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REVIEW ARTICLE

Current status of industrialized aquaculture in China: a review

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Abstract

Industrialized aquaculture is an essential trend for aquaculture development in China, owing to its considerable advantages in lower water consumption, higher productivity, and sustainability. However, information on its current status has been scarce up to now. This paper reviewed the current status and has identified existing problems as well as proposing possible solutions for the development of industrialized aquaculture in China. This field is still at an early stage of development and is mainly distributed in coastal regions. Major constraints on industrialized aquaculture include high capital and operational costs, the uncompetitive market price of aquatic products, uneven distribution of production and farming areas, a lack of suitably experienced managers and operators for recirculating aquaculture systems, and the coronavirus disease 2019 (COVID-19) pandemic. Possible solutions to these problems include technological innovations in systems optimization, the use of renewable energy sources and biofloc technology, the pollution-free certification of industrial aquaculture products, increased numbers of professionals in water quality control and waste management, and the financial assistance to companies and farmers along the aquaculture industrial chain.

Keywords Industrialized aquaculture · Production · Farmed species · Aquaculture models · Farming area

Fish are a valuable source of nutrients (e.g., protein, essential fatty acids, and trace elements) for human nutrition and play an essential role in global food security (Tacon and Metian 2013). According to the Food and Agriculture Organization (FAO), fish provided 17% of animal proteins and 7% of all proteins for the global population in 2017 (FAO 2020). Aquaculture has been the main supplier of fish for human consumption since 2014, accounting for 52% of the total in 2018 (FAO 2020). China is the world's largest aquaculture producer: in 2020, it produced 49.90 million tonnes of aquaculture fish, accounting for 57.03% of the global total (FAO 2022). However, the development of Chinese aquaculture has been confronted with many problems due to excessive use of traditional culture systems (e.g., ponds and cages), such as disease outbreaks, environmental pollution, and food safety concerns (Cao et al. 2007; Liu et al. 2017). These problems have seriously restricted the sustainable development of the Chinese aquaculture industry. There is an urgent need to improve this situation by developing culture systems in which fish production can be highly controllable and environmentally friendly, such as industrialized aquaculture (Lei et al. 2014).

Industrialized aquaculture is an important future trend for aquaculture development in China, owing to its advantages in saving water and land resources and promoting higher productivity and sustainability. However, little information on its current status has been available up to now. This paper reviews the current status of industrialized aquaculture in China and summarizes the main issues in its development, as well as proposing possible solutions for its future direction.

Definition of industrialized aquaculture in China

Industrialized aquaculture usually refers to land-based industrialized (indoor-tank) farming (Gui et al. 2018). It controls the water quality and water temperature for aquaculture through machinery or automation equipment following the principles of continuity and flow of the process; forms an independent system for fish breeding, fish

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hatchery, and commercial fish production; and makes it possible to carry out continuous nonseasonal production with high efficiency (FBMA 2021). According to government statistics, industrialized aquaculture systems can be defined as circulating filter type, warm drainage type, ordinary flow type, and warm water type (FBMA 2021).

Compared with traditional culture methods (e.g., ponds and cages), industrialized aquaculture systems have the following advantages:

(1) They have more controllable conditions, higher culture density, and more extended production periods. Industrialized aquaculture systems can achieve high-density culture, free aquaculture from climatic constraints, and prolong the fish growth period by controlling the physical and chemical factors (e.g., water temperature and dissolved oxygen) that are required for the optimal growth of fish.
(2) They save land and water resources: compared with conventional aquaculture systems, some industrialized aquaculture systems (e.g., recirculating aquaculture systems) use 90–99% less water and less than 1% of the land area (Ebeling and Timmons 2012).
(3) Their construction sites are more flexible. Conventional aquaculture systems need to be built close to the water source and are generally far from the aquatic products markets. However, owing to the systems' highly efficient utilization rate of water resources, industrialized aquaculture can be constructed in places where water resources are not abundant and are close to the aquatic products markets. This helps in cutting the cost of aquatic products distribution.
(4) They improve feed utilization and reduce pollutant emissions. The feed conversion ratio value in industrialized aquaculture systems ranges from 0.8 to 1.1 (Ahmed and Turchini 2021), while in conventional culture systems, it is between 1.3 and 1.7 (Naylor et al. 2021). Compared with traditional culture systems, industrialized aquaculture improves feed utilization and reduces the detrimental effects of aquaculture effluents on the environment.

