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Assessment of the Carbon Footprint of Large Yellow Croaker Farming on the Aquaculture Vessel in Deep Sea in China

Fei Fan, Jianli Zheng, Huang Liu * and Mingchao Cui

Fishery Machinery and Instrument Research Institute, Chinese Academy of Fishery Sciences, Shanghai 200092, China; fanfei@fmiri.ac.cn (F.F.); zhengjianli@fmiri.ac.cn (J.Z.); cuimingchao@fmiri.ac.cn (M.C.)
* Correspondence: liuhuang@fmiri.ac.cn

Abstract: The present study conducted a Life Cycle Assessment (LCA) to evaluate the carbon emissions associated with large yellow croaker farming on Aquaculture Vessel "Conson No. 1". The functional unit considered was 1 kg of fresh large yellow croakers delivered to a wholesaler. The life cycle of large yellow croaker farming on the aquaculture vessel was divided into five processes: feed production (FP), ship construction (SC), fingerling breeding (FB), adult fish farming (AF), and fish distribution (FD). Results showed that the carbon footprint (CF, kgCO_2e/kg LW) for the complete life cycle amounted to 6.2170 kgCO_2e/kg LW, while the CF per unit economic value of "Conson No. 1" large yellow croaker was estimated at 31 gCO_2e/CNY. Among all processes, AF and FP had the highest CF contribution rates at 69.30% and 24.86%, respectively. Notably, energy consumption by aquaculture equipment on board emerged as the primary contributor across all sources of CF comparative analysis demonstrated that the CF of marine fish farming on the aquaculture vessel was lower than that of closed aquaculture systems' average level and it was a viable option for implementing low-carbon aquaculture in the deep sea. In order to reduce energy consumption and promote a low-carbon economy in aquaculture vessels, several suggestions were proposed, including adjusting energy structure, enhancing energy efficiency, improving feed ratio, and optimizing feeding methods.

Keywords: large yellow croaker; aquaculture vessel; carbon footprint; LCA (life cycle assessment); carbon emission

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1. Introduction

Currently, there is a growing global focus on environmental and climate issues. The low-carbon economy, characterized by reduced energy consumption, minimal pollution, and decreased emissions, has emerged as the strategic choice of governments in addressing the prevailing climate change [1,2]. Given the rapid surge in national seafood demand, numerous researchers have shifted their focus towards the identification and assessment of carbon emissions within aquaculture, a topic of paramount importance [3]. Ayer et al. [4] employed the life cycle assessment (LCA) methodology to evaluate the potential environmental impact of salmon (*Salmo salar*) production under various farming modes, including net cages, marine floating bags, land-based closed flow-through systems, and recirculating systems. Chen Zhongxiang et al. [5] assessed and compared the global warming potential, energy consumption, acidification potential, and eutrophication potential associated with rainbow trout (*Oncorhynchus mykiss*) farming in net cages, land-based industrial recirculating systems, and land-based industrial flow-through systems. Samual-ftiwi et al. [6] conducted a comparative study on the environmental impact of rainbow trout (*Oncorhynchus mykiss*) farming in net cages, land-based industrial recirculating systems, and land-based industrial flow-through systems. Liu et al. [7] compared and analyzed the economic benefits and carbon footprint of Atlantic salmon (*Salmo salar*) farming in land-based closed recirculating systems and open net pens. Fu Xiaoyang et al. [8,9], from the perspective of aquaculture facility construction, calculated LCA carbon footprints for large yellow croaker aquaculture in traditional net cages as well as deep-sea net cages. Johansen et al. [10] assessed carbon footprints for supply chains involved in salmon aquaculture using a net cage system located in Norway. Robbet et al. [11] assessed the GHG (greenhouse gas) emissions of Bangladesh nile tilapia (*Oreochromis niloticus*), Indian carp (*Catla catla*, *Cirrhinus sus*, *Labeo calbasu*, *Labeo rohita*), and Vietnamese striped catfish (*Pangasianodon hypophthalmus*) in three different pond farming modes. Dong Yin et al. [12] evaluated and compared the energy consumption, global warming potential, acidification potential, eutrophication potential, and water resource consumption of an integrated fish farm model combining ponds and rice fields in the Yangtze River basin. Philis et al. [13] compared and analyzed the life cycle assessment carbon footprint of 24 kinds of salmon farming systems.

Given the crowded offshore aquaculture space and mounting ecological environment pressure, optimizing the spatial layout of mariculture and expanding from shallow sea farms to deeper and farther seas is an inevitable choice for transforming and upgrading the mariculture industry. Large aquaculture vessels with the capabilities of intensive large-scale marine aquaculture and comprehensive fishery production could effectively address diverse marine environments, conditions, and fishery production needs while resolving long-standing challenges associated with traditional open water aquaculture practices [14,15]. However, there is a research gap regarding carbon emissions in economic mariculture production processes in deep-sea environments. Therefore, it is crucial to conduct research on the identification and assessment of the carbon footprint associated with aquaculture processes on large marine vessels operating in far-deep waters. This study utilizes the world's first 100,000-ton large-scale aquaculture vessel, "Conson No. 1", as a case study to evaluate the LCA carbon footprint of cultivating the large yellow croaker species on an aquaculture vessel system. The research not only provides valuable insights for future low-carbon development within far-deep marine aquaculture systems but also establishes a scientific foundation for sustainable advancements within the aquaculture industry.

2. Data and Methods

2.1. Research Methods

The LCA involves the comprehensive evaluation of input, output, and potential environmental impacts throughout the entire life cycle of a product [16]. In aquaculture processes, various stages such as raw material production, processing, transportation, and on-site culturing are involved. These stages could be further categorized into seedling breeding, fingerling breeding, adult fish farming, and other developmental phases based on organism growth patterns. Due to variations in nutrient requirements and farm environmental conditions across different cultivation stages according to organisms' growth habits, significant disparities in environmental impacts arise. Therefore, employing the LCA methodology for assessing aquaculture systems is both appropriate and feasible.

2.2. Research Object and Scope of Measurement

2.2.1. Research Object

"Conson No. 1", an intelligent marine aquaculture vessel designed by the Fishery Machinery and Instrument Research Institute of the Chinese Academy of Fishery Sciences, commenced operations on 20 May 2022 (Figure 1). It has a total length of 249.9 m and a width of 45 m, featuring 15 aquaculture tanks. The annual production capacity for large yellow croakers is approximately 3700 t, with a stock density of around 18 kg/m^3 [17]. This study focuses on assessing the CF of the entire life cycle process of large yellow croaker farming on board "Conson No. 1". The functional unit considered is 1 kilogram of fresh large yellow croakers delivered to a wholesaler.

Figure 1. Aquaculture Vessel "Conson No. 1".

