

Comprehensive techno-economic evaluation of electrochemical recirculating aquaculture system based on AHP

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Abstract. Aiming at the current situation that there is a lack of comprehensive evaluation system for Recirculating Aquaculture System (RAS) technology, this study constructs a comprehensive techno-economic evaluation framework based on Analytic Hierarchy Process (AHP), and conducts an empirical comparison between seawater RAS (electrochemical method) and freshwater RAS (biological method) in a breeding base in Zhejiang Province. The AHP results show that the weight of technical indicators is the highest (52.3%), and pollutant removal rate (C1), operational stability (C2) and water environmental quality (C6) rank the top three sub-indicators; the consistency test $CR < 0.1$, indicating the system is reliable. Empirical results show that the ammonia nitrogen removal rate of seawater RAS reaches 78% and nitrite nitrogen removal rate reaches 95%, with good production benefits but excessively high infrastructure investment, and there is a risk of excessive SO_2 and CO emissions.

Keywords: Recirculating Aquaculture System (RAS), Analytic Hierarchy Process (AHP), electrochemical method, techno-economic analysis

1. Introduction

With the development of social economy and the rapid growth of population, the global consumption of fish continues to increase, and aquaculture has become a sustainable choice to meet the demand [1]. According to FAO data, the output of aquaculture reached 94.4 million tons in 2022, surpassing that of capture fisheries for the first time [2]. Aquaculture has a history of more than 2,000 years in China [3]. In recent years, China's aquaculture industry has shown a development trend of high density, high input, high output and low benefit [4], and the problem of water pollution has become increasingly prominent. The traditional aquaculture mode can no longer well balance the win-win situation of environmental and economic benefits [5]. The Recirculating Aquaculture System (RAS) can reduce water consumption, save energy [6], better control environmental parameters and eliminate the risk of escape, which is a more environmentally friendly technology [7].

At present, RAS water treatment mainly relies on biological purification technology, but in practical application, it faces problems such as large fluctuation of treatment effect and excessive tail water pollutants

[8]. Electrochemical water treatment of recirculating aquaculture system is a promising method. Through a series of physical and chemical reactions, pollutants are decomposed and transformed, with higher cost-effectiveness and lower environmental footprint, especially showing significant advantages in seawater treatment [9], and is considered as one of the leading directions for the development of RAS in the 21st century [10].

At present, in the existing evaluation studies of RAS, cost-benefit analysis is mostly adopted at the economic benefit level, water quality monitoring or life cycle assessment is focused at the environmental benefit level, and most technical studies are limited to the application of RAS based on biological method. However, the above studies mostly focus on single-dimensional evaluation, and lack a comprehensive evaluation framework for RAS, especially the systematic evaluation research on electrochemical RAS is still blank. Therefore, accurate evaluation of the technical level, environmental status and economic benefits of electrochemical RAS has become a hot research topic.

2. Research object

This study selects a recirculating aquaculture test base in Shangyu City, Zhejiang Province as the research object. As one of the early breeding bases in Zhejiang Province that has realized the operation of freshwater RAS (biological method), this base has introduced seawater RAS (electrochemical method) into production in recent years, forming a parallel pattern of two types of systems, which is typical and representative for comparative research.

The treatment process of electrochemical RAS is shown in Figure 1. Raw water is injected into the breeding tank after pretreatment, and the breeding water enters Tank 1 and Tank 2 in turn for electrochemical oxidation and dechlorination. The two tanks are mutually standby and operate circularly to ensure continuous operation. After treatment, the water flows back to the breeding tank to complete the cycle.

