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The environmental impact and development direction of grass carp, *Ctenopharyngodon idella*, aquaculture

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Abstract

Grass carp, *Ctenopharyngodon idella*, is the largest freshwater aquaculture fish species worldwide. However, its environmental impacts are increasingly controversial. In this paper, we considered the production of a 1500 g commercial grass carp as an example, analyzed through a life cycle assessment. The results showed that the indicators of global warming potential (GWP), acidification potential, eutrophication potential, freshwater eco-toxicity potential (FAETP), land competition (LC), and fossil energy consumption of producing 1 kg of grass carp were equivalent to 5.7267 kg of CO_2, 0.0648 kg of 1,4-DCB0, 0.0010 kg of P, 0.0276 kg of SO_2, 8.2951 m^2, 0.3491 kg of oil, respectively, and were mainly from feed processing and water pollution. Compared with pig, beef, and sheep production, grass carp production has lower environmental impacts, but in terms of GWP, FAETP, and LC were significantly higher than chicken production, especially water pollution and discharge, which is an important consideration. This study clarifies the direction of grass carp production and key focus areas include producing low carbon and nitrogen emission feed, application of ecological engineering aquaculture system, intelligent mechanization technology and equipment.

KEYWORDS
environmental impact, grass carp, life cycle assessment, low carbon green aquaculture

1 | INTRODUCTION

China is the largest aquaculture country worldwide, accounting for 57.7% of the world's inland aquaculture production in 2021 (FAO, 2022). In China in 2021, the production of aquaculture products, pork, mutton, beef, and chicken were 53.94, 52.96, 5.14, 6.98, and 14.7 million tons, respectively (FAMA, 2022; NBS, 2021). Aquaculture products have become the main source of animal protein for Chinese residents. In the global food system. despite the inland aquaculture especially in Asia has contributed the most to global production volumes and food security, the sustainability of aquaculture has been debated intensely since 2000, and the pressure on the aquaculture industry to embrace comprehensive sustainability (Naylor et al., 2021), in especial the water quality of aquaculture is deteriorating rapidly, diseases occur frequently, pollutant emissions have increased, and the production quality drops, posing severe challenges to the development of aquaculture (X. G. Liu, Che, et al., 2018; X. J. Liu, Luo, et al., 2018).

The Grass carp, *Ctenopharyngodon idella*, is a typical herbivorous fish belonging to Cyprinidae, it is widely distributed in China and has migrated to Asia, Europe, America, and Africa (NARC, 2014). Currently, the Grass carp is the most important freshwater aquaculture species in China, in 2021, the yield was 5.76 million tons accounting for 18.08% of China's total freshwater aquaculture production (FAMA, 2022). For sustainable grass carp production, we must consider the whole process of grass carp production to determine all the key aspects from fry cultivation, adult culture, capture and transportation to market, and analysis of the overall ecosystem including land, resource utilization, culture management, and consumption behavior. In addition, we should account for the framework of environmental footprints regarding the allocation of environmental impact responsibility throughout the production supply chain to establish an integrated framework for mapping, analysis, visualization, and sharing (Mackinson, 2010). At the same time, we also need to compare the environmental impact of major livestock and poultry animals and analyze the characteristics of grass carp production.

Life-cycle assessment (LCA) is a common tool used for assessing the environmental sustainability of products or systems (ISO14040, 2006; ISO14044, 2006). It has been widely applied in the environmental impact analysis of major livestock and poultry production and provided assistance in building a clean and efficient process system. For instance, the special topic of pig production (overview) (Zhang et al., 2017), Life cycle estimation and environmental impact assessment of beef cattle farms (Cheng et al., 2015), LCA of large-scale breeding of broilers (Niu & Han, 2018), and so forth. These studies provide data and references for we compare the environmental impacts of grass carp farming. LCA was used to assess aquaculture since the early 2000s. In the LCA of inland aquaculture, the research mainly focuses on the environmental impact of tilapia production (Boxman et al., 2017; Henriksson et al., 2017; Yacout et al., 2016), polyculture (Aubin et al., 2015; Kluts et al., 2012), and aquaculture of catfish (Bosma et al., 2011; Nhu et al., 2016). However, each aquaculture system has different environmental impacts. Bohnes et al. (2019) reviewed 65 LCA studies on aquaculture and aqua feed systems, and found that most reviews on the applications of LCAs to aquaculture systems have a narrow scope, and when a broader scope is adopted, they only considered a limited number of LCA studies. Overall, the analyses of existing studies demonstrated that important insights can be gained by applying LCA to aquaculture systems, and thus, encouraging an environmentally sustainable aquaculture sector, promoting its systematic use in the design of new aquaculture systems or policies, and/or evaluating and optimizing existing ones (Alexia & Alexis, 2019). It is gratifying that in recent years, there has been increasing related research and assistance provided for aquaculture. Such as in 2022, Viglia et al. (2022) analysis of energy and water use in the USA farmed catfish, toward a more resilient and sustainable production system. Scroggins et al. (2022) assessed total and renewable energy use in farmed catfish and wild-caught salmon, this is the first study to characterize current and potential renewable energy use among parts of the fisheries and aquaculture sectors in the U.S. Koehn et al. linked a nutrient richness index for different foods to LCAs of greenhouse gas (GHG) emissions in the production of these foods to evaluate nutritional benefits relative to this key indicator of environmental impacts. and proposed to disaggregate seafood by species and production method in "planetary health diet" advice (Koehn et al., 2022). Asche et al. (2022) proposed the externality and policy options for developing aquaculture.

