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Ecosystem Services of Ecosystem Approach to Mariculture: Providing an Unprecedented Opportunity for the Reform of China's Sustainable Aquaculture

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China is the biggest provider of mariculture products, and the industry is still growing rapidly. Increasing scientific evidence indicates that mariculture may provide valuable ecosystem goods and services in China. Here, we performed a systematic literature review of studies with the aim of understanding the ecosystem services of mariculture and a comprehensive review of ecosystem approaches that may improve mariculture ecosystem services and goods in China. We highlight four ecosystem services functions in China, including food supply, nutrient extraction, carbon sequestration, and biodiversity conservation. Given the further reform of China's mariculture, we outlined several ecosystem approaches including integrated multi-trophic aquaculture (IMTA), carrying capacity assessment and monitoring, marine spatial planning, and waste treatment and recirculating mariculture system. We conclude that the ecosystem services of the ecosystem approach to mariculture provide an unprecedented opportunity for the reform of China's sustainable aquaculture. Finally, a synthesis of sustainable development of mariculture, along with the five recommendations for future mariculture development in China, is outlined.

Keywords: mariculture, ecosystem service, techniques, management, IMTA, carrying capacity

INTRODUCTION

Globally, there is a growing concern over the sustainable development of mariculture. On September 23, 2021, the UN General held the Food System Summit 2021 to look at the delivery of the Sustainable Development Goals (SDGs) by 2030, and "Blue Foods" has become one of the future directions to achieve the 17 sustainable goals set by the 2030 Agenda, including end poverty and hunger, promote sustainable agriculture, ensure sustainable consumption, and conserve and sustainably use the oceans, seas, and marine resources for sustainable development. In China, the government also anchors sustainable development of mariculture goals in the 14th *Five-Year Plan for the National Economic and Social Development of PRC* (refer to as 14FYP hereafter) by demonstrating "prioritizing ecosystem and promoting green development". However, developing mariculture sustainability remains an ongoing challenge due to the large demand for aquatic products.

China is the world's biggest mariculture country (FAO, 2020) and has been producing more mariculture products than wild catch since 2008, and its mariculture production share in global production reached 65.9% in 2018. Mariculture has substantial impacts on ecosystem health and sustainable use. Along with the unprecedented and continuous expansion, China's mariculture industry has been received many undesirable environmental and ecological impacts in terms of seawater eutrophication (Islam, 2005), chemical's accumulation (Burridge et al., 2010; Liu et al., 2017), microplastic pollution (Chen et al., 2021), habitat destruction (Ahmed and Thompson 2018; Ottinger et al., 2016), biodiversity depletion (Ticina et al., 2020), and space competition between fish farmers and other marine stakeholders (Bostock et al., 2010). However, many peer experts such as Tang (2019) and Jiao (2018) suggested that mariculture can deliver a broad range of ecosystem services functions, and many unexpected environmental effects of mariculture can be alleviated even eliminated by the integration of advanced ecosystem approaches and appropriate management. Nevertheless, several questions arise regarding ecosystem-based techniques and management tools: What are the ecosystem services functions of mariculture in China? How could these diverse characteristics of ecosystem services functions of mariculture contribute to the designing of mariculture activities in meeting ecological and environmental issues? What and how current ecosystem based-management tools can help to achieve a sustainable, healthier mariculture production in a responsible manner better integrated with social-environmental issues? Given that China's aquaculture is transforming into a sustainable development pattern with low and high outputs, and this shift has started to exhibit positive effects, it is time to make a shift toward a better understanding what ecosystem services functions might be expected from mariculture and the ecosystem approach to mariculture—the enabling techniques, measures, and management tools that could ensure that mariculture activities generate substantial ecosystem services to nature and society.

In this paper, we provide a state-of-the-art review of the above considerations as they relate to the mariculture's ecosystem services and ecosystem approaches to mariculture in China, derived from a systematic literature review. Specifically, we first describe the mariculture's ecosystem services in China, including food supply, nutrient extraction, carbon sequestration, biodiversity conservation, and stock enhancement. We then identify ecosystem approaches that could improve the ecosystem functions of mariculture, including integrated multi-trophic aquaculture (IMTA), carrying capacity assessment and monitoring, marine spatial planning (MSP), and waste treatment and recirculating mariculture system. Finally, we provide a synthesis of sustainable development of mariculture lessons from the world, along with the future direction of mariculture in China.

