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Application of a U-Tube Oxygenator in a *Litopenaeus vannamei* Recirculating Aquaculture System: Efficiency and Management Models

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Abstract: This study investigated the dissolved oxygen (DO) variation pattern in a *Litopenaeus vannamei* recirculating aquaculture system (RAS) and established an oxygen-utilization rate (UR_{Oxygen}) model, pure oxygen addition (Q_{Oxygen}) model, and control model that linked a microscreen drum filter (MDF) with a U-tube oxygenator. The main objective was to promote the application of the U-tube oxygenator and achieve the efficient, accurate, and automated management of DO in an RAS. To avoid wasting oxygen and ensure production safety, it was recommended to maintain the effluent of the aquaculture pond at 6.9 ± 0.4 mg/L. The modeled relationship between the RAS flow (Q_{RAS}), Q_{Oxygen}, and UR_{Oxygen} was $UR_{\mathrm{Oxygen}} = 0.9626 \times (-105.3406 + 0.9911 Q_{\mathrm{RAS}} + 10.6202 Q_{\mathrm{Oxygen}} - 0.05964 Q_{\mathrm{RAS}} Q_{\mathrm{Oxygen}} - 1.2628 \times 10^{-3} Q_{\mathrm{RAS}}^2 - 0.1821 Q_{\mathrm{Oxygen}}^2 + 6.8888 \times 10^{-5} Q_{\mathrm{RAS}}^2 Q_{\mathrm{Oxygen}} + 6.3993 \times 10^{-4} Q_{\mathrm{RAS}} Q_{\mathrm{Oxygen}}^2)$. The modeled relationship between Q_{RAS}, daily feeding rate (M_{Feeding}), and Q_{Oxygen} was $Q_{\mathrm{Oxygen}} = 1.09 \times (-12.8633 - 0.02793 Q_{\mathrm{RAS}} + 0.9369 M_{\mathrm{Feeding}} - 8.9286 \times 10^{-4} M_{\mathrm{Feeding}} Q_{\mathrm{RAS}} + 5.6122 \times 10^{-5} Q_{\mathrm{RAS}}^2 - 2.3281 \times 10^{-3} M_{\mathrm{Feeding}}^2)$. The modeled relationship between the MDF backwashing period (T_{MDF}) and Q_{Oxygen} was $Q_{\mathrm{Oxygen}} = -11.57 \ln(T_{\mathrm{MDF}}) + 78.319$. This study provided a theoretical basis and novel methods for the management of DO in an RAS, thus promoting the healthy and stable development of an *L. vannamei* RAS.

Keywords: recirculating aquaculture system; U-tube oxygenator; dioxygen; models

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1. Introduction

As one of the most productive shrimp species, *Litopenaeus vannamei* has the advantages of a fast growth rate, adaptability to a wide range of conditions, and strong resistance, and is therefore widely used in aquaculture [1–3]. Compared to traditional farming models, recirculating aquaculture has attracted much attention due to its environmental sustainability, high yields, controllability, and high product quality [4]. There have been several studies of the high-density aquaculture of *L. vannamei* using a recirculating aquaculture system (RAS) [1,4–6].

The management of the aquatic environment is crucial during the operation of an RAS [7]. Dissolved oxygen (DO) is considered to be one of the main limiting factors, because it is necessary for the metabolic activities of aquatic animals and will, therefore, determine the production capacity of an RAS [7–9]. Aeration and the use of pure oxygen are the main methods used to increase the DO concentration in an RAS [8]. Due to the continuous development of aquaculture technology and equipment, the aquaculture capacity of RASs has constantly improved. Blower aeration cannot meet the oxygenation needs of an RAS because of its high energy consumption and low efficiency [7]. Du et al. (2021) showed that, during the high-density recirculating aquaculture of *L. vannamei*, blower aeration played a significant role in the early stage; with an increase in the biomass and feeding amount, it could not meet the increasing oxygenation requirement of the aquaculture system [4]. The DO in aquaculture water decreased sharply to below 5.0 mg/L in the middle and later stages of aquaculture, posing a safety risk [4]. Adding pure oxygen will achieve high-density aquaculture and a high yield in an RAS [4,7]. The equipment commonly used to add pure oxygen to an RAS includes oxygen cones, U-tube oxygenator, and jet pumps [7]. Using oxygen cones and jet pumps to add pure oxygen has a high efficiency but also a high energy consumption. In contrast, traditional U-tube oxygenation methods rely on simple equipment with low maintenance costs and no additional energy consumption, but they have a relatively low oxygen-utilization rate [7]. The high operating energy consumption is a disadvantage of RASs, with the energy consumption for oxygen enrichment (e.g., blast aeration, oxygen cone, and jet) accounting for 12–20% of the total [8,10–12]. Therefore, using a U-tube oxygenator is of great significance in reducing the operational energy consumption of an RAS.