To overcome the limitations of using literature review and estimation methods, we used raw data from all life stages and compared them with previous LCA to analyze the environmental impact of producing 1500 g of grass carp. Almost 90% of the processes were modeled based on the raw data. Referring to the LCA in aquaculture (Henriksson et al., 2012), we obtained data from a large-scale grass carp pond farm and a medium-sized aquatic product transportation company in Shanghai, East China, and supplemented data on feed production provided by a large feed manufacturer in Nantong, Jiangsu Province, East China. Thus, the credibility of our results regarding the accuracy and effectiveness of our conclusions improved. In this paper, we (1) for the first time, systematically analyze the quantitative data of all links from feeding to marketing in grass carp production worldwide; (2) clarify the environmental impact categories and impacts of each link in the production process of grass carp, and compared it with those of cattle, sheep, chicken, and pig production to establish the advantages and challenges of grass carp production; and (3) propose improvement measures for the main impact links, thereby providing guidance for the sustainable cultivation of grass carp in China.

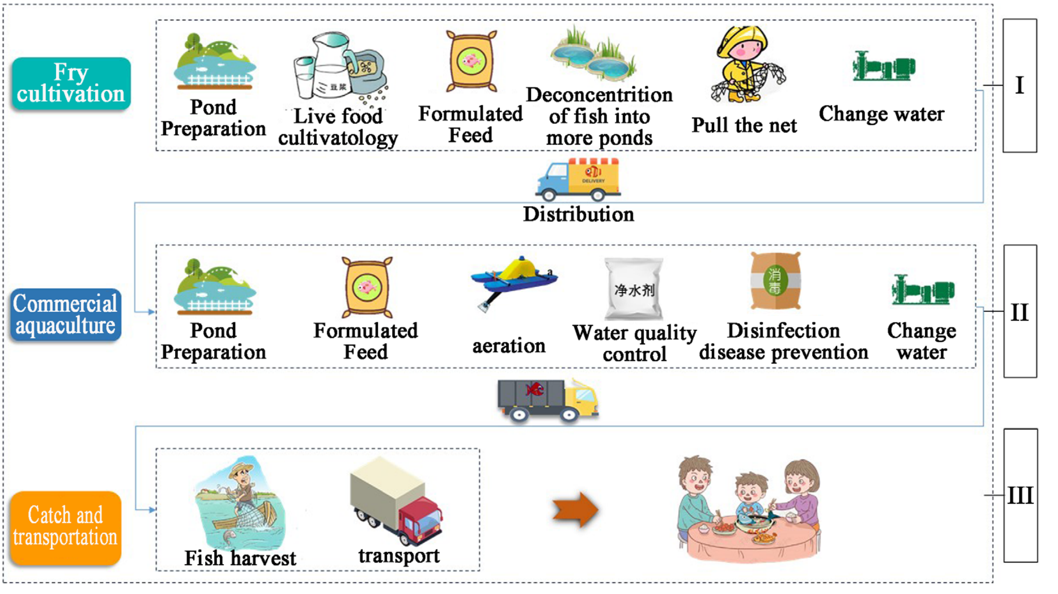
2 | MATERIALS AND METHODS

2.1 | Data collection

The grass carp were aquaculture across China, but mainly in Guangdong (16.23%) and Guangxi (5.44%) in South China, Hubei (15.89%), Hunan (10.94%), and Jiangxi (9.58%) in Central China, Jiangsu (7.36%) and Anhui (4.82%) in East China, Sichuan (4.82%) in Southwest China, and Shandong (4.82%) in North China (FAMA, 2020). In these areas, the grass carp aquaculture from fry to 1500 g of commercial fish was divided into three stages: (I) Fry cultivation stage: from fingerling cultivation to 150 g weight juvenile fish. (II) Adult fish culture stage: from juvenile to an adult fish weight of 1500 g. (III) Capture and transportation stage: this stage included catching and transporting commercial fish to market. The main production process is described in Figure 1a. The average period of grass carp aquaculture was 300–360 days (Lian, 2014; SQSB & NSC, 2018). The grass carp fry was cultivated for 120–150 days, which was divided into two stages. The first stage was from beginning to feeding to a weight of 150 g, which required about 20 days to cultivate 100,000 per mu (Chinese area unit: 667 m^2), then from larvae to 2–3 cm, which required feeding soybean milk at 1200–2000 kg per mu (2.5–3.0 kg soybean = 50 kg soybean milk), 75 kg of quicklime, 250–300 kg of organic fertilizer, 95% of organic fertilizer, 0.5 mg L^{-1} dip Terex, and net drawing once. The second stage involved culturing for 120 days, with the fry growing to 150 g; there were 5000 juvenile fish per mu, and the average survival rate was 85%. The feed coefficient of grass carp in the culture stage was 1.4–1.6 (Zhao et al., 2001). In this stage, usually used 35% of available chlorine powder (1 ppm) is for disinfection once. The water depth of the fry pond was 1.5 m on average. In the fry culture period, 150% of the water was changed, and net drawing and capture were conducted once. Generally, the radius of fry transportation was 500 m (D. S. Li, 1993; J. Li, 2020; J. K. Liu & He, 1992; Wang, 2000).