Farmed species in industrialized aquaculture in China

Farmed aquaculture species in China have similarities and differences when compared with developed countries (Table 1). Farmed species in European countries are concentrated on sturgeon (order Acipenseriformes), Atlantic salmon (*Salmo salar*), Arctic char (*Salvelinus alpinus*), rainbow trout (*Oncorhynchus mykiss*), European eel (*Anguilla anguilla*), Nile tilapia (*Oreochromis niloticus*), pike perch (*Stizostedion lucioperca*), and European lobster (*Homarus gammarus*). North American aquaculture focuses on oyster mussel (*Epioblasma capsaeformis*), Arctic char (*Salvelinus alpinus*), yellow perch (*Perca flavescens*), hybrid striped bass (*Morone chrysops* x *M. saxatilis*), and tilapia. Industrialized aquaculture in Japan focuses on Japanese eel (*Anguilla japonica*), pejerrey (*Odontesthes bonariensis*), Japanese flounder (*Paralichthys olivaceus silver*), kuruma shrimp (*Marsupenaeus japonicus*), white shrimp (*Penaeus vannamei*), and abalone (*Haliotis* sp.). Farmed species in China include grouper (*Epinephelus* sp.), large yellow croaker (*Pseudosciaena crocea*), half-smooth tongue sole (*Cynoglossus semilaevis*), giant river prawn (*Macrobrachium rosenbergii*), white shrimp, turbot (*Scophthalmus maximus*), and starry flounder (*Platichthys stellatus*); of these, turbot and half-smooth tongue sole are the main cultured species in industrialized aquaculture (Wang et al. 2013).

Industrialized aquaculture models in China

The development of industrialized aquaculture in China has been a process of gradual change over time. In the 1970s, industrialized aquaculture models were dominated by still water and flowing water aquaculture. In the 1980s, China introduced foreign recirculating aquaculture systems and

Table 1 Comparison of cultured species in industrialized aquaculture

Area	Farmed species	References
Europe	Atlantic salmon, rainbow trout, European eel, pike perch, Arctic char, sturgeon, Nile tilapia, and European lobster	Dalsgaard et al. (2013); Martins et al. (2010)
America	Mussels, Arctic char, rainbow trout, yellow perch, hybrid striped bass, and tilapia	Jones et al. (2005); Summerfelt et al. (2004); Tidwell (2012); Watanabe et al. (2002)
Japan	Japanese eel, pejerrey, Japanese flounder, kuruma shrimp, white shrimp, abalone, and tilapia	Takeuchi (2017)
China	Grouper, large yellow croaker, half-smooth tongue sole, giant river prawn, white shrimp, turbot, starry flounder, mud crab, eel, rainbow trout, abalone, and sturgeon	Feng et al. (2004); Gui et al. (2018); Li et al. (2011)

began to develop recirculating aquaculture; however, the introduced facilities were not widely applied due to the high capital and operating costs (Jing et al. 2018). At the end of the twentieth century, industrialized flowing water aquaculture characterized by "utility sheds + underground seawater" was widely promoted and applied; its advantages included economic efficiency, reduced environmental impact, and high yield (Lei 2010). In the twenty-first century, with the strategic demand for the benefits of a circular economy, energy-saving, and emissions reduction, the closed recirculating aquaculture model was developed in China (Fan and Fang 2020; Wang et al. 2013). At present, industrialized aquaculture models in China can be divided into three models: flowing water systems, recirculating aquaculture systems (RAS), and aquaponics systems (Fig. 1) (Cang 2019; Chen et al. 2009; Li et al. 2016).

Flowing water systems use underground water as the primary water source. After culture, the wastewater, enriched with nitrogen and phosphorus, is discharged directly (Fig. 1) (Cang 2019; Shen et al. 2014). Despite a higher production rate and a shorter culture period, this model has some drawbacks. These systems ignore ecological and environmental protection measures and use many resources (e.g., water, land, and electricity) with low efficiency; additionally, they overlook long-term interests, intensify intra-industry competition, and make it difficult to standardize the management and development of aquaculture (Cang et al. 2018).

