496	537	8.15	4,377.6
C6	42	1,618	249.8	93	1,195	546	491	7.77	3,817.1

engine power (main engine + auxiliary engine), group C ships constituted 46.56% of the total engine power in the study. This rate is approximately twice that of group A ships (23.19%) (Table 2).

Using Equation 1, the total emissions for each ship were calculated (Table 3). The total emissions from the 18 vessels in the study were 22,447.55 tonnes. Ship groups making an enormous contribution to the total emissions were listed as group C (38.86%) > group B (32.08%) > group A (29.06%) (Table 3).

The purse seine fishing vessels in group C made the largest contribution to total emissions in all emission categories. The purse seine fishing vessels in group C accounted for 40.26% of total NO_x emissions, 38.84% of SO_x emissions, 38.84% of CO_2 emissions, 39.84% of HC emissions, and 37.76% of PM emissions. While the purse seine fishing vessels in group B were in second place in terms of contribution to total emissions, their contribution rates were between 31.54% and 32.09%. These rates were between 28.14% and 30.70% for the purse seine fishing vessels in group A that made the least contribution to the total emissions (Table 3). The vessels included in the study were in the "port condition" for 60.90% of the entire operating time (Table 2).

Table 3. *Total emissions of each purse seine fishing vessel (Tonnes)*

Vessel	NO_x	SO_x	CO_2	HC	PM
A1	16.53	1.94	1,376.53	1.08	0.58
A2	10.22	1.33	945.38	0.74	0.40
A3	11.26	1.51	1,068.71	0.82	0.45
A4	16.71	1.57	1,123.22	0.81	0.85
A5	17.73	1.67	1,189.48	0.87	0.93
A6	10.86	1.01	718.06	0.52	0.54
B1	18.23	1.89	1,349.25	1.08	0.57
B2	23.53	2.73	1,925.81	1.55	0.82
B3	10.30	1.54	1,095.57	0.83	0.46
B4	13.58	1.26	956.94	0.67	0.69
B5	12.85	1.19	796.53	0.61	0.61
B6	15.10	1.35	965.34	0.65	0.70
C1	32.82	3.89	2,771.73	2.16	1.17
C2	20.56	1.89	1,344.03	1.12	0.57
C3	19.21	1.91	1,353.66	1.12	0.57
C4	18.95	1.77	1,263.34	0.96	0.93
C5	12.24	1.15	817.73	0.62	0.60
C6	15.46	1.44	1,029.89	0.80	0.77
Sum	296.13	31.03	22,091.19	16.99	12.20