2.2.2. Scope of Assessment

The scope encompassed the entire life cycle process of large yellow croaker aquaculture, from the cultivation and production of feed raw materials to the transportation of cultivated fish to wholesalers. This included activities such as feed material cultivation and production, feed transportation, the construction of the aquaculture vessel, seed and fingerling breeding, fingerling transportation, adult fish farming on board, primary shipborne processing, refrigeration and packaging, as well as fish commodity transportation. The system boundary for large yellow croaker farming on the aquaculture vessel was illustrated in Figure 2. The aquaculture cycle of the large yellow croaker was divided into five major processes: FP (feed production), SC (ship construction), FB (fingerling breeding), AF (adult fish farming), and FD (fish distribution). Specifically, there were two sub-processes, feed production (FPP) and feed transportation (FPT), within the FP. The SC process included the production and transportation of construction materials as well as ship construction. Within the FB process, there were two sub-processes: fingerling breeding (FBB) and fingerling transportation (FBT). The AF process consisted of five sub-processes, including aquaculture energy consumption (AFA), shipborne processing energy consumption (AFP), shipborne refrigeration (AFR), shipborne packaging (AFB), and load of aquaculture workers' consumption (AFW). Carbon emission sources related to the main activities involved in large yellow croaker culturing and production within this boundary had been identified for subsequent intensity assessment.

As a result of the aquaculture tank's maximum total water exchanges reaching 16 times per day, conditions for heterotrophic denitrification and anaerobic reactions were not present in the aquaculture tank and there was minimal sludge and residual feed remaining in the tank, leading to exclusion of N_2O and CH_4 emissions from aquaculture tanks during assessment.

As one of the background processes in the life cycle of large yellow croaker farming on aquaculture vessels, the carbon footprint of ship dismantling is quite small. Previous studies on the global warming potential (GWP) of ships life cycles had consistently reported small emissions during the ship disassembling stage. Li B.Y. [18] found that only 0.121% of GHG emissions were released throughout the entire life cycle of a 180,000-ton ship in 2010. Similarly, Ailong Fan [19] observed that GHG emissions from ship disassembling accounted for approximately 0.73%, while Nathanael Ko et al. [20] reported this contribution for that was around 0.4%. These literature findings collectively indicated that ship disassembling had an insignificant GWP across a vessel's entire life cycle, with most contributions being less than 1%. Therefore, considering its less impact (<0.7%) on the CF associated with the whole life cycle of large yellow croaker farming on aquaculture vessels, we did not include the carbon footprint from ship dismantling as part of this study.

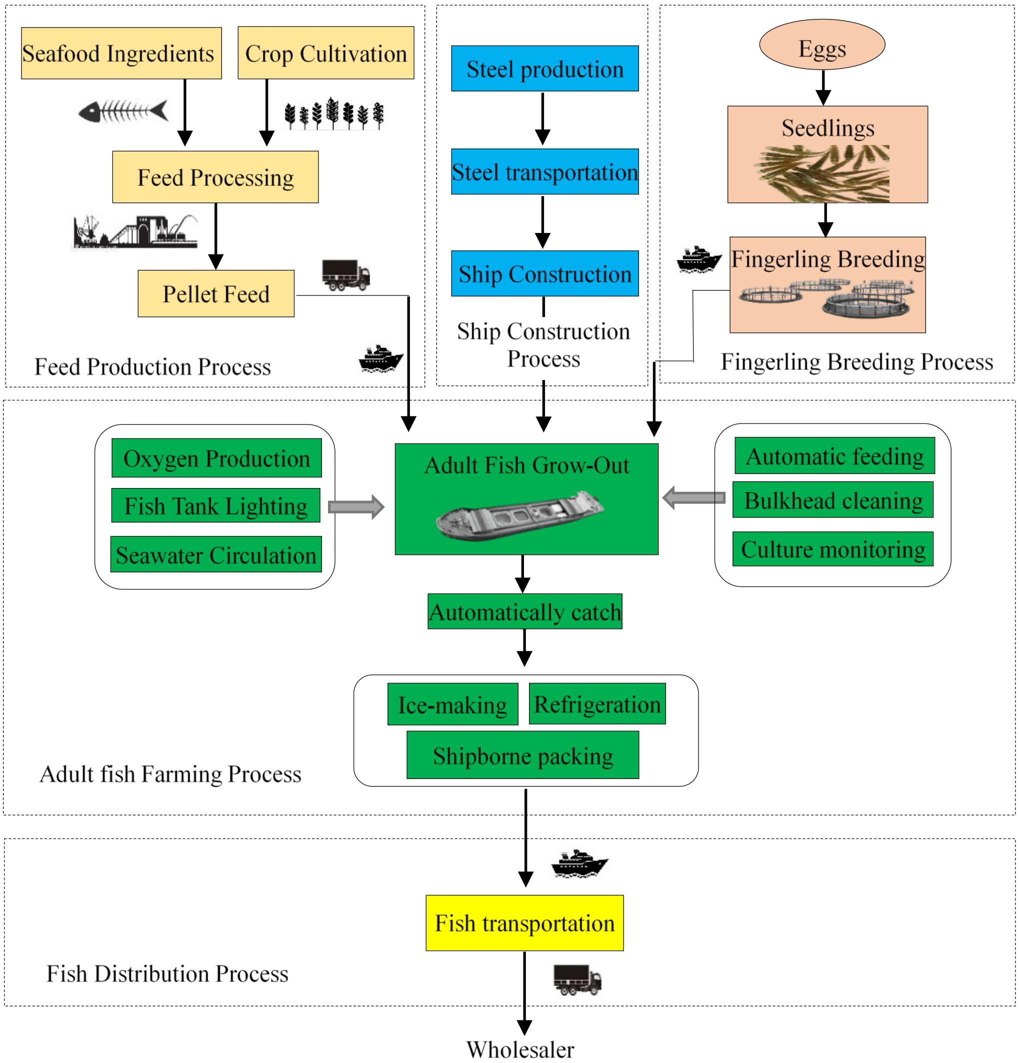

Figure 2. Boundary diagram of the LCA in large yellow croaker farming on the aquaculture vessel.

2.3. Data Sources and Processing

2.3.1. Data Sources

The list data were collected through a comprehensive approach, including questionnaires, literature reviews, and expert consultations. During the data collection process, four types of questionnaires were designed: feed questionnaires, fish transportation questionnaires, aquaculture vessel questionnaires, and fish distribution questionnaires. Direct data on processing capacity onboard, feed conversion rate (FCR), shipping distance of fingerlings, as well as shipping and land transportation distance of marketable large yellow croakers were obtained from the questionnaire. The loading information regarding farming and processing equipment onboard was derived from the design data of the "Conson No. 1" vessel. The processes involved in fish feed production (fish meal production, soybean meal production, wheat production, corn production, etc.) and fingerling breeding (hatchery operations for nursery and grow-up stages) were similar to those described by Ulf Johansen et al. [10], N.Pelletier et al. [21], and FAO's Fisheries and Aquaculture Technical Paper 626 [22]. The background data obtained from this literature were utilized to model the inputs of feed production and fingerling breeding processes. The quantification of carbon emissions during the construction process of the aquaculture vessel was based on the relevant research findings [18–20,23,24] regarding carbon emission assessment in ship life cycles. The carbon emission factors for each transportation in sub-process were based on relevant research conducted by Ulf Johansen et al. [10]. The diesel carbon emission factor, average low caloric value of commonly used fuels, carbon oxidation rate, and other calculation parameters were derived from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [25] and the China Greenhouse Gas Inventory Study (2007) [26]. The GWP of refrigerant was derived from the Fundamental Handbook of ASHRAE (2017) [27]. The literature study data in comparative analysis extracted from Web of Science, Springer Link, CNKI, and other databases were employed.