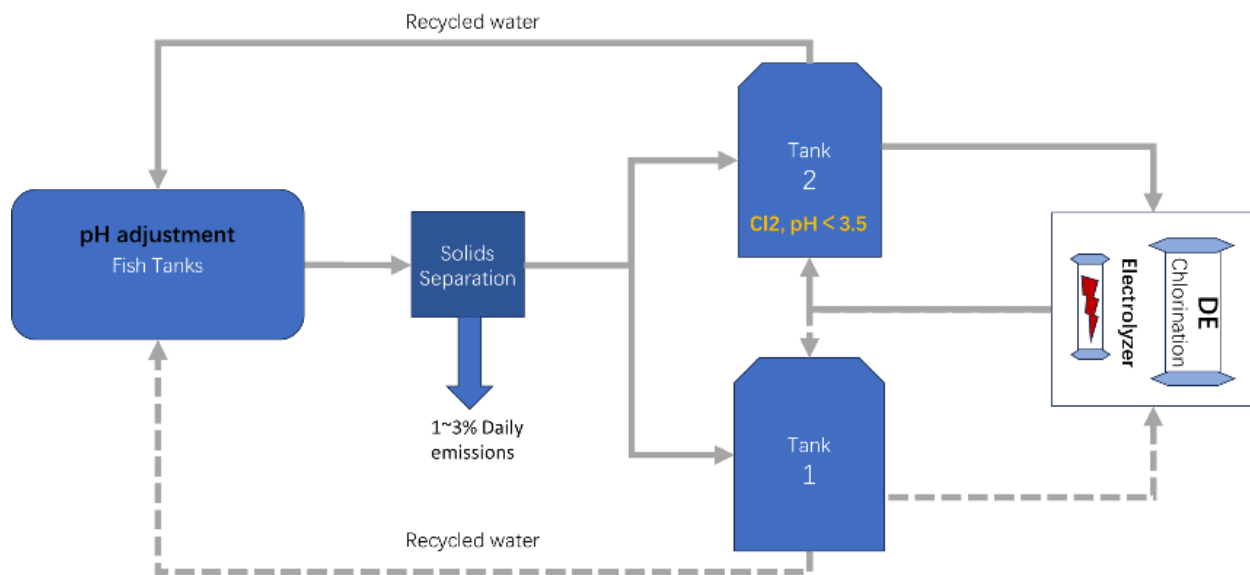


Figure 1. Electrochemical RAS treatment process

3. Methods and calculation

3.1. Research method

Analytic Hierarchy Process (AHP) is a systematic analysis method combining quantitative and qualitative analysis proposed by American operations research professor Saaty in the 1970s [11]. With its systematicness, structuring and flexibility, it is widely used in multi-criteria decision analysis and provides an effective solution for quantitative analysis of complex systems [12]. In view of the fact that RAS involves multi-dimensional factors such as technology, economy and environment, AHP can effectively integrate multiple criteria and provide a structured analysis framework for comprehensive evaluation of RAS.

3.2. Construction of techno-economic evaluation system for recirculating aquaculture system

Combined with the characteristics of RAS, a hierarchical structure with 3 criterion layers and 15 sub-index layers is designed in accordance with the principles of systematicness, accessibility, independence and operability. Technical indicators include pollutant removal rate, operational stability, resilience to loading shocks, automation capability, and operability and maintainability; environmental indicators include water environmental quality, ambient air quality, environmental noise emission, water consumption level and energy consumption level; economic indicators include infrastructure investment costs, land footprint, production input costs, operation and maintenance costs, and economic returns. The established hierarchical structure is shown in Figure 2. The index explanation is shown in Table 1.

