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Original Research Articles

Economic Benefits and Improvement Strategies for Clam Marine Aquaculture in China: A Comparative Analysis of Zhejiang, Tianjin, and Shandong

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In recent years, clam mariculture output in China has steadily increased. However, environmental pollution and high aquaculture intensity have led to frequent diseases and unstable economic benefits. This study analyzes field research data from clam farming in Zhejiang Province, Tianjin City, and Shandong Province, focusing on farming costs, revenue, break-even points, and net profit sensitivity. The findings reveal that (1) variable costs consistently exceeded fixed costs, particularly in seedling costs, labor, and water rental; (2) net profit and margins ranked highest in Zhejiang, followed by Tianjin and Shandong; (3) Zhejiang exhibited the lowest break-even operation rate and the largest price discrepancies; (4) sensitivity to selling prices was high across all regions, with Zhejiang showing the lowest sensitivity to variable costs. To enhance economic benefits and promote sustainable development, government authorities and industry stakeholders should focus on cultivating high-quality seeds, implementing scientific management, developing green aquaculture, and emphasizing brand development.

INTRODUCTION

With the overall development of the global economy and the continuous upgrading of consumer spending patterns, the demand for aquatic products has consistently increased, leading to the rapid expansion of the global shellfish aquaculture industry. According to data from the Food and Agriculture Organization of the United Nations (FAO), in 2021, the global apparent consumption of aquatic animal food (excluding algae) reached approximately 162 million tons (fresh weight equivalent), marking a significant increase from 28 million tons in 1961. China, Chile, Viet Nam, South Korea, and Japan are the main countries for shellfish culture. In 2022, the total output of shellfish culture in China was 15,695,800 tons, ranking first globally.[1] As a significant economic species among Bivalves, consumers highly favor clams due to their richness in protein, inorganic salts, and vitamins.[2]

Although the aquaculture output of Japan, South Korea, the United States, and several European countries remains at the forefront globally, these countries are facing challenges of unstable economic benefits and diminished market competitiveness due to environmental pollution and ecological degradation. Aquaculture production is closely linked to the environment. Compared to non-shellfish species, shellfish growth, mortality, and quality are more sensitive to environmental changes.[3] Due to the low bait utilization rate, scattered direct discharge of pollutants, and short-term concentrated discharges, as well as encroachment on marine protected areas and ecological protection boundaries, marine aquaculture increases nutrient content in some coastal waters, deteriorates water quality, causes frequent red tides, destroys species diversity, and threatens the safety of the marine ecological environment.[4] Marine pollution leads to more frequent diseases in farmed species, higher mortality, and lower quality of aquatic products.[5] Oysters cultured in France are frequently affected by infectious diseases, leading to large-scale mortality and suboptimal yields. The U.S. oyster aquaculture industry is constrained in its expansion by limited aquaculture lease areas and high start-up and maintenance costs.[6] The unit aquaculture output value, average export price, and the proportion of export volume to total output in South Korea are all lower than in other countries. The advantage in

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"quantity" is insufficient to compensate for the disadvantage in "efficiency".[7]

China is one of the world's largest shellfish-farming countries. In 2023, China's clam marine aquaculture production reached 4.4491 million tons, accounting for 27.03% of China's total shellfish marine aquaculture production and approximately 23.53% of the world's total shellfish marine aquaculture production.[8] Although China's shellfish aquaculture holds a production advantage, there remains significant room for improvement in economic returns.[9] Additionally, the clam aquaculture industry faces numerous challenges. Environmental pollution, severe ecosystem degradation, and over-intensive farming have resulted in frequent disease outbreaks and high mortality rates in Chinese clam farming. The clam industry consumes significant resources yet yields low output, and its economic benefits remain unstable. To promote the sustainable development of China's clam mariculture industry, strengthening cost-benefit analysis is crucial for exploring production potential, optimizing fund utilization, increasing production, reducing costs, and ultimately enhancing the economic benefits of clam mariculture.

In research on the economic benefits of aquaculture, as early as 1985, Shang et al.[10] conducted a micro-level analysis of its cost structure and economic returns. They identified feed, seed stock, and labor as the primary fixed costs in aquaculture. Subsequently, Gempesaw et al.[11] employed a comprehensive, dynamic, and stochastic capital budgeting computer simulation model to assess the cost-benefit, net present value, and other financial metrics of small-scale aquaculture models, evaluating their profitability. Cinemre et al.[12] analyzed the cost efficiency of trout aquaculture in terms of individual heterogeneity of farmers and found that farmers' experience and education levels play a significant role in influencing cost efficiency. Asche et al.[13] analyzed the economic benefits of salmon farms from the perspective of technology and resource allocation, concluding that both configuration and technical efficiency impact farm cost levels. Relevant research in China began in the 1970s, and primarily employed qualitative analysis methods. In recent years, some scholars have conducted quantitative research through farmer tracking. Yang et al.[14] and Yang et al.[15] analyzed the cost-benefit of Chinese flounder and turbot aquaculture, respectively, concluding that feed costs, electricity costs, and depreciation of unit fixed costs were the primary expenses. Lv et al.[16] and Peng et al.[17] identified feed costs as a primary expense in aquaculture. Gao et al.[18] studied shrimp and concluded that, alongside the aforementioned factors, labor costs also represent a significant expense. Some scholars have also examined the revenue performance of aquaculture at the firm level. Zhang et al.[19] noted that technology, stakeholder focus, and internal governance structure can effectively enhance the efficiency of aquaculture firms.

