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Original Research Articles

Research on the optimization of the industrial aquaculture management mode based on bioeconomic analysis: A case study of *Cynoglossus semilaevis* aquaculture in China

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Scientific management plays a pivotal role in driving the sustainable intensification of global aquaculture. Optimizing farming management modes and enhancing comprehensive aquaculture efficiency will contribute to enriching the "Blue Granary" while improving its ecological sustainability and resilience. Using *Cynoglossus semilaevis* Günther farmed in China as an example and utilizing multivariate statistical analysis on field survey data collected from major production regions between 2021 and 2024, this study aims to identify key factors influencing economic performance and help farmers to optimize their management strategies for this species. The results indicate that: within the surveyed production areas, the large-scale industrial recirculating aquaculture systems (RAS) mode showed significantly superior economic benefits; the grow-out rate, a pivotal factor affecting economic returns, is predominantly determined by the feminization rate of seedlings; utilities cost and labor cost are the major factors significantly influencing the total revenue of farming this species; while the industry currently exhibits diminishing returns to scale during the study period, it still retains notable economies of scale in unit cost efficiency. To accelerate the sustainable intensification of this industry, the study recommends farmers to adopt large-scale industrial RAS mode, prioritize high-quality seedlings, and optimize production and management modes. Furthermore, different level governments should increase subsidies for industrial RAS mode to curb adverse selection during the blue transformation of the industry, thereby promoting the high-quality development of global aquaculture.

INTRODUCTION

Sustainable intensification offers a new approach to resolve the tensions between food security and resource-environmental constraints.[1] In the aquaculture sector, this concept has been operationalized through sustainable intensive practices, as evidenced by the FAO documentation of successful cases across Asia-Pacific.[2] Particularly, Recirculating Aquaculture Systems (RAS) exemplify such sustainable intensification by enabling transformative upgrades through enhanced resource efficiency, controlled environments, and advanced technologies—collectively boosting productivity while reducing ecological impacts.[3]

In China's marine fish farming sector, industrialized aquaculture is predominantly practiced in regions such as Shandong, Tianjin, and Liaoning, with key species including *Scophthalmus maximus*, *Cynoglossus semilaevis* Günther (*C. semilaevis*), and *Epinephelus* spp.[4] Among these, *C. semilaevis* has emerged as an economically vital species for coastal farmers due to its delicate flavor, high farming efficiency, and strong economic returns.[5] Currently, the prevailing cultivation system for this species in China is the industrial flow-through aquaculture mode.[6] However, this system is characterized by high resource consumption, low recycling efficiency, and significant environmental pressure, failing to align with sustainable intensification goals. Industrial RAS mode, conversely, not only achieve water resource recycling and reuse but also effectively mitigate wastewater discharge and pollution.[7] The technological advantages of Industrial RAS mode directly decrease farmers' reliance on water resources while enhancing operational stability, aligning better with blue transformation objectives.[8] Yet, most *C. semilaevis* farmers persist with industrial flow-through aquaculture mode. As economically rational actors, farmers prioritize economic returns above all else. This raises a critical question: Is industrial RAS mode

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inherently less profitable than industrial flow-through aquaculture mode?

The economic performance of aquaculture production is influenced by multiple factors, including the quality/quantity of inputs and operational scale. According to economies of scale theory, production scale can significantly affect economic outcomes.[9] Effective management is a critical prerequisite for maximizing aquaculture profitability, with its efficacy being determined by both the manager's span of control and the production scale. However, most existing studies on the economic performance of aquaculture predominantly focus on cost-benefit analyses.[10,11] Few have attempted to optimize *C. semilaevis* management modes or identify key factors affecting profitability through the dual perspectives of aquaculture mode and aquaculture scale, making it difficult to provide robust decision-making support for the industry's sustainable intensification.

This study employs field survey data from *C. semilaevis* aquaculture operations, utilizing multivariate statistical analysis to examine the interactive effects of aquaculture mode and aquaculture scale on cost-benefit dynamics from a bioeconomic perspective. By identifying key economic performance determinants and exploring optimization pathways for industrialized aquaculture management modes under sustainable intensification requirements, the research aims to guide farmers in adopting blue transformation practices and ultimately drive high-quality development in the aquaculture sector.

MATERIALS AND METHODS

DATA SOURCE

The data for this study were collected between 2021 and 2024 by the Industrial Economics Research Team of the National Technology System for the Marine Fish Industry. Field interviews and questionnaires were administered to *C. semilaevis* farmers and enterprises in major production regions across China, including Shandong, Hebei, and Liaoning provinces. These regions were selected due to their early adoption of *C. semilaevis* farming, accumulated expertise, and high homogeneity in cultivation techniques and management practices. These factors ensure strong sample representativeness and comprehensively reflect current industry conditions.

An initial set of 49 survey responses was obtained. To ensure data reliability, key indicators such as costs, yields, and sales prices were cross-verified against regional market prices and typical revenue structures from industry reports during the same period.[12] Through this verification process, three invalid samples that significantly deviated from actual market conditions were identified and excluded, resulting in 46 valid datasets for analysis. Literature review indicates that sample sizes in fisheries bioeconomic studies typically range from 30 to 60.[13,14] However, it should be noted that although the sample size meets disciplinary norms, its spatial coverage is limited. This may hinder comprehensive representation of differences across various aquaculture regions at the national level, as well as the ability to capture dynamic changes in aquaculture economic parameters over the long term.

VARIABLE SELECTION

As a high-density intensive aquaculture species, the costs and profitability of *C. semilaevis* farming are closely tied to its biological growth characteristics. Consequently, variables in this study were categorized into three groups: biological variables, cost variables, and profitability variables. Based on relevant literature[10,12] and an analysis of input variables across *C. semilaevis* production stages, the biological variables included stocking density and grow-out rate, while cost variables encompassed seedling cost, feed cost, labor cost, utilities cost, depreciation of fixed assets, equipment repair cost, and other costs. Profitability variables comprised total revenue, net revenue, benefit-cost ratio, and return on sales ratio. The detailed definitions of these variables are presented in Table 1.