To address the problem of the low oxygen-utilization rate (UR_{Oxygen}) of a U-tube oxygenator, the following measures were taken in this study: removing carbon dioxide (CO_2), using a nano aeration device, and ensuring a suitable RAS flow (Q_{RAS}) [4,7]. Furthermore, the use of a U-tube oxygenator achieves the efficient management of DO in an RAS, which requires precise and automatic control of the pure oxygen flow (Q_{Oxygen}). The precise and automatic management of Q_{Oxygen} in an RAS can not only reduce resource waste but also prevent excessive DO concentration from harming breeding organisms [13,14]. The addition of pure oxygen in a traditional RAS is usually adjusted based on the monitoring results of DO detectors. When the DO concentration rises or falls to the warning concentration, it is adjusted by increasing or decreasing the Q_{Oxygen}. This DO regulation method is relatively simple but has a delayed effect, and the DO concentration in aquaculture water is therefore prone to instability. The key to achieving the precise and automatic control of pure oxygen addition in an RAS is to establish a mathematical model for process control [14]. Previous studies have proposed several models for the control of DO concentrations in aquaculture water. Ta and Wei (2018) proposed a simplified reverse understanding convolutional neural network prediction model to predict changes in the DO concentration of aquaculture water [15]. Ren et al. (2020) established a prediction model for the DO concentration in aquaculture water based on deep-belief networks [16]. Zhou et al. (2022) established a dynamic DO model in aquaculture water based on the theory of microporous aeration mass transfer and mass conservation equations and proposed a fuzzy rule-optimized single-neuron adaptive process identifier controller for the precise control of DO [14]. These studies have enriched the theory and methods used in DO management in aquaculture, and the models can effectively predict changes in the DO concentration, achieving precise control of DO. However, the construction of these models is based on laboratory-scale aquaculture systems, and the effects of their application at the production scale are not yet known.

No management model has yet been developed for controlling the DO concentration in a high-density *L. vannamei* RAS. This study was based on a production-scale *L. vannamei* RAS and aimed to promote the application of a U-tube oxygenator by constructing suitable DO management models for an *L. vannamei* RAS. In an *L. vannamei* RAS, most of the environmental factors that affect the DO concentration, such as temperature, salinity, and pH, are relatively stable. The Q_{RAS} and daily feeding rate (M_{Feeding}) have the most significant effects on the DO concentration. Therefore, this study used a response-surface methodology to investigate the relationship between Q_{Oxygen}, Q_{RAS}, and M_{Feeding}. A response-surface model (RSM) was constructed to guide the precise addition of pure oxygen in an *L. vannamei* RAS. Prior to this, the variation patterns of DO in an RAS and the oxygenation efficiency of a U-tube oxygenator were evaluated to provide guidance for DO management and the construction of Q_{Oxygen} models. Additionally, considering the close correlation between Q_{RAS}, $M_{Feeding}$, and the microscreen drum-filter (MDF) backwashing period (T_{MDF}) [17,18], a model of the relationship between T_{MDF} and Q_{Oxygen} was constructed. Using a T_{MDF} feedback control to Q_{Oxygen}, the automatic addition of pure oxygen during the cultivation of *L. vannamei* was achieved. This study is of great significance for achieving efficient DO management in an RAS, improving aquaculture performance, reducing energy consumption, and promoting the automation and intelligent operation of RASs.

2. Materials and Methods

2.1. Experimental Setup

The *L. vannamei* RAS (500 m^3) consisted of 12 aquaculture ponds (APs), 1 MDF, 1 buffer pool, 1 foam separator (FS), 3 moving bed biofilm reactor (MBBR), 1 U-tube oxygenator, and 1 disinfection equipment, as shown in Figure 1. The APs (6 m diameter, 1.5 m height) had an effective volume of approximately 34 m^3 (Sanshiliwan Fishery Technology Co., Ltd., Yantai, China). The filtration aperture of the MDF was 74 μm, the maximum processing capacity of which was 400 m^3/h. The volumes of the FS, MBBR, and U-tube oxygenator were approximately 6, 15, and 20 m^3, respectively. Three sets of MBBR were connected in parallel, with a fill rate of 50%, using circular polyethylene fillers (2.5 cm diameter, 0.4 cm thickness, and 64 holes). The height and diameter of the U-tube oxygenator were 4.5 m and 1.8 m, with 2.8 m above ground and 1.7 m below ground, as shown in Figure 1. The bottom of the U-tube oxygenator was equipped with a nano aeration device (WTB200, Tianmiao Marine Biotechnology Co., Ltd., Zibo, China) connected to a liquid oxygen tank with a gas source pressure of about 0.3 Mpa, with Q_{Oxygen} adjusted through a gas flow meter.