Many scholars have studied the economic benefits of clam mariculture. Zhang et al.[20] and Zhang et al.[21] analyzed the economic benefits of clam farming in Shandong Province and the Liaodong region, concluding that seedling costs, mudflat usage fees, and labor costs accounted for a relatively high proportion of total farming costs. Zhang et al.[22] used the cost-benefit method to analyze the aquaculture status of Hongdao clams, concluding that factors such as the selection of sea areas, differences in seedling species, and the density and timing of seedling casting influence culture efficiency. Yan et al.[23] compared the price, input-output ratio, and unit output of the off-season efficient pond ecological farming model for clams with the traditional farming model, concluding that the ecological farming model improves economic benefits. Zhu et al. ,[24] Wang et al. ,[25] and Li et al.[26] primarily focused on the production and output value of polyculture systems involving clams with shrimp, razor clams, mud snails, and others, concluding that the polyculture model has good economic benefits.

Based on a review of relevant literature, the following viewpoints can be roughly summarized: (1) Current analyses of the economic benefits of clams by scholars primarily focus on individual provinces, often neglecting the impact of factors such as climate conditions and the marine environment, with few comparisons of regional heterogeneity. (2) When analyzing the economic benefits of clams, scholars primarily focus on specific farming models, such as the polyculture or pond ecological farming models, which often makes it challenging to capture the differences in economic benefits across various farming models. (3) Scholars primarily adopt cost-benefit analysis and rely on absolute economic indicators such as output value and production volume. However, they often do not conduct in-depth sensitivity or break-even analyses and rarely utilize relative financial indicators like the cost-profit and sales-profit ratios. Relative indicators may be more suitable for comparing the performance of individual breeding operations of varying scales.

Therefore, this research used field survey data to examine the cost-benefit of clam marine aquaculture in Zhejiang Province, Tianjin City, and Shandong Province. It analyzed aquaculture costs, income, break-even points, and net profit sensitivity and provided relevant recommendations for improving the economic benefits of aquaculture farmers based on the research findings.

CURRENT STATUS OF CHINA'S CLAM AQUACULTURE INDUSTRY

CHINA'S CLAM MARICULTURE PRODUCTION

Clams, classified as mudflat shellfish, have high farming efficiency, strong adaptability, and environmental friendliness. The Bohai Sea, Yellow Sea, East China Sea, and South China Sea, from north to south, form China's coastal waters, with a coastline extending 18,000 kilometers. Fertile offshore waters and expansive mudflats provide ample space and ideal conditions for the development of marine clam farming. The primary clam species farmed in China include *Ruditapes Philippi arum*, *Ruditapes variegatus*, *Cyclina sinensis*, *Meretrix meretrix,* and the introduced *Mercenaria mercenaria*. Figure 1 illustrates the growing trend of China's clam mariculture production. From 2014 to 2023, total production increased from 3,967,000 tons to 4,449,100 tons, with an average annual growth rate of 1.28%. From

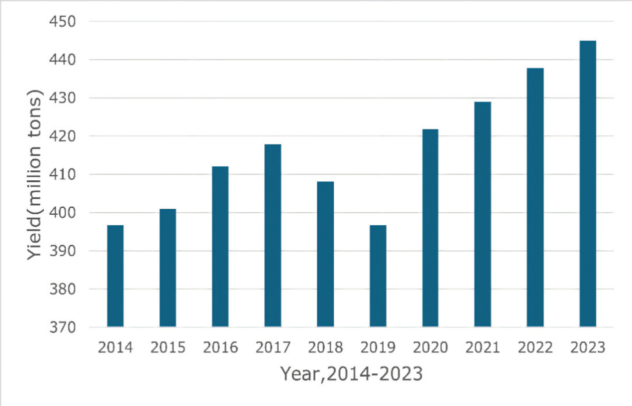

Figure 1. China's marine aquaculture production of clams (2014-2023)