RAS are the critical technology that enables aquaculture to meet the world's demand for aquatic products in an environmentally friendly manner (Ebeling and Timmons 2012). These systems control the water environment, remove harmful substances (e.g., NO_2^- and NH_3) from the aquaculture water, and realize the recycling of water resources through the extensive use of advanced technologies (Tidwell 2012). RAS are mainly composed of fish tanks, physical filtration devices (e.g., drum filters), biological filtration devices (e.g., fluidized bed filters), disinfection devices (e.g., ultraviolet light), and aeration devices (Figs. 1 and 2) (Losordo et al. 1998). Physical filtration devices remove solid waste (uneaten feed and feces) (Cripps and Bergheim 2000). Biological filtration devices convert NH_3 produced by fish metabolism into NO_3^- by microbial nitrification

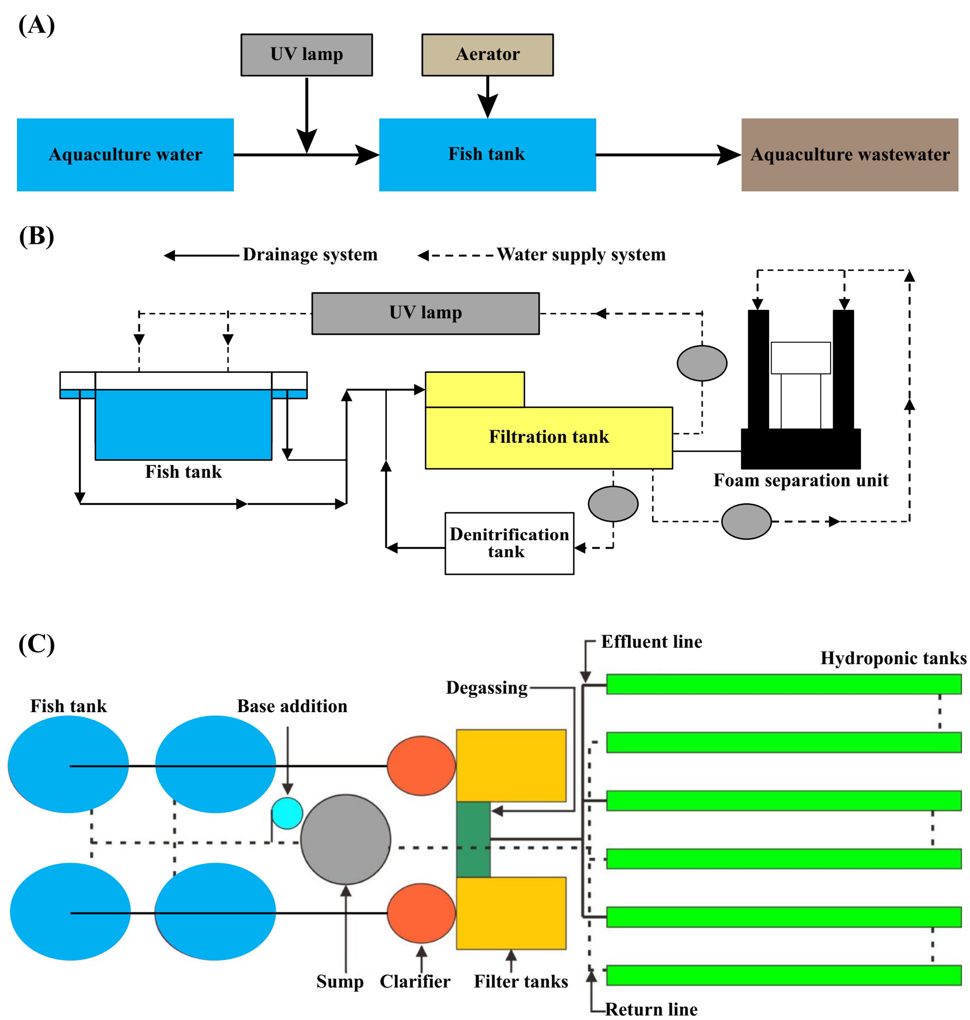

Fig. 1 Common models of industrialized aquaculture systems in China. **A** A flowing water system; **B** a recirculating aquaculture system; **C** an aquaponics system

Fig. 2 A recirculating aquaculture system in Luoning County, Luoyang, Henan, China

(Gutierrez-Wing and Malone 2006) or convert NH_3 into N_2 by microbial denitrification (van Rijn et al. 2006). Compared with conventional culture models, RAS have the advantages of little land occupation, infinite scalability, less water usage, and high production (Gui et al. 2018; Piedrahita 2003). RAS are becoming more popular in China, especially in Shandong, Tianjin, and Liaoning provinces. However, the proportion represented by this model in industrialized aquaculture is still low. Taking the coastal provinces of Liaoning, Hebei, Tianjin, and Shandong provinces as examples, the area occupied by RAS accounts for only 6.72% of the total area of industrialized aquaculture (Wang et al. 2013).