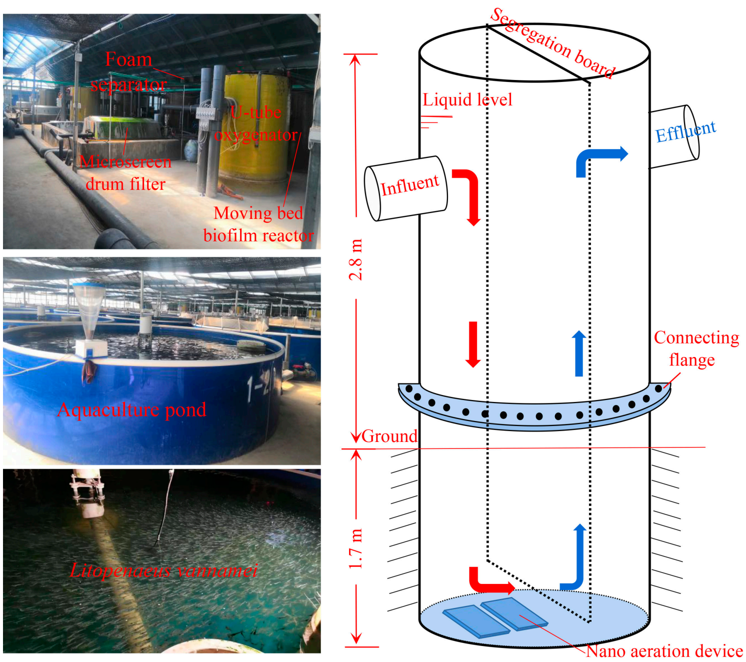

Figure 1. The *Litopenaeus vannamei* recirculating aquaculture system (RAS) (**left**) and the U-tube oxygenator structure diagram (**right**).

The aquaculture density was 800 tails/m^3, and the initial average body length and weight of *L. vannamei* were approximately 3.2 cm and 0.48 g, respectively. The $M_{Feeding}$ of *L. vannamei* was calculated to be approximately 12% of body weight and gradually decreased to 2.5% as the shrimps grew. After the experiment, the average body length and weight of the shrimp were 12.3 cm and 18.5 g, respectively. The survival rate of the shrimp was about 86%, and the feed conversion ratio was 1.12. The salinity, pH, and temperature of aquaculture water were 25 ppt, 6.8–7.8, and 26.3–27.8 °C, respectively.

2.2. Experimental Design

2.2.1. The Change Pattern of the DO Concentration in an RAS

In the early stage of the operation of the *L. vannamei* RAS, the DO concentration in the effluent of the AP, MDF, FS, and MBBR were collected every two days over a period of 17 days, and M_{Feeding} and Q_{Oxygen} were recorded at the same time. According to the changes in the DO concentration, the effects of MDF, FS, and MBBR on the DO concentration were analyzed. Additionally, the DO concentrations in the influent and effluent of the AP during the operation of the *L. vannamei* RAS were determined, and the changes in biomass and Q_{Oxygen} were recorded to analyze the oxygen-consumption rate (OCR) of the AP.

2.2.2. Construction of $\text{UR}_{\text{Oxygen}}$ and Q_{Oxygen} Models for the U-Tube Oxygenator

Using the central composite design (CCD) method, a standard method was used for the experimental design and construction of RSMs, which were used to determine UR_{Oxygen} and Q_{Oxygen} models for the U-tube oxygenator during the operation of the *L. vannamei* RAS. Using Q_{RAS} and Q_{Oxygen} as independent variables and UR_{Oxygen} as a response value, the effects of Q_{RAS} and Q_{Oxygen} were investigated on the UR_{Oxygen} of the U-tube oxygenator. Moreover, using Q_{RAS} and M_{Feeding} as independent variables and Q_{Oxygen} as response values, the effects of Q_{RAS} and M_{Feeding} on Q_{Oxygen} for the U-tube oxygenator were studied when the DO concentration in the AP effluent was 6.9 ± 0.4 mg/L (based on the results of study 2.2.1). The experimental independent variables and their levels are given in Table 1.