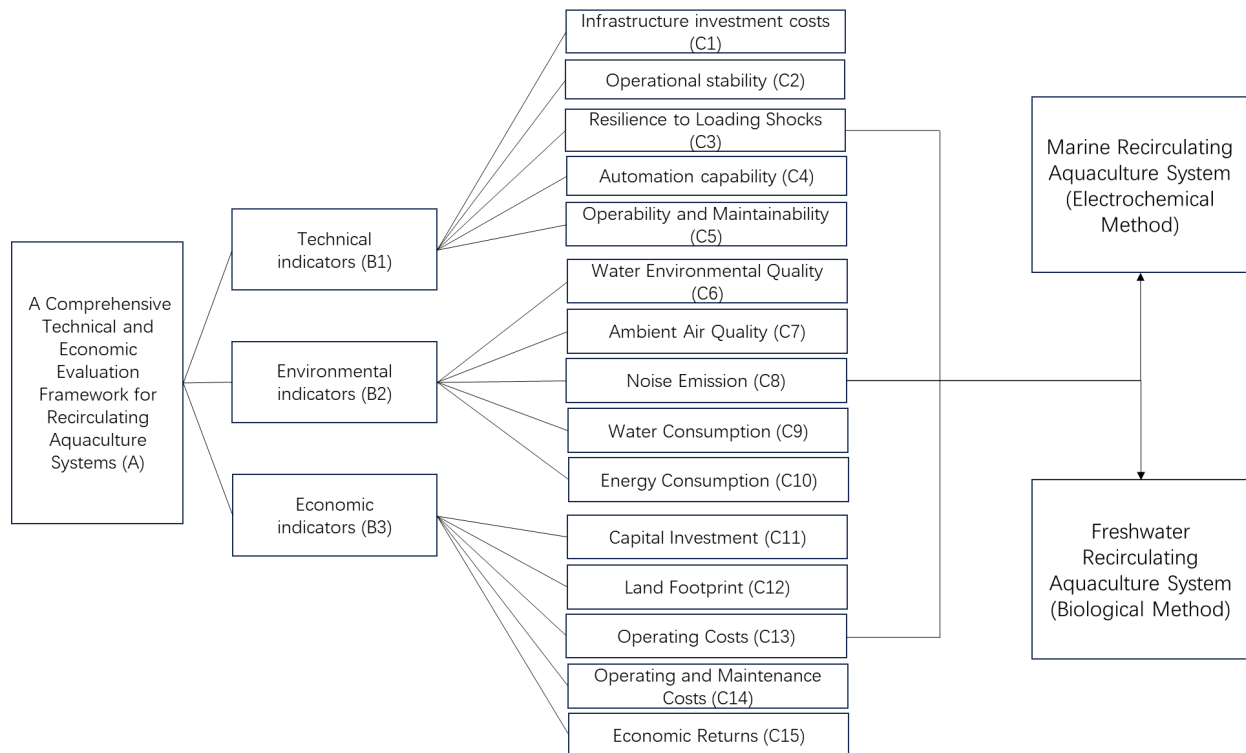


Figure 2. Hierarchical structure of technical and economic comprehensive evaluation system for recirculating aquaculture system

Table 1. Explanation of technical and economic comprehensive evaluation indicators for recirculating aquaculture system

Target Layer	Criterion Layer	Index Layer	Index Annotation
A Evaluation System of Recirculating Aquaculture System Target Layer	B1 Technical Indicators	C1 Pollutant Removal Rate	The removal capacity of the system for specific pollutants (such as ammonia nitrogen, nitrite nitrogen), expressed as a percentage.
		C2 Operational Stability	The operational stability of the system refers to the frequency of abnormalities, errors and other problems occurring in the whole process of equipment from startup to shutdown.
		C3 Resilience to Loading Shocks	The ability of equipment to maintain stable operation when the influent water quality changes suddenly (such as the influx of high-concentration wastewater).
		C4 Automation Capability	The automation capability refers to whether the system can perform automatic operation and the level of automatic operation.
		C5 Operability and Maintainability	The operability and maintainability of the system refer to whether the equipment operation is cumbersome and the complexity of the maintenance process.
	B2 Environmental Indicators	C6 Water Quality	The concentration of various pollutants (such as nitrite nitrogen, ammonia nitrogen, etc.) in the water body.
		C7 Ambient Air Quality	During operation, polluting gases are inevitably generated, affecting the local atmospheric environmental quality (SO ₂ , PM2.5, CO).
		C8 Environmental Noise Emission	Noise is inevitably generated during system operation, and the impact of noise on staff and surrounding environment needs to be considered.
		C9 Water Consumption Level	The water consumption level refers to the water consumption and utilization efficiency during the operation of the whole system.
		C10 Energy Consumption Level	The comprehensive energy consumption for producing aquaculture products.

Table 1. Continued

B3 Economic Indicators	C11 Infrastructure Investment Costs	The infrastructure investment costs are the capital construction investment part of the project construction funds, mainly including the costs of structures and equipment.
	C12 Land Footprint	The land use area required for facilities and equipment of different breeding systems.
	C13 Production Input Costs	Including seedling fee, bait fee, labor cost, water and electricity fee, drug consumption, etc.
	C14 Equipment Maintenance Costs	The equipment maintenance costs refer to equipment depreciation cost and equipment repair and protection cost.
	C15 Economic Returns	The ratio of cumulative net income to total initial investment during the project operation cycle.