In China, the 1500 g commercial grass carp production takes approximately 150–200 days. The yield average was 1500 kg per mu (MOA, 2002; SZQTS, 2017) and each 1 m^2 of pond water required 1.43 m^2 of land (MOA, 2011). To produce 1 kg of grass carp culture, approximately 3 m^3 of water is required, which involves emptying the pond once and emptying ~20%–30% of the pond 6–7 times. The grass carp are fed with green fodder and formula feed was 1:1 (weight ratio), and the feed coefficient of the adult grass carp culture stage was 1.6–1.89 (J. L. Li, 2020; Lin et al., 2006; J. K. Liu & He, 1992; Wang, 2000). The 80:20 modes (i.e., stocking 80% grass carp and

(a)



(b)

Supply chain stage	Stage	Material and energy input analysed
Fry cultivation	Pond preparation	Watering/pump, Disinfection/quick lime, available chlorine
	Biological bait cultivation	Fertiliser application, soybean milk processing/ milk machine
	Formula feed processing/ transportation/ feeding	Raw material acquisition and processing/water, electric, transportation/ truck, feeding/feeder
	Fry distribution	Water change/pump, catching, disinfectant
	Water change & aeration	Water change/pump, oxygenation/ aerator
	Draw net exercising	Labour and related materials
	Fishing & Transportation	Catch and loading, vehicle, water, oxygenation/aerator
Adult fish culture	Adult fish pond preparation	Water addition/pump, quicklime, available chlorine powder
	Formula feed process/ transportation/ feeding	Raw material acquisition and processing/water, electric, green fodder transportation/truck
	Change the water & aeration	Change the water/pump, oxygenation/ aerator
	Water quality control	EM bacteria, substrate improver and other biological agents (due to the lower usage, this was ignored)
	Disinfection	Fish drugs/strong chlorine, chlorine dioxide, dibromohydrin
	Water drainage	Drainage/pump
Fishing and transportation	Fishing	Manual catch (material and energy are ignored)
	Transportation to market	Aerator/pump, transportation/van

FIGURE 1 General framework and phases of grass carp process; (a) map of the supply chain showing fry cultivation, adult culture, capture, and transportation stages. These data represent China's grass carp production from 2015 to 2020 (FAMA, 2020, 2022); (b) he supply chain stage and its composition process.

20% bighead carp and silver carp) were used in the adult culture stage (Gui et al., 2019). The stock of grass carp was 1000 per mu, and the average survival was 85%. The average yield of grass carp and silver carp was 1500 and 350 kg, respectively (D. S. Li, 1993). The impeller and water wheel aerator were generally equipped in the grass carp ponds, with 0.75 kW per mu. In the fry culture stage, the aerator operated from August to October for 4–6 h daily, but in the adult fish culture stage from July to November, it was operated for 5–7 h daily. In grass carp pond aquaculture, a vibrating feeder was installed in a pond of 5–10 mu; feeder power ranged from 70 to 120 W. Feeding was carried out for 0.5 h thrice daily for 300 days (Chen, 2017). Because the catch of grass carp is artificial, the energy consumption was ignored. In the future, with extensive use of mechanical fishing, energy consumption will increase. By surveying, we found that the distance from the aquaculture pond to the market was generally within a radius of 50 km, the transport time was 1–1.5 h, and required the operation of a 3-kW aerator. The 5-ton live fish transport vehicle could carry 3 tons of adult grass carp.