Table 1. Influencing factors and their levels.

Responses	Factors	Levels			
		Low	High	−alpha	+alpha
UR_{Oxygen} (%)	QRAS (m^3/h)	266	337	251.3	351.7
	Q_{Oxygen} (L/min)	6.5	20.5	3.6	23.4
Q_{Oxygen} (L/min)	QRAS (m^3/h)	250	320	235.5	334.5
	M_{Feeding} (kg/d)	40	80	31.7	88.3

Based on the information given in Table 1, the corresponding experimental design was obtained through the Design Expert V.10 software, as shown in Table 2. Three parallel experiments were conducted in each group, and the average value was calculated (Table 2) and fed back to the Design Expert V.10 software to obtain the corresponding RSM model and its data-analysis results.

Table 2. The experimental matrix designed through a central composite design (CCD) method for the response values of oxygen-utilization rate (UR_{Oxygen}) and pure oxygen addition (Q_{Oxygen}).

Run	Factors		Response	Run	Factors		Response
	QRAS (m^3/h)	Q_{Oxygen} (L/min)	UR_{Oxygen} (%)		QRAS (m^3/h)	M_{Feeding} (kg/d)	Q_{Oxygen} (L/min)
1	301.5	23.4	58.16	1	334.5	60.0	14.5
2	301.5	13.5	66.57	2	250.0	40.0	7.5
3	301.5	13.5	65.12	3	235.5	60.0	19.0
4	337.0	6.5	75.65	4	250.0	80.0	26.5
5	337.0	20.5	65.17	5	285.0	31.7	4.5
6	301.5	13.5	66.78	6	285.0	60.0	16.0
7	266.0	20.5	55.12	7	285.0	60.0	16.5
8	266.0	6.5	65.78	8	285.0	88.3	25.0
9	351.7	13.5	70.35	9	320.0	40.0	5.0
10	301.5	13.5	65.85	10	285.0	60.0	16.5
11	301.5	3.6	78.12	11	285.0	60.0	16.5
12	301.5	13.5	64.78	12	285.0	60.0	16.0
13	251.3	13.5	60.12	13	320	80.0	21.5

Based on the above models and the actual farming situation, the Q_{Oxygen} during the cultivation of *L. vannamei* was set and the relevant data (Q_{RAS}, $M_{Feeding}$, Q_{Oxygen}, and T_{MDF}) was collected to modify the models. The connection between Q_{Oxygen} and T_{MDF} was analyzed, and a model was constructed of the relationship of Q_{Oxygen} and T_{MDF} to achieve the automatic management of Q_{Oxygen} in an RAS. The data was collected every day for a period of approximately 100 days.

2.2.3. The Analysis Method

The salinity, pH, temperature, and DO during the cultivation of *L. vannamei* were measured using a multiparameter water-quality detector (YSI-556, YSI Inc., Yellow Springs, OH, USA). A total of 500–600 shrimp were randomly caught in different APs, and the average weight of shrimp was calculated (m_{shrimp}, g). The total biomass ($M_{Biomass}$, kg) of *L. vannamei* in an RAS was estimated using Formula (1):

$$M_{Biomass} = \frac{nm_{Shrimp}}{1000} \tag{1}$$

where, n is the number of *L. vannamei* individuals in an RAS.

The RSM equation with response values of UR_{Oxygen} and Q_{Oxygen} was fitted in the form of a quadratic polynomial equation using a second-order model (2):

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j \tag{2}$$

where, Y, β_0, β_i, β_{ii}, and β_{ij} are the predicted response value, intercept parameter, linear coefficient, quadratic coefficient, and interaction coefficient, respectively; X_i and X_j are independent variables; and n is the number of influencing factors [19,20].

The calculation Formula (3) for the correction coefficient (θ) of the RSM was as follows:

$$\theta = \frac{1}{n} \sum_{i=1}^{n} \frac{A_i}{P_i} \tag{3}$$

where, A_i, P_i, and n are the actual value, predicted value, and the number of data sets, respectively.