The biological treatment (microbial nitrification and denitrification) of RAS produces the greenhouse gas N_2O, whose effect is more than 310 times greater than CO_2 in inducing global warming (Hu et al. 2012). In addition, a large quantity of NO_3^- and PO_4^- is present in the rearing water after treatments in RAS; water exchange is needed daily to reduce the concentrations of these substances (Lekang 2013). To reduce the potential impact of such compounds on the environment and fish health, aquaponic systems were developed. Aquaponics is a combination of aquaculture and hydroponics (Fig. 1) that uses vegetables in hydroponics systems to absorb waste (e.g., CO_2^-, NO_3^-, and PO_4^{3-}) from the rearing water and produce O_2. These systems achieve the double purpose of producing farmed fish and hydroponic vegetables (Goddek et al. 2015; Love et al. 2014). The International Standards Organization (ISO) 14,001 Environmental Management Standard (EMS) could be also effective in controlling and decreasing environmental effects of RAS. ISO 14001 EMS identifies all environmental aspects of activities, uses a logical and effective methodology to rank such aspects into order of significant impact upon the environment, focuses on the management system to seek to improve upon, and minimizes such significant environmental impacts (Whitelaw 2004).

Current status of industrialized aquaculture in China

According to government statistics, records on industrialized aquaculture production in China can be traced back to 2003 (FBMA 2022). At that time, the production from industrialized aquaculture accounted for 0.4% of total aquaculture production (FBMA 2022). After an 18-year effort, the production and farming area achieved great progress. In 2021, the total production and total farming water volume of industrialized aquaculture were 6.8×10^5 tonnes and 9.6×10^7 m^3, respectively (Fig. 3).

The farming area occupied by industrialized aquaculture increased from 3.3×10^7 m^3 in 2003 to 9.6×10^7 m^3 in 2021, with an annual growth rate of 6.2%. During that period, the

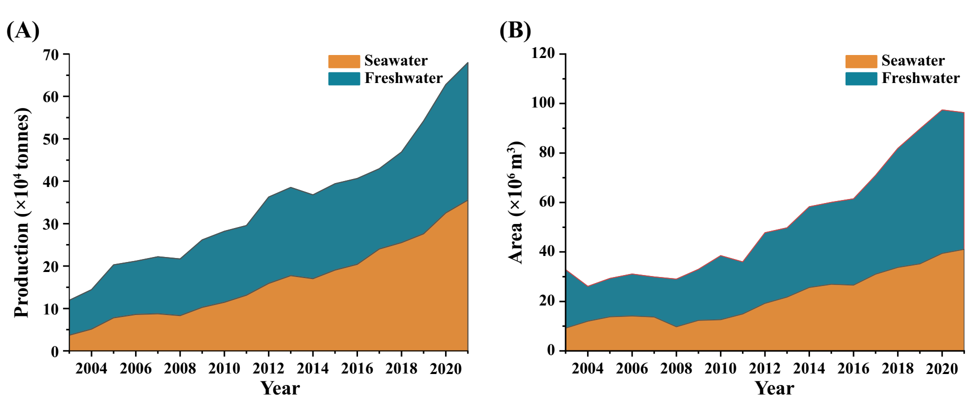

Fig. 3 Production (**A**) and farming area (**B**) of industrialized aquaculture in China from 2003 to 2021. Data from China fishery statistical yearbook 2004–2022

freshwater industrialized aquaculture area increased from 2.4×10^7 m^3 to 5.5×10^7 m^3 and seawater industrialized aquaculture from 9.2×10^6 m^3 to 4.1×10^7 m^3 (Fig. 3). From 2003 to 2021, industrialized aquaculture production in China increased from 1.2×10^5 tonnes to 6.8×10^5 tonnes, with an annual growth rate of 10.2%. During the same period, industrialized freshwater aquaculture production increased from 8.2×10^4 tonnes to 3.2×10^5 tonnes and industrialized seawater aquaculture production from 3.7×10^4 tonnes to 3.6×10^5 tonnes (Fig. 3). In the past 19 years, the proportion of industrialized aquaculture production has shown a significant increasing trend in China's total aquaculture production. In 2003, industrialized aquaculture production accounted for 0.4% of the total, while in 2021 it had increased to 1.3% (FBMA 2022).

Shandong and Fujian provinces rank high above others in industrialized aquaculture production and farming area. In 2021, these provinces occupied 57.1% of the total industrialized aquaculture production and 54.4% of the total industrialized aquaculture area (Fig. 4).