Data Source: China Fisheries Statistical Yearbook

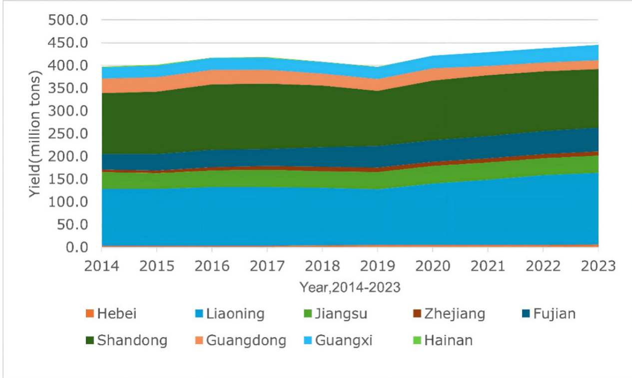

Figure 2. China's clam aquaculture production in major provinces (2014-2023)

Data Source: China Fisheries Statistical Yearbook

2018 to 2019, China's total clam aquaculture output decreased, primarily due to the impacts of typhoons "Mangkhut" and "Lekima," which caused marine pollution and clam mortality. Additionally, stricter marine ecological protection policies restricted the expansion of aquaculture. From 2020 to 2023, following post-disaster recovery and policy adjustments, clam aquaculture output in China rebounded.

CHINA'S CLAM MARICULTURE REGIONS

China's marine clam farming production areas are primarily distributed in Shandong, Liaoning, Jiangsu, Guangdong, Fujian, Guangxi, Hebei, Zhejiang, and Hainan provinces, among others. As shown in Figure 2, from 2014 to 2023, marine clam aquaculture production in Liaoning and Shandong provinces consistently remained at the forefront. In 2023, Liaoning Province produced 1.5171 million tons, ranking first nationally and accounting for 35.45% of the country's total aquaculture output. Shandong's production was 1.2846 million tons, ranking second, accounting for 28.87% of the national total. Together, the two provinces contributed 64.32% of China's total marine clam aquaculture output.

RESEARCH METHODS AND DATA SOURCES

RESEARCH METHODS

This study employed cost-benefit analysis to assess the economic benefits of clam aquaculture. This method evaluates projects or investments by comparing an activity's economic benefits and costs,[27] making it well-suited for the economic evaluation of aquaculture.[28] Cost-benefit analysis uses monetary metrics to estimate and measure inputs and outputs. Adjustments for the time value of money are necessary for longer evaluation periods. In addition, this study performed a break-even analysis and net profit sensitivity analysis to evaluate farmers' adaptability to market fluctuations and their capacity to withstand risks.

DATA SOURCES

The East China Sea borders Zhejiang Province to the east, while Tianjin is located in the northwest of Bohai Bay. As a municipality directly under the Central Government, Tianjin holds the same administrative status as a province, autonomous region, or special administrative region. Shandong Province is bordered by both the Bohai Sea and the Yellow Sea to the east. All three provinces (municipalities) have long coastlines and expansive tidal flats, making them main clam breeding areas. Shandong Province's clam production accounts for 28.87% of the national total. Meanwhile, Zhejiang Province primarily cultivates clams through bottom seeding and explores integrated ecological aquaculture, Tianjin relies on factory farming, and Shandong combines raft farming with bottom seeding. The three provinces (municipalities) each represent one of the major types of clam farming: bottom seeding, factory farming, and raft farming, and are considered relatively typical examples. The research team collected this study's data from July to August 2024 in three clam marine aquaculture areas in Zhejiang Province, Tianjin City, and Shandong Province (as shown in **Figure 3**). The costs and income of clam marine aquaculture were analyzed through one-on-one interviews with farmers and the compilation of questionnaire data. The total sample consisted of 11 households: 4 from Zhejiang Province, 4 from Tianjin City, and 3 from Shandong Province.

ECONOMIC BENEFIT ANALYSIS OF CLAM AQUACULTURE

COST ANALYSIS

The cost structure of clam marine aquaculture is shown in Figure 4. Variable costs are those that fluctuate with output; when production activities occur, these costs increase as production rises and decrease as production falls and include seed stock costs, water and electricity costs, labor wages, and other intermediate inputs. Other intermediate inputs refer to resources utilized in the production process but do not directly form part of the final product, including water conditioning agents, quicklime, sand, etc. Fixed costs