The amount of oxygen added (M_{Oxygen}, g/h), the increase in the DO concentration due to the U-tube oxygenator (M_{DO}, g/h), and the AP OCR (g O_2/(kg shrimp h)) were calculated using Formulas (4)–(6):

$$M_{Oxygen} = \frac{60 Q_{Oxygen} M_{O_2}}{V_m} \tag{4}$$

$$M_{DO} = Q_{RAS}(C_1 - C_0) \tag{5}$$

$$OCR = \frac{Q_{RAS}(C_2 - C_3)}{M_{Biomass}} \tag{6}$$

where, M_{O_2} (g/mol) is the relative molecular weight of O_2; Vm (L/mol) is the molar volume; C_1 and C_0 (mg/L) are the DO concentrations of the AP influent and MBBR effluent, respectively; and C_2 and C_3 (mg/L) are the DO concentrations of the AP influent and effluent, respectively.

3. Results and Discussion

3.1. The Change Pattern of the DO Concentration in an RAS

3.1.1. Effect of the Water-Treatment Units on the DO Concentration

Determining the variation pattern of the DO concentration in the effluent of the water-treatment units in an RAS is crucial for ensuring the correct addition of pure oxygen. Figure 2 shows the changes in the DO concentration in the AP, MDF, FS, and MBBR effluent when the $M_{Feeding}$, Q_{RAS}, and Q_{Oxygen} was 27–35 kg/day, 248–266 m^3/day, and 3.0–6.0 L/min, respectively. Figure 2 shows that the DO concentration in the MDF effluent was slightly lower than in the AP effluent, which could be attributed to the backwashing of the MDF. In comparison, the differences in the DO concentrations between the FS, MBBR effluent, and AP effluent were greater, which was related to the air-flotation and aeration processes in the FS and MBBR. Additionally, the DO concentration in the MBBR effluent was influenced by the metabolic process of microorganisms. The DO concentration data for the AP, FS, and MBBR effluent in Figure 2 were fitted to obtain three trend lines: y = 0.12x + 6.6811, R^2 = 0.9755 (AP effluent, Line 1); y = 0.051x + 7.255, R^2 = 0.8709 (FS effluent, Line 2); y = 0.0378x + 7.1219, R^2 = 0.8462 (MBBR effluent, Line 3). Significantly, lines one and two intersected at a certain point (8.32, 7.68), indicating that when the DO concentration in the AP effluent was <7.68 mg/L, and the air-flotation process of the FS could increase the DO concentration in the aquaculture water, otherwise it would lead to the escape of DO from aquaculture water. Additionally, the intersection point of lines one and three (5.36, 7.32) indicated that when the DO concentration in AP effluent was less than 7.32 mg/L, the aeration process of the MBBR could increase the DO concentration, otherwise it would lead to the escape of DO from aquaculture water. In addition to preventing the waste of resources, DO management in an RAS needs to ensure the healthy growth of breeding organisms and the efficient operation of the MBBR [7,21]. In previous studies, the DO concentration was typically maintained at 6.5–7.5 mg/L during the high-density aquaculture of *L. vannamei* [4,6,22]. Based on the studies referred to above, and, considering the normal growth of shrimp and the water-treatment performance of the biofilm during high-density aquaculture, it is recommended to maintain the DO concentration of the AP effluent at 6.9 ± 0.4 mg/L.

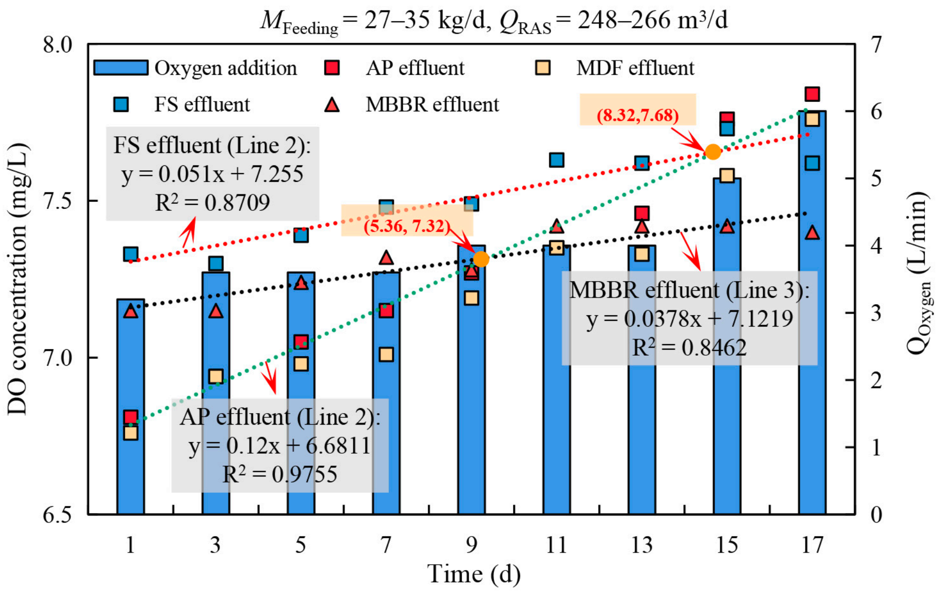

Figure 2. Changes in the dissolved oxygen (DO) concentration in the effluent from the aquaculture ponds (APs), microscreen drum filter (MDF), foam separator (FS), and moving bed biofilm reactor (MBBR).

