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REVIEW

REVIEWS IN Aquaculture

Advancements and hurdles of deeper-offshore aquaculture in China

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Abstract

Open offshore areas boast strong physical self-purification capacity and abundant non-fossil energy resources, such as wind, waves, and solar energy. Consequently, the global community anticipates nearshore aquaculture to transition towards offshore to help increase production, alleviate eutrophication, and reduce greenhouse gas emissions. To date, China has constructed over 40 sets of deeper-offshore aquaculture (DOA) infrastructures, encompassing various types of pens, cages and closed containment systems. Although DOA holds vast potential to address food security and aquaculture sustainability in China, its current development trajectory struggles to meet those goals and primarily achieves profitability by focusing on high-value species or products. For DOA to realize its potential, innovative production systems must tackle three key contradictions: enterprise profitability versus product affordability, clean energy-based products versus carbon-intensive products, and automated operation versus re-employment of coastal fish farmers. Resolving these contradictions requires the development of a large-scale, anti-typhoon offshore enclosure that integrates mariculture with other industries, such as wind farming, food processing, and tourism. This approach will foster a sustainable balance between profitability, environmental impact, and employment opportunities in the sector.

KEYWORDS

aquaculture, challenges, deeper-offshore, development strategies, innovation, sustainability

1 | INTRODUCTION

Since 1961, global consumption of aquatic foods has grown at an average annual rate of 3.0%, outpacing both the annual world population growth rate (1.6%) and the combined meat production rate of all terrestrial animals (2.8%) for the same period. With aquaculture production, including seaweed, surpassing capture production,[1] it plays an increasingly crucial role in ensuring food security and alleviating poverty and hunger. Aquatic animals use feed more efficiently than farmed terrestrial animals, so increasing consumption of farmed aquatic food products, especially mariculture products, could potentially reduce land requirements for feed crops as the global population is expected to reach 9.7 billion by 2050.[2,3]

Aquaculture presents significant potential for creating healthy, diversified, empowering and environmentally sustainable food systems, with production predicted to double by 2050.[4] As the world faces the pressing challenges of expanding population, resource constraints, water eutrophication, and climate change, the global community expects aquaculture to fulfil the goals of helping increase food production, relieve eutrophication, and reduce greenhouse gas emissions.[5–8]

In this instance deeper-offshore aquaculture (DOA) refers to mariculture activities in open offshore or archipelagic areas, utilizing strong storm-resistant infrastructures with rigid steel structures or closed containments and automatic feeding systems. DOA offers advantages such as vast space for expansion, strong physical self-purification capacity, access to non-fossil energy resources such as wind, waves, and solar energy, and reduced exposure to anthropogenic pollution sources.[9–12] If properly developed, DOA could be a viable approach to increasing seafood production, alleviating water eutrophication, and reducing greenhouse gas emissions. This article reviews the practices, challenges and development strategies of DOA in China, providing insights essential for the sustainable growth of this emerging mariculture production system worldwide.

2 | DOA PRACTICES IN CHINA

China is a leading aquatic food producer, contributing 57.5% of the world's farmed aquatic food products in 2020.[1] However, China ranks among the 13 most water-scarce countries globally, with its per capita water resources being only a quarter of the global average.[13] Additionally, China faces a shortage of arable land resources, with a per capita arable land area less than 40% of the global average.[14] The scarcity of water and arable land resources constraints further development of inland aquaculture in China through expanding aquaculture ponds or increasing water exchange rates. In this context, the Chinese have high expectations for mariculture to meet the rising demand for food and proteins, particularly for DOA.[15–17]

While nearshore bivalve and seaweed cultivation remain the primary components of China's mariculture (Figure 1a), their growth rates have slowed down substantially over the past decade (Figure 1b) due to the limited carrying capacity of nearshore waters and competition with other marine-related industries.[16] China's nearshore aquaculture area comprises around 40% of the total sea area within the −10 m isobath, close to the carrying capacity threshold.[18] In contrast, offshore fish farming has grown at an annual rate of 14.9% during the same period (Figure 1b).[19] This has led to a general trend in Chinese mariculture moving from the nearshore to offshore areas.

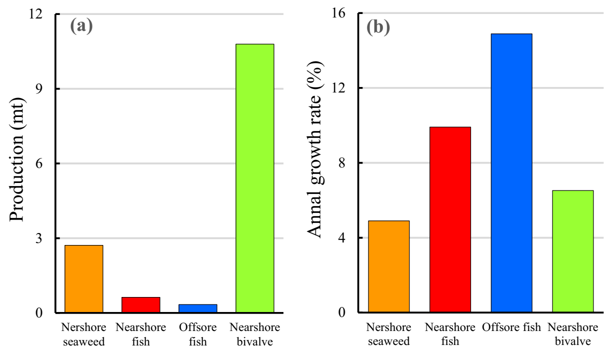


FIGURE 1 Status of China's mariculture. (a) Production of nearshore and offshore aquaculture; seaweed production expressed as dry weight.[19] (b) Average annual growth rates of nearshore and offshore aquaculture systems over the past decade.

2.1 | Definition of DOA

The great diversity of coastal hydrographical environments across different countries complicates the definition of offshore aquaculture and DOA. The United States has defined aquaculture in the exclusive economic zone of 3–200 nautical miles as offshore aquaculture.[20] Lovatelli et al. (2010)[9] defined offshore aquaculture based on hydrography, environment, access, operation, and exposure as the activity located in areas >2 km or out of sight from the coast, in water depths >50 m, and under the influence of strong hydrodynamic energy. Some scholars have also defined offshore aquaculture as the aquaculture practiced in open sea areas with water depths >20 m.[12,16,21]

The continental shelf of China is generally flat, and the scale of mariculture is enormous. Currently, bivalve and seaweed culture rafts in many Chinese sea areas have extended to the areas 15 km off the coast, where the water depth remains less than 20 m. Therefore, offshore aquaculture in China is defined as aquaculture activities in open sea areas with a depth of >20 m, employing wind-wave resistant facilities such as high-density polyethylene (HDPE) frame cages.[19]

In this review, DOA refers to mariculture activities located in open offshore areas or archipelagic areas using storm-resistant infrastructures typically composed of rigid steel structures or closed containments and automatic feeding systems. DOA possesses the potential to be operated in deeper-offshore areas or on high seas. In recent years, the term 'deep-sea aquaculture' has become more popular.[12,16,22,23] However, oceanologists and geologists do not consider the sea areas where mariculture activities take place as truly deep-sea locations. Therefore, DOA is a more appropriate term than 'deep-sea aquaculture'.[24]

In the 1980s, Sweden and the former Soviet Union began developing steel frame infrastructure for farming fish in open seas.[8,11] Subsequently, the United States developed several DOA infrastructures for offshore fish farming.[8] Although there were primitive fish culture cages in China 2200 years ago, the common modern cages were introduced to China from Japan in 1973.[25] It was not until 2017 that China built its first DOA infrastructure, an aquaculture vessel with a displacement of 3500 tons. Currently, Norway and China are at the forefront of DOA,[4,26–28] with a total of more than 40 sets of DOA infrastructures built in China mainly in the last 5 years (Table 1).