***Table 4.** Emissions of each purse seine fishing vessel according to different conditions (Tonnes)*

Vessel	Condition	NO_x	SO_x	CO_2	HC	PM
A1	Port	6.98	1.39	984.33	0.70	0.42
	Operation	1.43	0.25	189.51	0.25	0.08
	Navigation	8.12	0.29	202.70	0.14	0.09
A2	Port	4.64	0.98	696.25	0.49	0.29
	Operation	1.01	0.19	138.83	0.18	0.06
	Navigation	4.58	0.16	110.30	0.08	0.05
A3	Port	5.92	1.20	849.76	0.60	0.36
	Operation	0.83	0.15	111.46	0.15	0.05
	Navigation	4.51	0.16	107.49	0.08	0.05
A4	Port	7.01	0.70	504.34	0.35	0.54
	Operation	1.28	0.13	98.17	0.13	0.11
	Navigation	8.42	0.75	520.71	0.34	0.20
A5	Port	7.66	0.75	544.57	0.38	0.57
	Operation	1.59	0.16	121.62	0.16	0.13
	Navigation	8.47	0.75	523.29	0.34	0.23
A6	Port	5.07	0.48	350.63	0.24	0.35
	Operation	0.77	0.08	57.66	0.08	0.06
	Navigation	5.03	0.44	309.76	0.20	0.13
B1	Port	4.81	1.16	836.12	0.58	0.35
	Operation	1.58	0.32	237.69	0.31	0.10
	Navigation	11.85	0.41	275.44	0.19	0.12
B2	Port	8.43	1.83	1,297.80	0.92	0.55
	Operation	2.29	0.44	319.79	0.42	0.13
	Navigation	12.81	0.46	308.23	0.21	0.14
B3	Port	5.85	1.27	906.39	0.64	0.38
	Operation	0.71	0.13	99.34	0.13	0.04
	Navigation	3.74	0.13	89.84	0.06	0.04
B4	Port	6.35	0.61	493.06	0.30	0.44
	Operation	1.37	0.14	102.97	0.13	0.10
	Navigation	5.86	0.52	360.92	0.23	0.16
B5	Port	4.49	0.44	319.33	0.22	0.34
	Operation	0.86	0.09	13.06	0.09	0.07
	Navigation	7.51	0.67	464.14	0.30	0.20
B6	Port	5.97	0.53	385.23	0.27	0.32
	Operation	1.61	0.16	115.96	0.09	0.10
	Navigation	7.51	0.67	464.14	0.30	0.29
C1	Port	12.46	2.78	1,984.45	1.39	0.83
	Operation	2.58	0.49	368.01	0.48	0.15
	Navigation	17.78	0.62	419.27	0.29	0.19
C2	Port	4.76	1.01	719.22	0.51	0.30
	Operation	2.15	0.40	298.16	0.39	0.12
	Navigation	13.64	0.49	326.65	0.22	0.15
C3	Port	5.29	1.09	773.08	0.55	0.33
	Operation	2.17	0.39	294.13	0.38	0.12
	Navigation	11.75	0.42	286.45	0.19	0.13
C4	Port	6.06	0.60	431.04	0.30	0.45
	Operation	2.45	0.25	187.08	0.24	0.20
	Navigation	10.45	0.93	645.23	0.42	0.28
C5	Port	4.03	0.40	287.60	0.20	0.30
	Operation	1.56	0.16	119.56	0.16	0.13
	Navigation	6.65	0.59	410.57	0.27	0.18
C6	Port	5.57	0.54	388.55	0.27	0.39
	Operation	2.29	0.23	172.73	0.22	0.18
	Navigation	7.60	0.67	468.61	0.30	0.20
Sum		296.13	31.03	22,091.19	16.99	12.20

Accordingly, among the total emissions, the emission rate in the “port condition” was 57.45%, while the emission rate in the “navigation condition” was 28.81%, and the emission rate in the “operation condition” was 13.74% (Table 4).

In the “port condition”, the purse seine fishing vessels in group C made the greatest contribution to the total emissions with 35.93%, while the vessels in group B contributed 33.22% and the vessels in group A 30.84%. In the “operation condition”, the contribution of the vessels in group C to total emissions was 47.26%, whereas the contribution of the vessels in group B was 29.19% and in group A was 23.56%. In the “navigation condition”, the contribution rate of the vessels in group C to the total emissions was 40.69%, while the vessels in group B contributed 31.19% and the vessels in group A 28.11%. While the difference between the emission contribution rates of the groups is 5.09% (the difference between group C and group A) in the case of the port, this difference increases to 23.70% in the “operation condition” (Table 4). Because the total time spent by purse seine fishing vessels in each condition differed, the emissions per unit time were calculated to make a more consistent comparison. The emissions per unit time of each purse seine fishing vessel under different conditions are given in Table 5.

In the “port condition”, the emissions of the purse seine fishing vessels in group C per unit time varied between 2.01 times and 2.12 times more than the emissions produced by the purse seine fishing vessels in group A. While these ratios were similar in the “operation condition” (between 2.00 and 2.09), they decreased between 1.96 and 2.05 in the “navigation condition”. In all emission categories except HC, the highest emissions per hour were observed in the “navigation condition”. In the HC category, the highest emissions per hour occurred in the “operation condition”. This result was expected because HC has a higher emission factor (approximately two times) in the “operation condition” than in the other conditions (Table 1).