2.3.2. Data Processing

The carbon emission calculation employed the IPCC's carbon emission coefficient method, facilitated by Microsoft Excel 2016. Descriptive Statistics and non-parametric test methods from IBM SPSS 26 were utilized to compare and analyze the CF across different aquaculture modes.

2.4. Calculation Methods of Each Process

2.4.1. Process of Feed Production

The main nutritional components of feed for large yellow croaker farming on "Conson No. 1" were as follows: crude protein $\geqq$ 42%, crude fat $\geqq$ 6%, crude fiber $\leq$ 5%, ash $\leq$ 18%, water $\leq$ 12%, total phosphorus $\geqq$ 1.2%, and lysine $\geqq$ 2.2%. Feed materials for large yellow croakers included high quality fish meal, soybean meal, wheat, yeast, shrimp meal, fish oil, stable multivitamin complex minerals, etc., which were commonly used in fish feed formulation (Table 1).

Table 1. Ingredients for Yellow Croaker Feed Formula.

Ingredients	Content (%)
Fish meal	40–65
Soybean meal	5–25
Wheat	10–25
Fish oil	2–5
Yeast	2–4
Shrimp meal	2–5
Corn gluten meal	1–5
Complex minerals	1–2
Choline chloride	0.2–0.5
Multivitamin	0.2

The feed production adopted an industrial mode, and the carbon emission factors during the FPP process were calculated based on mean data from studies conducted by Ulf Johansen et al. [10], N. Pelletier, P et al. [21], and FAO 626 [22]. These studies shared similar processing technology and background data. The calculation method for the CF in the FP process was presented in Formula (1) in Table 2.

Table 2. Calculation formulas of the carbon footprint for each process.

Process	Formula and Definition and Interpretation
FP	(1) $EI_{FP} = (EF_{FPP} + EF_{L1} \times S_{L1} + EF_{S1} \times S_{S1}) \times FCR$ where EI_{FP} is the CF of the FD process, $kgCO_2e/kg$ LW, and EF_{FPP} is the carbon emission factor of the production activity in the FD process, $kgCO_2e/kg$ DM(feed dry matter). EF_{L1} and EF_{S1} are used to represent the carbon emission factor of the feed transportation by land and sea, respectively, with the values of 0.164×10^{-3} kg CO_2e/kg DM/km and 0.0068×10^{-3} kg CO_2e/kg DM/km. S_{L1} and S_{S1} indicate distances of feed transportation by land and sea, respectively, which were 200 km and 20 km; FCR was set a value of 1.30.

Table 2. *Cont.*

Process		Formula and Definition and Interpretation
SC		(2) $EI_{SC} = (EI_{AF} + EI_{SC}) \times R_{SC}$ where EI_{SC} is the CF of the SC process, $kgCO_2e/kg$ LW, and R_{SC} is the ratio of the CF of the SC process to the whole life cycle of the ship (excluding ship dismantling), 4.7%.
FB		(3) $EI_{FB} = EI_{FBB} + EF_{S2} \times S_{S2} \times (W_{water} + W_{fingerling})$ where EI_{FB} is the CF of the FB process, $kgCO_2e/kg$ LW; EF_{FBB} is the carbon emission factor of the breeding activity in FB process, $kgCO_2e/kg$ LW; EF_{S2} is the carbon emission factor of fingerling shipping, 0.06×10^{-3} $kgCO_2e/kg/km$ (including refrigeration); and S_{S2} is the shipping distance of fingerling ships, 20 km. $W_{fingerling}$ is the weight of the fingerling required for 1 kg of large yellow croaker breeding, 0.44 kg. W_{water} is the weight of the storage water required for fingerling storage and transportation, 17.76 kg.
AF	AFA	(4) $EI_{AFA} = TUL_A \times T \times SFC \div (1 - F) \times Qnet_{derv} \times EF_{derv} \div Q_a \times 10^{-7}$ where EI_{AFA} is the CF of energy consumption from aquaculture equipment, $kgCO_2e/kg$ LW. TUL_A is the total unit load of aquaculture equipment, 2810.4881 kwh; T is the running time, h, per year. SFC is the diesel generator unit fuel consumption, 180 g/kwh; F is the rate of diesel oil loss, 5%; $Qnet_{derv}$ is the average low calorific value of diesel oil, 433.3 TJ/10^4 t; EF_{derv} is diesel emission factor, 74,100 kg/TJ. Q_a is the annual catch production, 3700 t.
	AFP	(5) $EI_{AFP} = TUL_P \times T \times SFC \div (1 - F) \times Qnet_{derv} \times EF_{derv} \div Q_a \times 10^{-7}$ where EI_{AFP} is the CF of energy consumption from shipborne processing equipment, $kgCO_2e/kg$ LW. TUL_P is the total unit load of shipborne processing equipment, 298.6015 kwh.
	AFR	(6) $EI_{AFR} = W_{ice} \times 0.1\% \times R_{loss} \times GWP100_{R404}$ where EI_{AFR} is the CF of shipborne refrigeration, $kgCO_2e/kg$ LW. W_{ice} is the amount of ice needed by large yellow croakers, 0.25 kg. 0.1% is the proportion of refrigerant added to produce ice. R_{loss} is the refrigerant loss rate, 10%. $GWP100_{R404} = 3940$ kg CO_2e [27].
	AFB	(7) $EI_{AFB} = \sum EF_{AFBj} \times (W_{box} \div W_{fish})$ where EI_{AFB} is the LCA carbon footprint of shipboard packaging per 1 kg fish; EF_{box} is the life cycle carbon emission factor of the foam box; and EF_{AFBj} is the carbon emission factors of the foam box in each stage of the life cycle, including raw material processing stage, production stage, landfill disposal stage. W_{box} is the weight of the foam box, 0.2 kg. W_{fish} is the net weight of large yellow croakers in each package, 6 kg.
	AFW	(8) $EI_{AFW} = ((K \times N) \div Q_a) \times 10^{-3}$ where K is the productive GHG emission coefficient of aquaculture workers, and the GHG emission coefficient of workers is 10.5 kg/d/person, of which 25% is emitted due to aquaculture activity [3], $K = 10.5 \times 365 \times 0.25$. N is the number of aquaculture workers, N = 16.
FD		(9) $EI_{FD} = (EF_{S3} \times S_{S3} + EF_{L3} \times S_{L3}) \times W_T \times 10^{-3}$ where EI_{FD} is the CF of the fish distribution process. EF_{S3} and EF_{L3} are the carbon emission factors of shipping and land transportation of fish distribution, respectively: 0.042 $kgCO_2e/t$ km (including refrigeration) and 0.101 $kgCO_2e/t$ km (including refrigeration). S_{S3} and S_{L3} are the shipping and land transportation distances of marketable large yellow croaker, respectively: 20 km and 50 km. W_T is the total weight of an average 1 kg packaged marketable large yellow croaker, 1.33 kg.
TOTAL		(10) $EI = \sum EI_j$ where EI is the CF of the whole life cycle of large yellow croaker farming on the aquaculture vessel; EI_j is each process's CF throughout the whole life cycle; and EI_j includes EI_{FP}, EI_{SC}, EI_{FB}, EI_{AF}, and EI_{FD}. The unit is $kgCO_2e/kg$ LW.