Based on actual production conditions, this study categorized the collected samples into small-scale and large-scale farming groups using an annual production threshold of 30 tons. The aquaculture modes observed in the survey comprise industrial flow-through aquaculture mode and industrial RAS mode. Detailed classification criteria for these management modes are provided in Table 2.

RESEARCH METHODS

This study employed multivariate statistical analyses—including two-way analysis of variance (ANOVA), two-way multivariate analysis of variance (MANOVA), Cobb-Douglas production function, Mahalanobis distance and Fisher's linear discriminant analysis (LDA)—to analyze the biological, cost, and profitability variables defined in Table 1.

Two-way ANOVA was employed to examine the independent effects of aquaculture scale and aquaculture mode on *C. semilaevis* management and economic performance, while also investigating potential interaction effects that might influence producer profitability between two factors. In contrast, two-way MANOVA extended this approach by focusing on the combined effects of multiple independent variables.[15]

The Cobb-Douglas production function was applied to analyze the relationship between cost variables and total revenue in *C. semilaevis* aquaculture, aiming to identify specific factors influencing profitability.[14] By comparing the sum of cost variable exponents to 1, we assessed whether the industry exhibited increasing returns to scale under current technological conditions and explored whether expanding cost inputs can enhance total revenue. Assuming that five cost variables significantly affect total revenue, the Cobb-Douglas production function is defined as:

$$TR = AC_1^{\beta_1} C_2^{\beta_2} C_3^{\beta_3} C_4^{\beta_4} C_5^{\beta_5} \quad (1)$$

In equation (1), TR denoted the total revenue, C_i(i=1,2,3,4,5) represented the five cost variables significantly influencing TR, and β_i(i=1,2,3,4,5) indicated the percentage change in TR resulting from a 1% variation in cost

Table 1. Description of research variables for *C. semilaevis* aquaculture in main production areas.

Variables	*Meaning*	*Unit*	*Meaning or remark*
Biological variables			
SD	Stocking density	kg/m²	The weight of *C. semilaevis* seedlings per square meter
GR	Grow-out rate	%	The ratio of the final mature *C. semilaevis* count to the initial stocking number
Cost variables			The cost per kilogram of culturing a *C. semilaevis* to adulthood, representing the unit cost of each type of input
SC	Seedling cost	CNY/kg	/
FC	Feed cost	CNY/kg	/
LC	Labor cost	CNY/kg	Including both permanent and temporary employees
UC	Utilities cost	CNY/kg	Including the cost of electricity, water, and coal
DFA	Depreciation of fixed assets	CNY/kg	The annual amortization cost calculated using the straight-line depreciation method
ERC	Equipment repair cost	CNY/kg	/
OC	Other costs	CNY/kg	Including costs for fish medicine, transportation, water resources fees, etc
TC	Total costs	CNY/kg	/
Profitability variables			
TR	Total revenue	CNY/kg	The ratio of total revenue to production for the entire aquaculture farm
NR	Net revenue	CNY/kg	The difference between total revenue and total costs
BCR	Benefit-cost ratio	/	The ratio of total revenue to total costs
ROS	Return on sales ratio	%	The ratio of net revenue to total revenue

Table 2. Classification table of four management modes for *C. semilaevis* aquaculture in main production areas

	Industrial flow-through aquaculture	*Industrial RAS*
Small scale	Small-scale industrial flow-through aquaculture mode (SF)	Small-scale industrial RAS mode (SR)
Large scale	Large-scale industrial flow-through aquaculture mode (LF)	Large-scale industrial RAS mode (LR)

variable C_i, where A was a constant. To mitigate heteroscedasticity and increase the stability of the data, logarithmic transformation was applied to both sides of the equation, yielding the linearized form in Equation (2):

$$lnTR = \beta_1 \ln C_1 + \beta_2 \ln C_2 + \beta_3 \ln C_3 + \beta_4 \ln C_4 + \beta_5 \ln C_5 + \ln A \quad (2)$$

To explore the characteristics and key driving factors of different management modes for *C. semilaevis*, Mahalanobis distance was used to assess intergroup differences and identify the pair of groups with the greatest disparity. Fisher's LDA was employed for dimensionality reduction and classification, as well as to identify the primary discriminant variables. Detailed methodological descriptions are provided in the Appendix.

RESULTS

The basic data from the survey of 46 aquaculture farmers were statistically analyzed and classified according to aquaculture scale and aquaculture modes, with results summarized in Table 3.

Building on it, further statistical analysis was conducted on the data related to aquaculture management modes, yielding the characteristics of biological, cost, and profitability variables across different management modes, as shown in Table 4.

ANALYSIS OF VARIANCE

A two-way ANOVA and a two-way MANOVA were conducted for the three categories of variables, with results presented in Tables 5 and 6.

For biological variables, the two-way ANOVA results indicated that stocking density was significantly influenced by aquaculture scale ($P < 0.01$) and aquaculture mode ($P < 0.0001$), but not by their interaction, meaning no new effect arose when both factors interacted.

Regarding aquaculture scale, small-scale aquaculture exhibited higher stocking densities than large-scale aquaculture. In terms of aquaculture mode, industrial RAS mode showed higher stocking densities compared to industrial flow-through aquaculture mode (Table 3). Among the management modes, SR demonstrated the highest stocking density at 11.07 kg/m², approximately 1.54 times that of LF. However, grow-out rate was not significantly affected by aquaculture scale, aquaculture mode, or their interaction (Table 5). The mean grow-out rates across the four manage-

Table 3. Basic information of *C. semilaevis* aquaculture farms in main production areas