3.3. Calculation of weight and scheme score

A structured questionnaire was designed using the 1~9 and reciprocal scale method (see Table 2). Experts in the fields of aquaculture and water treatment were invited to conduct pairwise comparisons of evaluation indicators at the same level and different types of RAS systems with the same indicator to quantify their relative importance. The questionnaire was distributed electronically with a built-in consistency test mechanism to ensure data reliability.

Finally, 15 valid questionnaires were collected, including 10 from water treatment experts and 5 from aquaculture experts.

Table 2. Meaning of importance judgment scale

Scale	Meaning	Expression
1	Equally important	Element A is equally important as element B
3	Slightly important	Element A is slightly more important than element B
5	Moderately important	Element A is obviously more important than element B
7	Very important	Element A is much more important than element B
9	Extremely important	Element A is absolutely more important than element B
2, 4, 6, 8	Intermediate state between adjacent evaluation criteria	
Reciprocal	If the judgment a_{ij} is obtained by comparing factor i with factor j , then the judgment $a_{ji} = 1/a_{ij}$ is obtained by comparing factor j with factor i	

According to the questionnaire results, AHP was used to determine the weights of the criterion layer, the index layer and the scores of the two systems on 15 indicators. The process is as follows:

(1) Construct the judgment matrix of each layer

$$A = \begin{Bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{Bmatrix} \tag{1}$$

(2) Calculate the maximum eigenvector of the judgment matrix

① Calculate the product of elements in each row of the judgment matrix M_i

$$M_i = \prod_{j=1}^n a_{ij} (i, j = 1, 2, \dots, n) \quad (2)$$

② Calculate the n th root of M_i : W_i

$$W_i = \sqrt[n]{M_i} \quad (3)$$

③ Normalize W_i to obtain the weight W

$$W = \frac{W_i}{\sum_{j=1}^n W_j} \quad (4)$$

④ Calculate the maximum eigenvalue λ_{max} of the judgment matrix

$$\lambda_{max} = \sum_{i=1}^n \frac{(AW)_i}{nW_i} (i, j = 1, 2, \dots, n) \quad (5)$$

(3) Consistency test

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

$$CR = \frac{CI}{RI} \quad (7)$$

The judgment matrix A-B of the comprehensive evaluation criterion layer of RAS is shown in Table 3. The weight value, comprehensive weight value for the total target and ranking of each index in the index layer are shown in Table 4. The scores of seawater RAS and freshwater RAS in the 3 criterion layers and 15 sub-index layers are shown in Table 5.

Table 3. Judgment matrix A-B

A	B1	B2	B3	Weight Value
B1	1.000	2.639	1.830	0.523
B2	0.379	1.000	1.123	0.233
B3	0.546	0.890	1.000	0.244

$$\lambda_{max} = 3.0259, CI = 0.0129, RI = 0.58, CR = CI/RI = 0.0223 \leq 0.1.$$

Similarly, the technical, environmental and economic index layers were calculated, and the CR values were 0.013, 0.046, 0.023 and 0.072 respectively, all less than the critical value of 0.1, passing the consistency test.

Table 4. Weight value, comprehensive weight value and ranking of indicators in layer C

Index	B1 Technical	B2 Environmental	B3 Economic	Comprehensive Weight W	Ranking
	Indicators	Indicators	Indicators		
	0.523	0.233	0.244		
C1 Pollutant Removal Rate	0.297			0.155	1
C2 Operational Stability	0.286			0.150	2
C3 Resilience to Loading Shocks	0.197			0.103	4
C4 Automation Capability	0.120			0.063	6
C5 Operability and Maintainability	0.100			0.052	8
C6 Water Environmental Quality		0.458		0.112	3
C7 Ambient Air Quality		0.193		0.047	10
C8 Environmental Noise Emission		0.089		0.022	15
C9 Water Consumption Level		0.137		0.033	12
C10 Energy Consumption Level		0.123		0.030	13
C11 Infrastructure Investment Costs			0.279	0.065	5
C12 Land Footprint			0.119	0.028	14
C13 Production Input Costs			0.207	0.048	9
C14 Equipment Maintenance Costs			0.159	0.037	11
C15 Economic Returns			0.236	0.055	7
CR < 0.10					

Table 5. Weight calculation of each scheme

Index Layer	Sub-index Layer	Score	Seawater RAS	Score	Freshwater RAS	Score
Technical Indicators	C1	15.5	59.25		40.75	
	C2	15.0	38.00		62.00	
	C3	10.3	58.82	26.96	41.18	25.4
	C4	6.3	67.60		32.40	
	C5	5.2	33.29		66.71	