Classifying DOA infrastructures is challenging due to its diverse types.[27–30] If based on their relationship with the seabed, DOA infrastructures can be divided into pens and cages; if based on water permeability, they can be divided into closed containments and pens or cages; and if based on their status in water layers, they can be divided into floating, submersible, and semi-submersible cages. In this review, the types of DOA infrastructures are categorized into six groups: offshore pens, stabilized cages, floating cages, submersible cages, semi-submersible cages, and closed containments (Table 2).

TABLE 1 Deeper-offshore aquaculture infrastructures built in China.

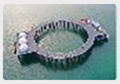
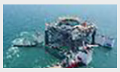
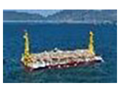
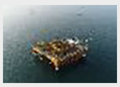
No.	Images	Name and type	Company and location	Parameters	Status
1		'Lanzuan 1', Offshore pen	Mingbo Aquatic; Operating in Laizhou Bay of the Bohai Sea	400 m in perimeter; Culture volume of 160,000 m^3	Built in 2018 In operation
2		'Lanzuan 2', Offshore pen	Mingbo Aquatic; Operating in Laizhou Bay of the Bohai Sea	160 m in perimeter; Culture volume of 20,000 m^3	Built in 2020 In operation
3		'Dachendao', Offshore pen	Jiaojiang Xinglang Mariculture; Operating in the Jiaojiang Sea area of the East China Sea	360 m in perimeter; Culture volume of 50,000 m^3	Built in 2021 In operation
4		'Changjing 1', Stabilized cage	Yantai Jinghai Marine Fishery; Operating in the Changdao Sea area of Bohai Sea	66 m long and 66 m wide; Culture volume of 64,000 m^3	Built in 2019 In operation
5		'Genghai 1', Stabilized cage	Shandong Modern Fisheries Corporation; Operating in the Yantai Sea area of the Bohai Sea	80 m in diameter total; Culture volume of 27,000 m^3	Built in 2020 In operation
6–13		'Jinghai 001' series, Stabilized cage	Yantai Jinghai Marine Fishery; Operating in the Changdao Sea area of the Bohai Sea	68 m long and 68 m wide; Culture volume of 70,000 m^3	Built in 2021–2023 In operation
14		'Dehai 1', Floating cage	Zhuhai Xinpingmao Fishery; Operating in the Wanshan Sea area of the South China Sea	91.3 m long and 27.6 m wide; Culture volume of 30,000 m^3	Built in 2018 In operation
15		'Tianan Lanjing', Floating cage	Penglai ZhongbaiJinglu Shipping; Operating in the Changdao Sea area of the Bohai Sea	52 m in perimeter; Culture volume of 31,000 m^3	Built in 2020 In operation
16		'Kenhuang 1', Vessel-shaped floating cage	Zhejiang Guangsheng Fishery Operation in Taizhou Sea area of the East China Sea	A single point mooring system without turbine; 148 m long, culture volume of 63,500 m^3	Built in 2022
17		'Wanqu Hengzhou', Submersible cage	Zhuhai Agriculture Investment Holding; Operating in the Hengzhou Sea area of the South China Sea	Damping structures; Culture volume of 91,000 m^3	Built in 2021 In operation
18		'Zhenyu 1', Rotatable floating cage	Shanghai Zhenhua Heavy Industry Group; Operating in the Lianjiang Sea area of the East China Sea	Rugby cage; Culture volume of 13,000 m^3	Built in 2022 In operation
19–21		'Taiyu 1' series, Rotatable floating cage	Fujian Taiyuan Shipping; In the Dinghai Bay of the East China Sea	Octagonal cage; Culture volume of 10,000 m^3	Built in 2021 In operation
22–23		'Dinghai 1' and 'Dinghai 2' Rotatable floating cage	Fujian Xinmao Fishery; Operating in the Lianjiang Sea area of the East China Sea	Octagonal cage; Culture volume of 15,800 m^3	Built in 2022 In operation
24–25		'Qiandong 1' series, Rotatable floating cage	Fujian Qiandong Marine Granary Tech; Operating in the Lianjiang Sea area of the East China Sea	Octagonal cage; Culture volume of 20,000 m^3	Built in 2022 In operation
26		'Zhenyu 2', Liftable floating cage	Shanghai Zhenhua Heavy Industry Group; Operating in the Lianjiang Sea area of the East China Sea	Liftable cage; Culture volume of 20,000 m^3	Built in 2022 In operation
27		'Deep Blue 1', Submersible cage	Rizhao Wanzefeng Fishery; Operating at 120 nm to the Yellow Sea	Submersed in summer; Culture volume of 50,000 m^3	Built in 2018 In operation

TABLE 1 (Continued)

No.	Images	Name and type	Company and location	Parameters	Status
28		'Shenghai 1', Submersible cage	Zhejiang Shenlan Marine S & T Co., Ltd. Operation in Zhoushan Sea area of the East China Sea	110 m in perimeter and culture volume of 10,000 m^3	Built in 2020 In operation
29		'Ningde 1', Semi-Submersible cage	Ningde Jinao Industry; Operating in the Sishuang Sea area of the East China Sea	Submersed under bad conditions; Culture volume of 50,000 m^3	Built in 2022 In operation
30		'Penghu', Semi-submersible cage	Guangzhou Institute of Energy Conversion, CAS; Operating in the Wanshan Sea area of the South China Sea	Wave power fish farm; Culture volume of 10,000 m^3	Built in 2019 In operation
31		'Hongdong 1', Semi-submersible cage	Fujian Mintou Deep-sea Aquaculture Equipment Leasing; Operating in the Dinghai Bay of the East China Sea	Multi-functional platform for tourism etc.; Culture volume of 62,000 m^3	Built in 2022 In operation
32		'Fubao 1', Semi-submersible cage	Fujian Zhongxin Yongfeng Industry; Operating in the Lianjiang Sea area of the East China Sea	37.3 m long and 33.3 m wide; 12,960 drawer-like net boxes for abalone farming	Built in 2019 In operation
33		'Guobao 1', Semi-submersible cage	Shandong Nanhuangcheng Marine Development; Operating in the Changdao Sea area of the Bohai Sea	36 m long and 36 m wide; 36,988 drawer-like net boxes for abalone farming	Built in 2020 In operation
34		'Lulan Yuyang 61699', Aquaculture vessel	Rizhao Wanzefeng Fishery; Operating at 120 nm to the Yellow Sea	86 m long, 18 m wide, and 14 tanks; Culture volume of 2000 m^3 for salmonid farming	Built in 2017 In operation
35		'Minde', Aquaculture vessel	Hainan Minde Marine Development; Operating in the Haikou Sea area of the South China Sea	98.2 m long, 22.8 m wide and side opening; Culture volume of 6200 m^3	Built in 2020 In modification
36		'Guoxin 001', Aquaculture vessel	Qingdao Guoxin Development; Operation in the Yellow Sea and the East China Sea	96.8 m long, 16.6 m wide; Culture volume of 945 m^3	Built in 2021 In operation
37		'Guoxin 1', Aquaculture vessel	Qingdao Guoxin Development; Roaming among the Chinese Seas	249.9 m long and 45 m wide; Culture volume of 90,000 m^3	Built in 2022 In operation
38		'Haixia 1', Semi-submersible cage	Fuding City Construction Investment; Operated in the Fuding Sea area of the East China Sea	The net cage is 141 m in diameter and 12 m high; Culture volume of 150,000 m^3	Built in 2020 Scraped
39		'Lanxin', Floating cage	Weihai Haien Lanhai Aquaculture; Trialled in the north Yellow Sea	For salmonid farming; Culture volume of 60,000 m^3	Built in 2020 Scraped
40		'Zhenbao 1', Semi-submersible cage	Fujian Zhongxin Yongfeng Industry; Operating in the Lianjiang Sea area of the East China Sea	24.6 m long and 16.6 m wide; 5000 drawer-like net boxes for abalone farming	Built in 2018 Scraped
41		'Zhenbao 2', Semi-submersible cage	Shanghai Zhenhua Heavy Industry Group; Operating in the Putian Sea area of the East China Sea	23 m long and 15 m wide; 5000 drawer-like net boxes for abalone farming;	Built in 2019 Scraped
42		'Shaobing', Submersible cage	Weihai Haien Lanhai Aquaculture; Trialled in the North Yellow Sea	For salmonid farming; Culture volume of about 500 m^3	Built in 2019 Scraped
43		'Ocean Farm 1', Semi-submersible cage	Ocean Farming AS, Norway; built at CSIC, Qingdao, China	110 m in diameters, high 69 m, with culture volume of 150,000 m^3	Built in 2017 In operation in Norway