	Aquaculture scale		*Aquaculture mode*	
	Small scale	*Large scale*	*Industrial flow-through aquaculture*	*Industrial RAS*
Number of aquaculture farms	23	23	18	28
Biological variables				
SD	10.43±2.05	8.70±2.04	8.07±1.84	10.52±1.88
GR	27.74±7.03	31.30±13.25	26.56±7.03	31.43±12.16
Cost variables				
SC	9.37±3.52	6.93±2.93	9.82±3.60	7.07±2.90
FC	35.78±7.55	28.27±11.04	40.88±5.53	26.34±8.05
LC	15.18±6.00	10.85±5.51	9.72±5.00	15.13±5.87
UC	12.84±4.23	9.24±3.88	8.85±3.32	12.44±4.49
DFA	5.02±2.74	7.84±3.40	4.60±2.72	7.61±3.25
ERC	2.25±1.42	1.27±0.79	1.03±0.75	2.23±1.27
OC	2.31±1.89	1.29±1.06	1.28±1.03	2.14±1.82
TC	82.74±8.13	65.69±7.87	76.17±11.05	72.96±12.13
Profitability variables				
TR	114.74±17.57	105.05±12.09	95.83±9.68	118.94±11.61
NR	32.00±16.89	39.36±12.36	19.66±10.56	45.98±5.35
BCR	1.39±0.21	1.61±0.22	1.27±0.16	1.65±0.15
ROS	0.26±0.12	0.37±0.09	0.20±0.10	0.39±0.06

The values are expressed in the form of mean ± standard deviation.

Table 4. Basic information of *C. semilaevis* aquaculture farms in main production areas under four management modes

Variables	*SF*	*SR*	*LF*	*LR*
Number of aquaculture farms	8	15	10	13
Biological variables				
SD	9.21±1.69	11.07±1.97	7.17±1.46	9.88±1.62
GR	26.00±5.68	28.67±7.67	27.00±8.23	34.62±15.61
Cost variables				
SC	12.16±2.55	7.88±3.07	7.95±3.27	6.14±2.49
FC	43.12±5.02	31.87±5.46	39.08±5.48	19.96±5.36
LC	12.39±5.57	16.66±5.86	7.59±3.41	13.35±5.59
UC	9.94±3.41	14.38±3.88	7.98±3.15	10.21±4.22
DFA	4.06±3.35	5.54±2.33	5.03±2.20	10.00±2.42
ERC	1.08±0.78	2.87±1.29	0.98±0.78	1.49±0.75
OC	1.53±0.95	2.72±2.15	1.08±1.09	1.46±1.05
TC	84.28±9.05	81.92±7.80	69.68±7.87	62.62±6.61
Profitability variables				
TR	94.84±8.16	125.35±10.24	96.62±11.11	111.54±8.40
NR	10.56±5.62	43.43±5.46	26.94±7.32	48.92±3.50
BCR	1.13±0.07	1.53±0.08	1.39±0.11	1.79±0.08
ROS	0.11±0.06	0.35±0.03	0.28±0.06	0.44±0.03

The values are expressed in the form of mean ± standard deviation.

ment modes were comparable, with a maximum difference of 8.62% (Table 4).

From the perspective of cost variables, total costs was significantly influenced by aquaculture scale ($P < 0.0001$) and aquaculture mode ($P < 0.05$). Specifically, small-scale aquaculture exhibited higher unit total costs compared to large-scale aquaculture, and the industrial flow-through aquaculture mode had higher unit total costs than the in-

Table 5. Two-way ANOVA of aquaculture scale and aquaculture mode for *C. semilaevis* aquaculture farms in the main production areas

Variables	*Aquaculture scale(S)*	*Aquaculture mode(M)*	*S×M*
Biological variables			
SD	11.517***(0.0015)	19.421***(<0.0001)	0.648(0.4253)
GR	1.340(0.2540)	2.735(0.1060)	0.609(0.4400)
Cost variables			
SC	8.292***(0.0062)	11.766***(0.0014)	1.999(0.1648)
FC	22.516***(<0.0001)	88.928***(<0.0001)	5.834**(0.0202)
LC	7.681***(0.0083)	9.878***(0.0031)	0.214(0.6450)
UC	10.520***(0.0023)	8.307***(0.0062)	0.928(0.3410)
DFA	14.295***(0.0005)	18.534***(0.0015)	5.199**(0.0277)
ERC	11.680***(0.0014)	14.570***(0.0004)	4.720**(0.0355)
OC	5.233**(0.0273)	2.863*(0.0981)	0.787(0.3799)
TC	56.050***(<0.0001)	4.208**(0.0465)	1.007(0.3214)
Profitability variables			
TR	11.654***(0.0014)	58.885***(<0.0001)	7.119**(0.0108)
NR	20.640***(<0.0001)	266.480**(<0.0001)	10.650***(0.0022)
BCR	75.313***(<0.0001)	232.464***(<0.0001)	0.018(0.8940)
ROS	67.913***(<0.0001)	231.456***(<0.0001)	7.755***(0.0080)

The data in the table are represented as F-values (P-values). ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

Table 6. Two-way MANOVA of aquaculture scale and aquaculture mode for *C. semilaevis* aquaculture farms in the main production areas

Factors	*Statistical standards*	*Biological variables*	*Cost variables*	*Profitability variables*
Aquaculture scale(S)	Pillai's Trace	5.6232***(0.0069)	17.7139***(<0.0001)	20.6380***(<0.0001)
	Wilks' Lambda	5.6232***(0.0069)	17.7139***(<0.0001)	20.6380***(<0.0001)
	Hotelling's Trace	5.6232***(0.0069)	17.7139***(<0.0001)	20.6380***(<0.0001)
	Roy's Largest Root	5.6232***(0.0069)	17.7139***(<0.0001)	20.6380***(<0.0001)
Aquaculture mode(M)	Pillai's Trace	14.6728***(<0.0001)	15.7676***(<0.0001)	66.8350***(<0.0001)
	Wilks' Lambda	14.6728***(<0.0001)	15.7676***(<0.0001)	66.8350***(<0.0001)
	Hotelling's Trace	14.6728***(<0.0001)	15.7676***(<0.0001)	66.8350***(<0.0001)
	Roy's Largest Root	14.6728***(<0.0001)	15.7676***(<0.0001)	66.8350***(<0.0001)
S×M	Pillai's Trace	0.9086(0.4110)	4.7211***(0.0008)	19.4630***(<0.0001)
	Wilks' Lambda	0.9086(0.4110)	4.7211***(0.0008)	19.4630***(<0.0001)
	Hotelling's Trace	0.9086(0.4110)	4.7211***(0.0008)	19.4630***(<0.0001)
	Roy's Largest Root	0.9086(0.4110)	4.7211***(0.0008)	19.4630***(<0.0001)