In Table 3, the total emissions produced by each vessel according to emission types were presented. The total emissions produced by the 18 vessels that constituted the sample are as follows: 296.13 tons of NO_x, 31.03 tons of SO_x, 22,091.19 tons of CO_2, 16.99 tons of HC, and 12.20 tonnes of PM. In the study, 18 purse seine fishing vessels were examined as a sample that were allowed to catch in the 2017/2018 fishing season. The 18 purse seine fishing vessels examined as a sample in the study constituted approximately 13% of the 139 active purse seine fishing vessels with a length of 20 m and above in the Black Sea in the 2017/2018 fishing season. In the 2020/2021 fishing season (from 1 September 2020 to 15 April 2021), this rate was approximately 9% of 209 purse seine fishing vessels with a

Table 5. *Emissions of each purse seine fishing vessel under different conditions per hour (10^{-3} tons)*

	Port					Operation					Navigation				
Vessel	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**
A1	2.07	0.41	292.08	0.21	0.12	1.89	0.34	251.34	0.33	0.10	6.99	0.25	174.44	0.12	0.08
A2	2.26	0.48	338.64	0.24	0.14	2.06	0.38	284.50	0.37	0.11	8.02	0.29	193.16	0.13	0.09
A3	2.01	0.41	287.96	0.20	0.12	1.81	0.32	242.84	0.32	0.10	6.75	0.24	160.91	0.11	0.07
A4	2.25	0.22	162.17	0.11	0.17	2.09	0.21	160.41	0.21	0.17	8.37	0.74	517.60	0.33	0.20
A5	3.01	0.30	214.06	0.15	0.22	2.76	0.28	210.42	0.27	0.22	10.73	0.95	662.39	0.43	0.28
A6	1.69	0.16	116.76	0.08	0.12	1.50	0.15	113.06	0.15	0.11	5.43	0.48	334.16	0.22	0.14
B1	3.77	0.91	656.29	0.46	0.27	3.62	0.73	545.16	0.71	0.22	15.95	0.55	370.72	0.25	0.16
B2	2.97	0.65	457.13	0.32	0.19	2.71	0.52	378.89	0.50	0.16	10.86	0.39	261.21	0.18	0.12
B3	2.94	0.64	455.93	0.32	0.19	2.72	0.51	382.08	0.50	0.15	10.86	0.38	261.16	0.18	0.12
B4	2.31	0.22	179.69	0.11	0.16	2.06	0.21	154.84	0.20	0.15	7.41	0.65	456.28	0.29	0.20
B5	2.27	0.22	161.60	0.11	0.17	2.08	0.21	31.78	0.21	0.17	8.12	0.72	501.77	0.32	0.22
B6	3.38	0.30	218.39	0.15	0.18	2.82	0.27	202.73	0.15	0.17	5.53	0.49	341.28	0.22	0.21
C1	4.45	0.99	708.73	0.50	0.30	4.15	0.79	592.61	0.77	0.24	16.97	0.60	400.07	0.27	0.18
C2	4.60	0.98	694.90	0.49	0.29	4.21	0.78	583.48	0.76	0.23	16.48	0.59	394.51	0.27	0.18
C3	4.54	0.94	664.15	0.47	0.28	4.12	0.75	559.19	0.73	0.22	15.65	0.56	381.42	0.26	0.17
C4	5.01	0.49	356.23	0.25	0.38	4.59	0.47	350.33	0.46	0.37	17.89	1.59	1104.85	0.71	0.48
C5	3.43	0.34	244.77	0.17	0.26	3.15	0.32	241.05	0.31	0.25	12.37	1.10	764.56	0.49	0.33
C6	4.66	0.45	325.15	0.22	0.33	4.19	0.42	316.36	0.41	0.32	15.49	1.37	954.40	0.62	0.41