Industrialized freshwater aquaculture

Fujian, Shandong, Hubei, Jiangxi, and Anhui are the main provinces of industrialized freshwater aquaculture, together accounting for 73.6% and 60.5%, respectively, of the total industrialized freshwater aquaculture production and area in 2021 (Fig. 5). Between 2011 and 2021, industrialized freshwater aquaculture production in Zhejiang and Jiangxi provinces changed the most. Jiangxi province increased from 0 (0.0%) to 20,721 tonnes (6.4%), while Zhejiang province decreased from 79,671 tonnes (48.4%) to 12,610 tonnes (3.9%). Fujian and Jiangsu provinces showed a steady upward trend, respectively, increasing from 34,194 and 15,564 tonnes in 2011 to 91,893 and 19,383 tonnes in 2021 (Fig. 5).

Industrialized seawater aquaculture

Shandong, Liaoning, Fujian, Jiangsu, and Hainan are the main provinces of industrialized seawater aquaculture in China, together accounting for 88.9% and 79.2%, respectively, of the total industrialized seawater aquaculture production and area in 2021 (Fig. 6). Among the five provinces, Shandong has the highest production and Jiangsu the lowest. Industrialized seawater aquaculture production in Shandong province rose from 58,601 tonnes (44.6%) in 2011 to 177,037 tonnes (49.8%) in 2021. During the past 10 years, Jiangsu province rose from 7,517 tonnes (5.7%) to 20,272 tonnes (5.7%) (Fig. 6).

In terms of the proportion of production, Fujian and Hainan provinces showed a steadily increasing trend, from 6.2% and 1.9% in 2011 to 12.4% and 7.3% in 2021, respectively. Liaoning province showed a downward trend, from 30.9% in 2011 to 13.8% in 2021. Jiangsu and Hebei maintained relatively stable proportions, accounting for 5.7% and 5.3% of the total seawater industrialized aquaculture production in 2021 (Fig. 6).

Existing problems and possible solutions for industrialized aquaculture in China

Current industrialized aquaculture in China has made important breakthroughs in aquaculture theory and technology, such as the increasing maturity of RAS production and management systems, and the wide application of improved and new technologies (e.g., automation and intelligent control) (Chang et al. 2020; Xu et al. 2022; Zhu et al. 2022a). However, there are still many problems that limit the sustainable development of industrialized aquaculture (Shao et al. 2021; Xin et al. 2019).

Firstly, high capital and operational costs limit the broad application of industrialized aquaculture in China (Zhang et al. 2020). High capital costs are the main limitations of industrialized aquaculture (e.g., RAS) (Badiola et al. 2012; Murray et al. 2014; Zhu et al. 2022b). Engle et al. (2020) examined the cost structures of RAS for Atlantic salmon, trout, and tilapia and found that capital costs were the greatest cost for RAS, representing 23–57% of the total costs. In addition, high energy consumption (e.g., heating, water treatment, oxygenation, and pumps) is the main factor contributing to the elevated operational costs of industrialized aquaculture (Aubin et al. 2006; Badiola et al. 2018; Colt et al. 2008). Energy use in RAS

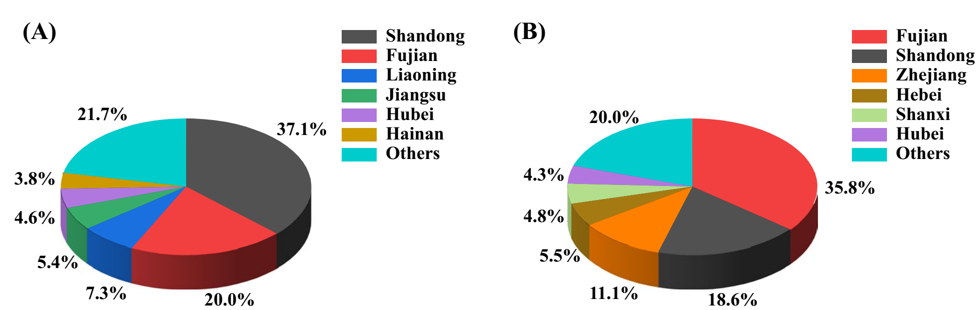

Fig. 4 Industrialized production (**A**) and farming area (**B**) of major provinces in 2021. Data from China fishery statistical yearbook 2022