The data in the table are represented as F-values (P-values). ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

dustrial RAS mode (Table 3). Within small-scale aquaculture, the industrial RAS mode showed slightly lower unit total costs than the industrial flow-through aquaculture mode (Table 4). Regarding cost composition, the costs for seedling, feed, depreciation of fixed assets, and equipment repair were all significantly influenced by aquaculture scale, aquaculture mode, and their interaction ($P < 0.05$, Table 5). However, seedling cost, labor cost, and utilities cost were not significant for the interaction term, and other costs was significant only for aquaculture scale ($P < 0.05$, Table 5).

For profitability variables, total revenue, net revenue, and return on sales ratio were significantly influenced by aquaculture scale, aquaculture mode, and their interaction ($P < 0.05$). However, the benefit-cost ratio was not significant for the interaction term.In terms of aquaculture scale, large-scale aquaculture outperformed small-scale aquaculture in profitability. Regarding aquaculture mode, industrial RAS mode demonstrated superior profitability relative to industrial flow-through aquaculture mode (Table 3). Among the four management modes, LR achieved the highest profitability indicators (Table 4).

Table 7. Cobb-Douglas production function of *C. semilaevis* in the main production area

	Constant term/Cost variable							
	Constant (ln A)	ln SC	ln FC	ln LC	ln UC	ln DFA	ln ERC	ln OC
Coefficient (β_i)	3.1185***	0.0680***	0.1210***	0.1553***	0.1726***	0.1408***	0.0317***	0.0097
Standard error	0.2667	0.0415	0.0599	0.0287	0.0365	0.0260	0.0182	0.0164
T value	13.034	3.149	3.095	3.715	4.858	3.501	1.235	0.608
Pr > |t|	<0.0001	0.0079	0.0075	<0.0001	<0.0001	<0.0001	0.0089	0.3881

R^2 is 0.8185; F-statistic is 11.85. ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

The two-way MANOVA results indicated that both sets of cost and profitability variables were significantly influenced by aquaculture scale, aquaculture mode, and their interaction across all test criteria (P < 0.01), whereas no significant interaction effects were observed for biological variables (Table 6).

COBB-DOUGLAS PRODUCTION FUNCTION ANALYSIS

Using the Cobb-Douglas production function, we conducted a multiple regression analysis (Table 7) with various cost variables as independent variables and total revenue as the dependent variable after logarithmic transformation. This established the production function for *C. semilaevis* farming industry in the main production areas, formalized in Equation (3).

$$\begin{aligned} lnTR = {} & 0.0680lnSC + 0.1210lnFC + 0.1553lnLC \\ & +0.1726lnUC + 0.1408lnDFA \\ & +0.0317lnERC + 3.1185 \end{aligned} \quad (3)$$

Among the cost variables examined in this study, seedling cost, feed cost, labor cost, utilities cost, depreciation of fixed assets, and equipment repair cost all demonstrated statistically significant positive effects on total revenue (P < 0.01), with elasticities of 0.0680, 0.1210, 0.1553, 0.1726, 0.1408, and 0.0317, respectively (Table 7). Specifically, labor and utilities cost had the highest elasticity coefficients, indicating that they are the primary factors influencing the total revenue of *C. semilaevis* farming. Other costs also had a positive effect on total revenue, though its impact was not statistically significant.

ANALYSIS BY OTHER METHODS

Mahalanobis Distance: Specific results are shown in Table 8 (see Appendix). Based on Mahalanobis distances derived from biological variables, the lowest similarity (greatest distance: 1.8100; P < 0.05) was observed between LF and SR. Combining with Table 4, it can be seen that the grow-out rates difference between these two modes is small, while the stocking density difference is large; hence, the difference in biological performance is not highly correlated with the grow-out rate. For cost and profitability variables, the lowest similarity was found between LR and SF, with the largest distances of 2.4656 (P < 0.01) and 2.7692 (P < 0.01), respectively.

Fisher's LDA: Using either cost variables or profitability variables, all 46 samples were successfully classified into four groups via Fisher's LDA, with almost no overlap among the samples from different farms, indicating a clear clustering relationship. For cost variables, combined with the Mahalanobis distance results, the analysis showed that the LR is mainly located in the second quadrant, while the SF is primarily in the fourth quadrant (Figure 1, see Appendix). The main factors driving the differentiation between these two management modes were equipment repair cost and seedling cost (Table 9, see Appendix). Similarly, for profitability variables, combined with the Mahalanobis distance results, both the LR and SF are located on the negative axis of Y_5 (Figure 2, see Appendix). Their differentiation is primarily determined by the Y_4 axis, with the key factors being the benefit-cost ratio and the return on sales ratio (Table 10, see Appendix).

DISCUSSION

BIOLOGICAL VARIABLE

In high-density intensive aquaculture, the grow-out rate determines the final harvestable quantity of marketable fish and serves as a core factor for enhancing economic returns and achieving sustainable intensification. Selecting an appropriate stocking density is often considered a key strategy to improve the grow-out rate. Taking *Dicentrarchus labrax*, *Salmo salar*, and *Oncorhynchus mykiss* in industrial aquaculture modes as examples, once the stocking density exceeds a specific threshold and continues to increase, the feed conversion efficiency and nutritional quality of the farmed fish often decrease significantly, ultimately affecting the final survival rate.[16] However, the two-way ANOVA confirmed that stocking density, while varying significantly across modes and scales, did not exert a statistically significant influence on the grow-out rate(Table 5), which remained consistently around 29% across all groups(Tables 3 and 4). This suggests that under current production conditions, stocking density is not the primary constraint on grow-out rates.