(Continues)

TABLE 1 (Continued)

No.	Images	Name and type	Company and location	Parameters	Status
44		'Jostein Albert', Vessel-shaped floating cage	Norwegian Nordlaks, built at CIMC Raffles, Yantai, China	Dynamic positioning with turbine; 385 m long, 59.5 m wide, culture volume of 400,000 m^3	Built in 2020 In operation in Norway
45		'Haiwei 1', Semi-submersible cage	Guangdong Haiwei Agricultural Group Co., LTD; Operating in the Zhanjiang Sea area of the South China Sea	46 m long and 23 m wide, culture volume of 15,000 m^3	Built in 2022 In operation

TABLE 2 Types and features of deeper-offshore aquaculture infrastructures.

Types		Features and cases
Offshore pens or enclosures		Rigid steel or concrete structure or copper alloy net; less cost to build, but weak resistance to storm and waves and restricted to relatively shallow waters; The 'Lanzuan 1' (No. 1 in Table 1)
Stabilized cages		Stabilized to the seabed by pile legs or central column; easy to operate, but lacks of structure elasticity and l restricted to relatively shallow waters; The 'Jinghai 001' (No. 6)
Floating cages	Floating platform cages	Gravity-based equipment; resilience to wave forces, but easy to deformation; The 'Dehai 1' (No. 14)
	Rotatable or liftable cages	Exposed to the air partly; antifouling, but high structure loads; The 'Dinghai 1' (No. 21)
	Vessel-shaped floating cages	With and without turbomachinery; great ability to withstand storms, but high carbon footprints or prone to hypoxia; 'Jostein Albert'
Submersible cages or submerged cages	Integrated submersible or submerged cages	With a feeding system in superstructure; avoidance of bad surface conditions, but high operating costs; beware of fish body malformation; The 'Deep Blue 1' (No. 26)
	Simple submersible or submerged cages	Without a feeding system on it; Avoidance of bad surface conditions, simple structure, but need a service vessel or barge for feed delivery; beware of fish body malformation; The former 'Deep Blue 1' and 'Aquapod™'
Semi-submersible cages	Semi-submersible fish cages	Less affected by wave loadings and has a multi-function platform, but high construction cost; The 'Ningde 1' (No. 27)
	Semi-submersible abalone cages	Feed is delivered to drawer-like net boxes severally; less affected by wave loadings but feeding is complicated; The 'Fubao 1' (No. 30)
Closed containments	Aquaculture vessels	Movable to search for a suitable farming site or to avoid unfavourable conditions; high cost and high carbon footprint; The 'Guoxin 1' (No. 35)
	Sea-based aquaculture tanks	Prevention of sea lice, but high cost and high carbon footprint; The 'Neptun'

2.2 | Offshore pens

Offshore pens, which utilize rigid steel, concrete structures, or copper alloy nets, are often employed for fish farming in China's archipelagic areas. The primary distinction between offshore pens and offshore cages lies in the absence of a bottom net in pens, which exposes them to the natural seabed, whereas cages possess a permeable bottom net and usually float on the water surface or are suspended in the water column. Though offshore pens are less expensive to construct, they lack structural elasticity and have a limited capacity to withstand strong storms. Therefore, they are often placed in archipelagic areas or on the leeward side of a peninsula.

The 'Lanzuan 1' (No. 1 in Table 1) and the 'Dachendao' (No. 3) are typical offshore pens in China. The former has a circumference of 400 m[31] and is located in the Laizhou Bay of the Bohai Sea, on the leeward side of the Shandong Peninsula. The pen is used for farming groupers (only in summer), spotted knifejaw (*Oplegnathus punctatus*), and tongue sole (*Cynoglossus semilaevis*). It features two walking corridors and two multi-functional platforms for recreational fishing, sight-seeing, and catering. The 'Dachendao' is situated in the Taizhou Sea area of the East China Sea, with a 360-m perimeter, and is used for cultivating large yellow croakers (*Larimichthys crocea*). The upper part of the netting is made of ultra-high molecular weight polyethylene, and the lower part is made of a copper alloy.[31]

2.3 | Stabilized cages

Stabilized cages are steel frame cages stabilized in the waters by pile legs or central columns. These types of cages are easy to operate but have high structural loads, limited structural elasticity, and are restricted to relatively shallow waters. The 'Jinghai 001' (No. 6) is an example of pile leg cages in China, located in the Yantai Sea area of the Bohai Sea. It has a culture volume of 70,000 m^3, mainly used for farming black snapper (*Sebastodes fuscescens*) and sea bass (*Lateolabrax japonicus*).

2.4 | Floating cages

Floating cages are a type of DOA that relies on the buoyancy provided by a floating platform. They include floating platform cages, rotatable or liftable cages, and vessel-shaped floating cages (Table 2). Floating platform cages maintain their netting shape through the floating platform and the gravity of sinkers. They have high resilience to wave forces but can easily deform under strong currents. The 'Dehai 1' (No. 14) and the 'Tianan Lanjing' (No. 15) are typical floating platform cages. The former has a culture volume of 30,000 m^3 for farming large yellow croakers and cobia (*Rachycentron canadum*) in the Zhuhai Sea area of the South China Sea.

Rotatable or liftable cages are designed for antifouling applications. A portion of the cage can be exposed to air, allowing sunlight to kill biofoulers when the underwater net mesh becomes excessively fouled. The 'Dinghai 1' (No. 22) is a typical rotatable cage for farming large yellow croakers with a culture volume of 15,800 m^3. The 'Zhenyu 2' (No. 26) cage can be lifted for antifouling or harvesting purposes. Antifouling is crucial for improving the safety and efficiency of DOA,[32] but the cages' resistance to strong typhoons requires further testing.

Vessel-shaped floating cages feature robust, storm-resistant steel frames with or without turbomachinery. The 'Kenhuang 1' (No. 16) is a vessel-shaped cage with a single-point mooring system without a turbine, while the 'Jostein Albert' (No. 44) is a powered vessel-shaped cage built in China and operated in Norway. The former measures 148 m in length and has a culture volume of 63,500 m^3 for farming large yellow croakers, while the latter spans 385 m and has a culture volume of 400,000 m^3 for farming salmon.[33] The advantage of the vessel-shaped floating cages is their exceptional ability to withstand strong storms, but their net cage units located at the stern without turbomachinery are prone to hypoxia sometimes due to their elongated structure.[34] In contrast, powered cages can adjust their direction to avoid hypoxia, but this comes at the cost of an increased carbon footprint and higher operational expenses.