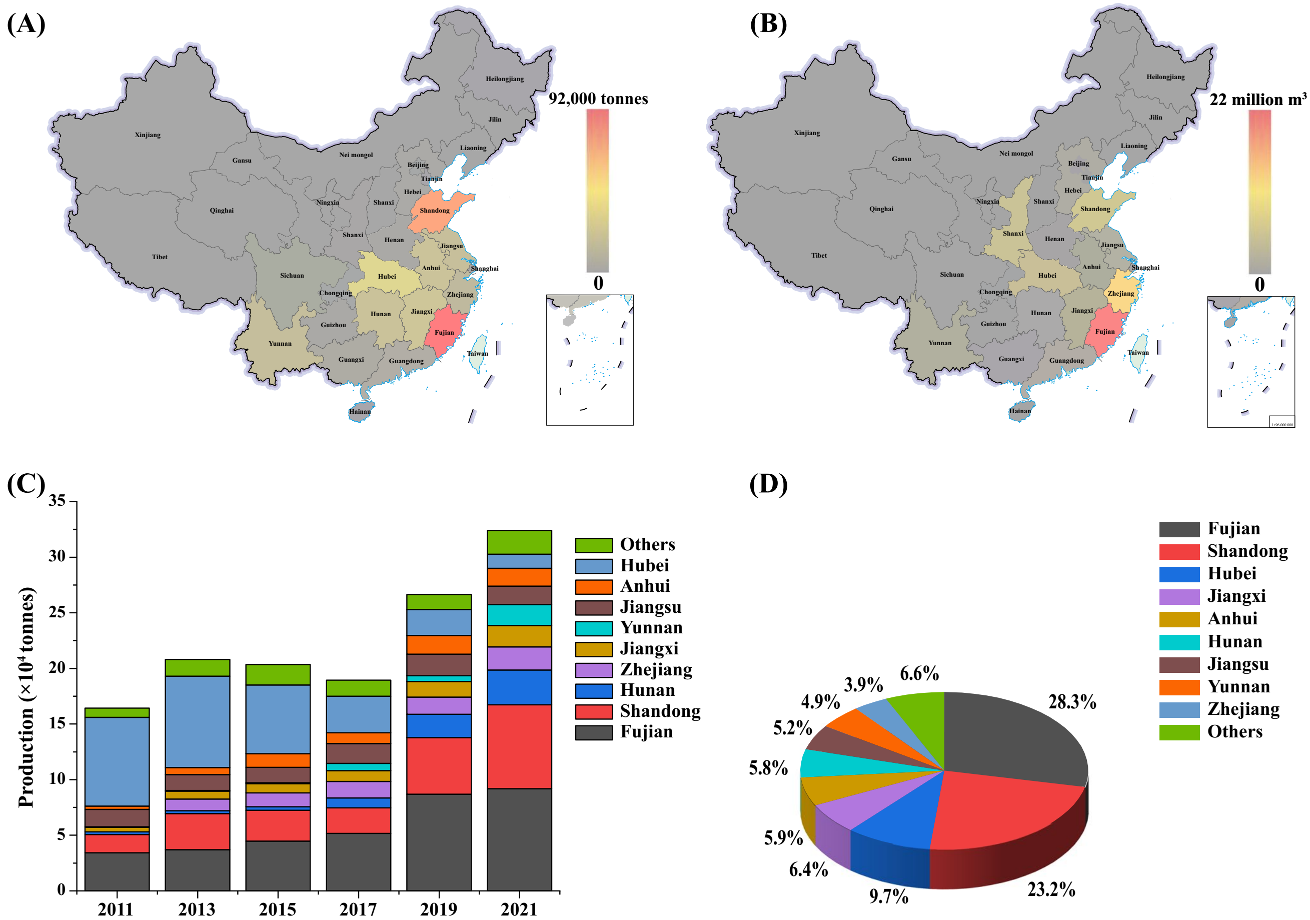

Fig. 5 Current status of industrialized freshwater aquaculture in China. Distribution of industrialized freshwater aquaculture production (**A**) and farming area (**B**) in 2021; **C** industrialized freshwater aquaculture production in China from 2011 to 2021; **D** the proportion of industrialized freshwater aquaculture production of the main regions in 2021. Data from China fishery statistical yearbook 2012–2022

ranges from 2.9 to 81.5 kWh per kg fish produced (Badiola et al. 2018). Moreover, feed cost is an integral part of operational cost in industrialized aquaculture (Murray et al. 2014). In RAS-producing salmon, tilapia, and trout, feed costs were considered the second-greatest cost (Engle et al. 2020; Zhu et al. 2022b). Technological innovations in systems with low cost and suitable design could reduce the capital and operational costs, and promote wider adoption of industrialized aquaculture (Ahmed and Turchini 2021). The use of renewable energy sources (such as geothermal and solar energy) can reduce the operational costs in industrialized aquaculture (Badiola et al. 2018; Farghally et al. 2014; Fuller 2007; Wei 2020). Biofloc technology (BFT), a technique for enhancing water quality and producing proteinaceous feed in aquaculture through balancing carbon and nitrogen in the system (Crab et al. 2007; De Schryver et al. 2008), has been proven helpful in supplying feed for aquatic animals (Han and Su 2022; Khanjani and Sharifinia 2020; Kuhn et al. 2009).