Table 5. Continued

Environmental Indicators	C6	11.2	55.42		44.58	
	C7	4.7	41.46		58.54	
	C8	2.2	35.76	11.59	64.24	12.77
	C9	3.3	63.34		36.66	
	C10	3.0	18.98		81.02	
Economic Indicators	C11	6.5	30.45		69.55	
	C12	2.8	61.87		38.13	
	C13	4.8	29.78	9.37	70.22	13.91
	C14	3.7	25.21		74.79	
	C15	5.5	60.13		39.87	
Comprehensive Score			47.92		52.08	

3.4. Relevant data

Systematic on-site data collection was carried out from July 2024 to August 2025 using various methods such as direct observation, experimental monitoring and inquiry with breeding personnel. The experiment focused on monitoring the environmental impacts of RAS, including water quality parameters such as ammonia nitrogen and nitrite nitrogen, air indicators such as CO, PM2.5 and SO₂, and noise parameters such as equivalent continuous A-weighted sound level.

Table 6. Field data

Index Layer	Sub-index Layer	Parameter	Seawater RAS	Freshwater RAS
Technical	C1	Ammonia nitrogen	78%±2%	36%±5.65%
		Nitrite nitrogen	95%±4%	15%±0.94%
	C2	Annual failure times	1 time	0 time
	C3	Water quality regulation level	Excellent	General
	C4	Automation capability	High	General
C5	Operability and maintainability	Complex operation, difficult maintenance	Simple operation, convenient maintenance	

Table 6. Continued

Environmental Economic	C6 (Breeding Water)	Ammonia nitrogen	(0.224 ± 0.142) mg/L	(0.675 ± 0.142) mg/L
		Nitrite nitrogen	(0.009 ± 0.022) mg/L	(0.354 ± 0.0024) mg/L
		SO ₂	2400 µg/m ³	16 µg/m ³
		CO	18 mg/m ³	0.80 mg/m ³
	C7 (Peak Value)	PM2.5	170 µg/m ³	50 µg/m ³
		O ₃	420 µg/m ³	250 µg/m ³
		NO ₂	35 µg/m ³	16 µg/m ³
	C8	Noise	76.1 dB(A)	60.2 dB(A)
	C9	Water resources	Summer: 4.93 m ³ /d; Winter: 1.83 m ³ /d; Spring and Autumn: 3.15 m ³ /d	Summer: 5.25 m ³ /d; Winter: 2.38 m ³ /d; Spring and Autumn: 3.82 m ³ /d
	C10	Electric energy	319.07 kWh/d	102.18 kWh/d
	C11	Infrastructure cost	1.9896 million yuan	704,500 yuan
	C12	Land footprint	80 m ²	72 m ²
Index Layer Technical	C13	Production input cost	1660.92 yuan/d	864.53 yuan/d
	C14	Operation and maintenance cost	215,500 yuan/year	78,500 yuan/year
	C15	Return on investment	8.75%	-3.72%

4. Results and discussion

4.1. Analysis of RAS evaluation system

This study constructs a four-level evaluation model, conducts pairwise comparisons using the 1-9 scale method, and summarizes expert judgments using the geometric mean method. The consistency test results show that the consistency ratios of the judgment matrices at the criterion layer are all less than the critical value of 0.1, passing the consistency test. In the weight distribution of the criterion layer, the weight of technical indicators is the highest (52.3%), significantly higher than environmental (24.4%) and economic indicators (23.3%). From the perspective of global weight, pollutant removal rate (15.5%), operational stability (15.0%) and water environmental quality (11.2%) constitute the three core indicators of the evaluation system. The scheme layer evaluation results show that seawater RAS is slightly superior in technical indicators (51.5%), while freshwater RAS performs better in economic (59.8%) and environmental indicators (52.4%).

Finally, seawater RAS lags behind freshwater RAS with a comprehensive score of 47.9 (52.1 for freshwater RAS).