Based on interviews with farmers and existing research, it is inferred that the key factor affecting the grow-out rate of *C. semilaevis* may lie in the feminization rate of its seedlings. Similar to tilapia, *C. semilaevis* also exhibits sig-

nificant sexual growth dimorphism. In natural populations, existing research demonstrates that conventional seedlings typically yield only about 10%-30% female fish, with significant growth sexual dimorphism - females grow 2-4 times faster than males.[17] Furthermore, unidirectional natural sex reversal during nursery phases converts some females into pseudomales, further reducing female proportions in production systems.[18] The dual challenges of slow male growth and male-biased populations severely constrain farm productivity and profitability, representing a critical bottleneck for sustainable intensification. Farmer interviews revealed that most operations cull portions of male seedling during nursery phases to concentrate female cultivation, ensuring economic viability. This practice explains why all four management modes achieved comparable final grow-out rates, independent of aquaculture scale, aquaculture mode, or their interactions. To improve *C. semilaevis* grow-out rate and advance sustainable intensification goals, we recommend farmers adopt high-quality seedlings like the "Tayou No.1" variety. Studies show that this variety not only demonstrates faster growth rates and stronger disease resistance, but can also increase the proportion of physiological female fish to approximately 40%.[19] Concurrently, researchers are advised to focus on breakthroughs in feminization rates of *C. semilaevis* seedling, aiming to further increase the proportion of physiological female fish while maintaining or enhancing the growth speed and disease resistance advantages of "Tayou No.1". These advancements will accelerate China's development as a global leader in industrial *C. semilaevis* aquaculture.

COST VARIABLE

Effective cost management constitutes a foundational pillar for enhancing competitiveness and advancing sustainable intensification in modern production systems. Research demonstrated that LR exhibited significantly lower unit production costs than the other three management modes (Table 4). A cost composition analysis across all *C. semilaevis* farms exhibited that feed cost represented the largest share of total production expenditures. This phenomenon aligns with the general rule observed in the intensive aquaculture of species such as *Lateolabrax maculatus* and rainbow trout, where feed constitutes the largest cost item.[10,11] From the perspective of aquaculture modes, industrial RAS mode incurred substantially lower expenditures on seedling and feed compared to the industrial flow-through aquaculture mode. This is likely because the RAS maintains a stable water recirculation rate of 10-17 times per day, ensuring optimal water flow dynamics. This characteristic helps slow down the accumulation of solid feed residues in fish tanks and lowers the FCR, thereby significantly improving feed utilization efficiency and growth performance.[20] As a result, the production of *C. semilaevis* in the industrial RAS mode has increased substantially, with lower unit seedling cost and unit feed cost. Of course, this advantage may also be partly attributed to the more sophisticated management equipment typically associated with this mode.

However, industrial RAS mode demonstrated slightly higher costs in depreciation of fixed assets, labor cost, equipment repair cost, and utilities cost compared to industrial flow-through aquaculture mode. The reasons for this can be attributed to several factors. First, the industrial RAS mode is equipped with a more complex set of facilities, such as microfilters, protein skimmers, and biological filters, which are expensive and require a higher level of expertise from the staff of the farm. Consequently, the industrial RAS mode incurred higher depreciation of fixed assets, equipment repair cost, and labor cost compared to industrial flow-through aquaculture mode. This is similar to the report by Badiola et al., where high initial investment and the demand for specialized manpower are common challenges faced by the RAS mode.[21] However, while some studies suggest that industrial RAS mode offer advantages in electricity, water, and coal savings compared to industrial flow-through aquaculture mode,[6,20] its actual performance often falls short of theoretical potential due to operational challenges. The technical sophistication of RAS requires specialized knowledge, which often exceeds the skill set of available farmers, creating a fundamental mismatch. This discrepancy compels a reversion to traditional, often manual, management practices. Such a downgrade in management ultimately creates a performance bottleneck that caps the system's potential efficiency. It is recommended that future aquaculture farmers hire employees with higher educational attainment and provide regular training to enhance their professional skills. This will help fully leverage the green, efficient, and economical performance of industrial RAS mode and advance sustainable intensification in the fisheries. To this end, it is suggested that the government establish a specialized subsidy for talent in RAS technology, offering direct financial support or tax reductions to farms that conduct skill certification training. This will alleviate the financial burden on aquaculture farmers, accelerate the cultivation of professional talent, and provide a strong human resource foundation for the efficient operation of industrial RAS mode. Secondly, a seven-month tracking experiment demonstrated that the optimal stocking density for industrial RAS mode is 8.96 kg/m² to achieve the best aquaculture performance.[22] However, field survey data revealed that many farmers who chose industrial RAS mode maintain stocking densities exceeding this recommended threshold. Higher stocking densities lead to increased concentrations of metabolic waste such as ammonia nitrogen, phosphorus, and nitrite in the water, resulting in more severe pollution.[23] To mitigate the biological impacts of this pollution, farmers must increase water circulation frequency and the number of pumps to improve water quality, which consequently significantly raises electricity cost. Therefore, it is recommended that farmers adjust stocking densities to the advised level of 8.96 kg/m^2 according to their actual conditions. This measure not only effectively reduces metabolic waste concentrations, alleviates water pollution, and improves the aquaculture environment, but also decreases electricity expenses and optimizes production costs, thereby achieving dual enhancement of both economic and ecological benefits while promoting sustainable intensification.

The theory of economies of scale suggests that the aquaculture scale of farms significantly influences input-output efficiency in the production process,[9] which aligns with the findings of this study: under large-scale farming conditions, all unit cost inputs (except depreciation of fixed assets) were lower than those in small-scale farms (Tables 3 and 4), demonstrating superior performance. This phenomenon can be explained by the cost-sharing benefits and improved production efficiency derived from economies of scale.