2.5 | Submersible and submerged cages

The terms 'submersible cages' and 'submerged cages' are often used in the literature of offshore aquaculture[12,27,28] and share similar structures. The distinct difference between them is the primary mode of operation. The primary mode for the normal operating conditions of the submersible cages is on the surface, whereas that of the submerged cages is in a submerged position.

Submersible cages may need to be sunk into the water temporarily to avoid adverse weather conditions,[29] benefit from low-temperature water beneath the thermocline,[35] or reduce sea lice infestations.[36] However, long-term submerged culture can cause gas loss in the swim bladders of physostomous fish (e.g., *Salmoniformes*, *Cypriniformes* and *Clupeiformes*) and malformation in farmed fish.[37,38] Therefore, floating culture is the norm for these species. In contrast, physoclistous fish (e.g., *Perciformes*) and most aquatic invertebrates can thrive in water for long period without access to atmospheric air. Thus, submerged cages can be used as the normal mode for these species, with cages floated only during maintenance or harvesting.

Submersible cages can be classified as integrated and simple (Table 2). Integrated submersible cages come equipped with feeding systems in their superstructure, enabling self-sustaining submerged culture for a specific duration. Simple submersible cages lack feeding systems, requiring service vessels or barges for feed delivery while submerged. These cages can effectively avoid storms and do not need structures as robust as floating cages. However, they have higher operating costs than floating cages due to reduced visibility during the submerged period.

The 'Deep Blue 1' (No. 27), located 120 nautical miles southeast of Qingdao in the Yellow Sea, is an integrated submersible cage with a culture volume of 50,000 m^3 for farming salmonids.[35] The surface water of the Chinese seas is too warm in summer to culture cold-water fish species using floating cages. However, there is a cold-water mass beneath the thermocline in the central Yellow Sea in summer,[39] where water temperature and dissolved oxygen levels are suitable for culturing salmonids.[35,40] In summer, the 'Deep Blue 1' submerges below 20 m depth, allowing farmed fish to survive the warm season. When the water temperature drops below 18°C in late autumn, the cage is brought back and floated to the surface, enabling year-round salmonid farming. Salmonids are physostomous fish that often swim to the water surface to replenish gas in their swim bladders and maintain buoyancy.[38] When the 'Deep Blue 1' is submerged during summer for several months, air domes are needed for the fish to replenish gas in their swim bladders.[35,38]

Russian 'Sadco' and American 'Aquapod™' are examples of simple submersible cages.[9,27] In fact, the 'Deep Blue 1' mentioned above was initially a simple submersible cage, but after modifications, including the addition of a tube tower with a feeding system, it was transformed into an integrated submersible cage.

2.6 | Semi-submersible cages

Semi-submersible cages are the most popular type of infrastructure used in DOA worldwide.[9,11,27,28] The main difference between floating cages and semi-submersible cages is that the buoyancy of the former is provided by the buoyant tanks (pontoons) on the water surface, whereas the buoyancy of the latter is provided mainly by larger buoyant tanks (pontoons) below the water surface.

These can be ballasted or de-ballasted to match payload and freeboard needs, as well as to raise the platform from a deep to shallow draft. Compared with submersible cages, semi-submersible cages are designed to have small water-plan areas, which are less affected by wave loadings. A multi-function platform on the semi-submersible cage can be used for aquaculture operations, tourism, game fishing, and catering.

The 'Ningde 1' (No. 29) in the Ningde Sea area of the East China Sea is a semi-submersible cage with a culture volume of 65,000 m^3 for culturing large yellow croaker. When a typhoon approaches or harmful algal blooms occur around the farming area, parts of the infrastructure can be submerged in deeper water to avoid the effects of the typhoon or harmful algal blooms. The 'Penghu' (No. 30) in the Zhuhai Sea area of the South China Sea possesses a culture volume of 15,000 m^3 to culture golden pompano (*Trachinotus ovatus*) and groupers. Power is provided by wave energy generators.[33]

The 'Fubao 1' (No. 32) is a semi-submersible abalone cage located in the Lianjiang Sea area of the East China Sea and possesses 12,960 drawer-like net boxes for abalone farming.[41] During feeding, the boxes are lifted above the water. After feeding, the boxes are submerged in water. More labourers or complex facilities are required to feed the animals.

2.7 | Closed containments

Closed containments include aquaculture vessels and sea-based aquaculture tanks. Aquaculture vessels powered with turbomachinery are movable to search for suitable farming sites or to avoid unfavourable conditions such as typhoons or harmful algae blooms. Sea-based aquaculture tanks have been tested to protect farmed salmons from sea lice in Norway.[27,28]

The 'Lulan Yuyang 61699' (No. 34) is the first aquaculture vessel in China, converted from a flush deck vessel in 2017. It possesses a culture volume of 2000 m^3 and is locates in the cold-water mass area of the Yellow Sea for culturing salmonids by pumping cold water beneath the thermocline in summer and pumping surface water in other seasons.[35] The 'Guoxin 1' (No. 37) has a culture volume of 90,000 m^3 and moves among the Chinese seas depending on the seasons (water temperature) to culture large yellow croaker.

Sea-based mariculture tanks do not currently exist in China. However, the 'Neptun' and the 'Hauge Aqua' have been trialled or designed in Norway. The 'Neptun' is 40 m in internal diameter and 22 m in depth, and is made from glass fibre reinforced polymer elements and reinforced with steel in areas that bear the most stress.[27]

Both aquaculture vessels and sea-based aquaculture tanks need to refresh their water constantly in order to maintain proper temperature, sufficient oxygen and waste removal. Therefore, comparing with other DOA types, offshore closed containments consume a substantial amount of diesel and have higher operation costs and larger carbon footprints, which can affect the market competitiveness of their products.[27,42,43]

3 | CHALLENGES TO ADDRESS

Since the 'Brown Bear' was converted to a floating hatchery vessel for coho salmon (*Oncorhynchus kisutch*) in Puget Sound of Manchester, USA, in 1971[44] and some steel structure DOA infrastructure capable of farming fish in high sea conditions were developed in 1980s,[9,11] DOA worldwide has gone through more than 50 years of history. Although DOA has the advantages of vast space for expansion, tremendous carrying capacity, reduced conflict with other sea users, lower exposure to human sources of pollution, and fewer parasitic diseases, its development has not met expectations in the past,[9–12] except in China and Norway.[27,28,45] By developing DOA, Norwegians hope to reduce nutrient pollution of fjords and sea lice infestations in salmon,[46,47] whereas the Chinese aim to reduce nutrient pollution of nearshore areas and ensure food security.[15,16] The 'Blue Granary' plan has been put forward to accelerate DOA in China.[15,17]

In addition to technical difficulties, the disadvantages of DOA also include high investment intensity, high risk, unclear property rights, and a lack of corresponding legal protection.[42] The Western public is also concerned about its potential environmental impact and ecological risks.[8,24,48] An expert evaluation has shown that both advantages and disadvantages of offshore aquaculture are very prominent.[49] The sustainability of current DOA in China is not high because it addresses little issues like food security, employment, CO_2 emissions, although it can significantly improve the quality of farmed fish, save arable land and reduce freshwater consumption.[49] The following parts will focus the issues of food security, employment and CO_2 emissions.