4.2. Comprehensive evaluation of electrochemical RAS

As shown in Figure 3 and Figure 4, the evaluation result of technical indicators is: seawater RAS > freshwater RAS. Among them, seawater RAS has obvious advantages in pollutant removal rate, resilience to loading shocks and automation capability; seawater RAS is inferior to freshwater RAS in operational stability and operability and maintainability. Seawater RAS has a high degree of automation and is suitable for technology-intensive scenarios, but lacks operational stability and operational convenience.

The evaluation result of environmental indicators is: freshwater RAS > seawater RAS. Seawater RAS has advantages in water environmental quality and water consumption level, but the weight of water consumption index is relatively low, and other indicators are worse than freshwater RAS. Meanwhile, expert opinions suggest that attention should be paid to the potential safety hazards of the electrochemical method, including the risk of hydrogen evolution explosion and the generation of chlorinated toxic substances.

The evaluation result of economic indicators is: freshwater RAS > seawater RAS. Among them, freshwater RAS has significant advantages in three core cost indicators: infrastructure investment cost, production input cost and equipment maintenance cost, while seawater RAS only performs better in land footprint and economic returns. Seawater RAS has a high infrastructure investment cost, which is an obvious shortcoming, but has certain advantages in economic returns.

In summary, the core advantages of seawater RAS are concentrated in technical indicators, including pollutant removal rate (C1), resilience to loading shocks (C3) and automation capability (C4), as well as environmental benefit indicators such as water environmental quality (C6) and water consumption level (C9). Seawater RAS is advanced in technology but has high infrastructure investment, poor operational stability and potential safety hazards, and is suitable for technology-intensive scenarios with high technical requirements.