length of 20 m and above in the Black Sea [34]. Considering these data, a proportional estimation of the total emissions produced by purse seine fishing vessels in the Black Sea region and Türkiye in the 2020/2021 fishing season has been made. The purse seine fishing vessels of the 2020/2021 fishing season were classified into size groups in a similar way as in the study (groups A, B and C), and the emissions were calculated for each size group. In Table 6, the average emissions of 18 purse seine fishing vessels are given for each size group. In studies where access to the main dataset is not possible or data processing is extremely challenging due to the dataset's size, emission predictions can be made by relying on a sample group with similar ship characteristics and operational features. There are studies in the literature that have been conducted using this method. In their study, Koričan et al. [3] established a validation group consisting of 12 vessels, including 10 purse seiners and 2 trawlers, to assess the emissions caused by the Croatian fishing fleet, which comprises 163 purse seiners and 82 trawlers.

5. Discussion

This study investigated exhaust emissions produced by purse seine fishing vessels operating in the Black Sea. The "bottom-up" method, which is frequently used in the literature and has a higher consistency than other methods, was used for emission calculations. Contrary to the study of Demirci and Karagüzel [35], which concluded that the highest emissions occurred in the "operation condition", in this study, it was determined that the largest share of the contribution to the total emission occurred in the "port condition". The most important factor leading to this result is the long stay of the ships in the port. Ay et al. [36] also included the "auxiliary engine/main engine power" ratios per ship for different ship types in their study. This rate was found to be higher in fishing vessels than in other ship types. The ships in the study were "in port condition" for an average of 60% of the examination duration (Table 2). The primary source of emissions in the port is the boilers and auxiliary engines operating to meet the electricity needs. The inadequacy of infrastructure to meet the electricity needs of ships at fishing ports in Türkiye is one of the main causes of emissions in the port. Such vessels in group A were in port for 66.65% of the entire working time, the vessels in group B for an average of 59.60%, and the vessels in group C for 53.45% (Table 2). The largest emissions were observed "in port condition", similar to the results of Song and Shon [37]. Nunes et al. [18] estimated that CO_2, NO_x, and SO_x emissions represent more than 95% of navigation and in-port emissions.

It was observed that the total emissions of the vessels in group C were higher than those in groups A and B in all emission categories in port, operation, and navigation conditions. Therefore, the high emissions produced by the vessels in group C, which have the lowest total working

Table 6. *Average emissions for each size group and estimated emissions in the Black Sea and Türkiye (Tonnes)*

Sample purse seiners							
	Size definition	**Num.**	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**
Group A	20 m≤ and <30 m	6	13.89	1.50	1,070.23	0.81	0.62
Group B	30 m≤ and <40 m	6	15.60	1.66	1,181.57	0.90	0.64
Group C	40 m≤	6	19.87	2.01	1,430.06	1.13	0.77
Sum		18	296.13	31.03	22,091.19	16.99	12.20
Purse seiners in the Black Sea							
	Size definition	**Num.**	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**
Group A in the Black Sea	20 m≤ and <30 m	51	839.05	87.92	62,591.71	48.14	34.57
Group B in the Black Sea	30 m≤ and <40 m	91	1,497.12	156.87	111,683.25	85.89	61.68
Group C in the Black Sea	40 m≤	67	1,102.28	115.50	82,228.33	63.24	45.41
Sum in the Black Sea		209	3,438.44	360.29	256,503.30	197.27	141.67
Purse seiners in Türkiye							
	Size Definition	**Num.**	**NO_x**	**SO_x**	**CO_2**	**HC**	**PM**
Group A in Türkiye	20 m≤ and <30 m	107	1,760.35	184.46	131,319.87	101.00	72.53
Group B in Türkiye	30 m≤ and <40 m	153	2,517.14	263.76	187,775.14	144.42	103.71
Group C in Türkiye	40 m≤	92	1,513.57	158.60	112,910.54	86.84	62.36
Sum in Türkiye		352	5,791.06	606.81	432,005.55	332.25	238.60

time (25.60%), can be attributed to their high engine power. This result confirms the conclusion of previous studies that "increasing engine power also increases the emissions" [18,38,39]. In this respect, the main engine power and ship size are among the most important parameters in terms of the amount of emissions from fishing vessels. Some studies in the literature reveal the relationship between the size and tonnage of a ship and its fuel consumption [38].