To ensure that DOA achieves the goals of the 'Blue Granary' plan, that is, legally and sustainably producing sufficient, stable and safe aquatic products, the DOA development in China must address several key challenges in addition to regulatory obstacles. Particularly, three pairs of contradictions must be effectively dealt with: striking a balance between enterprise profitability versus product affordability, navigating the relationship between energy use and carbon emissions, and reconciling automated operation with the re-employment of coastal fish farmers.

3.1 | Enterprise profitability vs. product affordability

DOA is a capital-intensive aquaculture activity with high start-up costs and high operation costs owing to the harsh offshore environmental conditions.[12,43,50] From the participating enterprise's perspective, in the current coexistence of ponds and nearshore aquaculture in China, DOA can only be profitable by farming the high-value species or products that are difficult to cultivate elsewhere or by gaining additional benefits (premium).

Among all six types of DOA infrastructures (listed in Table 2), offshore pens have the lowest in start-up costs, about 188 CNY/m^3. The start-up costs for DOA cages range from 500 to 2246 CNY/m^3, while 4375–8750 CNY/m^3 for aquaculture vessels.[51] The operational costs of mariculture are clearly related to mariculture types and equipment used. In Norway, the operational cost for open cages (30.6 NOK/kg) is lower than that of sea-based containment tanks (37.9 NOK/kg), as open cages in the sea can make full use of marine ecosystem services, such as physical self-purification.[28,49]

Aquaculture vessels are perhaps the most controversial type of DOA. The 'Lulan Yuyang 61699' (No. 34 in Table 1) was originally built for salmonid grow-out. However, after 2 years of field trials, it was found that the production cost was much higher than that of the submersible cage 'Deep Blue 1'. Hence, the current functions of the vessel have been changed from grow-out to primary processing and fish transportation (for parrs and harvest). In another trial, rainbow trout with an average weight of 25 g were stocked in an aquaculture vessel and reached a final weight of 3.7 kg after an 11-month culture period. However, a huge amount of diesel was consumed.[43] It is probably owing to high operational costs that few aquaculture vessels are still in operation outside China. At least five huge aquaculture vessels are to be built in China. Therefore, the economic feasibility of aquaculture vessels requires urgently to be studied in China.

The 'Deep Blue 1' and the 'Lulan Yuyang 61699' are used around the centre of the Yellow Sea to culture higher-value salmonids, which cannot survive the summer in other sea areas in China.[35,38] One of the goals of DOA is to minimize fish diseases.[27,46,47,50] In Norway, more than 10% of the cost of farming Atlantic salmon in fjords is for the prevention of sea lice,[12] while the density of sea lice is low and the disease is nothing serious in deeper-offshore waters in China.

The quality of large yellow croaker farmed in offshore pens is significantly better than that farmed in nearshore net cages, resulting in a much higher price for the former.[52] In addition, aquaculture vessels, like the 'Guoxin 1', can move seasonally to different seas, which can prompt the growth of farmed fish if properly arranged.[27]

The market price of aquatic products is closely related to the supply. From the perspective of sustainable profits of participating enterprises, the current DOA models are unable to produce abundant low-priced products that ordinary people can afford, which is a vital goal of China's DOA development. This contradiction between the affordability of DOA products and the profitability of participating enterprises should be addressed in the future development of DOA.

3.2 | Use of renewable energy vs. carbon-intensive products

Open offshore areas possess strong physical self-purification capacity and abundant renewable energy sources such as wave, wind, and solar energy.[11,53,54] Therefore, DOA is expected to become a high-productivity, low-pollution and low-carbon activity if renewable energy sources are used to support DOA operation. However, due to the limited scale of renewable energy and simplistic mariculture models, current DOA practices generally consume diesel and have a high carbon footprint.[27,42,43]

In China, the current synergy between wind farms and offshore aquaculture is mainly limited to sharing the same sea area. Only if a large enough and integrated DOA is invented can wind farms be substantially integrated with DOA to produce profitable products with low-carbon or even negative-carbon emissions.

The development of renewable energy-based DOA is the only way to address the high carbon footprints of their products. Several sets of DOA equipment use photovoltaic power as a supplementary energy source in China to reduce the carbon footprints of their products. The 'Peng Hu' aquaculture platform is powered by wave energy generators,[33] but its profitability has not yet to be verified.

Although no consensus has been reached on whether the operation of wind turbines will affect the growth of farmed fish,[55,56] many scholars and organizations have generally accepted the concept of integrating offshore aquaculture with the wind farms.[11,57,58] The current synergy between wind farming and offshore aquaculture in China is mainly limited to sharing the same sea area rather than reducing the carbon footprint of farmed fish products. There is an urgent need to develop novel DOA models that substantially integrate mariculture with wind farms or other renewable energy industries.

3.3 | Automated operation vs. re-employment of coastal fish farmers

Approximately 827,000 people are engaged in China's coastal aquaculture, mainly focusing on seawater ponds and nearshore farming.[19] Due to the implementation of strict environmental protection supervision, integrated coastal zone management and other policies, China's coastal aquaculture has begun to shift towards offshore operations on a large scale.[16] Whether these unemployed fish farmers from coastal aquaculture can be re-employed with the development of offshore aquaculture or DOA has become a prominent issue from the livelihood points of view (Figure 2).

Considering production safety and enterprise profitability, DOA generally adopts automated operations, meaning that the current DOA development pattern is unable to address the aforementioned re-employment problem. To ensure a smooth transition from coastal aquaculture to offshore aquaculture or DOA, it is necessary to innovate new DOA types, by which the re-employment issue can potentially be solved through the integrated development of multiple industries.

4 | INNOVATIONS OF DOA PRODUCTION SYSTEMS

DOA was conceived in the Global North as a solution to aquaculture sustainability,[9,48,59] while in China, DOA is expected to address both food security and sustainability of aquaculture. China's nearshore aquaculture is close to it carrying capacity threshold,[18] yet the country still has vast offshore areas available for DOA development.[10,60] The 'Blue Granary' plan, therefore, has been put forward to accelerate offshore aquaculture, particularly DOA.[15,17]