Figure 3. Distribution map of data source regions

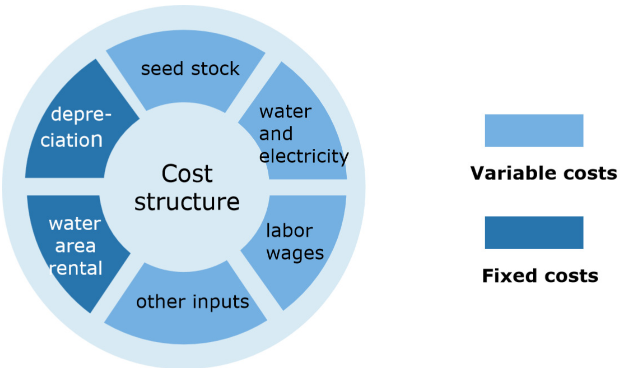

Figure 4. Cost structure of clam aquaculture

remain constant regardless of output over a certain period. These costs stay unchanged no matter how many products are produced, including water area rental fees and fixed asset depreciation. Fixed assets include buildings, aerators, and water quality testing machines with a useful life. This study reasonably assesses service life based on industry standards, equipment manufacturer recommendations, actual usage frequency, and maintenance conditions. The straight-line depreciation method was selected to address depreciation, ensuring an accurate reflection of fixed asset value.

The aquaculture cost analysis was conducted based on actual survey data, and the results were presented in Table 1. In terms of total cost and cost structure, in 2024, the unit total cost of clam marine aquaculture in Zhejiang Province, Tianjin City, and Shandong Province is 10.26 yuan/jin, 1.22 yuan/jin, and 1.91 yuan/jin, respectively. In Zhejiang Province, the variable and fixed costs of clam farming accounted for 55.88% and 44.12% of the total costs, respectively. In Tianjin, the variable and fixed costs accounted for 69.16% and 30.84%, and in Shandong Province, they accounted for 81.71% and 18.29%, respectively. Variations in farming models across different regions result in varying proportions of fixed and variable costs. Zhejiang Province implements refined management practices for clam cultivation, using modern technology and equipment to optimize conditions and maximize both production and revenue. Therefore, Zhejiang Province uses advanced production equipment to strictly control the cultivation process, resulting in a higher proportion of fixed costs. Shandong Province uses extensive management for clam cultivation, primarily relying on natural resources to sustain cultivation activities. Therefore, Shandong Province has a lower demand for equipment, resulting in a lower fixed cost ratio.

In terms of variable costs, the variable costs of clam mariculture in Zhejiang Province, Tianjin and Shandong Province were 5.73 yuan/jin, 0.84 yuan/jin and 1.56 yuan/jin, respectively, with large differences in the cost structure. In Zhejiang Province, seed stock costs and other intermediate inputs, such as biological agents and lime, accounted for 41.16% and 10.56% of the total cost, respectively. In Tianjin, seed stock costs and labor wages accounted for 16.21% and 50.28% of the total cost, respectively. Most clams farmed in Zhejiang Province were purchased from other provinces, such as Hebei, leading to a high dependence on external seed stock and relatively high seed prices. Zhejiang clam farmers and enterprises regularly used sand and lime for pond cleaning to improve and optimize the aquaculture environment, preventing substrate acidification and water eutrophication.[29] As a result, the proportion of other intermediate inputs was relatively high. Clam farmers and enterprises in Tianjin collaborated with scientific research institutes to purchase clam seedlings from local breeding bases. However, the high level of economic development and urban living standards in Tianjin resulted in elevated labor wages. In Shandong Province, seed stock costs and labor wages for clam farming accounted for 54.36% and 25.96% of the total cost, respectively, while water and electricity costs and other intermediate inputs accounted for a relatively small proportion.

In terms of fixed costs, water area rental fees accounted for the highest proportion. Farmers and enterprises must lease water areas for aquaculture production activities, which requires them to pay water area rent. The proportion of water area rental fees for clam farming in Zhejiang Province, Tianjin City, and Shandong Province relative to total costs was 41.03%, 28.32%, and 16.03%, respectively, with amounts of 4.21 yuan/jin, 0.35 yuan/jin, and 0.31 yuan/jin, respectively. The water rental price in Zhejiang Province was relatively high. The second was fixed asset depreciation. In Zhejiang Province, Tianjin City, and Shandong Province, fixed asset depreciation for clam culture accounted for 3.09%, 0.12%, and 2.26% of total costs, respectively, with amounts of 0.32 yuan/jin, 0.03 yuan/jin, and 0.04 yuan/jin, respectively. This was because Zhejiang Province emphasized scientific management of clam farming and continuously introduced new equipment, such as water quality monitoring systems, leading to higher depreciation of fixed assets.