Secondly, the selling price of farmed species in industrialized aquaculture does not have a comparative advantage over other culture systems. The fish market price is a crucial factor in determining the profitability of industrialized aquaculture (Arifa et al. 2022; Mohammad et al. 2018; Pham et al. 2016). Economic analysis of RAS for goldfish (*Carassius auratus*) suggested that the market price of fish is the most sensitive parameter affecting the system's profitability (Mohammad et al. 2018). However, the high capital and operational costs to produce farmed species and access markets similar to other culture methods (e.g., pond culture) do not make the fish market price attractive. The break-even price in industrialized aquaculture and the market selling price of turbot was 42.9 RMB/kg and 38.0 RMB/kg, respectively, in one study (Zhao 2015). With the improvement of living standards, people are paying more attention to health and are willing to pay extra for pollution-free and environmentally friendly agricultural products (Liu and Wang 2022). Compared with traditional culture models, industrialized aquaculture has a considerable

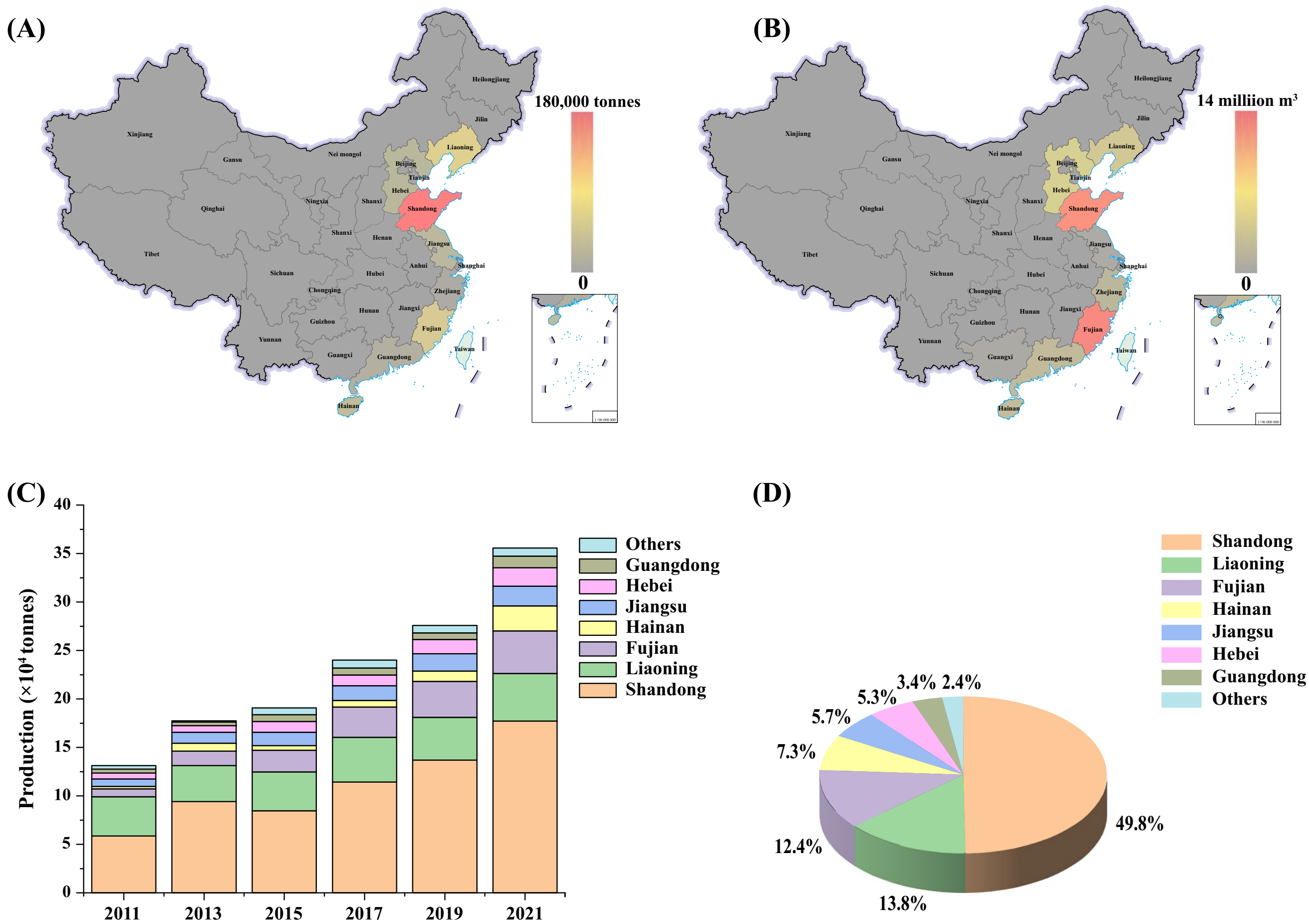

Fig. 6 Current status of industrialized seawater aquaculture in China. Distribution of industrialized seawater aquaculture production (**A**) and farming area (**B**) in 2021; **C** industrialized seawater aquaculture production in China from 2011 to 2021; **D** the proportion of industrialized seawater aquaculture production of the main regions in 2021. Data from China fishery statistical yearbook 2012–2022

advantage in controlling fish production and producing pollution-free aquatic products. Thus, increasing the pollution-free certification and enhancing the advantages of green brands of industrialized aquaculture products could improve their market competitiveness.

Thirdly, industrialized aquaculture technology is still at an early stage, and regional development is uneven. At present, flowing water aquaculture is the main model of industrialized aquaculture in China (Cang 2019; Zhang et al. 2020; Zhao 2015). Cang (2019) studied industrialized aquaculture models for turbot and found that the farming area of flowing water aquaculture accounted for 97.9% of the total industrialized aquaculture area. As mentioned above, industrialized aquaculture in China mainly exists in coastal provinces (such as Shandong and Fujian provinces) and is seldom found in inland regions or underdeveloped coastal regions. According to government statistics, in 2020 about half of provinces in China had less than 1,000 tonnes of industrialized freshwater aquaculture production; for marine industrialized aquaculture production, Guangxi, an underdeveloped coastal province, had only 569 tonnes (FBMA 2021). In order to decrease the detrimental effects of flowing water systems on the environment, sufficient funding is needed to promote the transformation of culture models from flowing water aquaculture to closed recirculating aquaculture and aquaponics (Zhang et al. 2020). Additionally, coastal regions should fully exploit their technological advantages, invest necessary elements in industrialized aquaculture, and continuously optimize their production systems. Inland regions should fully utilize their resource advantages and improve their industrialized aquaculture technology (Zhong et al. 2022).