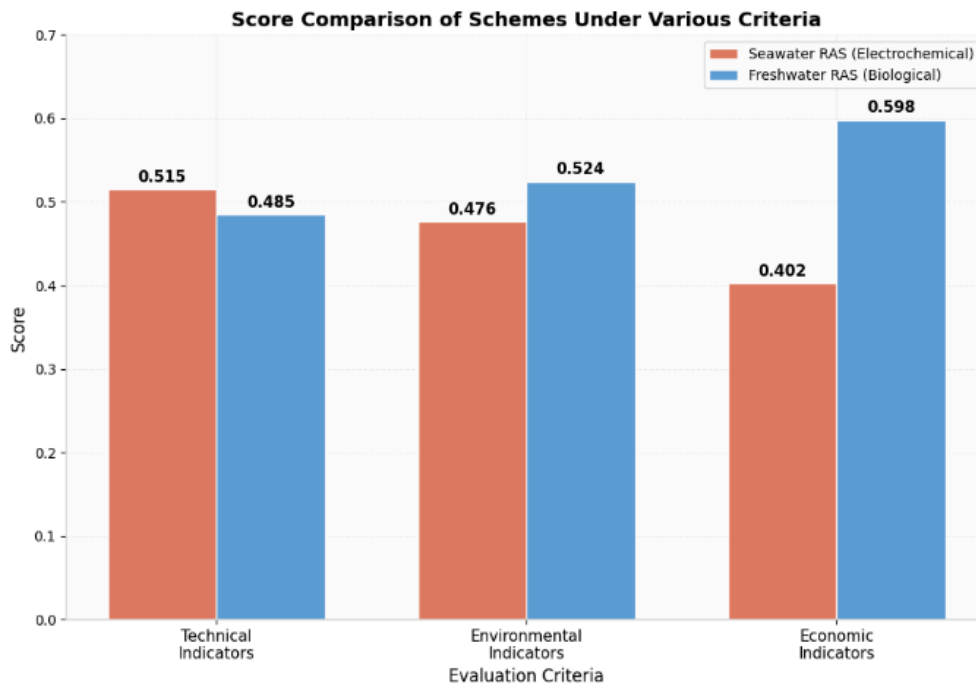


Figure 3. Scores of indicator layer

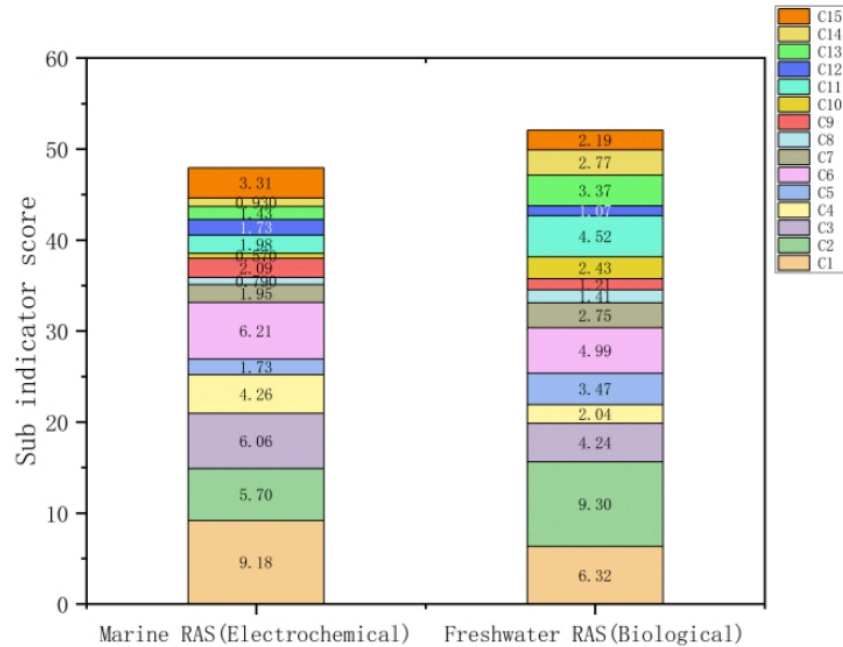


Figure 4. Score of sub-indicators

4.3. Verification based on field data

The field data are shown in Table 6. The ammonia nitrogen removal rate of seawater RAS is $78\% \pm 2\%$ and nitrite nitrogen removal rate is $95\% \pm 4\%$, which are better than those of freshwater RAS ($36\% \pm 5.65\%$, $15\% \pm 0.94\%$); seawater RAS fails once a year, and freshwater RAS fails 0 times; seawater RAS has higher resilience to loading shocks and automation degree, but more complex operation and maintenance.

In terms of environmental indicators, seawater RAS has better water environmental quality (ammonia nitrogen 0.224mg/L , nitrite nitrogen 0.009mg/L), but poor ambient air quality (excessive SO_2 $2400\mu\text{g}/\text{m}^3$ and CO $18\text{mg}/\text{m}^3$), noise 76.1 dB(A) higher than freshwater RAS 60.2 dB(A) , and power consumption $319.07\text{kWh}/\text{d}$ significantly higher than $102.18\text{kWh}/\text{d}$.

In terms of economic indicators, the infrastructure cost of seawater RAS is 1.9896 million yuan, and annual operation and maintenance cost is 215,500 yuan, much higher than those of freshwater RAS (704,500 yuan, 78,500 yuan); the return on investment of seawater RAS is 8.75% , and that of freshwater RAS is -3.72% . The above data obtained from on-site and experiments verify the feasibility of the technical evaluation system of recirculating aquaculture system.

5. Conclusions

(1) A comprehensive techno-economic evaluation system of electrochemical RAS based on AHP is constructed, and the weight structure of "technical indicators (52.3%) > environmental indicators (24.4%) \approx economic indicators (23.3%)" is established, filling the methodological gap of comprehensive evaluation. The evaluation results of the sub-index layer are: pollutant removal rate (C1) > operational stability (C2) > water environmental quality (C6) > resilience to loading shocks (C3) > infrastructure investment costs (C11) > automation capability (C4) > economic returns (C15) > operability and maintainability (C5) > production

input costs (C13) > ambient air quality (C7) > equipment maintenance costs (C14) > water consumption level (C9) > energy consumption level (C10) > land footprint (C12) > environmental noise emission (C8).

(2) The established evaluation system is used to evaluate and compare seawater RAS and freshwater RAS, and the reliability of the system is verified through case empirical research. Seawater RAS (electrochemical method) has significant advantages in pollutant removal rate (ammonia nitrogen 78%, nitrite nitrogen 95%) and automation degree, but has shortcomings such as poor operational stability, environmental safety hazards (excessive SO₂, CO, etc.) and high economic cost (infrastructure 1.9896 million yuan); under the benchmark weight, the comprehensive score of freshwater RAS (biological method) is 52.1, which is better than 47.9 of seawater RAS (electrochemical method); seawater RAS (electrochemical method) is suitable for technology-intensive scenarios with extremely high requirements for effluent quality and strong automation demand.

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