2.2 | Data analysis

The life cycle inventory data of all identified materials and data streams were obtained from the Eco invent database (v3.3) (Weidema et al., 2013). To widely assess the environmental impact of commercial grass carp production on air, water, and land in China, we imported Eco invent data produced by the Institute of Life Sciences of Leiden University (Frischknecht & Rebitzer, 2005), and upgraded the database based on data from China's local electric power and energy, and data on local professional materials, energy sources, and transportation from the Beijing University of Technology (Nie et al., 2001). The whole aquaculture process of the grass carp production supply chain to establish an integrated framework for mapping, analysis, visualization, and sharing (Mackinson, 2010). This integrated framework would facilitate sustainability research based on the whole production chain (Fang, 2016; Hellweg & Mila, 2014; O'Rourke, 2014). The data comes from the Chinese Fisheries Statistical Yearbook, the Food and Agriculture Organization of the United Nations (FAO), and literature on grass carp farming. This study also investigated representative inland aquaculture farms and feed mills in China. Therefore, the results were accurate and reliable, this data represents the average level of the environmental impact of inland aquaculture. We used ReCiPe2016 (Huijbregts et al., 2017). To evaluate the environmental impact of the grass carp production process from feeding to market, we selected the LCA index of the global warming potential (GWP), Acidification Potential (AP), eutrophication potential (EP), freshwater eco-toxicity potential (FAETP), land competition (LC), and fossil energy consumption (FEC).

2.3 | Grass carp production framework and phases of LCA

Primary data on material and energy flow were collected for 15 designated processes at these three stages of the grass carp production chain (Figure 1b). The culture period ranged from 330 to 360 days, during which fish were fed 2550 g of granular formula feed and 1500 g of green feed, 7.2 g of water disinfection drugs (10 kg ha^{-1}), and 257 g of quick lime (3000 kg ha^{-1}) were used. In addition, some water quality control agents were used. There are three key output streams during the whole production process and 4.5 m^3 of wastewater was discharged as a result of water exchange. Total nitrogen (TN), total phosphorus (TP), biological oxygen demand (BOD_5), and chemical oxygen demand (COD_{Mn}) were 10.9, 0.75, 28, and 90 mg L^{-1}, respectively (X. G. Liu, 2011). The energy consumption caused by the aerators, feeders, pump, and transporting was 0.324 kWh (450 kWh ha^{-1}), 0.0324 kWh (45 kWh ha^{-1}), and 0.175 kWh (243 kWh ha^{-1}), respectively. The carbon dioxide (CO_2) emitted from transportation was 1.2 kg (1667 kg ha^{-1}). As CO_2 is easily dissolved in water and absorbed by algae and plants, the CO_2 exhaled during growth is negligible. The average survival from fry to commercial fish was 90% (X. G. Liu, Che, et al., 2018; X. J. Liu, Luo, et al., 2018). In the adult harvesting and transportation stage, the output stream included energy and water consumption for maintaining the survival of grass carp.

3 | RESULTS

3.1 | Environmental impact of grass carp aquaculture

From the production supply chain environment analysis tool (SCEnAT) (Koh et al., 2011), the GWP, AP, FAETP, FEC, EP, and LP of producing 1500 g of commercial grass carp were 9.9604 kg CO_2 equivalent (eq), 41.2016 $\times$ 10^{-3} kg