MATERIALS AND METHODS

To obtain an overview of mariculture's ecosystem service functions, and technologies literature in China, we first conducted a systematic review of articles published in Web of Science from 2001 to 2021. In China, four main ecosystem services were proposed: (1) food supply, (2) nutrient extraction, (3) carbon sequestration, and (4) biodiversity conservation and stock enhancement. Hence, articles on studies that reported the ecosystem services functions of mariculture such as food supply, nutrient extraction, carbon sequestration, stock enhancement, and biodiversity conservation were considered. Still, mariculture improvement methods and technologies such as IMTA, carrying capacity assessment, marine spatial planning, and monitoring were also considered. We searched the Web of Science to find articles using the following key terms: "mariculture" OR "marine aquaculture*" OR "integrated multi-trophic aquaculture*" and "food supply*" OR "nutrient extraction*" OR "bioremediation" OR "carbon sequestration" OR "carbon sink" OR "stock enhancement" OR "biodiversity" OR "biodiversity conservation", OR "marine spatial planning" OR "carrying capacity" OR "monitoring" OR "waste treat" OR "sustainable" and "China" or "Chinese". Over 800 articles were manually screened on an individual basis. Most articles were excluded by title alone, while the rest were included or excluded after reviewing the abstract or full text. Specifically, we retained articles that focused on quantitatively assessing the positive effect of nutrient extraction of mariculture, carbon sequestration, quantitatively assessing the biodiversity and stock enhancement function of mariculture carrying capacity of mariculture, monitoring and modeling, MSP of mariculture, and waste treatment and recirculating aquaculture. We then categorized these articles according to their evaluation objectives and findings and retained articles that focus on the ecosystem service of mariculture. According to these articles, six articles examined the food supply function of mariculture, 14 articles quantitatively assessed the nutrient extraction of mariculture, nine articles mentioned the carbon sequestration, five articles quantitative assessed the biodiversity and stock enhancement function of mariculture, nine articles quantitatively assessed the value of ecosystem service of mariculture, 15 articles quantitatively assessed the carrying capacity of mariculture, six articles were related to monitoring of the mariculture ecosystem, nine articles were associated with MSP of mariculture, and five articles were related to waste treatment and recirculating aquaculture. Several articles were considered more than once, as they contained different ecosystem service functions of mariculture.

ECOSYSTEM SERVICES OF MARICULTURE IN CHINA

Mariculture is a double-edged sword in China (Meng and Feagin, 2019), namely, mariculture can have both negative and positive impacts on the ecosystem. Consequently, mariculture cannot be viewed as a risk-free solution to the sustainable development of agriculture in China (Li et al., 2011). However, an increased number of studies indicate that mariculture could provide valuable ecosystem services functions in China, including food supply, nutrient extraction, carbon sequestration, biodiversity conservation, and stock enhancement. Undoubtedly, "ecological priority" and "ecological and environmental sustainability" have been put in the first place for future mariculture initiatives in China. In the following, we give a brief state-of-the-art summary that focuses on the positive effects of mariculture in China to demonstrate the main ecosystem functions of mariculture in China.

Food Supply

China's developing mariculture has made a significant contribution to ensuring food security and against hunger since the 1980s when the coastal capture fishery of China faced serious over-exploitation issues (Yu and Han, 2020). Aquatic foods of mariculture food supply in China include finfish, crustaceans (mainly crabs and shrimp), cephalopods (mainly octopus and squids), mollusks (mainly bivalve), algae (mainly macroalgae), and other aquatic animals (mainly sea cucumbers). The total mariculture production in China increased 12.5-fold between 1990 and 2020 (**Figure 1A**). China's mariculture production has exceeded capture fisheries production between 2000 and 2010 (**Figure 1B**). Notably, mollusks and algae mariculture development during the past 30 years have supported the dramatic increase in mariculture since 1990, while the production of finfish and crustaceans keep pace with the increase in mariculture production. However, the finfish and cephalopods produced from capture fishery are higher than that from mariculture production. The finfish and cephalopods food supply are still dependent on the wild catch production (**Figure 1B**). Regardless of the unbalanced supply amount of different aquatic foods, mariculture still became the most important part of the aquatic food supply. For example, the mariculture production supplies over 20 million tons in 2020, about onefold more than capture fishery production. With the flourishing of mariculture production, the mariculture alone supplies more than 15 kg/cap/year of edible aquatic food consumption for China in 2020 (**Figure1C**), which is higher than the world's average aquatic (including both marine and freshwater food) consumption (14.6 kg/cap/year). In other words, mariculture helps China to get rid of hunger.

In the past decade, multiple reviews have investigated the nutrition of different aquatic foods (mainly animals, plants, and microorganisms) and their functions to improve human health (Golden et al., 2021). Overall, aquatic foods can provide hundreds of nutrients, such as minerals, vitamins, protein, and fatty acids (such as docosahexaenoic acid and eicosapentaenoic acid, DHA, and EPA). Still, aquatic foods are the most important sources of several key micronutrients, omega-3 long-chain polyunsaturated fatty acids, and vitamins, which can reduce meat intake, fill the nutrient gap, and support the vulnerability