PROFITABILITY VARIABLES

Profitability provides the economic foundation for sustainable intensification and serves as a key driver for building a fisheries powerhouse. The two-way ANOVA results indicated that both aquaculture scale and aquaculture mode significantly influenced all profitability indicators (Table 5). Among the four management modes, LR mode achieved the highest profitability, a success attributable to the dual advantage of economies of scale and the precision offered by RAS technology. From the perspective of aquaculture scale, profitability analysis indicated that small-scale farms had higher stocking densities and similar grow-out rates, thereby yielding higher unit revenues compared to large-scale farms. However, the theory of economies of scale suggests that large-scale farms inherently possess advantages in achieving lower unit costs. Furthermore, their ability to market larger batches of mature fish in a single cycle provides farmers with stronger negotiating leverage. Consequently, after deducting all production costs, large-scale farms ultimately showed superior performance in net revenue, benefit-cost ratio, and return on sales ratio compared to small-scale farms. From the perspective of aquaculture modes, Tables 3 and 4 demonstrated that industrial RAS mode outperform industrial flow-through aquaculture mode across all profitability variables. This difference may be related to the capacity for precise control over the culture cycle and time to market. Existing studies experimentally demonstrated that under identical environmental conditions, *C. semilaevis* cultured in RAS exhibit approximately 20% faster growth rates. When combined with large-scale farms, this approach can reduce the production cycle by at least two months.[24]Therefore, farmers adopting RAS are able to more precisely plan the growth stages and market timing of fish. Utilizing RAS technology to achieve off-season production or precisely timed market entry in order to obtain price premiums is a common strategy in international high-end aquaculture. The early market entry of fish products creates temporary scarcity in market supply, capitalizing on the prevalent consumer preference for freshness and the inelastic seasonal demand in seafood consumption. This timing disparity in supply weakens buyer bargaining power, resulting in a short-term seller's market structure. Within this structure, where supply is lower than demand, producers gain price-setting power, enabling them to secure market premiums above the equilibrium price. However, the high initial investments and technical complexity of industrial RAS mode create significant adoption barriers. Capital-constrained farmers often persist with traditional industrial flow-through aquaculture mode, triggering an adverse selection problem akin to a "lemons market". To counteract this, we recommend that relevant authorities should substantially increase RAS subsidies to reduce transition costs, incentivize green technology adoption, and ensure the sustainability of industrial upgrading.

COBB-DOUGLAS PRODUCTION FUNCTION

In the fisheries sector, particularly in aquaculture, advancing sustainable intensification efforts primarily depends on enhancing economic efficiency, with accurate identification of key influencing factors being critically important. Within this context, the proper application of the Cobb-Douglas production function provides aquaculture operators with a robust analytical tool to achieve this goal. The analysis identified labor and utilities costs as the most influential drivers of total revenue, with the highest output elasticities. This finding highlights that under current practices, revenue generation depends more on managerial effectiveness achieved through skilled labor for biological oversight, and on system efficiency gained via optimized energy and water use, than on marginal increases in feed inputs that are already near-optimal.

Furthermore, the study found that the overall production elasticity coefficient of seven cost factors was 0.6894 (<1), indicating that the *C. semilaevis* industry is currently in a stage of decreasing returns to scale—where the proportional increase in output is lower than the increase in factor inputs—a trend counterproductive to sustainable intensification. However, from the perspective of unit costs, the industry still exhibits certain economies of scale, but this potential is constrained by multiple factors. This coexistence of diminishing returns to scale and economies of scale in unit costs may reflect that the industry is in a transition period from traditional to modernized modes, where improvements in management and technological capabilities have not yet fully kept pace with the expansion in scale. Field research revealed that farmers faced a dual challenge of insufficient working capital and a shortage of young and middle-aged labor under the current unpredictable market conditions. At present, the workforce in *C. semilaevis* aquaculture is predominantly composed of employees aged 55 and above. As this aging labor force experiences declining innovation capacity, reduced efficiency in information acquisition and dissemination, and a narrowing span of effective management, operational costs are likely to rise and operational efficiency may decrease to some extent. Consequently, it is recommended that farmers drive industrial transformation and upgrading through technological innovation, management optimization, and labor structure improvements to break through the constraints of diminishing returns and propel the aquaculture sector toward resilient and sustainable development.

To sum up, the main conclusions of this research are as follows: First point, among the four management modes, LR aligns most closely with strategic goals for sustainable intensification, demonstrating significant advantages. For *C. semilaevis*, this mode not only achieves optimal eco-

nomic returns and profitability but also optimizes resource utilization and reduces environmental impacts, making it the best choice for farmers. In contrast, SF underperform across all metrics, with equipment repair cost, seedling cost, benefit-cost ratio, and return on sales ratio identified as the primary differentiating factors. Second point, grow-out rate is a critical determinant of economic efficiency in *C. semilaevis* farming, and the feminization rate of seedlings is the key factor influencing grow-out rate. Enhancing feminization rates should be a priority for scientific research and technology promotion. Third point, labor cost affects the biological management quality of *C. semilaevis* aquaculture, while utilities cost influences the facility operational efficiency of the farm. These two factors collectively determine final production yields and are the dominant drivers of total revenue. Finally, during the study period, the *C. semilaevis* industry exhibited diminishing returns to scale from the perspective of overall input-output elasticity, yet benefited from lower unit costs at larger scales, indicating persistent economies of scale in cost efficiency.

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AUTHORS' CONTRIBUTION

Conceptualization: Zhengyong Yang (Equal), Yongai Guo (Equal). Writing – review & editing: Zhengyong Yang (Equal), Yongai Guo (Equal), Zhipeng Hao (Equal). Funding acquisition: Zhengyong Yang (Lead). Resources: Zhengyong Yang (Lead). Supervision: Zhengyong Yang (Lead). Methodology: Yongai Guo (Lead). Formal Analysis: Yongai Guo (Equal), Zhipeng Hao (Equal). Investigation: Yongai Guo (Equal), Zhipeng Hao (Equal). Writing – original draft: Yongai Guo (Lead).

COMPETING OF INTEREST – COPE

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

INFORMED CONSENT STATEMENT

All authors and institutions have confirmed this manuscript for publication.