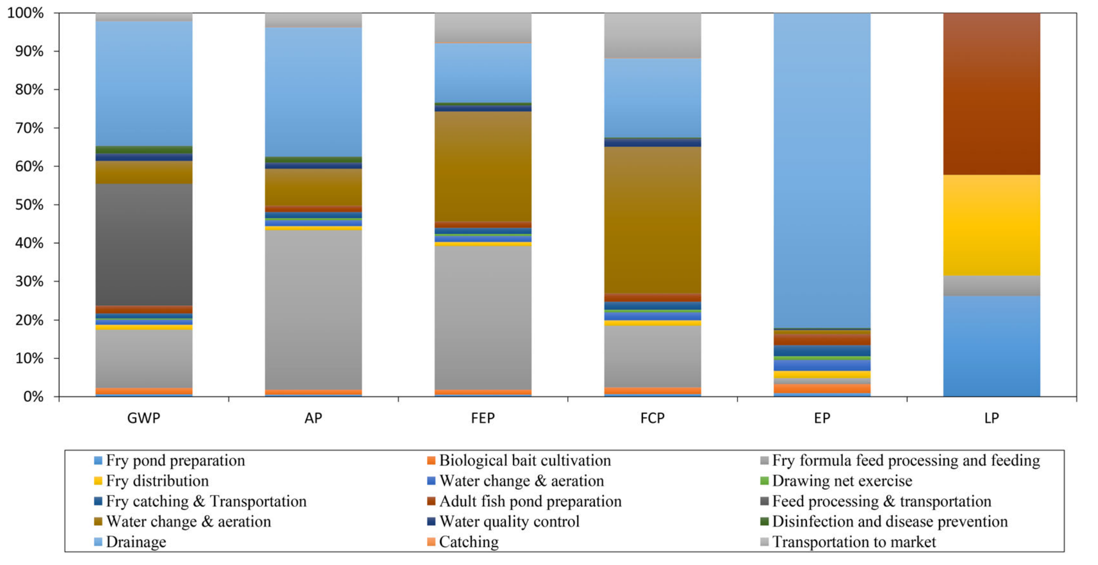


FIGURE 2 Process group environmental impact. Each colored bar section represents the environmental impact of process groups at fry cultivation, adult fish culture, and capture and transportation stages.

SO_2 eq, 99.8681 × 10^{-3} kg 1,4-DCB eq, 0.6863 kg oil eq, 5.8132 × 10^{-3} kg P eq, and 12.443 m^2 crop eq, respectively. Among them, the GWP, AP, FAETP, FCP, EP, and LP in the fry cultivation stage were 0.685 kg CO_2 eq, 2.665 × 10^{-3} kg SO_2 eq, 6.408 × 10^{-3} kg 1,4-DCB eq, 0.047 kg oil eq, 0.696 × 10^{-3} kg P eq, and 1.232 m^2 crop eq, respectively. In the adult culture stage, the same variables were 9.208 kg CO_2 eq, 38.389 × 10^{-3} kg SO_2 eq, 92.316× 10^{-3} kg 1,4-DCB eq, 0.616 kg oil eq, and 5.111 × 10^{-3} kg P eq, and 11.211 m^2 crop eq, respectively. In the capture and transportation stages, the same variables were 0.068 kg CO_2 eq, 0.207 × 10^{-3} kg SO_2 eq, 1.145 × 10^{-3} kg 1,4-DCB eq, 0.023 kg oil eq, 0.0006 × 10^{-3} kg P eq, and 0.00 m^2 crop eq, respectively (Figure 2).

3.2 | Environmental impact at different stages

From the LCA report, the GWP, AP, FEP, FCP, EP, and LP were the highest in the adult fish culture stage, accounting for 92.44%, 93.04%, 92.44%, 89.80%, 87.92%, and 90.10%, respectively. This was followed by the fry cultivation stage, with the same variables accounting for 6.88%, 6.46%, 6.42%, 6.90%, 11.97%, and 9.90%, respectively. The lowest was in the capture and transport stages, with the same variables accounting for 7.34%, 0.02%, 0.12%, 2.52%, 0.00%, and 0.00%, respectively. According to the analysis of production links, we found that, in the highest LCA, the GWP, AP, FAETP, LC, and FEC were caused by the feed production processing, were 86%, 99%, 97%, 76%, 25% and 90% (blue bar in Figure 2). In our research, the feed was purchased from professional feed factories, and the biological bait was cultivated in ponds. The green fodder was planted in a pond ridge. The environmental impact of biological bait was in EP. Another discovery is the EP from the aquaculture stage was the most important environmental factor in grass carp production, accounting for 77.34%. From the LCA, the GWP, AP, FAETP, LC, and FEC were mainly caused by the feed production processing. The EP was mainly caused as a result of the aquaculture process (Figure 3).