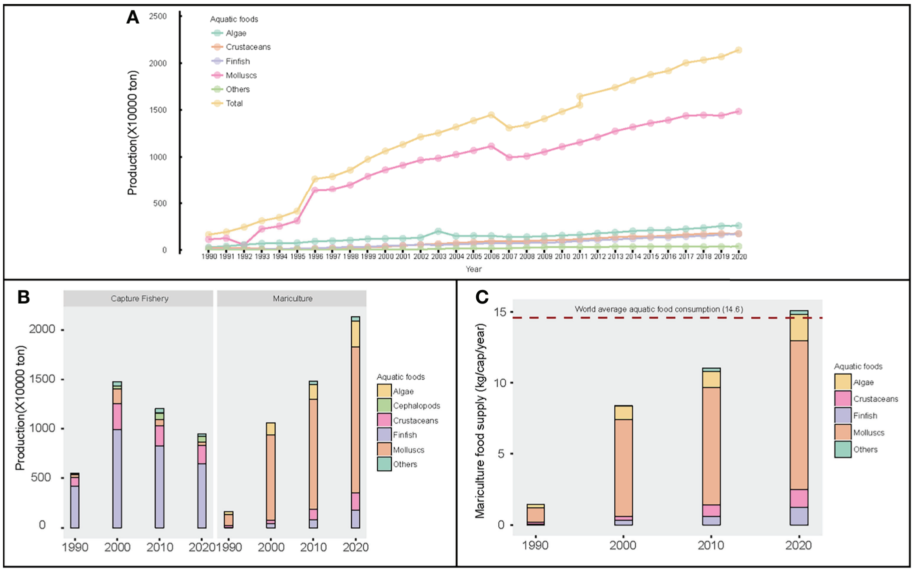

FIGURE 1 | Food supply function of mariculture in China. **(A)** The total and selected group mariculture production of China between 1990 and 2020. **(B)** The production and comparison between capture fishery production and mariculture production of China in 1990, 2000, 2010, and 2020. **(C)**. Per capita aquatic food consumption for selected groups (kg/cap/year) in China. China demonstrates a high level of edible mariculture product per capita in relation to global edible aquatic consumption (14.6 kg/cap/year, including freshwater and marine aquatic foods). By 2020, China's mariculture food supply alone is higher than the world's average aquatic consumption.

of human beings (He, 2010). Along with China's policy converted from the past emphasis on increasing production to achieving sustainable development, China's mariculture has replaced capture fishery in nutrient supply in China. Take the finfish, the most high-nutrient-value aquatic food, for example, after reaching about 15 Mt capture fishery production in 1999, China's finfish resources mainly consisted of small and low-value pelagic fish, instead of the previous high-nutrient carnivore fish like large yellow croaker (Liang and Pauly, 2019). Along with the depletion of several high-nutrient value finfish, the mariculture growth rate grew continuously after 2000 and produced more than 1.7 Mt of high-nutrient-value finfish such as large yellow croaker, groupers, and sea bass. The rapid development of mariculture like the finfish cultural system demonstrates the capability to reduce, even fill the nutrient gap under the production reduction in capture fishery background.

Nutrient Extraction

Nutrient extraction is the most widely known ecosystem service of mariculture, and significant progress has been made in mariculture's nutrient extraction in recent years (Naylor et al., 2021). To prevent eutrophication, recent nutrient criteria emphasized the importance of controlling phosphorus and nitrogen due to the increasing link between nitrogen pollution and cultural eutrophication (Xiao et al., 2017; Liang et al., 2019). Globally, molluscan and seaweed mariculture are two well-known ways to remove inorganic nutrients and reduce potential adverse environmental impacts (Rosa et al., 2018; Qi et al., 2019). In China, molluscan and seaweed mariculture production together accounts for 69% and 12% of China's total mariculture production, respectively (Fishery Administration of the Ministry of Agriculture, 2021). Basically, most molluscan and seaweed cultivation in China does not require feed, and it is effective in enhancing water purification and water clarity by assimilation of excess nutrient produced by anthropogenic activities (Duan et al., 2019). The formation processes of mariculture nutrient extraction are complex but through at least four pathways. First, seaweed can absorb dissolved nitrate and phosphate in seawater and convert dissolved inorganic nitrate and phosphate into particle organic matters during their growth (Xie et al., 2020). Second, mollusks, especially filter-feeding bivalves, can filter particle organic matter and then accumulate nitrogen and phosphorous (Mahmood et al., 2016). Third, a large quantity of nitrate and phosphate was removed from the water through harvesting seaweed and mollusk. Ultimately, the sedimentation of seaweed detritus and fecal or pseudo-fecal of mollusk could promote the deposition of nitrogen and phosphate pool (Wu et al., 2015). All of these demonstrate that no-fed species mariculture is an indispensable way of nutrient extraction and their potential ability is species and area specific.

Conversely, fed species such as finfish and shrimp mariculture may release nutrients and cause nutrient pollution eutrophication in the adjacent water (Kang and Xu, 2016; Yang et al., 2021). For example, Cao et al. (2007) assessed the nutrient release of pond-based shrimp mariculture, and the release rate of shrimp is about N of 45.8 kg/t, P of 10.1 kg/t, and chemical oxygen demand (COD) of 49.65 kg/t. In the finfish cage mariculture system, nitrogen excretion quantities of the finfish in Nanshan Bay are about 2.81t–15.59 t/season. However, the nutrient pollution caused by fed species mariculture can be alleviated through the deployment of IMTA. The practice of IMTA in China (Fang et al., 2016) showed that the nutrient pollution caused by 1 kg finfish mariculture can be eliminated by the culture of 6.1–9.2 kg extractive species. Combined with China's mariculture production of fed and non-fed groups, the fed/non-fed mariculture ratio is about 10:1; therefore, China's mariculture can provide nutrient extraction function.