Fourthly, there remains a lack of suitably experienced RAS managers and operators. Industrialized aquaculture emphasizes multi-professional work and needs more specialized and competent people in its workforce (Badiola et al. 2012; Zhu et al. 2022b). Poor management due to a lack of professionals in water quality control, water chemistry, and waste management is a major factor leading to the failure of RAS operations (Badiola et al. 2012; Zhang et al. 2020; Zhu et al. 2022b). Therefore, it is necessary to train people in the responsibility of managing industrialized aquaculture systems.

Finally, the development of industrialized aquaculture has been adversely affected by the coronavirus disease 2019 (COVID-19) pandemic. The COVID-19 pandemic, and the measures being taken to contain the epidemic, has made a negative impact on the aquaculture sector (including industrialized aquaculture) in China (Yuan et al. 2022). These adversely effects include the disruption of the normal management of fish farmers, a decline in fish price and the market demand for fish and aquatic products, an overstock of aquatic products in aqua farms, and an increase in production costs and financial difficulty in operation for fish farmers (Chang et al. 2022; Yuan et al. 2022; Zhang et al. 2021). A series of strategies have been recommended to deal with these problems, such as the support of free legal advice and financial assistance to companies and farmers along the aquaculture industrial chain (Chang et al. 2022; Yuan et al. 2022).

Conclusion

Industrialized aquaculture is an environmentally friendly and sustainable culture model, possessing considerable advantages over traditional culture systems in saving water and resources, increasing production and food security of aquatic products, and reducing pollutant emissions. At present, industrialized aquaculture is still at an early stage of development and is mainly distributed in coastal regions. The development of industrialized aquaculture is restricted by high capital and operational costs, the uncompetitive market price of fish, uneven distribution of industrialized aquaculture, a lack of suitably experienced RAS managers and operators, and the COVID-19 pandemic. Possible solutions to these problems include technological innovations in systems optimization, the use of renewable energy sources and biofloc technology, the pollution-free certification of industrialized aquaculture products, more trained professionals in water quality control and waste management, and the financial assistance to companies and farmers along the aquaculture industrial chain.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish All authors have reviewed and approved the manuscript for publication.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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