2.4.2. Process of Ship Construction

The carbon footprint of the ship construction process primarily arises from the production and transportation of construction materials, as well as the shipbuilding procedures. In previous studies on the GWP of the life cycle of large-scale ships with tens of thousands of tons, Li B.Y. [18] reported that during the shipbuilding stage of a 180,000-ton ship in 2010, approximately 4.92% of the GHG emissions were released throughout its entire life cycle (excluding ship dismantling). Louise L.K. et al. [23], in their study conducted in 2015 on a DWT = 50,000-ton ship, found that the CF attributed to ship construction accounted for around 4% of the CF across the entire life cycle (excluding ship dismantling). Similarly, Pham K.Q. et al. [24] discovered in their research conducted in 2021 that for a DWT = 74,300-ton ship, GHG emissions from ship construction contributed approximately 2% to the GWP throughout its entire life cycle (excluding ship dismantling). Furthermore, some findings from studies focusing on lighter ships had also been similar. Ailong Fan [19] found that for a DWT = 7500-ton ship, GHG emissions accounted for about 4.64%, and Nathanael Ko et al. [20] reported that for an LDT = 4108-ton ship, the contribution was approximately 4.46%. All these literature findings consistently indicate that the GWP contribution from ship construction throughout a ship's whole life cycle ranges from 2–5%, predominantly at around 4%, regardless of the size of the ship. Therefore, this study adopted a ratio value of 4%.

The carbon footprint calculation method for the ship construction process could be seen in Formula (2) presented in Table 2.

2.4.3. Process of Fingerling Breeding

The large yellow croaker seedlings were incubated in the indoor hatchery of Sandu Ao Conson Farm, Xiapu County, Ningde City, Fujian Province, and the fish fingerlings were incubated in open net cages in coastal waters. Subsequently, the fish fingerlings were reared in open net cages located in coastal waters. Once the fingerlings reached a weight of approximately 200 g, they were transported and released into the aquaculture tanks of the aquaculture vessel. The overall process of fingerling breeding (FB) included various stages such as hatchery management, nursery care, fingerling breeding, and transportation. The fingerlings used for seeding large yellow croakers in this case weighed between 150–250 g per tail, with a calculated average of 200 g. The transport density was set at 100–150 tails per cubic meter, and a calculated value of 125 tails per cubic meter was considered. The FCR was determined to be 1.30. The average caught size of adult fish was about 500 g, with a survival rate averaging about 90%. The carbon emission footprint from hatchery to fingerlings (FBB) was estimated based on the research conducted by Ulf Johansen et al. [10]. The carbon footprint calculation method for the FB process can be seen in Formula (3) presented in Table 2.

2.4.4. Process of Adult Fish Farming

- Aquaculture energy consumption

The energy consumption of the large yellow croaker farming process primarily encompassed the aquaculture water exchange system, the aquaculture tank oxygenation system, the emergency oxygenation system, the automatic feeding system, the adult fish catching system, the fish tank illumination system, the aquaculture video monitoring system, and other direct energy consumption. Based on research data, the total energy consumption of "Conson No. 1" was calculated for the main aquaculture equipment units on the vessel under specific aquaculture conditions. The diesel carbon emission factor was derived from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventory [25] and the average low caloric value of commonly used fuels was derived from the China Greenhouse Gas Inventory Study (2007) [26]. The CF calculation method for the AFC process is presented in Formula (4) in Table 2.

- Shipborne processing energy consumption

After the fish were caught, half of the large yellow croaker yield was processed and packaged onboard, while the other half was directly transported to shore for reprocessing. The energy consumption analysis of "Conson No. 1" under aquaculture conditions considered all fish initially processed onboard. Based on operation data, the total energy consumption of shipborne processing equipment units was calculated using a shipborne processing capacity of 50 t/8 h. The CF calculation method for the AFP process is presented in Formula (5) in Table 2.

- Shipborne refrigeration

The CF of ice production for the refrigeration and preservation of large yellow croakers was calculated in the AFR sub-process. R404a was used as the refrigerant for both the ice transfer machine and ice slurry equipment on board. Based on an average addition rate of 1 kg refrigerant per 1RT, it was necessary to add 1 kg of refrigerant to produce 1 ton of ice. According to the questionnaire, fish requiring refrigeration should follow a ratio of 4:1 for adding ice. The Global Warming Potential over a 100-year period (GWP100) value for R404a was obtained from the Fundamental Handbook of ASHRAE (2017) [27]. The CF calculation method for the AFR process is shown in Formula (6) in Table 2.

- Shipborne packaging

The primary packaging material used for the "Conson No. 1" marketable fish was a polystyrene (EPS) white foam box, with inner dimensions of 45 cm × 26 cm × 18 cm and outer dimensions of 50 cm × 30 cm × 22 cm. The weight of the packaging itself was approximately 200 g. Each box contained 12 pieces of the product. In this case, the disposal of packaging materials was considered based on a scenario where half of them were recycled and the other half were buried.

Referring to the research of Sun C.H. et al. [28] on LCA carbon emission of packaging, the carbon emission factors of the foam box in each sub-process of the life cycle are shown in Table 3:

Table 3. The carbon footprint of each sub-process in the life cycle of foam packaging.

Life Cycle Stage	EF_{box} of Foam Box ($kgCO_2e/kg$)	Data Source
Raw material processing	3.040	China Postal Industry Report (2014) [28]
Production	0.758	Su Y, et al. 2020 [29]
Landfill disposal	0.117	Commercial database GaBi 8.0 [28]

The CF calculation method of the AFB process is presented in Formula (7) in Table 2.

- Load of aquaculture workers' consumption

The CF of the large yellow croaker aquaculture activities on the ship should cover the aquaculture activities load of the aquaculture workers.

The CF of the aquaculture activities load of the aquaculture workers was based on the research method of Yang J.P et al. [30]. The personnel load was related to the number of aquaculture workers and annual yield. The CF calculation method of the AFW process is shown in Formula (8) in Table 2.

2.4.5. Process of Fish Distribution

In the FD process, the primary focus was on evaluating the CF associated with transportation fuel consumption for shipping packaged large yellow croakers to the dock and subsequently transporting them to the wholesaler. The CF calculation method for the FD process is presented in Formula (9) in Table 2, Calculation formulas of the carbon footprint for each process.

The CF calculation for the whole life cycle of large yellow croaker farming on the aquaculture vessel is represented by Formula (10) in Table 2.

2.5. Measurement Method of the Carbon Footprint for a Unit Commodity Price

The unit commodity price of the aquaculture body was calculated using the EI_f formula, as expressed in Equation (11).

$$EI_f = EI \div M_f \times 1000 \quad (11)$$

where EI_f represents the CF of large yellow croaker farming on the aquaculture vessel, measured as CO_2 equivalent emission per unit commodity price used the unit gCO_2e/CNY, and M_f is the commodity price in CNY/kg, sourced from data collected at the Conson Aquatic Products Flagship Store and Tmall supermarket.