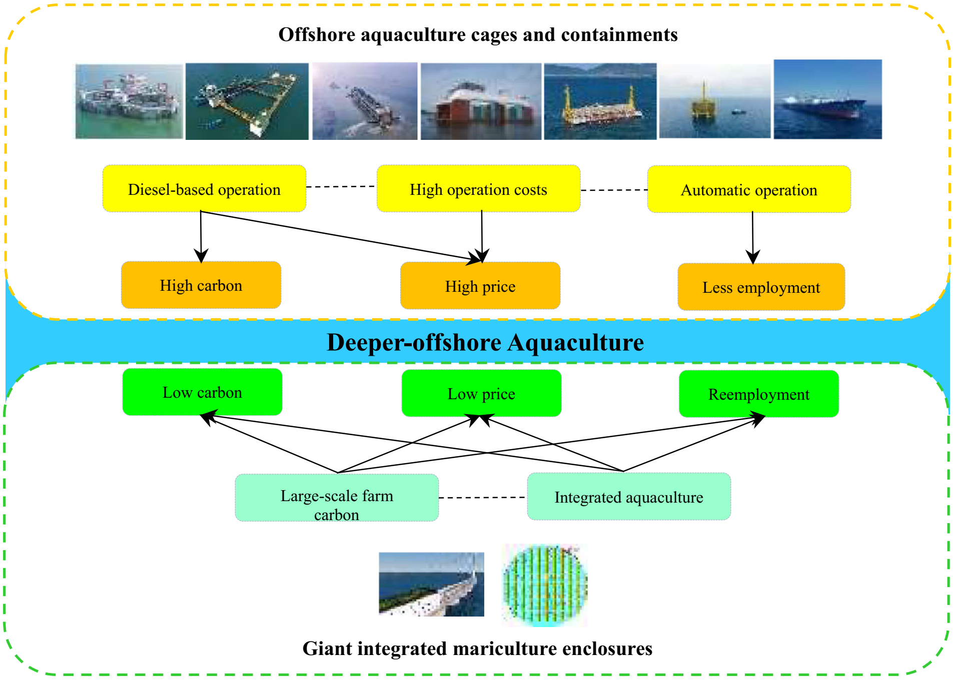


FIGURE 2 Economic, social, and ecological features of different types of deeper-offshore aquaculture models.

With the active involvement of numerous shipbuilding and marine engineering equipment manufacturing enterprises and huge government subsidies, more than 40 DOA equipment have been built in China. Nevertheless, most of the current DOA in China are basically characterized by high-priced and carbon-intensive products, and decreased employment opportunities (Figure 2). The current DOA patterns only address the concerns of participating enterprises rather than the broader concerns of the government and the public, which include the sustainable production of sufficient, affordable and safe aquatic products. The development of DOA in China must simultaneously consider both market demands for high-quality aquatic products and the public food basket. To meet the latter demand, it is essential to innovate new DOA types.

As mentioned above, the three pairs of contradictions could potentially be solved or balanced through innovation in large-scale integrated DOA systems, such as a giant integrated mariculture enclosure (Figure 2). Such systems could not only produce abundant, affordable, aquatic products with low carbon emissions but also ensure profitability for enterprises.

One of the most important reasons for the three characteristics of high price, high carbon emissions, and less employment in the current DOA is the adoption of an industrial monoculture model.[61] Integrated aquaculture which involves the culture of aquatic species within or together with other activities, or ecological aquaculture, is the most effective way of improving the economic, social, and ecological benefits of DOA.[61,62]

Multi-trophic integrated aquaculture, where fed species, such as finfish, are integrated with inorganic extractive species, is a typical example of integrated aquaculture. This approach can improve feed conversion efficiency, reduce nutrient pollution, diversify products, and reduce CO_2 emissions.[63–66] The nutrient retention potentials of integrated aquaculture systems can reach 50%–75% for nitrogen, 40%–65% for phosphorous, and 40%–75% for carbon.[66] Additionally, co-culturing macroalgae can significantly reduce the partial pressure of CO_2 in the water of the system.[67] In a global review of offshore finfish aquaculture, California Environmental Associates (CEA) highlights that small-scale offshore farming projects will face significant challenges in becoming profitable operations.[26] Only with the development of large-scale DOA can wind farms be substantially integrated with DOA to produce products with low-carbon or even negative-carbon emissions. As the scale of DOA and integrated aquaculture increases, the re-employment issue can also be effectively addressed (Figure 2).

Experts from China Communications Construction Co., Ltd. and the Ocean University of China have proposed an innovative DOA system called the Offshore Mariculture Town in the East China Sea.[45,68] The Town is an enormous integrated mariculture farm surrounded by a circular anti-typhoon structure (Figure 3a), in which mariculture is integrated with other industrial activities, such as wind turbines, food processing, and tourism (Figure 3b).

Lin (2022)[68] has designed typhoon protection infrastructures with perimeters of 9.4 km and 15.7 km, in which fish can be farmed by common high-density polyethylene cages. If 10% of the surrounding area is devoted to fish farming, the construction cost per unit of water body is about one-tenth that of DOA cages and closed containments.

Due to enormous scale of the town, it can not only efficiently produce a large amount of safe and affordable aquatic products for ordinary people, but also make it possible to hire more workers and multiply its economic benefits by integrating mariculture with other

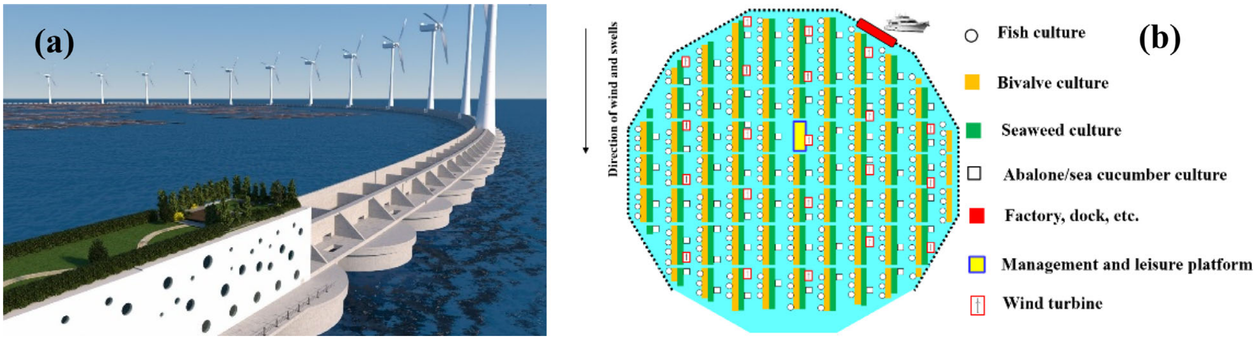


FIGURE 3 Conceptual diagram of the Offshore Mariculture Town in the East China Sea. (a) Typhoon protection infrastructure of the town[68]; (b) integrated mariculture with other activities in the town.[45]

industries such as wind farming, food processing, logistics, and tourism.

The main success experience of large-scale inland aquaculture in China is the culture of low-trophic-level fish species.[69] Therefore, in addition to adopting large-scale farming models and an integrated multi-trophic aquaculture approach, the selection and domestication of low-trophic-level fish suitable for farming in DOA is also an important task.

Although constructing the Offshore Mariculture Town requires a substantial investment, which may be challenging to initiate, it is one of the most effective DOA models for achieving the triple-win of the environment, economy and people's livelihood. Moreover, it could help address the trilemma of simultaneously increasing production, reducing nutrient discharge, and reducing greenhouse gas emission from aquaculture systems.

5 | POLICY RECOMMENDATION

The healthy development of DOA encompasses environmental, economic, and societal aspects, necessitating the active participation of the government, businesses, scholars, and other stakeholders. The government should formulate and implement detailed, targeted development plans to achieve the objectives and goals of the 'Blue Granary' plan. We recommend the following initiating measures:

1. Strengthen comparative studies of different DOA types and formulate a national sustainable development plan for DOA;
2. Incorporate the construction of the anti-typhoon infrastructure for offshore mariculture towns into the plans of national major agricultural infrastructure and new rural construction (an action plan on rural construction to improve people's livelihoods in rural areas and facilitate the country's rural revitalization drive in China) in order to guide the transition from nearshore to offshore aquaculture;
3. Introduce policies that encourage the integrated development of multiple industries, such as mariculture, food processing, cold chain logistics, wind farming, and tourism, in order to establish novel DOA paradigms that result in a triple-win of environmental protection, economic development, and improved livelihoods;
4. Implement multi-sectoral coordinated management policies to promote the healthy and orderly development of the DOA in the exclusive economic zones;
5. Support related research on the domestication and breeding of farmed fish species, carrying capacity of DOA, fish-oriented intellectual technology, and more.