DATA AVAILABILITY STATEMENT

The data are available from the authors on reasonable request.

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APPENDIX

OTHER RESEARCH METHODS

Mahalanobis distance was used to measure the similarity between samples, taking into account the correlation among features.[25] The definition is as follows:

$$D_{ij}^2 = (\overline{x_i} - \overline{x_j})^T C^{-1} (\overline{x_i} - \overline{x_J}) \quad (4)$$

In equation (4), D_{ij}^2 represents the Mahalanobis distance between categories i and j, $\overline{x_i}$ is the mean vector of the variables for category i , $\overline{x_j}$ is the mean vector for category j, and C^{-1} is the inverse of the sample covariance matrix C. In this study, Mahalanobis distances between the four management modes were calculated using three sets of variables to examine differences in aquaculture performance.

Fisher's LDA was employed to establish multiple linear discriminant functions, which map the original high-dimensional data into a lower-dimensional space, identifying canonical variables that indicate a set of quantifiable metrics [26]. This method provided a visualization tool to discern differences among the four management modes, thereby offering actionable insights for *C. semilaevis* farmers to refine their aquaculture strategies. The method constructs a discriminant function based on analysis of variance as follows:

$$Y_i = C_1X_1 + C_2X_2 + \ldots + C_nX_n \quad (5)$$

In equation (5), the coefficients C_i(i= 1, 2, ..., n) are determined based on the principle of discriminant analysis, which aims to maximize between-group variance while minimizing within-group variance. Here, X_i(i=1, 2, ..., n) denote the variables under study. Given that the biological variables in this study were limited to two dimensions with insufficient discriminative power, the method was primarily applied to cost variables and profitability variables.

MAHALANOBIS DISTANCE ANALYSIS

FISHER'S LINEAR DISCRIMINANT ANALYSIS

Regardless of whether cost or profitability variables were used, all 46 samples were successfully classified into four distinct groups through Fisher's LDA. Table 9 presents the results for the four management modes based on cost variables, with the linear discriminant functions derived as follows:

$$Y_1 = -0.094SC + 0.218FC + 0.097LC + 0.207UC - 0.051DFC + 0.683ERC - 0.002OC - 10.642 \quad (6)$$

$$Y_2 = -0.156SC + 0.001FC + 0.130LC + 0.186UC + 0.211DFC + 0.542ERC + 0.197OC - 5.141 \quad (7)$$

$$Y_3 = 0.300SC - 0.018FC + 0.069LC + 0.020UC + 0.127DFC - 0.147ERC - 0.096OC - 3.375 \quad (8)$$

The three linear discriminant functions (Y_1, Y_2, Y_3) were evaluated using Wilks' Lambda tests. The results demonstrated that both Y_1 and Y_2 functions showed statistically significant classification effects ($P < 0.01$), indicating good model fit. Collectively, these two functions accounted for 97.1% of the cumulative variance contribution, with canonical correlation coefficients exceeding 0.80. For the sake of model simplification, Y_1 and Y_2 were selected as the classification basis. Figure 1 showed a scatter plot created using the Y_1 and Y_2 functions, where virtually no overlap was observed among all aquaculture farm samples, and the four management modes exhibited clear clustering relationships. Among them, LR was primarily located in the second quadrant, with the main contributing factors being seedling cost (-0.094) and equipment repair cost (0.542) (Table 9 and Figure 1).

Similarly, profitability variables could also be significantly differentiated ($P < 0.001$) through three linear discriminant functions Y_4, Y_5, and Y_6 (Table 10), with the following functions:

$$Y_4 = 0.019TR + 0.033NR + 6.636BCR + 5.556ROS - 15.043 \quad (9)$$

$$Y_5 = 0.039TR - 0.029NR - 35.694BCR + 72.527ROS + 27.417 \quad (10)$$

$$Y_6 = 0.043TR + 0.166NR + 14.304BCR - 53.021ROS - 15.399 \quad (11)$$

Figure 2, plotted with the principal discriminant functions Y_4 and Y_5 as the horizontal and vertical axes respectively, again demonstrated distinct differences among the four management modes. LR was predominantly located in the fourth quadrant, primarily influenced by the benefit-cost ratio (6.636 and -35.694).

Table 8. A matrix of Mahalanobis distances between four management modes of *C. semilaevis* in the main production area

Variable name		*SF*	*SR*	*LF*	*LR*
Biological variables	SF	0(1.0000)	0.9028(0.3334)	0.9370(0.2815)	0.9322(0.2695)
	SR		0(1.0000)	1.8100***(0.0030)	0.7233(0.4211)
	LF			0(1.0000)	1.5583***(0.0085)
	LR				0(1.0000)
Cost variables	SF	0(1.0000)	1.9811(0.1406)	1.4815(0.5141)	2.4656***(0.0028)
	SR		0(1.0000)	2.1622**(0.0201)	2.2118***(0.0099)
	LF			0(1.0000)	2.1133**(0.0101)
	LR				0(1.0000)
Profitability variables	SF	0(1.0000)	2.5070***(0.0004)	2.4576***(0.0006)	2.7692***(0.0001)
	SR		0(1.0000)	1.8754**(0.0179)	2.0536***(0.0039)
	LF			0(1.0000)	2.3463***(0.0001)
	LR				0(1.0000)

The data in the table are represented as F-values (P-values). ***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

Table 9. Fisher's LDA of four management modes (Cost variable)

	Y_1	Y_2	Y_3
Cost variables			
SC	-0.094	-0.156	0.300
FC	0.218	0.001	-0.018
LC	0.097	0.130	0.069
UC	0.207	0.186	0.020
DFA	-0.051	0.211	0.127
ERC	0.683	0.542	-0.147
OC	-0.002	0.197	-0.096
Constant	-10.642	-5.141	-3.375
P Value	0.000	0.000	0.176
Eigenvalue	4.283	2.931	0.214
Canonical correlation coefficient	0.900	0.863	0.420
Variance contribution rate (%)	57.7	39.5	2.9
Cumulative variance contribution rate (%)	57.7	97.1	100
Functions at group centroids			
SF	1.417	-1.829	0.764
SR	1.840	1.733	-0.123
LF	-0.061	-2.101	-0.618
LR	-2.948	0.741	0.147