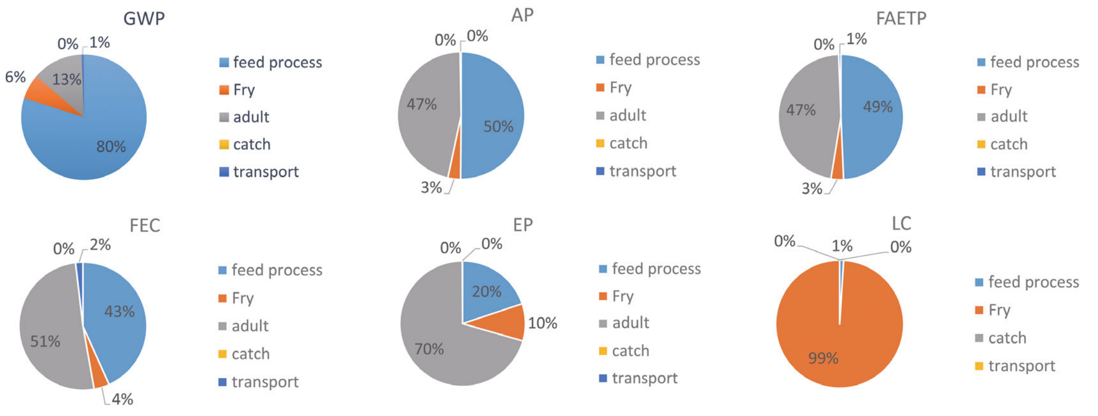
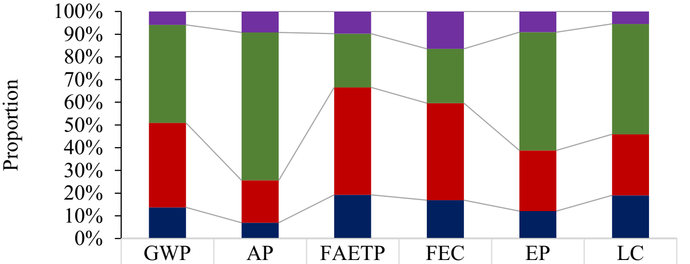


FIGURE 3 Environmental impact in different production stages.



	GWP	AP	FAETP	FEC	EP	LC
Chicken	3.7212	0.0556	0.0497	0.5094	0.0011	3.5947
Mutton	27.0969	0.3911	0.1195	0.7408	0.0062	31.8197
Beef	23.4187	0.1119	0.2395	1.3244	0.0032	17.5381
Grass carp	8.5900	0.0415	0.0972	0.5236	0.0014	12.4427

FIGURE 4 Comparison of environmental impact with other main livestock.

3.3 | Environmental impact characteristics of grass carp aquaculture

To reflect on the advantages and challenges of grass carp production and reduce the environmental impact, we compared the world average environmental impact of beef, mutton, and chicken with that of grass carp. As observed from Figure 4, the environmental impact of producing the same weight of chicken was the lowest, followed by grass carp. The GWP, AP, FEP, LP, and FCP of grass carp of the same weight were significantly lower than those of beef and mutton (regardless of water content). However, the EP of producing 1500 g of grass carp was higher than that of chicken and beef (Figure 4). According to the analysis, the wastewater and waste gas from grass carp production in China contributed extensively to the EP.

4 | HOW TO REDUCE THE ENVIRONMENTAL IMPACT OF GRASS CARP PRODUCTION

From 1955 to 2020, the output of China's inland aquaculture increased 96 times (FAMA, 2022). The high-speed development is from the artificial reproduction of major Cyprinids, and the invention of the aerator and fully nutritious formula feed (X. G. Liu, Che, et al., 2018; X. J. Liu, Luo, et al., 2018). By 2030, about 59% of aquatic products will come from aquaculture, and carp, catfish, shrimp, salmon, and trout will continue to grow (FAO, 2022). Compared with the livestock production, inland aquaculture has obvious environmental advantages and high production efficiency. Therefore, effectively improving the utilization of feed, and adopting an ecological engineering aquaculture system can effectively reduce the environmental impact of inland aquaculture to promote the green and high-quality development of inland aquaculture has great significance. According to the environmental impact analysis, we suggest:

4.1 | Producing low carbon and nitrogen emission feed and adopting precision feeding technology

From the LCA, the GWP, AP, FAETP, LC, and FEC were mainly caused by the feed production processing, and the EP in the culture process was more than 70% and the feed coefficient determines the environmental impact of aquaculture. In China, the average feed coefficient of grass carp culture was 1.8 (Tongwei, 2012). In the process of grass carp pond culture, production was increased by increasing the feed amount, but the feed utilization will decrease (Luo & Xu, 2017). However, if the density of fish was too low, then the output will reduce although the feed is less. Therefore, the price will rise. In addition, in the global grass carp market, the environmental impact of feed can be "exported" by importing cheaper raw materials from other countries. Although this is a means to manage environmental impact, we need new solutions to make the system more sustainable. Such solutions can be implemented in different parts of the supply chain including feed processing, culturing, and market. Improving the efficiency of formulated feed processing, reducing the feed coefficient and energy consumption in the culture process, and reducing mortality in the capture and transportation stage can reduce the environmental impact, which now seems to be possible. Another potential solution is changing from formula feeding to feeding in specific areas and periods depending on the changes in grass carp growth in different areas (X. G. Liu, Che, et al., 2018; X. J. Liu, Luo, et al., 2018). A more radical solution would be to improve grass carp varieties to improve the absorption of C and N in feed, but there remain challenges to achieving this goal. In fact, in a series of adjusted feeding formulas, the GWP of grass carp culture was greatly reduced (Samuel et al., 2013). One possible consequence of reducing feed while maintaining production may be a decrease in protein content in grass carp meat. At present, the protein content of the feed is an important consideration in commercial contracts with feed manufacturers. The protein content of formulated grass carp feed is 20%–30% in China (Cho & Bureau, 2015; B. Li et al., 2014; SQSB & NSC, 2018) in the culture period with supplemented green feed (generally 1 kg grass carp fed with 1 kg green fodder). Because there is more sediment generated by using green fodder and increased AP (43.65% of LCA), LP (8.99% of LCA), and EP, green fodder is rarely used for grass carp aquaculture.