Further advancements in breeding, feed innovation and disease prevention will ensure a solid underpinning for the healthy development of DOA.

AUTHOR CONTRIBUTIONS

Shuanglin Dong: Conceptualization; writing original draft. **Yun-wei Dong:** Conceptualization; visualization; writing – review and editing. **Liu-Yi Huang:** Conceptualization; data curation. **Yangen Zhou:** Data collection; writing – review and editing. **Ling Cao:** Writing – review and editing. **Xiang-Li Tian:** Writing – review and editing. **Li-Min Han:** Writing – review and editing. **Da-Hai Li:** Writing – review and editing.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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REFERENCES

1. FAO. *The State of the World Fisheries and Aquaculture – Towards Blue Transformation*. FAO; 2022. doi:10.4060/cc0461en
2. Froehlich HE, Runge CA, Gentry RR, Gaines SD, Halpern BS. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc Natl Acad Sci U S A*. 2018;115:5295-5300.

3. Jillian PF, Mailloux NA, Love DC, et al. Feed conversion efficiency in aquaculture: do we measure it correctly? *Environ Res Lett*. 2018;13: 024017.
4. Naylor RL, Sumaila UR, Kishore A, et al. Blue food demand across geographic and temporal scales. *Nat Commun*. 2021;12:5413.
5. Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. *Science*. 2018;360:987-992.
6. Gephart JA, Henriksson PJG, Parker RWR, et al. Environmental performance of blue foods. *Nature*. 2021;597:360-366.
7. Golden CD, Koehn JZ, Shepon A, et al. Aquatic foods to nourish nations. *Nature*. 2021;598:315-320.
8. Naylor RL, Hardy RW, Buschmann AH, et al. A 20-year retrospective review of global aquaculture. *Nature*. 2021;591:551-563.
9. Lovatelli A, Aguilar-Manjarrez J, Soto D, eds. Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges. *FAO Fisheries and Aquaculture Proceedings No. 24*. FAO; 2010.
10. Kapetsky JM, Aguilar-Manjarrez J, Jenness J. A global assessment of potential for offshore mariculture development from a spatial perspective. *FAO Fisheries and Aquaculture Technical Paper No. 549*. FAO; 2013.
11. Holm P, Buck BH, Langan R. Introduction: new approaches to sustainable offshore food production and the development of offshore platforms. In: Buck BH, Langan R, eds. *Aquaculture Perspective of Multi-Use Sites in the Open Ocean: the Untapped Potential for Marine Resources in the Anthropocene*. Springer; 2017:1-20.
12. Morro B, Davidson K, Adams TP, et al. Offshore aquaculture of finfish: big expectations at sea. *Rev Aquacult*. 2022;14(2):791-815.
13. Wu PT, Feng H, Niu WQ, et al. Research emphasis and reflection of strategy for water saving agriculture in China. *Sci Technol Rev*. 2006;24(5):86-88. http://www.kjdb.org/CN/Y2006/V24/I0605/86 (in Chinese).
14. Zhou TY, Tian B. Strategic thinking on population and food security in China under the new situation. *China Econ Rev*. 2021;(7):36-40. (in Chinese).
15. Han LM, Li DH. Blue food system: guarantee of China's food security. *Issues Agric Econ*. 2015;36(1):24-29. doi:10.13246/j.cnki.iae.2015.01.005 (in Chinese).
16. Mai KS, Xu H, Xue CH, et al. Study on strategies for developing offshore as the sew spaces for mariculture in China. *Strategic Study CAE*. 2016;18(3):90-95. doi:10.15302/J-SSCAE-2016.03.015 (in Chinese).
17. Li B, Liu Z. Measurement and evolution of high-quality development level of marine fishery in China. *Chin Geogr Sci*. 2022;32(2):251-267. (in Chinese).
18. Li DH, Han LM. Study on building a new safeguard system of food security by ordinating land and sea. *Soc Sci J*. 2019;(6):109-117. http://www.shkxjk.com/CN/Y2019/V0/I6/109 (in Chinese).
19. Fisheries Administration Bureau of China, MARA of China, National Fisheries Technology Extension Station, Chinese Society of Fisheries. *China Fisheries Statistics Yearbook*. China Agriculture Press; 2022 (in Chinese).
20. USCOP (U.S. Commission on Ocean Policy). *An Ocean Blueprint for the 21st Century*. USCOP; 2004.
21. Lester SE, Gentry RR, Kappel CV, White C, Gaines SD. Offshore aquaculture in the United States: untapped potential in need of smart policy. *Proc Natl Acad Sci U S A*. 2018;115(28):7162-7165.
22. Wang PH, Chen ZG, Feng YK. Many-objective optimization for a deep-sea aquaculture vessel based on an improved RBF neural network surrogate model. *J Mar Sci Technol*. 2020;26(2):582-605.
23. Guan HJ, Sun ZZ, Zhao AW. Spatio-temporal evolution and influencing factors of net carbon sink in marine aquaculture in China. *Front Environ Sci*. 2022;10:978073. doi:10.3389/fenvs.2022.978073
24. Gentry RR, Lester SE, Kappel CV, et al. Offshore aquaculture: spatial planning principles for sustainable development. *Ecol Evol*. 2017;7(2): 733-743.
25. Gao QF, Dong SL. Cage farming of fish in open waters. In: Dong SL, Tian XL, Gao QF, Dong YW, eds. *Aquaculture Ecology*. Science Press/Springer Nature; 2023. doi:10.1007/978-981-19-5486-3
26. CEA (California Environmental Associates). Offshore finfish aquaculture – global review and U.S. Prospects. 2018. https://www.packard.org/insights/resource/offshore-finfish-aquaculture-global-review-and-u-s-prospects/
27. Chu YI, Wang CM, Park JC, Lader PF. Review of cage and containment tank designs for offshore fish farming. *Aquaculture*. 2020;519: 734928.
28. Wang Z. Modern aquaculture structure. In: Cui WC, Fu SX, Hu ZQ, eds. *Encyclopedia of Ocean Engineering*. Springer Nature; 2021. doi:10.1007/978-981-10-6963-5_328-1
29. Scott DCB, Muir JF. Offshore cage systems: a practical overview. In: Muir J, Basurco B, eds. *Mediterranean Offshore Mariculture*. CIHEAM-IAMZ; 2000:79-89.
30. Ng CW, Jiang RR. Classification principles for very large floating structures. In: Wang CM, ed. *WCFS2019: Proceedings of the World Conference on Floating Solutions, Lecture Notes in Civil Engineering, 41*. Springer Nature; 2019:235-251.
31. Song W, Han XC, Xie ZL, et al. Development status and the prospect of deep-sea large-scale fence culture in China. *Prog Fish Sci*. 2022; 43(6):111-120. (in Chinese).
32. Dürr S, Watson DI. Biofouling and antifouling in aquaculture. In: Dürr S, Thomason JC, eds. *Biofouling*. Blackwell Publishing Ltd; 2010: 267-287.
33. Chen KX, Sheng SW, Zhang YQ, et al. Technology status and development trend of ocean engineering aquaculture cage. *Adv New Renew Energy*. 2020;8(5):440-446. doi:10.3969/j.issn.2095-560X.2020.05.013 (in Chinese).
34. Li L, Jiang ZY, Wang JG, Ong MC. Numerical study on the heading misalignment and current velocity reduction of a vessel-shaped offshore fish farm. *J Offshore Mech Arctic Eng*. 2019;141(5): 051602.
35. Dong SL. Researching progresses and prospects in large Salmonidae farming in cold water mass of Yellow Sea. *Period Ocean Univ China*. 2019;49(3):1-6. doi:10.16441/j.cnki.hdxb.20180303 (in Chinese).
36. Hevroy EM, Boxaspen K, Oppedal F, et al. The effect of artificial light treatment and depth on the infestation of the sea louse *Lepeophtheirus salmonis* on Atlantic salmon (*Salmo salar* L.) culture. *Aquaculture*. 2003;220:1-14.
37. Dempster T, Juell JE, Fosseidengen JE, Fredheim A, Lader P. Behaviour and growth of Atlantic salmon (*Salmo salar* L.) subjected to short-term submergence in commercial scale sea-cages. *Aquaculture*. 2008; 276:103-111.
38. Yu JF, Dong SL, Zhou YG, Guo Y, Gao Q, Dong Y. Effects of different types of air supplementation on rainbow trout confined underwater. *Aquacult Eng*. 2022;96:102214.
39. Li GX, Giao LL, Dong P, et al. Hydrodynamic condition and suspended sediment diffusion in the Yellow Sea and East China Sea. *J Geophys Res Oceans*. 2016;121:6204-6222.
40. Yu SE, Dong SL, Zhang ZX, et al. Mapping the potential for offshore aquaculture of salmonids in the Yellow Sea. *Mar Life Sci Technol*. 2022;4:329-342.
41. Zhang WK, Xu CX. China's the largest intelligent environmental protection platform for abalone farming at deeper-offshore area in China. *Fish Sci Technol Inf*. 2019;46(5):299. http://sckjqb.ijournals.cn/sckjqb/article/abstract/20190511?st=article_issue (in Chinese).
42. Klinger D, Naylor R. Searching for solutions in aquaculture: charting a sustainable course. *Annu Rev Environ Resour*. 2012;37(1):247-276.
43. Bilen S, Kızak V, Gezen AM. Floating fish farm unit (3FU). Is it an appropriate method for salmonid production? *Mar Sci Technol Bull*. 2013;1(2):9-13.
44. Nash CE. *The History of Aquaculture*. Wiley-Blackwell; 2011.