BENEFIT ANALYSIS

Revenue is measured by total revenue per unit, net profit, cost-profit ratio, and sales profit margin. Total revenue per unit reflects the market price of clams. Net profit represents

Table 1. Cost Structure of Clam Aquaculture in Zhejiang, Tianjin, and Shandong Provinces (2024)

Cost Items		Zhejiang Province		Tianjin City		Shandong Province	
		Amount (yuan/jin)	Cost share(%)	Amount (yuan/jin)	Cost share(%)	Amount (yuan/jin)	Cost share(%)
Variable Costs	Seed Stock	4.22	41.16	0.20	16.21	1.04	54.36
	Water and Electricity	0.34	3.28	0.03	2.67	0.01	0.52
	Labor	0.09	0.88	0.61	50.28	0.50	25.96
	Other Intermediate Inputs	1.08	10.56	0	0	0.02	0.87
	Subtotal	5.73	55.88	0.84	69.16	1.56	81.71
Fixed Costs	Water Area Rental	4.21	41.03	0.35	28.32	0.31	16.03
	Fixed Asset Depreciation	0.32	3.09	0.03	0.12	0.04	2.26
	Subtotal	4.53	44.12	0.38	30.84	0.35	18.29
	Total Unit Cost	10.26	100.00	1.22	100.00	1.91	100.00

Note: 1 RMB ≈ 0.14 USD ; 1 jin = 0.5 kg
Data Source: Compiled by the research team from survey data.

the difference between revenue and cost. Cost-profit ratio reflects the profit per unit cost and measures farmers' cost profitability. reflects farmers' profitability in the sales process.

Table 2 showed the revenues of clam marine aquaculture in Zhejiang Province, Tianjin Municipality, and Shandong Province. In terms of net profit, the net profit of clam farming in Zhejiang Province, Tianjin City, and Shandong Province was 7.24 yuan/jin, 0.81 yuan/jin, and 0.99 yuan/jin, respectively. The cost-profit ratio of farmed clams in Zhejiang Province was the highest, at 70.57%, followed by Tianjin at 66.22%, and Shandong Province at 51.57%. This indicated that the profit per unit cost of farmed clams in Zhejiang Province was higher, and its cost control was more efficient. Zhejiang had the highest sales profit margin for farmed clams at 41.37%, followed by Tianjin and Shandong at 39.84% and 34.02%, respectively. This was primarily because Zhejiang Province adopted a multi-nutrient integrated farming method, cultivating clams alongside shrimp and crabs. Multi-nutrient integrated farming method is a sustainable model designed to minimize environmental impact and enhance economic benefits by cultivating species from different trophic levels in the same water body, forming an interdependent ecosystem. This approach reduced pollution, improved material utilization, and enhanced clam quality. In Tianjin and Shandong Province, clams were primarily farmed using monoculture practices. In certain local waters, the large-scale single-species and single-mode farming resulted in excessively high densities. This placed significant pressure on the ecological environment of aquaculture areas, and, to some extent, restricted the growth rate of clams and their ability to resist diseases, thereby affecting the quality of clams.[30]

UNCERTAINTY ANALYSIS

BREAK-EVEN ANALYSIS

Break-even analysis identifies the price or production volume necessary to achieve break-even (where total costs equal total returns)[31] and is employed to evaluate a farmer's ability to withstand cost fluctuations and change.

Table 3 showed the break-even situation of clam farming in Zhejiang Province, Tianjin City, and Shandong Province in 2024. The break-even operating rate was defined as the ratio of the break-even price of clams to the actual sales price. A smaller ratio indicated a stronger ability of the farmer to withstand risks in clam farming. The break-even operating rates for clam farming in Tianjin and Shandong were 40.30% and 45.48%, respectively, while in Zhejiang it was 34.13%. Clam farming in Zhejiang demonstrated the strongest ability to avoid market risks, whereas clam farming in Tianjin and Shandong was more susceptible to market price fluctuations. The larger the gap between the actual sales price and the breakeven price, the more profitable clam farming became for farmers and companies. The difference between the actual sales price and the break-even price for farmed clams in Zhejiang Province, Tianjin City, and Shandong Province was 7.24 yuan/jin, 0.81 yuan/jin, and 0.99 yuan/jin, respectively. Clam farming in Zhejiang Province offered a substantial profit margin.

SENSITIVITY ANALYSIS

This paper selected fixed costs, variable costs, and sales prices as influencing factors to conduct a sensitivity analysis on net profit. The net profit sensitivity coefficient referred to the ratio of the percentage change in net profit to the percentage change in a specific influencing factor. It was used to measure how sensitive net profit was to changes in that factor. A higher sensitivity coefficient indicated a greater influence of the factor on net profit fluc-

Table 2. Revenue Situation of Clam Aquaculture in Zhejiang, Tianjin, and Shandong (2024)

	Zhejiang Province	Tianjin City	Shandong Province
Unit total cost (yuan/jin)	10.26	1.22	1.91
Unit total revenue (yuan/jin)	17.50	2.03	2.90
Net profit (yuan/jin)	7.24	0.81	0.99
Cost-profit ratio (%)	70.57	66.22	51.57
Sales profit margin (%)	41.37	39.84	34.02

Note: 1 RMB ≈ 0.14 USD ; 1 jin = 0.5 kg
Data Source: Compiled by the research team from survey data.