3. Results

3.1. Carbon Footprint and Contribution Rate of Each Process

The whole life cycle CF of 1 kg of fresh large yellow croakers delivered to the wholesaler was 6.2170 $kgCO_2e$/kg LW. The commodity price carbon footprint of large yellow croaker farming on aquaculture vessel "Conson No. 1" was 31 g CO_2e/CNY (China Yuan), which represented a greenhouse gas emission equivalent of 31 gCO_2 for one CNY of sales.

Table 4 presents the CF and contribution rates for each process and sub-process. The CF of the FP process amounted to 1.5456 $kgCO_2e$/kg LW, while that of FB process was measured at 0.1758 $kgCO_2e$/kg LW. The SC process stood at 0.1795 $kgCO_2e$/kg LW. In contrast, the AF process exhibited a significantly higher carbon footprint of 4.3083 $kgCO_2e$/kg LW, whereas the FD process demonstrated a remarkably low carbon footprint of only 0.0078 $kgCO_2e$/kg LW. Among these processes, it was noteworthy that the highest CF could be attributed to the AF process with a significant share reaching up to approximately 69%. Furthermore, in individual sub-processes within these five main processes, it became evident that aquaculture energy consumption held the highest CF followed by feed production with respective contribution rates amounting to approximately 65% and 24%.

Table 4. Carbon footprint and contribution rates of each process within LCA system boundary.

Process		CF and Contribution Rate		Sub-Processes		CF and Contribution Rate	
		$kgCO_2e$/kg LW	%			$kgCO_2e$/kg LW	%
FP	EI_{FP}	1.5456	24.86	FPP	EI_{FPP}	1.5028	24.17
				FPT	EI_{FPT}	0.0428	0.69
SC	EI_{SC}	0.1795	2.89				
FB	EI_{FB}	0.1758	2.83	FBB	EI_{FBB}	0.1540	2.48
				FBT	EI_{FBT}	0.0218	0.35
AF	EI_{AF}	4.3083	69.30	AFA	EI_{AFA}	4.048	65.11
				AFP	EI_{AFP}	0.0291	0.47
				AFR	EI_{AFR}	0.0985	1.58
				AFB	EI_{AFB}	0.1286	2.07
				AFW	EI_{AFW}	0.0041	0.07
FD	EI_{FD}	0.0078	0.13				
Total	EI	6.2170					

The primary source of a high CF in terms of energy consumption in fish farming on board was electric power required for the aquaculture equipment. Among these, the highest electricity consumption was attributed to the operation of aquaculture sea pumps, as depicted in Figure 3. "Conson No. 1" was specifically designed to replicate ocean currents, creating a rotational flow field that is conducive for fish swimming, while maintaining a constant water flow rate of 0.2~0.4 m/s in the aquaculture tank. Fifteen seawater pumps with high power were utilized to supply low head and high-flow water for aquaculture purposes, ensuring a continuous injection of high-quality seawater from a depth of 40 m into the tank. It resulted in a maximum total water exchange frequency of up to 16 times per day, thereby guaranteeing an optimal marine environment for densely populated fish shoals at all times. The CF associated with the fifteen aquaculture seawater pumps amounted to 3.1623 kg CO_2e/kg LW, accounting for approximately 50.87% of the entire life cycle and representing around 78.12% of all aquaculture equipment onboard.

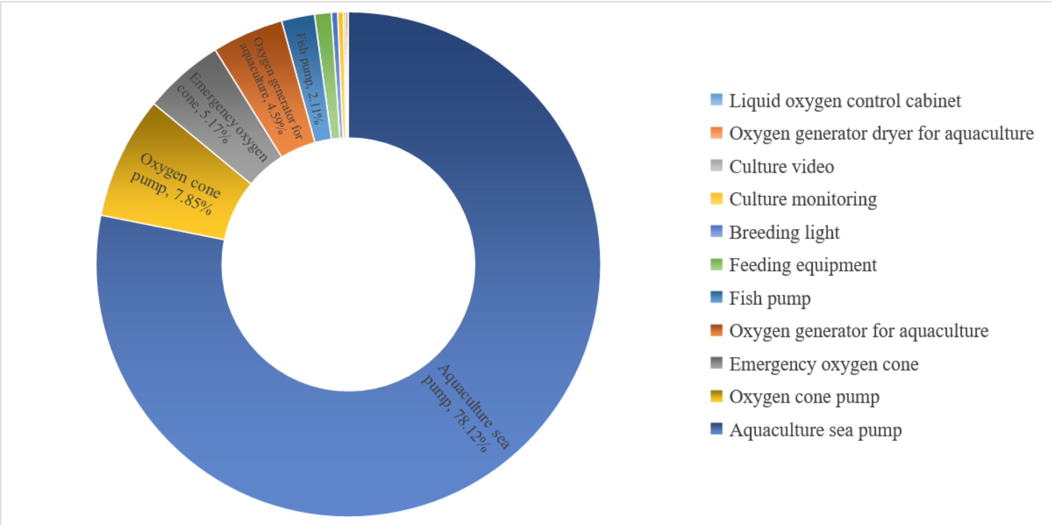

Figure 3. Comparison of the carbon footprint of the aquaculture equipment energy consumption on board.

Therefore, the energy consumption of aquaculture equipment and feed production processes were identified as the CF key processes. The type of energy and the efficiency of energy utilization in aquaculture equipment operation were the most critical determinants for CF of large yellow croaker farming on the aquaculture vessel, followed by FCR.

3.2. Comparison of the Carbon Footprint of Marine Fish Farming in Different Systems

The reference pertained to studies on the CF of mariculture that employed the LCA method. However, direct comparison was challenging due to variations in system boundaries across studies. To facilitate easy comparison, we selected CF values (listed in Table 5) within consistent system boundaries from feed planting initiation to aquaculture completion (excluding aquaculture facility construction, processing and packaging, distribution, and other processes).

Table 5. Carbon footprint of marine fish farming in different systems (from feed planting to end of farming).