45. Dong SL, Dong YW, Huang LY, et al. Toward offshore aquaculture in China: opportunities, challenges and development strategies. *J Fish China*. 2023;47(2):1-12. doi:10.11964/jfc.20220913684 (in Chinese).
46. Costello MJ. Ecology of sea lice parasitic on farmed and wild fish. *Trends Parasitol*. 2006;22(10):475-483.
47. Barrett LT, Oppedal F, Robinson N, Dempster T. Prevention not cure: a review of methods to avoid sea lice infestations in salmon aquaculture. *Rev Aquacult*. 2020;12(4):2527-2543.
48. Lester SE, Stevens JM, Gentry RR, et al. Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. *Nat Commun*. 2018;9:945.
49. Dong SL, Dong YW, Cao L, et al. Optimization of aquaculture sustainability through ecological intensification in China. *Rev Aquacult*. 2022; 14:1249-1259.
50. Kirchhoff NT, Rough KM, Nowak BF. Moving cages further offshore: effects on southern bluefin tuna, *T. maccoyii*, parasites, health and performance. *PLoS One*. 2011;6:e23705.
51. Xu YF, Xu H, Liu H, et al. Research on the development way of deep-sea mariculture in China. *Fish Modern*. 2021;48(1):9-15. doi:10.3969/j.issn.1007-9580.2021.01.002 (in Chinese).
52. Zou GH, Song W, Xie ZL. Deep-sea large-scale pen culture technology of large yellow croaker. *China Fish*. 2021;(6):57-60. https://mall.cnki.net/magazine/Article/SICA202106023.htm (in Chinese).
53. Isaacs JD, Schmitta WR. Ocean energy: forms and prospects. *Science*. 1980;207(4428):265-273.
54. Sherman P, Chen XY, Mcelroy M. Offshore wind: an opportunity for cost-competitive decarbonization of China's energy economy. *Sci Adv*. 2020;6(8):1-8. doi:10.1126/sciadv.aax9571
55. Wahlberg M, Westerberg H. Hearing in fish and their reactions to sounds from offshore wind farms. *Mar Ecol Prog Ser*. 2005;288: 295-309.
56. Wilhelmsson D, Malm T, Öhman MC. The influence of offshore wind power on demersal fish. *ICES J Mar Sci*. 2006;63(5):775-784.
57. Kaiser MJ, Snyder B, Yu YK. A review of the feasibility, costs, and benefits of platform-based open ocean aquaculture in the Gulf of Mexico. *Ocean Coast Manag*. 2011;54(10):721-730.
58. Wever L, Krause G, Buck BH. Lessons from stakeholder dialogues on marine aquaculture in offshore wind farms: perceived potentials, constraints and research gaps. *Mar Policy*. 2015;51:251-259.
59. Belton B, Reardon T, Zilberman D. Sustainable commoditization of seafood. *Nat Sustain*. 2020;3(9):677-684.
60. Hou J, Zhou WF, Wang LM, et al. Spatial analysis of the potential of deep-sea aquaculture in China. *Resour Sci*. 2020;42(7):1325-1337. doi:10.18402/resci.2020.07.09 (in Chinese).
61. Costa-Pierce B. Sustainable ecological aquaculture systems: the need for a new social contract for aquaculture development. *Mar Technol Soc J*. 2010;44(3):88-112.
62. Soto K. Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper. 529*. FAO; 2009.
63. Tang QS, Zhang JH, Fang JG. Shellfish and seaweed mariculture increase atmospheric CO_2 absorption by coastal ecosystems. *Mar Ecol Prog*. 2011;424:97-105.
64. Chopin T. Progression of the integrated multi-trophic aquaculture (IMTA) concept and upscaling of IMTA systems towards commercialization. *Aquacult Europe*. 2012;36(4):5-12.
65. Fang JG, Zhang JH, Xiao T, Huang D, Liu S. Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. *Aquacult Environ Interact*. 2016;8:201-205.
66. Nederlof MAJ, Verdegem MCJ, Smaal AC, Jansen HM. Nutrient retention efficiencies in integrated multi-trophic aquaculture. *Rev Aquacult*. 2021;14:1194-1212.
67. Han TT, Shi RJ, Qi ZH, Huang H, Wu F, Gong X. Biogenic acidification of Portuguese oyster *Magallana angulata* mariculture can be mediated through introducing brown seaweed *Sargassum hemiphyllum*. *Aquaculture*. 2020;520:734972.
68. Lin M. Developing large-scale deep sea aquaculture: problems, modes and realization ways. *J Manag World*. 2022;12:39-58. doi:10.19744/j.cnki.11-1235/f.2022.0177 (in Chinese).
69. Gui JF, Tan QS, Li ZJ, et al., eds. *Aquaculture in China: Success Stories and Modern Trends*. John Wiley & Sons Ltd; 2018.

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