Table 3. Break-even Situation of Clam Aquaculture in Zhejiang, Tianjin, and Shandong (2024)

	Zhejiang Province	Tianjin city	Shandong Province
Break-even Operating Rate (%)	34.13	40.30	45.48
Break-even Price (yuan/jin)	10.26	1.22	1.91
Actual Selling Price (yuan/jin)	17.50	2.03	2.90
Pirce difference (yuan/jin)	7.24	0.81	0.99

Note: 1 RMB ≈ 0.14 USD ; 1 jin = 0.5 kg
Data Source: Compiled by the research team from survey data.

Table 4. Net Profit Sensitivity of Clam Aquaculture in Zhejiang, Tianjin, and Shandong (2024)

	Zhejiang Province	Tianjin Citye	Shandong Province
Fixed costs	-0.63	-0.47	-0.35
Variable costs	-0.79	-1.03	-1.58
Price	2.42	2.51	2.93

Data Source: Compiled by the research team from survey data.

tuations. A positive sensitivity coefficient implied that net profit changed in the same direction as the influencing factor. As shown in Table 4, the sensitivity coefficient of net profit to sales price was the highest in clam mariculture across Zhejiang Province, Tianjin, and Shandong Province, followed by variable costs and lastly fixed costs, indicating that net profit was most affected by sales price fluctuations. The sensitivity coefficients of net profit to sales price and variable costs in Zhejiang Province were both lower than those in Tianjin and Shandong Province, indicating that changes in sales price and variable costs had less impact on the net profit of clam farming in Zhejiang Province.

The angle between the straight line and the horizontal axis in Figure 5 reflected the sensitivity of the variable factors to net profit. Changes in sales price had the greatest impact on net profit, followed by variable costs, while fixed costs had a smaller impact. Therefore, increasing the sales price had the most significant impact on improving the economic benefits of clam marine aquaculture. Additionally, reducing variable costs was another important strategy for enhancing economic benefits.

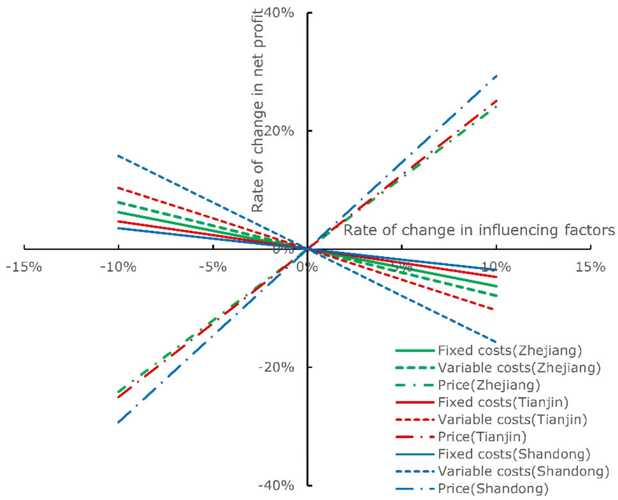

Figure 5. Net Profit Sensitivity Analysis for Clam Aquaculture

Data Source: Compiled by the research team from survey data.

CONCLUSION AND DISCUSSION

CONCLUSION

China is a major clam farming country. While production has continued to grow in recent years, problems such as aquaculture diseases and excessive farming density have also been exposed, affecting economic benefits and the sustainable development of the industry. This research investigated 11 clam farmers in Zhejiang Province, Tianjin City, and Shandong Province, and used cost-benefit analysis, break-even analysis, and net profit sensitivity analysis to compare and analyze their economic benefits. The results show that:

1. The total unit cost of clam farming is highest in Zhejiang Province, followed by Shandong Province and finally Tianjin. The variable costs of the three provinces (municipalities) were all higher than the fixed costs. The variable costs of clam farming in Zhejiang Province, Tianjin City, and Shandong Province accounted for 55.88%, 69.16%, and 81.71% of the total costs, respectively. The utilization rate of fixed assets in various aquaculture industries in Zhejiang Province was relatively high, and most of them used equipment such as water quality testing. In terms of cost structure, among the fixed costs, the main ones in Zhejiang Province were seed stock costs and other intermediate inputs, while the main ones in Tianjin and Shandong Province were seed stock costs and labor wages. The seed stock costs were the lowest in Tianjin, which was mainly due to the fact that the clams farmed in Tianjin were mainly purchased from local seedling breeding bases, where the seedling price was low. Among the fixed costs, water area rental fees and depreciation of fixed assets were the main expenditure items.
2. The net profits from clam farming in all three provinces (municipalities) were positive, indicating that clam farming remained profitable. Zhejiang Province had the highest cost-benefit ratio among the three provinces (municipalities). This was due to Zhejiang's focus on refined management and superior cost control, whereas Shandong Province predominantly used extensive management methods in clam farming. The highest sales profit margin was recorded in Zhejiang Province. In Zhejiang Province, clams were primarily farmed alongside shrimp and crabs. The clam products were of high quality, with good taste, making them more popular among consumers.
3. The break-even rate for clam farming in Zhejiang Province was the lowest, and the difference between the actual sales price and the break-even price was the largest. This was primarily due to the fact that most clam farmers in Zhejiang Province had joined agricultural cooperatives, which to some extent addressed issues such as outdated technical management and delayed market information, thereby enhancing their ability to withstand risks.
4. The net profit of clam farming in Zhejiang Province, Tianjin City, and Shandong Province was highly sensitive to price. The net profit of clam farming in Zhejiang Province was the least sensitive to variable costs and sales prices, with sensitivity coefficients of -0.79 and 2.42, respectively. Changes in price and variable costs resulted in minimal changes to net profit, indicating greater stability in farming operations.