In China, although there is no standard procedure to evaluate the overall nutrient extraction counting system, many scientists have carried out research using a variety of methods for the estimation or assessment of the nutrient extraction potential in the mariculture ecosystem. Collectively, three methods are documented: first, in most studies, the assessment of mariculture nutrient extraction is based on the nitrogen and phosphate content and yield of mariculture products. Second, several studies used laboratory-based assessment to measure the nutrient absorbing rate of cultural species and then establish nutrient-extraction-counting assessment *in situ*. Third, many studies measured the biodeposition rate of cultural species and then assessed nutrient transport to sediment (**Table 1**).

Carbon Sequestration

Like nutrient extraction functions of mariculture, carbon sequestration is widely recognized as another ecosystem services function of mariculture. In the past decade, the Chinese government has stressed on the various occasion that the country aims to facilitate the adoption of an ambitious, and realistic carbon emission peak goal before 2030 and would strive for "carbon neutrality" by 2060 (Gao et al., 2022). In this context, mariculture could be useful to remove excess carbon from the oceans and reduce CO_2 levels indirectly in the atmosphere through two pathways: biological pump and microbial carbon pump (Longhurst and Harrison, 1989; Jiao et al., 2011).

The previously published review on blue carbon sinks calculated that more than half of global carbon is captured by marine life (Nellemann et al., 2009). In 2005, Zhang et al. (2005) pointed out the first systematic assessment of carbon sequestration of mariculture in China and proposed the carbon sequestration fisheries concept—defined as non-fed mariculture that can remove a mass of carbon and has great potential for carbon sequestration and has been argued for more than 15 years because only a small proportion (about 1.4%) of CO_2 should be transported to the seafloor by biological pump (BP) for long-term sequestration, and the removal carbon is mainly respired into CO_2 after consumption (Jiao et al., 2018). Fortunately, recent studies focusing on the mechanisms of carbon cycling, especially microbial carbon pump (MCP) in the marine system, have unveiled the full picture on how mariculture contribute to carbon sequestration. Among different cultural species, seaweed and bivalve could be useful to remove excess carbon from the oceans and reduce CO_2 levels indirectly in the atmosphere

TABLE 1 | Nutrient extraction assessment of mariculture in China.

Method	Cultural species	Nutrient extraction	Reference
Content assessment	Mussel	N: 160.3 mg/ind/a P: 36.7 mg/ind/a	Gao et al. (2008)
Biodeposition rate	fouling communities	N: 0.11 g/m^2 P: 0.98 × 10^{-2} g/m^2	Qi et al. (2015)
Content assessment	Seaweed	In oyster farm: C: 15,016.90 ± 6,241.78 mg/thallus N: 1,112.45 ± 459.81 mg/thallus P: 134.69 ± 55.46 mg/thallus In finfish cage: C: 2,457.46 ± 1,073.78 mg/thallus N: 180.27 ± 75.23 mg/thallus P: 13.69 ± 5.88 mg/thallus	Yu et al. (2016)
Lab *in situ* assessment	Seaweed–oyster	MC-Control N/P: 38.1 ± 11.0 MC-Seaweed N/P: 92.5 ± 25.6 MC-Bivalve N/P: 36.4 ± 10.9 MC-Integrate N/P: 32.0 ± 16.3	Wang et al. (2017)
Content assessment	Seaweed	China's large scale kelp farm: N: 75,000t P: 9,500t	Xiao et al. (2017).

through two pathways: biological pump and microbial carbon pump (Duarte et al., 2017). In a recent review by Zhang et al. (2017), the carbon fixed in mariculture is characterized by four forms: carbon fixed in cultural organisms (0.677 Tg of C/year), particulate organic carbon (POC, 0.944 Tg of C/year), dissolved organic carbon (0.822–0.915 Tg of C/year) in seawater, and buried carbon in sediments (0.14 Tg of C/year). Over the last decade, trends in the carbon sequestration performance of mariculture have been highly warranted. For example, the *National Science Review* published a review characterizing the blue carbon strategy in China. In this review, Jiao et al. (2018) pointed out that the dissolved organic carbon (DOC) released from cultural seaweed is even higher than the total burial flux of organic carbon from coastal blue carbon in China. Therefore, mariculture could become an important part of blue carbon in the future.

Despite the direct carbon sequestration functions of mariculture, a most recent published article in *Nature* creates a cohesive model that unites terrestrial foods with nearly 3,000 taxa of aquatic foods to understand the future impact of aquatic foods on human nutrition, and results revealed that mariculture fisheries nearly always produce fewer greenhouse gas emissions than terrestrial foods (Golden et al., 2021). In other words, mariculture foods can be considered low-carbon foods compared with other foods, which make a great contribution to carbon mitigation against the background of growing global demand for foods.