In summary, a carbon-nitrogen-phosphorus balanced formula needs to be developed to improve the nitrogen and phosphorus conversion rate. Feed processing technology needs to be improved upon, including the production of easily absorbed feed (such as fermented feed). The collection and processing efficiency of raw materials should be improved and carbon emissions should be reduced. Concurrently, precision feeding technology and equipment to reduce feed waste should be promoted.

4.2 | Application of ecological engineering high energy efficiency aquaculture system

Except for feed processing, the FEC mainly comes from oxygenation and water exchange in the culture stage, among that the oxygenation, water exchange, and feeder production 60%, 30%, and 6% accounted for the FEC, respectively. Grass carp production in China in 2014 was 537.68 $\times$ 10^4 tons according to the "first agricultural non-point source pollution survey in China" (Shen et al., 2018) it has produced 15.119 $\times$ 10^4 tons TN, 3.155 × 10^4 tons TP, 23.915 × 10^4 tons COD, and 0.776 × 10^4 tons ammonia. Unlike beef, mutton, and chicken, in the fry and adult fish culture stage, the water exchange and drainage contributed 69.87% to EP in the LCA of grass carp production, which is the situation of pond grass carp culture in China. Owing to the rapid development of pond aquaculture in the 1970s to 1980s in China, the phenomenon of pond "aging" intensified following long-term use of the ponds. Poor facilities and extensive management practices have increased the environmental impact (X. G. Liu, 2011). According to an investigative report on aquaculture pollution in China in 2013, the aquaculture pollutants were COD (1,424,000 tons), TN (76,750,000 tons), NH_4^+-N (15,140,000 tons), and TP (13,650,000 tons), with COD, TN, and TP accounting for 4.20%, 3.00%, and 5.50% of agricultural pollutant emissions, respectively (Shen et al., 2018). Since 2000, the Chinese government has attempted to improve pond aquaculture by adopting ecological engineering principles in aquaculture, which has saved water and reduced emissions by more than 50% compared with traditional aquaculture practices (X. G. Liu et al., 2014). This has greatly reduced EP during grass carp production. In addition, the government has been building greenhouses to shorten cultural time and reduce the environmental impact in different regions. For example, in spring, grass carp fry has been transported from Guangdong, Hainan, and other tropical areas to be cultivated in greenhouses in Jiangsu, Hubei, and other areas of northwest China. Such practices have shortened the cultivation period to 60 days to reach the market and reduced environmental impacts. According to the second national survey of agricultural non-point source pollution in China, after 10 years of promoting pond aquaculture ecological engineering technology, the unit output emission intensity of COD, TN, and TP in aquaculture has decreased by 20.0%, 23.8%, and 30.7%, respectively (MEP, 2020).

The separation of ponds by constructing facilities and sequential batch culture is a new method of pond culture developed in recent years. In this system, different-sized fingerlings are divided into different ponds. By differing the conditions of culture, the energy efficiency can be improved by more than 15%, and the N and P emissions could be reduced by more than 25%. Simultaneously, the optimal capacity of the pond can be maintained through batch marketing (Gui et al., 2019; MEP, 2020). In addition, planting corn, grass, and other economic crops in pond ridges, using