In this study, the total emissions in the "navigation condition" were higher than those in the "operation condition" for all emission types. This result is in contrast to the study of Liu et al. [25], which made instant emission measurements on fishing vessels with the help of an emission measuring device. The difference between the operation and navigation times of the purse seine vessels in this study may be the main reason for the difference between the studies. Indeed, the total operating time of the ships in this study was 9,823 h, while the total navigation time was 14,706 h. In other words, the navigation time was approximately 50% more than the operation time. As a requirement of purse seine fishing, navigation time is higher than operation time to reach the fishing area and detect shoals. In this respect, reductions in exhaust gas emission values will be possible with technological developments in detecting shoals and some methods that purse seiners will spend less time for navigation. Another study on emissions contributed to marine fishing in China revealed that GHG emissions, which were 16,479 million tons in 2001, increased to 18,601 million tons in 2020, and a significant portion of these GHG emissions is attributed to trawl and purse seine fishing operations [40].

To prevent air pollution produced by ships and take the necessary precautions, the sources causing the pollution should be determined correctly. In the long term, the effect of seemingly small increases in emissions per unit time on general air pollution is quite large. Therefore, the emissions per unit time are important data that can be used for this purpose. In the study, it was concluded that although more than half of the total emissions occurred in the "port condition", the emissions per unit time occurred most in the "navigation condition". Thus, it has been revealed that not only the total emissions but also the emissions per unit time increase with increasing engine power. This result is valuable because it highlights the importance of calculating emissions per unit time.

CO_2 emissions from fishing vessels in 2016 were approximately 207 million tons [6]. In addition, the International Maritime Organization (IMO) 2014 GHG Study stated that 22 million tons of CO_2 were produced globally in 2012 by 22,130 fishing vessels of 100 GT or more. As a result of the estimation made in this study, CO_2 emissions from purse seine fishing vessels in Türkiye were calculated as approximately 432 thousand tons. This accounts for 0.21% of total global CO_2 emissions and 1.96% of IMO's CO_2 emissions from fishing vessels. According to the IMO data, CO_2 emissions per fishing vessel were 994.13 tonnes, while in this study, CO_2 emission per vessel was calculated as 1227.29 tons. This value is 23.45% higher than the IMO average. While this value is observed to be above the IMO average, when compared to the study conducted by Chassot et al. [41] on purse seine, it appears to be significantly lower than their calculated CO_2 emissions per ship (2077 tonnes).

The estimated emissions for Türkiye were compared with the results of studies in different countries [1,16]. Accordingly, the estimated annual NO_x, SO_x, and CO_2 emissions in Türkiye are 24.05, 57.79, and 25.77 times higher than the annual NO_x, SO_x, and CO_2 emissions of purse seiners in the UK, respectively. Additionally, they are 61.22 and 39.15 times higher than the annual NO_x and SO_x emissions of fishing vessels in the Texas area. One of the main reasons for the large emission difference between Türkiye and the other two countries is that the UK and US waters are largely in the Emission Control Area (ECA) / Sulphur Emission Control Area (SECA) region. This result shows the effectiveness of the ECA/SECA region implementation in reducing air pollution. The expansion of ECA and SECA regions around the world, especially in closed basins with heavy maritime traffic such as the Mediterranean and the Black Sea, can be one of the most effective steps toward reducing global air pollution.

6. Conclusion

Combating air pollution is a serious issue that countries cannot cope with alone and that all countries must deal with in a joint effort. This cooperation becomes even more important when considering emissions from a global industry such as shipping. Therefore, in this study, emissions originating from purse seine fishing vessels in the Black Sea region, which constitute 1.96% of the world's fishing vessel fleet of 100 GT and above, were calculated [32]. As a result of this study, it has been determined that purse seiners in the Black Sea region produce more than 260,000 tons of exhaust emissions per year. This represents approximately 60% of the annual emissions produced by purse seiners only in Türkiye. Considering the fishing activities in the other Black Sea countries, such emissions will be much higher.