Biodiversity Conservation and Stock Enhancement

Since China proposed 13 FYP, China places more emphasis on the restoration and sustainability of mariculture ecosystems and is responsible for maintaining a wide range of ecosystem values, particularly through conservation and sustainable use of biodiversity. Although aquaculture and stock enhancement are two distinctly different areas, mariculture can provide support for biodiversity conservation and stock enhancement functions (Lorenzen et al., 2013; Theuerkauf et al., 2021). Mariculture provides biodiversity and stock enhancement through at least two pathways: first, as of 2015, 167 billion juveniles of nine marine species groups were cultured and released along the Chinese coast. Hence, the success of biodiversity conservation and stock enhancement activities depends upon mariculture-based artificial breeding and cultural juvenile release (Liu et al., 2022). Second, the mariculture system, especially suspended or elevated rafts and cages, can be viewed as three-dimension habitat and can positively influence the structure and function of wild macrofaunal communities through at least three pathways: provision of structured habitat, provision of food resources, and enhanced reproduction and recruitment. In China, field studies showed that mariculture infrastructure can introduce considerable diverse structures into the natural environment and act as a floating aggregation device, and the waste of fish meal can have a positive effect on the benthos polychaete community and provide an additional food source for the fish community (Fang et al., 2017; Zhou et al., 2019). Such positive influence is possible only under the presupposition that mariculture activities cannot cause destructive habitat conversion on the adjacent key habitats, such as mangrove, seagrass, oyster reef, and saltmarsh (Herbeck et al., 2020). Appropriately, a definition of sustainable mariculture development in China should include both supplementations with hatchery-produced seed and promotion of wild populations. Hence, the combination of mariculture and stock enhancement received growing attention in recent years, and China will have increased mariculture-based measures in the future to protect and restore habitats for marine species, as the country will continue to strive for better protection of biodiversity.

Assessment of China's Mariculture Ecosystem Services Value

As mentioned above, the ecosystem service functions supported by mariculture have gained substantial focus. Consequently, the assessment of mariculture ecosystem services value, especially social–economic value is of interest to many ocean-related bodies to guide the policymaking and management of the ecosystem. In China, mariculture's ecosystem service value has been involved in the nationwide and regional ecosystem services value assessment since 2000 (Chen and Zhang, 2000; Lin et al., 2019; You et al., 2019; Gao et al., 2020). For instance, Chen and Zhang (2000) estimated that the marine ecosystem service value is about 21,736×10^8 yuan/a, and the mariculture ecosystem has been included; You et al. (2019) estimated the ecosystem service value (17.4×10^8 yuan/a to 53.7×10^8 yuan/a) from 1997 to 2015, and using stepwise regression and path analysis methods, mariculture has been identified as a main driving force of ecosystem service value of Quanzhou Bay. Compared with nationwide and regional ecosystem service values assessment, studies on the ecosystem service value of the mariculture system are relatively rare. One representative study is the benefit–cost analysis of the Sanggou bay mariculture ecosystem based on ecosystem services (Zheng et al., 2009); the result showed that the net present value of ecosystem service (including food production, oxygen production, climate regulation, and waste treatment) of mariculture in Sanggou bay is about 1.12–1.33×10^8 yuan/a. Another example is the valuation of shrimp ecosystem services in Leizhou; in this study, Liu et al. (2010) used the market method, carbon tax rate method, reforestation cost method, and contingent valuation method to estimate the net value of ecosystem service of the shrimp ecosystem in Leizhou (about 3.9 × 10^8 yuan/a). However, according to Costanza's calculation method (Costanza et al., 1997; Costanza et al., 2017), several non-marketing ecosystem service values of mariculture are still unknown (such as erosion control and sediment retention, biological control, and refugia) or cannot be quantitatively assessed (such as genetic resources, recreation, carbon sequestration, nutrient extraction, and culture). Therefore, the ecosystem service value of mariculture must be thoroughly studied and assessed quantitatively before the social–economic value of mariculture can be fully integrated into the mariculture ecosystem service value assessment.

ECOSYSTEM APPROACHES TO MARICULTURE IN CHINA

Since the Chinese central government proposed the National 13th Five-Year Plan in 2016, environmental protection has been given national priority on par with economic development, and the conservation of marine ecosystems has attracted unprecedented attention in China (Council, 2016). Consequently, the sustainability of mariculture in China essentially capitalizes on existing favorable features of a marine area and combines the natural attributes of the sea environment of the region with various levels of technology. Ecosystem Approach to Aquaculture (EAA) is defined as "a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and the resilience of interlinked social-ecological systems" (FAO, 2011). The development of mariculture ecosystem service functions and transformation of China's mariculture industry have resulted in a variety of concepts and EAA to avoid unwanted ecological effects and improve the performance of mariculture deployment, either technique or management tools. In China, the extension of different applied sustainable aquaculture modes and tools, such as polyculture and integrated multi-trophic aquaculture, carrying capacity assessment and marine spatial planning, and waste treatment and recirculating aquaculture is reported.

Integrated Multi-Trophic Aquaculture

The original concept of IMTA was defined as the incorporation of species from different positions or nutrient levels in the same system (Chopin and Robinson, 2004). With the rapid development of the sustainable EAA, which demands both sustainable practices at the level of the target cultural species, and taking responsibility for its interactions in the ecosystem context, the IMTA now refers to a suitable approach to address such concerns, which is to limit aquaculture nutrients and organic matter outputs through bio-mitigation, with both economic and environmental sustainability (Chang et al., 2020).