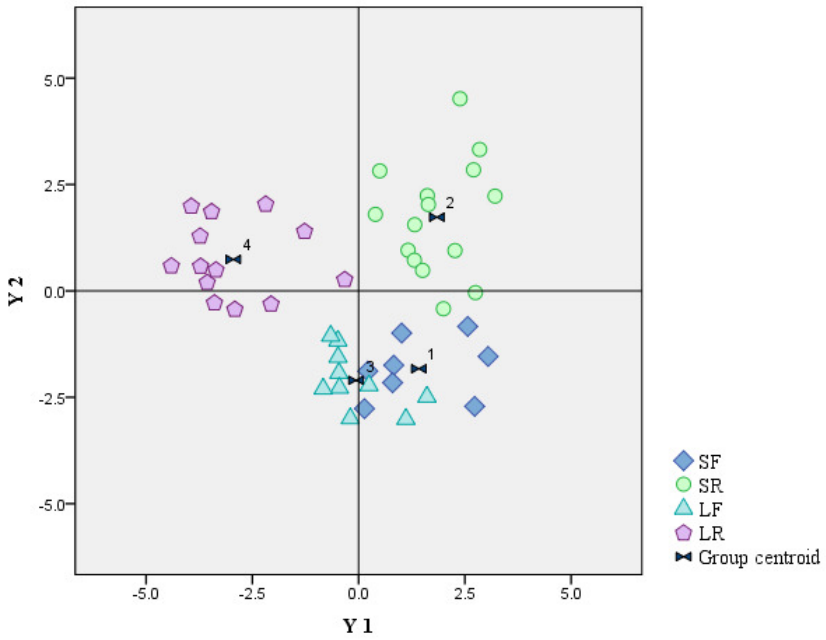


Figure 1. Distribution of four management modes for typical variables Y_1 and Y_2 (Cost variable)

Table 10. Fisher's LDA of four management modes (Profitability variable)

	Y_4	Y_5	Y_6
Profitability variables			
TR	0.019	0.039	0.043
NR	0.033	-0.029	0.166
BCR	6.636	-35.694	14.304
ROS	5.556	72.527	-53.021
Constant	-15.043	27.417	-15.399
P Value	0.000	0.000	0.000
Eigenvalue	8.002	2.071	0.895
Canonical correlation coefficient	0.943	0.821	0.687
Variance contribution rate (%)	73	18.9	8.2
Cumulative variance contribution rate (%)	73	91.8	100
Functions at group centroids			
SF	-4.750	-1.403	0.712
SR	0.919	1.484	0.802
LF	-1.523	0.884	-1.531
LR	3.035	-1.529	-0.185

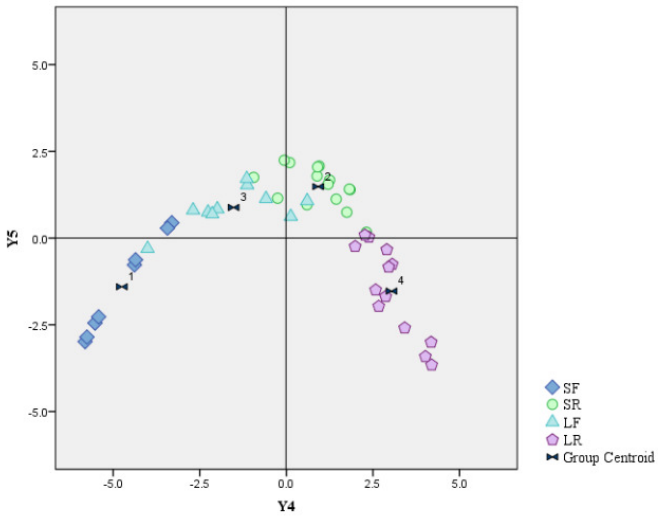


Figure 2. Distribution of four management modes for two typical variables Y_4 and Y_5 (Profitability variables)

Table 11. Summary of Research Results

Analysis dimension	*Core discovery*	*Management implications and action suggestions*
Biological dimension	1.Grow-out rate is a critical determinant of economic efficiency in *C. semilaevis* farming, and the feminization rate of seedlings is the key factor influencing grow-out rate.	1.It is recommended that farmers select high-quality seedlings with a high feminization rate (such as "Tayou No. 1").
	2.Although stocking density varies among different management modes, it does not have a significant impact on the grow-out rate.	2.Encourage research institutions to make further breakthroughs in sex control technology for seedlings to increase the proportion of physiological females.
Cost dimension	1.The unit total cost of LR is the lowest.	1.Promote LR and optimize the stocking density to the recommended value of 8.96 kg/m².
	2.The industrial RAS mode demonstrates significant advantages in seedling and feed costs, but incurs higher expenses in depreciation of fixed assets, labor, and equipment repair.	2.Enhance employees training to improve professional skills, with the government providing subsidies for RAS technology and support for talent training programs.
Profitability dimension	The LR demonstrates the best overall performance in profitability, which can be partly attributed to economies of scale and the precise control over the breeding cycle and market timing.	1.Encourage the adoption of LR to achieve higher profitability. 2.The government should increase subsidies for the transition to RAS to address the issue of adverse selection during this process.
Cobb-Douglas production function aspect	1.Labor and utility costs are the key determinants of total revenue. 2.While the industry faces diminishing returns to scale, economies of scale in unit costs persist.	It is recommended that farmers promote industrial transformation and upgrading through technological upgrades, management optimization, and improvements to the labor force structure to break through the predicament of diminishing returns to scale.
Comprehensive comparison of management modes	Optimal Recommendation: LR Least Recommended: SF Key differentiating factors: Equipment repair cost, seedling cost, benefit-cost ratio, and return on sales ratio.	Vigorously developing LR is the most effective pathway to achieve sustainable intensification and high-quality, high-efficiency development.