Aquaculture System	Area, Open Degree	CF [j]	Sources of Literature/Variety/Nation
Aquaculture vessel	Sea-based, closed	5.77	this study, 2023; Large yellow croaker; China
LBCC-RAS [a]	Land-based, closed	38.09	Chen Z.X. et al. [5], 2011; Rainbow trout; China
LBCC-FAS [b]	Land-based, closed	33.16	Chen Z. X. et al. [5], 2011; Rainbow trout; China
Land-sea relay farming	Land-sea relay, closed-open relay	15.84	Hou H. C. [31], 2022; Tiger puffer; China
LBCC-RAS [c]	Land-based, closed	13.62	B. Samuel-Fitwi [6], 2013; Rainbow trout; Denmark
ONP [c]	Sea-based, open	12.80	Robert Parker [32], 2018; Salmon; Australia
LBCC-RAS [a]	Land-based, closed	10.30	Nathan W. Ayer [4], 2009; Salmon; Canada

Table 5. *Cont.*

Aquaculture System	Area, Open Degree	CF [j]	Sources of Literature/Variety/Nation
Low-tech aquaponic	Land-based, closed	8.80	Francesco Bordignon [33], 2022; Rainbow trout; Italy
ONP [c]	Sea-based, open	8.59	White A [34], 2013; Salmon; Australia
LBCC-RAS [a]	Land-based, closed	7.01	Yajie Liu et al. [7], 2016; Salmon; USA
LBSC-RAS [d]	Land-based, semi-closed	6.38	Majid Dekamin [35], 2015; Rainbow trout; Iran
LBCC-RAS [a]	Land-based, closed	6.10	Majid Dekamin [35], 2015; Rainbow trout; Iran
LBCC-RAS [a]	Land-based, closed	5.79	J. Aubin [36], 2009; Turbot; France
LBCC-RAS [a]	Land-based, closed	5.62	Aurelie Wilfart [37], 2013; Rainbow trout; France
LBCC-FAS [b]	Land-based, closed	5.41	Nathan W. Ayer [4], 2009; Salmon; Canada
ONP [c]	Sea-based, open	3.80	Ulf Johansen et al. [10], 2022; Salmon; Norway
I-FAS [e]	Land-based, closed	3.56	B. Samuel-Fitwi [6], 2013; Rainbow trout; Germany
ONP [c]	Sea-based, open	3.39	Yajie Liu et al. [7], 2016; Salmon; Nordic Region
Net cages	Sea-based, open	3.32	J. Aubin [36], 2009; Perch; Greece
LBCC-FAS [b]	Land-based, closed	2.99	Aurelie Wilfart [37], 2013; Salmon; France
ONP [c]	Sea-based, open	2.82	Ytrestoyl T [38], 2011; Salmon; Norway
SWAS [f]	Sea-based, semi-closed	2.81	McGrath KP [39], 2015; Salmon; Canada
Freshwater raceways	Land-based, closed	2.54	J. Aubin [36], 2009; Rainbow trout; France
Net cages	Sea-based, open	2.32	Joachim Boissy [40], 2011; Salmon; Scotland
ONP [c]	Sea-based, open	2.31	Nathan.Ayer [41], 2016; Salmon; Chile
ONP [c]	Sea-based, open	2.30	Ellingsen H [42], 2006; Salmon; Norway
Marine floating bag	Sea-based, open	2.25	Nathan W. Ayer [4], 2009; Salmon; Canada
E-FAS [g]	Land-based, closed	2.24	B. Samuel-Fitwi [6], 2013; Rainbow trout; Germany
Net cages	Sea-based, open	2.22	Joachim Boissy [40], 2011; Rainbow trout; France
Marine floating concrete tank	Sea-based, open	2.08	Nathan.Ayer [41], 2016; Salmon; Chile
Net cage	Sea-based, open	2.07	Khaled Abdou [43], 2017; Sea bream;Tunisia
ONP [c]	Sea-based, open	2.07	Nathan W. Ayer [4], 2009; Salmon; Canada
ONP [c]	Sea-based, open	2.00	Winther U [44], 2009; Salmon; Norway
RSF [h]	land-based, closed	1.99	Emmanuelle Roque d O'rbcastel [45], 2009; Rainbow trout; Denmark
FTF [i]	Land-based, closed	1.99	Emmanuelle Roque d O'rbcastel [45], 2009; Rainbow trout; France
Net cages	Sea-based, open	1.58	Khaled Abdou [43], 2017; Sea bass; Tunisia
LBCC-FAS [b]	Land-based, closed	1.16	Majid Dekamin [35], 2015; Rainbow trout; Iran

a = Land-based recirculating system; b = Land-based industrial flow-through system; c = Open net pen; d = Semi-closed recirculating system; e = Intensive flowthrough aquaculture system; f = Floating, flowthrough, solid-walled aquaculture system; g = Extensive flowthrough aquaculture; h = Recirculation system farm; i = Flow through system; j = The unit of CF was $kgCO_2e/kg$ LW.

The literature encompassed CF study findings of various marine fish species (salmon, rainbow trout, sea bass, sea bream, turbot) farmed in different aquaculture systems across 16 countries worldwide. It included the CF results of 15 farming systems from feed planting to end of farming (before).

In order to facilitate a comparison between aquaculture systems, the 37 studies were categorized into two groups based on their farming methods, Group A representing the closed farming mode and Group B representing the sea-based farming mode. Subsequently, separate comparative analyses were conducted for each group.

The mean value and median value of Group A, as determined by the SPSS descriptive statistics method, were 8.627 and 5.770 (kgCO_2e/kg LW), respectively, as shown in Table 6. The distribution of the CF in Group A was found to be abnormal based on the one-sample Kolmogorov-Smirnov test. Therefore, a one-sample Wilcoxon Signed Rank test was conducted to assess the consistency between the median CF of Group A and the hypothesized value of 6.20 (kgCO_2e/kg LW). The hypothesized value would be a selected value within the range of 8.627 to 5.770 (kgCO_2e/kg LW), with a significance level (p-value) greater than 0.8, which presented the overall median level. It was observed that the p-value for the population of Group A samples was calculated as 0.821, which was greater than 0.05, thus confirming that the hypothesis regarding a median value of 6.20 (kgCO_2e/kg LW). for Group A samples population was valid.

Table 6. One-Sample Kolmogorov-Smirnov Test Result of Group A.

Variable	N	Mean	Median	Interquartile Range	Test	Wilcoxon Test Statistic	p
CF	21	8.627	5.770	6.874	6.2	109	0.821

In Figure 4, the CF of large yellow croaker farming on an aquaculture vessel was determined to be 5.77 kgCO_2e/kg LW, which was equivalent to the median value measured in group A samples and lower than the median value of the entire population of group A. Furthermore, it was significantly lower than the average CF value of Group A, as depicted in Figure 4's comparison chart for CF values in Group A. These findings demonstrated that the CF of intensive closed aquaculture vessel systems was below the average level observed in closed aquaculture systems overall. However, when compared to SWAS, its CF was higher due to two main factors: firstly, SWAS was a semi-closed system floating on the sea surface with flowing water and with fixed walls, which could be considered a kind of aquaculture system between an ONP and a closed flow-through system; secondly, the installations of the SWAS were typically located in near-shallow sea areas where energy consumption tends to be lower.