There are several IMTA modes in China with the local condition and characteristics of cultural organisms (**Figure 2**). The finfish–bivalve–seaweed (**Figure2A**) and finfish–seaweed (**Figure2B**) IMTA mode is popular in Zhejiang, Fujian, and Guangdong provinces; these implementations can alleviate the negative environmental and ecological effects of finfish culture, such as eutrophication. For instance, finfish culture produces waste (uneaten fishmeal, faces, and dissolve nutrients) in the water, and the filtered bivalve can remove the particle organic matter (POM), while the seaweed can absorb the dissolved nutrient in the water (Wei et al., 2017; Xie et al., 2020). The bivalve–seaweed (**Figure 2C**) mode is deployed in nearly all coastal provinces of China. Extractive filter bivalves and seaweed are the main mariculture groups in China; they can improve water quality and contribute to carbon sequestration. However, a large density of bivalve culture has a potential negative influence on the water quality through excreting dissolved inorganic nutrient and feces and pseudofeces; therefore, seaweed mariculture is effective in reducing nitrogen load from bivalve and enhance the beneficial functions of the mariculture system. The pond-based IMTA (**Figures 2D–F**) modes are also well-developed in China, especially in seawater shrimp farming. In the shrimp-centric mariculture system, the coculture of shrimp, fish, crab, and mollusks provides comprehensive benefits at the ecosystem and economic levels. Specifically, the shrimp–finfish–bivalve (**Figure 2D**) IMTA mode links multi-trophic level so that fish can consume diseased shrimp, and benthos mollusk can utilize the uneaten forage of shrimp (Liu, 2010). The shrimp–crab (**Figure 2E**) IMTA mode is popular in China; crab takes up uneaten forage of shrimp and creates more economic benefit. The shrimp–bivalve (**Figure 2F**) IMTA mode is popular in Shandong and Jiangsu province. Shrimp and bivalve are

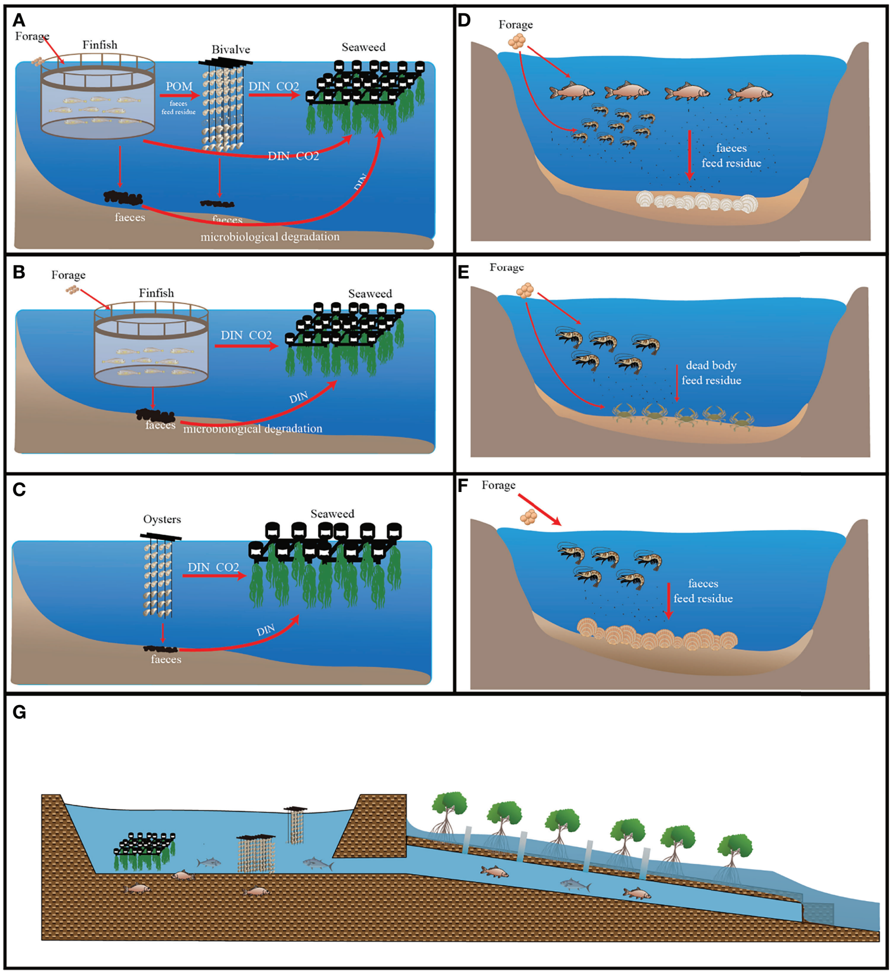

FIGURE 2 | Integrated multi-trophic aquaculture (IMTA) mode in China. **(A)** Cage culture of finfish and long-line culture of bivalve and seaweed. **(B)** Cage culture of finfish and long-line culture of seaweed. **(C)** Long-line culture of bivalve and seaweed. **(D)** Pond culture of finfish, shrimp, and bivalve. **(E)** Pond culture of shrimp and crab. **(F)** Pond culture of shrimp and bivalve. **(G)** Natural habitat (mangrove)-based IMTA mode.

inhabited in different water column and therefore provides combined benefits of food source and waste reduction: shrimp feed on forage and the bivalve utilized the waste of shrimp. In the past decade, natural habitat restoration has been considered an important component of ecological civilization in China. Therefore, scientists in China have improved the cultural technique innovation for integration of natural habitat restoration and eco-friendly IMTA mode. In Guangxi province, scientists have developed a mangrove-restoration-based IMTA mode, which can improve connectivity between the natural habitat and the mariculture system (Xu et al., 2011).