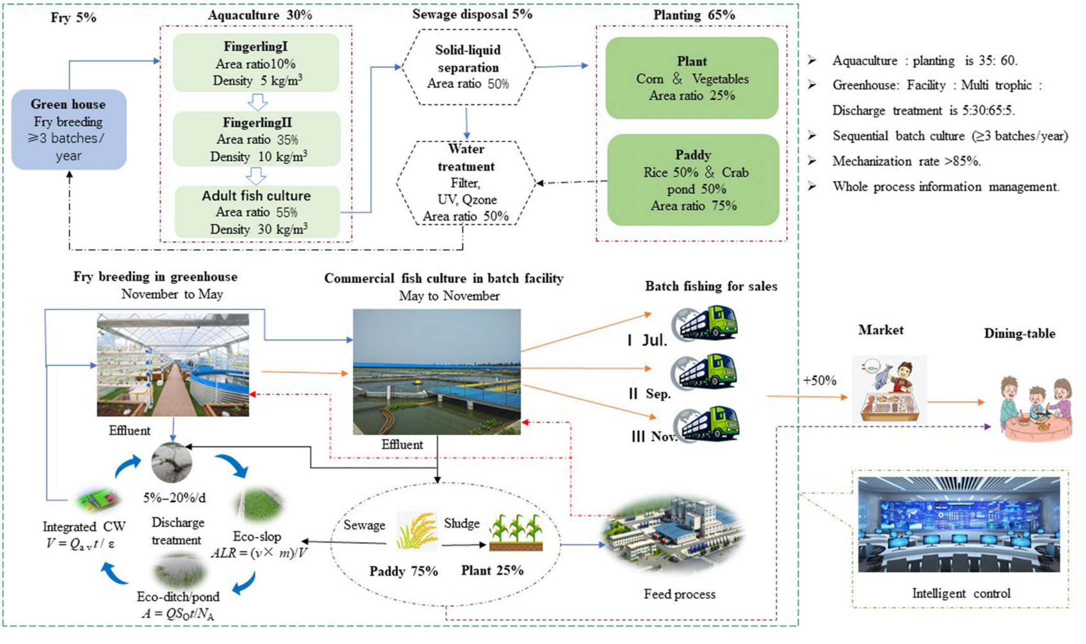


FIGURE 5 The low environmental impact grass carp production system.

the sediment from the pond as fertilizer for these plants every year, and continuously harvesting corn straw and grass to feed grass carp can reduce nutrient emissions (Chen, 2013).

Based on successful cases, an ecologically engineered and energy-efficient aquaculture mode needs to be established, such as the South–North aquaculture relay, indoor and outdoor combination, multi-nutrient level sequential aquaculture, fish light complementation, pond ecological engineering, and so forth. The aim is to establish an energy-efficient aquaculture system (Figure 5).

4.3 | Applying mechanized and intelligent technology and equipment in aquaculture systems

According to an investigation, the feed waste caused by improper feeding in the aquaculture process reaches 10%–20%, It not only increases the breeding cost but also increases the environmental pollution. Hence, there is a need to promote intelligent mechanization technology and equipment to increase the intelligent feeding, efficient oxygenation, precise water quality control, mechanical fishing, and other equipment systems, to form an intelligent mechanized production system for the entire process.

5 | OUTLOOK

Aquaculture products and practices are diverse; consequently, the impacts on the environment are different, and therefore people have varying views on aquaculture. In response to rapid global development, it is necessary to consider the global aquaculture structure from a new perspective. Additional actions need to be taken to solve the conflict between aquaculture development and environmental impacts and establish a low-carbon and pollution-reduction approach to aquaculture.

Food production and consumption cause approximately one-third of total GHG emissions (Tara, 2011; Tubiello et al., 2015; Vermeulen et al., 2012), and therefore delivering food security challenges not only the capacity of our production system but also its environmental sustainability (Foley et al., 2011; Godfray et al., 2010; Horton et al., 2016; Tilman et al., 2002). Human-animal protein mainly comes from livestock, poultry, and aquatic products. Aquaculture is a faster food production sector than other major animal protein production. Since 1961, the annual growth rate of global fish consumption has been twice that of population growth, more than the sum of all terrestrial animal meat (FAO, 2018). It is predicted that, by 2030, the total output of global aquatic products will reach 201 million tons, with aquaculture being the significant contributor to this increase. The scale and value of the global aquaculture market are dominated by China (FAO, 2018). According to current production, the annual output of grass carp production in China will be more than 6.4 million tons by 2030. Therefore, the environmental impact of grass carp production will become a major challenge for Chinese aquaculture in the 21st century. To increase grass carp production while decreasing pollution, we should focus on the conflict between food supply and reducing environmental impacts.

AUTHOR CONTRIBUTIONS

Liu Xing-Guo: Conceptualization; methodology; formal analysis; writing-original draft; validation. **Shen Hong-ye**: Formal analysis; writing-original draft; writing-review and editing. **Gu Zhao-jun**: Formal analysis; investigation; software. **Cheng Guofeng**: Formal analysis; investigation. **Wang Jie**: Methodology; validation. **Zhu Hao**: Conceptualization.

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DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the findings of this study are available within the paper.

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