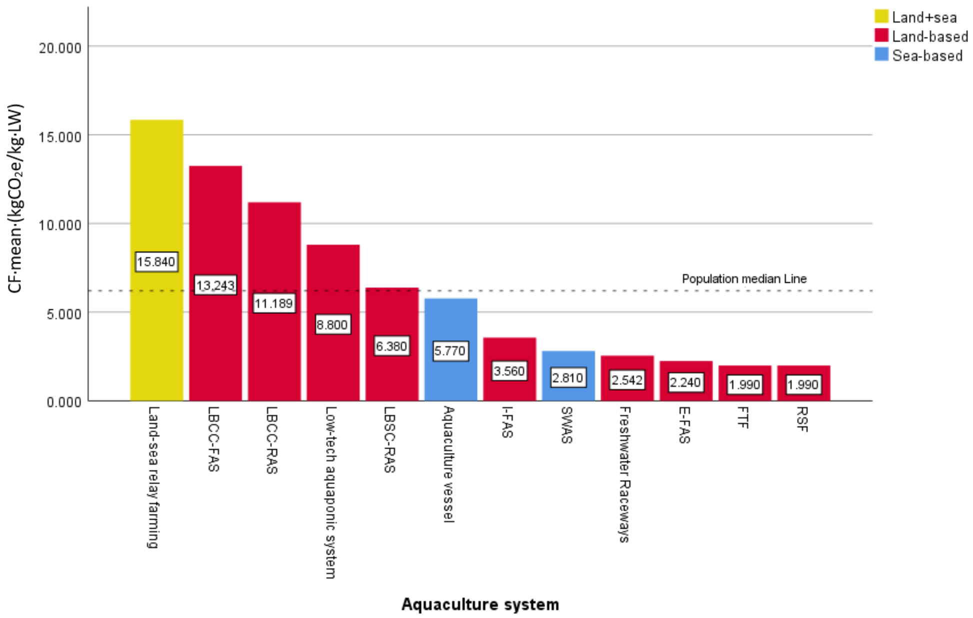

Figure 4. Comparison of the carbon footprint of closed aquaculture system Group A.

The mean value and median value of Group B, as determined by the SPSS descriptive statistics method, were 4.228 and 2.320 ($kgCO_2e/kg$ LW), respectively, as shown in Table 7. The distribution of the CF in Group B was found to be abnormal based on the one-sample Kolmogorov-Smirnov test. Therefore, a one-sample Wilcoxon Signed Rank test was conducted to assess the consistency between the median CF of Group B and the hypothesized value of 2.90 ($kgCO_2e/kg$ LW). The selected value for the hypothesized value fell within the range of 4.228 and 2.320 ($kgCO_2e/kg$ LW), with $p > 0.8$. The results indicated that the p-value for the population samples from Group B was calculated as 0.856, which was greater than the significance level of 0.05, thus supporting the validity of our hypothesis regarding a median value of 2.90 ($kgCO_2e/kg$ LW) for Group A samples.

Table 7. One-Sample Kolmogorov-Smirnov Test Result of Group B.

Variable	N	Mean	Median	Interquartile Range	Test	Wilcoxon Test Statistic	p
CF	19	4.228	2.320	1.72	2.90	90.5	0.856

In the comparison of sea-based aquaculture modes (Figure 5), the CF of large yellow croaker farming on an aquaculture vessel exceeded the measured median value of 2.32 ($kgCO_2e/kg$ LW), as well as the median value of the sample population and the average value of the sample of 4.228 ($kgCO_2e/kg$ LW). This was evident from Figure 5, which illustrates a higher CF for aquaculture vessels compared to other sea-based aquaculture modes due to their enclosed nature and high energy consumption. Moreover, land-sea relay farming exhibited the highest CF due to additional energy consumption associated with sea-land conversion transportation [31].

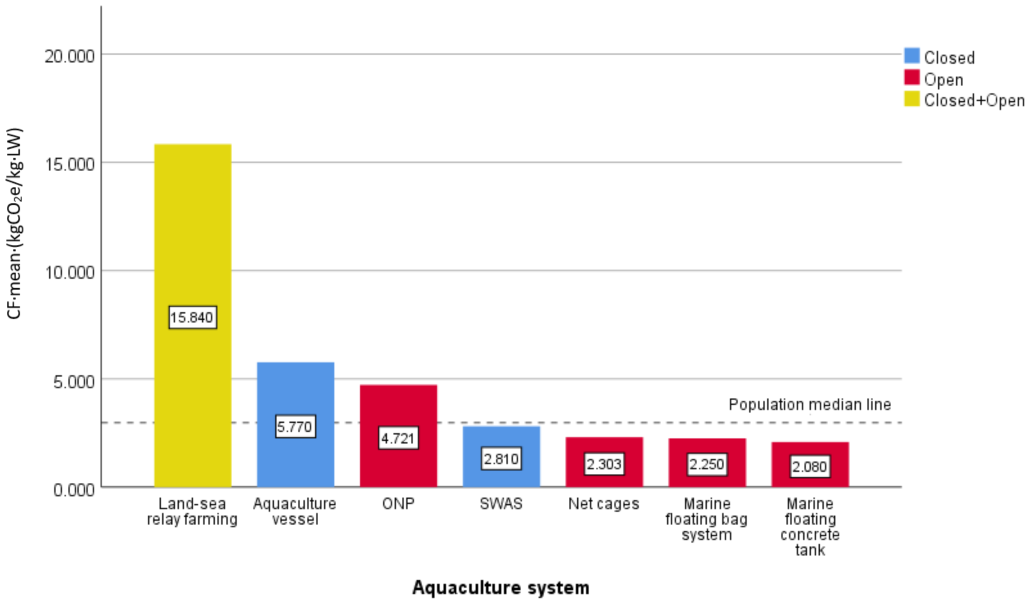

Figure 5. Comparison of the carbon footprint of sea-based aquaculture system Group B.

4. Discussion and Suggestions

4.1. Discussion

- The intensive and closed aquaculture system relying on modern industry would promote aquaculture from small-scale and low-input farm systems to high-intensity intensive farm systems. The processes adopt mechanization or automation operation, and the CF level will be increased with the increase of external energy [46]. However, aquaculture vessels enable the transfer of traditional industrial closed systems to far-reaching seas while achieving intensive and efficient cultivation in deep-sea environments. With a controllable aquaculture environment, the fish stocking density and output were higher. Additionally, the effect of management, harvest, quality and safety were easy to control and the products were able to be balanced and listed. Therefore, the intensive and closed aquaculture mode would be the inevitable transformation and development direction of the aquaculture industry to a low-carbon economy [46,47], which was consistent with Dalia M. M. Yacout et al. [48], Wang X.H. et al. [46] and Wang H.H. et al. [47]. On the aquaculture vessel, the fish stocking density could reach 4 to 6 times that of traditional cages with a survival rate exceeding 90%. The higher stock density of the aquaculture system enables a reduction in the environmental impact of the unit aquaculture body [48]. Studies have found that the carbon footprint level of fish farming on aquaculture vessels was lower than those observed in overall average closed systems. Given the excessive use of offshore aquaculture areas, promoting deep-sea aquaculture becomes imperative. As a new type of deep-sea aquaculture system, it is expected to promote sustainable development within aquaculture.