Carrying Capacity Assessment and Monitoring

Quantitative and comprehensive carrying capacity assessment and monitoring were the foundation of the ecosystem approach to aquaculture and executed for mariculture ecosystem management and codified in marine policy worldwide (Brugère et al., 2019). In general, negative environmental and ecological impacts may ensue if the mariculture system is overdense; therefore, carrying capacity assessment can control the density more scientifically and increase the production in the relatively sufficient sea space. In China, the characteristic of carrying capacity fall into five categories: physical carrying capacity, production carrying capacity, ecological carrying capacity, social carrying capacity, and environmental carrying capacity (Fang et al., 2020). The carrying capacity methods in China generally fall into four categories: mass-balanced methods, environmental threshold method, population dynamics with hydrodynamics, and ecological footprint methods (**Table 2**). Collectively, most carrying capacity assessment in China belongs to production carrying capacity, which aims to achieve maximum sustainable mariculture yield of cultural product. Still, many representative mariculture areas have focused on a broad scale assessment of directions and patterns of change to achieve long-term management and planning of comprehensive benefits based on the combination of biological, ecological, economic, and social

TABLE 2 | Carrying capacity assessment of mariculture in China.

Method	Type	Carrying capacity	Reference
Mass-balanced	Production carrying capacity	Fish: 5.8 t/ha	Xu et al. (2011)
Mass-balanced	Ecological carrying capacity	Bivalve: 976 t/km^2	Gao et al. (2020)
Mass-balanced	Production carrying capacity	Bivalve: 118 t/km^2	Han et al. (2017)
Environmental threshold	Environmental carrying capacity	Phosphorus: 0.216 mg/L; nitrogen: 0.039 mg/L	Cai and Sun (2007)
Population dynamics with hydrodynamics	Physical carrying capacity	Bivalve seeding densities: 60,000–105,000 ind/ha	Zhao et al. (2019)
Mass-balanced	Production carrying capacity	Seeding density: Clams:345ind./m^2 Oyster: 60 ind./m^2 Mussel: 165 ind./m^2 Scallops: 80 ind./cage.	Liu et al. (2020)
Population dynamics with hydrodynamics	Production carrying capacity	Scallop:17.6 t/ha Oyster:45.8 t/ha	Nunes et al. (2003).
Energy ecological footprint	Physical carrying capacity	Energy ecological footprint area(1953.19 ha) about 14 times greater than energy carrying capacity (135.88 ha) and about 293 times greater than actual physical area(6.67 ha)	Zhao et al. (2013)
Ecological dynamic system numerical models	Physical carrying capacity	Fish cage: circumference of 40 m and the depth of 8 m	Zhao et al.(2020)
Mass-balanced	Production and physical carrying capacity	Bivalve: 19,881.95 t. Suitable area: 461.83 hm	Zhu et al.(2011)
Population dynamics with hydrodynamics	Ecological carrying capacity	Oyster: 38,564 t	Sequeira et al. (2008).

factors. An example is the ecosystem carrying capacity-based management framework in Sanggou Bay IMTA pilot; despite the carrying capacity, this framework also integrated hydrodynamic modeling while considering ecosystem resilience and redundancy. Meanwhile, other works attempted to provide ecosystem models that incorporate social, economic, and ecological sectors in Sanggou Bay (Shi et al., 2013). Such a form of ecological–economic modeling seems highly warranted and fortunately is ongoing in some northern China's IMTA pilot areas.

In recent decades, different technological tools such as remote sensing and undersea observation net have been used to provide comprehensive social–environmental data for carrying capacity assessment and scientific-based management. Among them, remote sensing can contribute to the quantitative assessment of mariculture areas by giving an instantaneous overview over large areas of the Earth's surface, which has been widely used in mariculture research (Meaden and Aguilar-Manjarrez, 2013), including coastal area monitoring, environmental elements determination, mariculture site selection and mapping, mariculture infrastructure classification, and mariculture dynamic detection (Wong et al., 2019; Duan et al., 2020; Fu et al., 2021). In the context of real-time environmental monitoring, inspired by the successful experience in Japan, Korea and some western countries' marine ecosystem management, undersea observation networks have been integrated into the mariculture system monitoring in China. The undersea observation networks permit the monitoring of the ecosystem in real time and from a great distance. For example, Shandong province has built up 24 real-time seafloor observation stations in IMTA pilots, which contain continuous monitoring of the biotic (ROV and acoustic monitoring) and abiotic (hydrodynamic, current velocity, water quality, temperature, DO, Chla, turbidity) factors in mariculture system. Once the data are obtained, all the data are sent to the big data center for ecological assessment and management. Therefore, the importance of monitoring the mariculture system has been highlighted by the Chinese government.

Marine Spatial Planning

Marine spatial planning is accepted as a robust management tool for EAA. In China, a growing demand for nutrition, foods, and ecosystem services means an expansion of mariculture activities in the oceans and coastal areas and increased pressure on the environment and spatial conflict with other resources. These issues include direct and indirect competition for marine space between different zones and stakeholders, unexpected environmental (water quality, disease risk, fish meal) impacts, and ecological impacts (primarily related to species invasion, erosion of adjacent habitat, and genetic pollution). These issues all negatively impact public perception of mariculture (Ahmed and Thompson 2018; Chopin et al., 2012; Edwards, 2015; Carballeira Braña et al., 2021).