DISCUSSION

First, Zhejiang recorded the highest unit total cost of clam aquaculture. The variable costs in the three provinces (municipalities) were all higher than the fixed costs, with seed stock costs, labor wages, and water area rental fees accounting for a significant proportion. These findings are consistent with those of Wyban et al.[32] and Macfadyen et al. .[33] The former identified shrimp seed, feed, and labor costs as the primary expenses in shrimp farming, while the latter emphasized that skill level and management practices positively affect the economic benefits of aquaculture. Both studies, however, are based on aquaculture data from the same region. This study compared the cost structure of marine clam aquaculture across Zhejiang, Tianjin, and Shandong. Although these regions differ in terms of economic development, aquaculture models, and management levels, seed stock costs, labor wages, and water area rental fees remain the primary cost components. The calculation of net profit and cost-profit ratio further confirmed the role of investment in equipment and management in enhancing aquaculture efficiency.

Second, the net profit, cost-profit ratio, and sales profit margin in Zhejiang Province were significantly higher than those in Shandong Province and Tianjin City. This was primarily attributed to the implementation of the polyculture model involving clams, shrimp, and crabs. Xie et al. ,[34] Song et al. ,[35] and Ge et al.[36] also found that the polyculture model in aquaculture maximizes water resource utilization and effectively enhances economic benefits. However, scholars primarily evaluate economic benefits using absolute financial indicators such as output and output value. This study used a combination of relative and absolute financial indicators to provide a more comprehensive and objective evaluation of the economic benefits of the polyculture model involving clams, fish, and shrimp.

Third, the break-even rate for clam farming in Zhejiang Province was the lowest, the difference between the actual sales price and the break-even price was the largest, and the net profit was less sensitive to price fluctuations and changes in variable costs, indicating that its farming system exhibited greater stability and risk resistance. Ridler et al.[37] employed a capital budgeting model, taking into account risk factors, to demonstrate that integrated multi-trophic aquaculture enhances profitability while mitigating financial risk through diversification. Shi et al.[38] also demonstrated that integrated trophic aquaculture of kelp and scallop carries lower economic risks compared to monoculture. This study further employed break-even analysis and sensitivity analysis to confirm that the polyculture model can effectively enhance farmers' ability to withstand risks, and clarified that Zhejiang Province was able to mitigate the impact of market fluctuations by optimizing cost structure and adjusting sales strategies.

RECOMMENDATIONS

The sustainable development of agriculture should focus on three key aspects: avoiding adverse environmental impacts, being accessible and effective for farmers, and increasing productivity.[39] The government should focus on the following key aspects when promoting the economic benefits of clam aquaculture, as well as guiding and regulating its healthy, sustainable, and stable development:

1. Strengthen the seed breeding system and improve seedling quality. Mudflat shellfish are a category in China's marine aquaculture that started relatively late in terms of breeding development, with breeding techniques being particularly challenging.[40] The survey revealed that clam farmers and enterprises in Shandong and Zhejiang Provinces rely heavily on purchasing seed stock from other provinces. Relevant departments should guide clam farmers and enterprises to collaborate with scientific research institutes to strengthen seedling breeding and establish large-scale seedling breeding bases, ensuring a sufficient supply of high-quality seedlings for production. While actively cultivating local seedlings, it is also essential to introduce clam varieties from neighboring provinces. Relevant departments should improve laws and regulations and strengthen the quality inspection and quarantine of seedlings introduced from other regions. Relevant departments can selectively introduce robust, disease-resistant, and stress-resistant varieties based on the region's specific water quality, substrate conditions, temperature, and salinity, and conduct demonstration breeding and promotion.
2. Improve farming practices and emphasize scientific management. With labor and water resources becoming increasingly limited, simply increasing investment in fishing vessels to drive growth is unsustainable. Continuous improvement of breeding technology is regarded as the most viable option for ensuring the sustainable development of China's aquaculture industry.[41] The investigation revealed that labor wages for clam farming in Tianjin and Shandong Province were relatively high. On one hand, relevant departments should actively promote the mechanization and scaling of clam farming, apply modern aquaculture Internet of Things technology in fisheries, and utilize intelligent water quality monitoring systems to promptly assess and regulate water quality, thereby effectively controlling costs. On the other hand, relevant departments should also strengthen professional skills training for farmers, provide technical services such as water quality testing, disease diagnosis, and medication guidance, and offer support regarding seedling timing and breeding density.
3. Transition the development strategy and advance sustainable aquaculture. The concept of green, low-carbon, and eco-friendly aquaculture represents the future development direction of China's aquaculture, with filter-feeding shellfish farming serving as a strong foundation for the efficient and low-carbon development of the industry.[42] Relevant departments should establish appropriate aquaculture density based on the substrate conditions of local tidal flats, enhance supervision, and prevent over-breeding. Additionally, the integrated farming of clams, shrimp, and fish can effectively improve water body utilization, reduce water pollution, increase the efficiency of input materials, lower costs, and balance both economic and ecological benefits. Local areas can develop integrated breeding systems based on local conditions, optimize the matching of different species, and effectively enhance economic benefits.
4. Strengthen the integration of production and marketing, with an emphasis on brand development. Given the high sensitivity of net profits from clam farming in the three provinces (municipalities) to sales prices, relevant departments should establish flexible and efficient industry associations and cooperatives to disseminate market information and provide technical guidance, thereby enhancing the ability of farmers and enterprises to mitigate market risks. Additionally, local governments can draw inspiration from public brands like "Rushan Oyster" and "Hongdao Clam" and apply for public brand or origin certification. Farmers may apply for green certification and trademarks. Relevant departments should enhance the visibility and influence of local clam products by organizing trade fairs and expositions and leveraging rural e-commerce and short video platforms for promotion. They should fully utilize digital platforms, expand sales channels, explore brand value, and cultivate a clam industry with local characteristics.

INSIGHTS FOR GLOBAL AQUACULTURE

Balancing cost control with sustainability and improving profitability through technological and management innovation are universal challenges. The research methods, conclusions, and countermeasures proposed in this paper may offer insights and inspiration for breeding other aquatic species and for the aquaculture industry globally.

On the one hand, this study employed cost-benefit analysis, break-even analysis, and sensitivity analysis to evaluate the economic benefits of clam mariculture. These methods are applicable to assessing the economic benefits of aquaculture for other aquatic species, such as fish and shrimp. Specifically, sensitivity analysis helps farmers and policymakers assess how changes in variable costs, fixed costs, and sales prices affect profitability, and evaluate the capacity of farmers or companies to manage risks, enabling them to devise better countermeasures. This approach is applicable to all types of aquaculture industries globally.

On the other hand, drawing on clam farming data from three provinces (municipalities) in China, this study provided valuable insights for the clam marine aquaculture industry in other countries. The results showed that variable costs, including seedlings and labor, significantly impacted economic benefits. Other countries or regions could have improved economic outcomes by advancing aquaculture techniques and optimizing cost management practices. In addition, environmental pollution and high aquaculture density led to an increased risk of disease, and other countries or regions could have developed sustainable aquaculture practices according to local conditions. Finally, the sensitivity of sales prices highlighted that farmers or companies could have enhanced profits through brand development, a strategy with global applicability.

RESEARCH DEFICIENCY AND FUTURE PROSPECTS

There are still areas worth further exploration in this study. We suggest that future research can be advanced in the following four aspects:(1) While this study selected data only on clam marine aquaculture from three provinces (municipalities) in China, it may not fully reflect the diversity of aquaculture practices across the country. Future studies could expand the sample range to include more regions with diverse climates, ecological environments, and farming patterns to enhance the generalizability of the findings and deepen the understanding of aquaculture differences across the country. (2) While this study focused on the economic benefits of clam mariculture, it paid less attention to its social and ecological aspects. Additionally, the study was primarily based on cross-sectional data from 2024, without considering the trends in economic benefits over time. Future research could integrate social and ecological factors to further analyze the impacts of clam farming on local communities and the environment, including water quality monitoring and biodiversity changes. Additionally, future research could incorporate longitudinal data to analyze long-term trends in clam aquaculture and its ongoing impacts on economic benefits and ecosystems. (3) While this study briefly mentioned global aquaculture trends, it did not compare Chinese clam farming with practices in Japan, South Korea, or the United States. Future research could analyze the global status of Chinese clam farming through such comparisons. (4) The study did not sufficiently explore policy recommendations and technological innovations, and future research could specify how stakeholders (government, private sector, farmers) can implement strategies. Moreover, future research could focus on improving the efficiency and sustainability of clam farming through technological innovation.

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AUTHORS' CONTRIBUTION

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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