- Through a comparative analysis of the literature on the carbon footprint of marine fish culturing systems, it was found that closed aquaculture vessels exhibited higher carbon footprint levels compared to open and semi-closed systems. Large-scale intensive closed aquaculture vessels effectively isolate the aquaculture system from the surrounding ecosystem, reducing direct ecological impacts faced by open systems and enhancing their resistance to environmental disturbances. To simulate an ecologically sustainable deep-sea aquaculture environment and create a stable growth environment for cultured organisms with high production quality and increased stock density, additional technical measures were required to mimic natural conditions in the deep sea. The incorporation of a 24 h uninterrupted seawater circulation system in the aquaculture tanks ensures full integration of tank water with deep-sea water; however, this also contributes significantly to carbon emissions due to the large electricity consumption of these equipment operations. Therefore, it is imperative to reduce energy consumption by optimizing energy utilization efficiency and adjusting energy utilization structures within the aquaculture vessel. Furthermore, from the environmental point of view, a high fish-stocking density determined a lower impact per kg increase of fish produced, especially in terms of global warming and cumulative energy demand [48]. Research focusing on feed formulation optimization and feeding methods would be beneficial in improving fish stocking densities.
- "Conson No. 1" is the world's first 100,000-ton aquaculture vessel, and currently the only large-scale deep-sea aquaculture vessel in operation in China. To enhance the sustainable development capacity of this deep-sea marine aquaculture system and further facilitate the transition of the marine aquaculture industry towards low-carbon practices, we will leverage extensive long-term operational data from "Conson No. 1" to explore viable alternative energy sources for deep-sea aquaculture production on aquaculture vessels. Additionally, the systemic impact of various carbon reduction measures on aquaculture systems should be considered comprehensively so that a sustainable carbon reduction path will be found for deep-sea aquaculture systems.

4.2. Suggestions

- Adjust the structure of energy utilization. The adoption of green and low-carbon alternative fuels is imperative, along with the promotion of clean energy sources such as offshore wind energy, photovoltaic energy, biodiesel, methanol, "green ammonia", and "green hydrogen" for application in aquaculture vessels. Extensive research should be conducted on hybrid power combination systems of far-reaching sea vessels, including combinations such as diesel engine and sail, sail and solar power, diesel–methanol dual fuel power, and sail and solar power. Substituting the common grid mix with renewable sources like photovoltaic systems could significantly mitigate the environmental impact associated with electricity generation, particularly in terms of global warming [48].

- Enhance energy utilization efficiency. Rationally set the water exchange cycle rate; effectively recover and utilize the potential energy and part of the kinetic energy in the seawater exchange system of the aquaculture tank; explore and apply energy efficiency technical measures with high maturity such as profile optimization, coating drag reduction and energy-saving appendage in ship design and construction; and enhance ship operational management through information and intelligent technology to improve overall energy efficiency.
- Optimize feed formula and improve feeding method. The theory and technology of nutrition regulation for large yellow croakers should be flexibly applied to fully meet the nutritional requirements of the species during different growth stages, farming methods, seasons, and regions. While the digestibility of raw materials and the processing requirements of various raw materials should be fully considered, feed raw materials with low EF value should be selected. The match between feed N content and fish needs should be studied in order to determine it accurately while improving feed N efficiency through phytase supplementation. Leveraging the controllable conditions advantage of aquaculture tanks, combined with specifications, feeding conditions, feed size, and feeding rate specific to large yellow croakers, promoting their growth could be achieved by increasing feeding frequency and rate.

5. Conclusions

The large-scale aquaculture vessel transfers the traditional land-based industrial closed aquaculture system to the far-reaching sea. In view of the current unclear carbon footprint research on economic marine fish aquaculture in aquaculture vessels, this study took the world's first 100,000-ton large aquaculture vessel, "Conson No. 1", as an example and evaluated the carbon footprint of the whole life cycle process of large yellow croaker farming on the aquaculture vessel in the far-reaching sea. It will provide reference for the development of marine fish low-carbon aquaculture in the far-reaching sea. The study calculated and summarized the CF of five major proceses of feed production, ship constrution, fingerling breeding, adult fish farming, and fish distribution. The results showed that the CF of the whole life cycle of 1 kg large yellow croaker delivered to a wholesaler was 6.2170 kgCO_2e/kg LW. The commodity price CF of large yellow croaker farming on the aquaculture vessel "Conson No. 1" was 31 g CO_2e/CNY. The adult fish farming process emerged as the primary contributor to carbon emissions, with aquaculture energy consumption being a key sub-process followed by feed production. Factors such as equipment energy type and efficiency, along with FCR, were identified as impact factors affecting carbon emissions throughout the life cycle.

The aquaculture vessel system could effectively replicate a stable natural environment in clean offshore areas, offering advantages such as higher stock density, superior aquaculture quality, and longer service life compared to other closed aquaculture systems. Being an innovative, intensive, and closed aquaculture system that had successfully achieved stable and intensive farming environments in the far-reaching sea for the first time, the carbon footprint of the aquaculture vessel was lower than the overall average level of closed systems. Therefore, it represented an optimal choice of marine aquaculture industry development in the low-carbon economy direction. Currently, the power consumption of aquaculture equipment significantly impacts the carbon footprint of fish farming on aquaculture vessels. In future research endeavors, we would focus on adjusting energy utilization structures and enhancing energy efficiency, as well as optimizing feed formulas and improving feeding methods, as to further explore the potential for carbon reduction of fish farming modes on aquaculture vessels.

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Nomenclature

Symbols	
EF	Emission factor (e.g., kgCO_2e/kg DM/km)
EI	Emission intensity, i.e., the emissions per unit of output, e.g., kgCO_2e/kg LW
Q_a	Annual catch production (t)
W	Weight (kg)
TUL	Total unit load of equipment (kwh)
T	Running time (h)
SFC	Diesel generator unit fuel consumption (g/kwh)
F	Diesel oil loss rate (%)
$Qnet_{derv}$	Average low calorific value of diesel oil (TJ/10^4 t)
EF_{derv}	Diesel emission factor (kg/TJ)
R	*R*efrigerant loss rate (%)
GWP	Global Warming Potential
$GWP100_{R404}$	Greenhouse effect of R404 over 100 years(kg CO_2e)
K	Productive GHG emission coefficient of aquaculture workers
N	Number of aquaculture workers
EI_f	Emission intensity of unit commodity price (g CO_2e/CNY)
M_f	Commodity price (CNY/kg)
Acronym	
CF	Carbon footprint expressed in terms of CO_2 equivalent
LCA	Life cycle assessment
LW	Live weight
DM	Dry matter
FCR	Feed conversion rate
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
CF	Carbon footprint of per unit of product weight
FP	Feed production process
SC	Ship construction process
FB	Fingerling breeding process
AF	Adult fish farming process
FD	Fish distribution process
FPP	Feed production sub-process of FP
FPT	Feed transportation sub-process of FP
FBB	Fingerling breeding sub-process of FB
FBT	Fingerling transportation sub-process of FB
AFA	Aquaculture energy consumption sub-process of AF
AFP	Shipborne processing energy consumption sub-process of AF
AFR	Shipborne refrigeration sub-process of AF
AFB	Shipborne packaging sub-process of AF
AFW	Load of aquaculture workers sub-process of AF
LBCC-FAS	Land-based industrial flow-through system
LBCC-RAS	Land-based closed recirculating system
ONP	Open net pen
LBSC-RAS	Semi-closed recirculating system

I-FAS	Intensive recirculating aquaculture systems
SWAS	Floating, flow-through, solid-walled aquaculture system
E-FAS	Extensive flow-through aquaculture system
RSF	Recirculation system farm
FTF	Flow-through system
IPCC	Intergovernmental Panel on Climate Change
CNY	Chinese Yuan

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