To solve the spatial conflict in marine space and alleviate the unexpected environment–ecological effect of mariculture, the Chinese government has delivered MSP in two ways: the first is named Marine Functional Zoning (MFZ), which governs the utilization of marine space by different stakeholders from the national to the local scale (Council, 2015; Yu and Li, 2020). Meanwhile, the government also formulated Tidal Flat Planning (TFP) in mariculture waters to strengthen the regulation of mariculture space (MOA, 2017). Under the guidance of regulation, policy, scientific advice, and practices, the adoption of mariculture MSP in the Yellow China Sea, the East China Sea, and the South China Sea begins to follow the designed orient frameworks (Teng et al., 2021). Accordingly, the MFZ clarifies the priority of fishers and fish farmers in territorial space including their rights in zones for fishery and mariculture. Still, there are limited rights in zones for recreation and zones for conservation, while the MFZ forbids mariculture activities in zones for industry and urban use, port and shipping, miners and energy utilization, special utilization, and marine protected area (MPA). Since the 13 FYP, China sought to fight and limit the aquaculture activities against MFZ and TFP by conducting a series of inspections, especially Central Environmental Protection Inspection. Such inspections resulted in the local government using a clear-cut approach to remove mariculture activities when mariculture communities violated the MFZ and TFP (Miao and Xue, 2021). Notably, the expansion of MPAs will continue to occupy traditional mariculture areas and cause problems to fish farming communities (especially small-scale communities). The spatial exclusion effect between mariculture and MPA will undoubtedly continue in coastal China, since MPAs in China are permanent and restrict reservation.

Waste Treatment and Recirculating Mariculture System

The ministry of China has been accelerating the establishment of systems for the management of wastewater discharge from mariculture and marine waste governance. In China, the natural-based IMTA and recirculating aquaculture systems are two technologies to tackle the major environmental challenges associated with fed species culture systems and land-based mariculture systems (Fei et al., 2011; Song et al., 2019; Hu et al., 2021). The application of natural-based IMTA has advantages in the nearshore waters by using some low-value biofouling species. For instance, the finfish-polychaete IMTA mode could utilize the particulate organic waste from intensive mariculture and is appropriate for sediment recovery in the culture system (Fang et al., 2017). In the context of recirculating mariculture system, the said system has lower water requirements and could tackle the major environmental issues caused by cage culture systems. Subsequently, some high-value species like salmon have been cultured in the indoor recirculating system in China (Song et al., 2019).

OPPORTUNITY AND RECOMMENDATION FOR THE REFORM OF CHINA'S SUSTAINABLE MARICULTURE

Overall, optimizing the overall arrangement of mariculture green development goal in 14 FYP, together with newly introduced ecosystem service functions of mariculture and innovations in technique or management tools of EAA in our state-of-the-art review, is rapidly providing an opportunity for the reform of China's sustainable mariculture to meet with SDG goals by 2030. Accordingly, we put forward the following specific recommendations.

First, in the last decades, mariculture enhanced the aquatic food supply under capture fishery reduction background. However, as fisheries resource conservation becomes a top priority of marine fishery management in China, China's mariculture industry should produce more finfish to fill the gap of the high-nutrient value aquatic product.

Second, observation data and previous experience have shown that extractive species, particularly molluscan and seaweed cultures, are effective in nutrient extraction and carbon sequestration. However, the nutrient extraction and carbon sequestration functions of mariculture systems are complicated, and standard protocols for both nutrient-accounting and carbon-counting systems of mariculture system are still lacking. Therefore, we suggest that China establish standard protocols and nutrient- and carbon-counting systems for the mariculture system's ecosystem service functions. Such applications can make China's mariculture green development goal, carbon emission peak goal and carbon neutrality goal essentially meaningful.

Third, mariculture activities have always been considered to have negative effects on natural habitats and wild species; however, our reviews show that mariculture can have biodiversity conservation and stock enhancement functions if appropriately managed. In this case, China's scientists should provide more detailed knowledge of how mariculture activities interact and affect the wild species and explore sustainable development modes like mangrove restoration-based IMTA.

Fourth, mariculture is a double-edged sword. To avoid unwanted ecological effects and improve the performance of mariculture deployment, China required the highly efficient and flexible use of different IMTA modes, carrying capacity assessment, monitoring (remote sensing and undersea observation networks), and waste treatment techniques and then regulated the mariculture activities based on MSP.

Ultimately, China should strengthen cooperation with fish farming stakeholders, integrating the government, mariculture community, scholars, and non-government organizations in the mariculture system's management. This will be conducive to reduce management costs and improve the livelihoods of small-scale mariculture communities.

AUTHOR CONTRIBUTIONS

X-JZ, JH-F, and L-FH contributed to the conception and design of the study. X-JZ and JH-F wrote the original draft of the manuscript. BX and LY collected the data. X-JZ and S-YS analyzed the data. L-FH provided funding acquisition and validated the manuscript. All authors contributed to the article and approved the submitted version.

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