To keep exhaust emissions originating from fishing vessels in the Black Sea under regular control, it is essential for riparian countries to work together. For this purpose, the scope of the BAGIS system used in this study can be expanded, and a joint instant monitoring and coordination center can be established with other Black Sea countries.

Because unregistered fishing activities cannot be included in the studies, there is no doubt that the actual emissions are higher than the calculated. Technological developments that will enable instant monitoring of all seas and ships to prevent uncontrolled emissions will be an important step in global emission control.

Approximately 60% of the motorized fishing fleet of 20 m and above in Türkiye are purse seine fishing vessels examined in this study [42]. Similar to this study, studies to be conducted for specific types of fishing vessels and determination of the main emission sources in each type of vessel can serve as a reference for taking precautions specific to vessel types. In addition, studies on new fishing techniques or ship designs that will lead to minimum emissions while providing maximum catch in global fishing activities can also help reduce air pollution from fishing.

The "bottom-up" method used in this study is very useful in emission estimation because it can process data from the AIS system. The use of AIS data in emission calculations allows local determination of emissions. Thus, it can be determined where to focus for emission control. However, the lack of data from AIS devices revealed that AIS devices used on fishing vessels should also be developed and standardized. In addition, the correct processing of the ship's operational status depends on whether the crew on the ship has set the "ship status" setting. For this reason, training the personnel working on the fishing vessels on this subject is also extremely important.

In this study, the estimated emissions produced by purse seiners across Türkiye were calculated as approximately 440,000 tons. The fact that such emissions are quite high compared to the countries in the ECA/SECA region is one of the most important results of the study. As in this study, a comparison of the exhaust emissions produced in the special areas declared as ECA/SECA regions and the other areas can provide a basis for evaluating the effectiveness of the special area implementation.

In terms of future studies; conducting research that encompasses the entire Black Sea region to reveal the emissions caused by purse seiners would be beneficial. Studies can be conducted to estimate emissions based on the working conditions and real data of other types of fishing vessels besides purse seiners, such as trawlers. Comparisons can be made between emissions caused by different types of fishing activities; emissions from surface fishing and deep-sea fishing can be compared. Thus, emission values caused by fishing activities based on different fish species can be evaluated.

Differences in emission levels among fishing vessels are believed to stem primarily from variations in engine power. Therefore, developing a global monitoring system integrated into fishing vessels could enable real-time and simultaneous tracking of GHG emissions from fishing vessels worldwide. This system could serve as an effective resource when determining measures to achieve the IMO's zero-emission goals. By providing real-time monitoring and assessment of emissions from vessels, it can assist in understanding variations among fishing vessels of different sizes. Such a monitoring system can contribute to supporting sustainability efforts in the maritime industry by facilitating the development of more specific strategies, considering various types of vessels and their engine powers, in pursuit of the IMO's zero-emission goals.

In this study, ship size is equated with ship length. On the other hand, ships intended for deep-sea fishing may prioritize stability and seaworthiness, while fishing ships operating in shallow waters may prioritize manoeuvrability. In this context, future studies may consider characteristics that affect the design and manoeuvrability of ships, such as the ship's beam, ship's length/beam ratio, and total sea surface area, in addition to the ship's length. Thus, optimum ship design ideas that will contribute to reducing GHG emissions can be proposed.

Authorship Contributions

Concept design: E. Özkaya, and Ö. Uğurlu, Data Collection or Processing: E. Özkaya, and Ö. Uğurlu, Analysis or Interpretation: E. Özkaya, Literature Review: E. Özkaya, and A. Y. Kaya, Writing, Reviewing and Editing: E. Özkaya, A. Y. Kaya, F. Tonoğlu, Ö. Uğurlu, and J. Wang.

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