3.1.2. The OCR of the APs

The OCR of the APs during the cultivation of *L. vannamei* is shown in Figure 3. The results showed that, when the biomass of *L. vannamei* increased from about 180 to 5220 kg, the pure oxygen addition in the RAS increased from 600.00 to 2228.57 g/h, and the DO consumption in the APs increased from 384.40 to 1261.19 g/h. The biomass of the shrimp increased by about 31.64 times, while the DO consumption in the APs increased by about 3.28 times. The OCR of the AP decreased from the initial amount of around

0.8 g O_2/(kg shrimp h) to around 0.25 g O_2/(kg shrimp h). This was mainly because the OCR of *L. vannamei* was inversely proportional to the wet weight of the shrimp [23,24]. Walker et al. (2009) found that the OCR of *L. vannamei* (3–25 g/shrimp) ranged from 0.7 g O_2/(kg shrimp h) to 0.3 g O_2/(kg shrimp h) [25]. In a recent study, Kır et al. (2023) indicated that the OCR of 16 ± 1.5 g *L. vannaeus* in water with a salinity of 30 ppt and temperature of 27 °C was equivalent to approximately 0.3 g O_2/(kg shrimp h) [9]. The OCR of the APs was close to that of the shrimp because the RAS in this study gave prominence to the removal of suspended solids, as shown by Du et al. (2021) [4], and Xu et al. (2021, 2022) [6,18]. The water in the APs was clear, resulting in the low oxygen consumption of microorganisms [4].

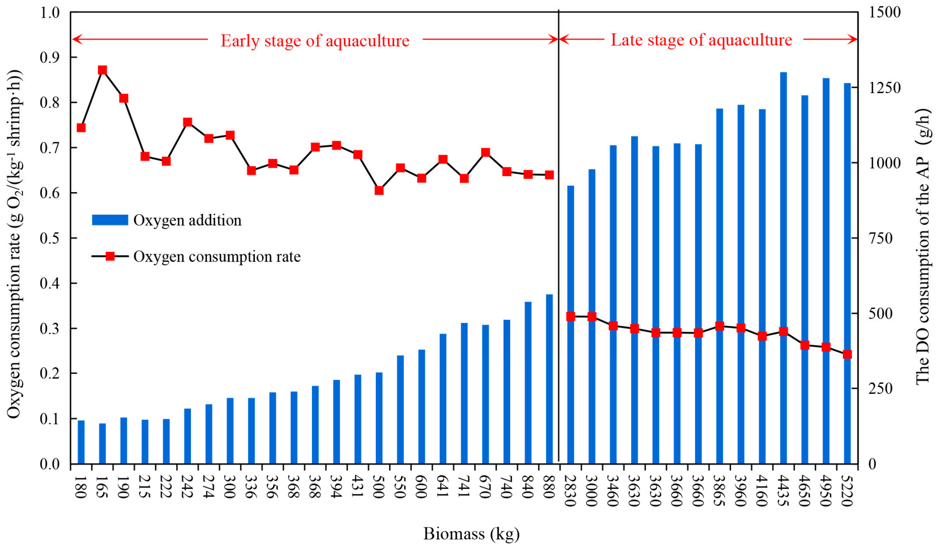

Figure 3. The oxygen-consumption rate (OCR) of the aquaculture ponds (APs) during the early and late stages of aquaculture.

3.2. Models

3.2.1. Response-Surface Models Related Data Analysis

The analysis of variance results for the RSM data are shown in Table 3. The R^2, *Adj-*R^2, and *Pred-*R^2 values of models one and two were 0.9906 and 0.9883, 0.9773 and 0.9799, and 0.9001 and 0.9197, respectively. The high R^2, *Adj-*R^2, and *Pred-*R^2 values with small differences suggested a good accuracy and applicability between the data and the models, and the RSMs could effectively predict UR_{Oxygen} and Q_{Oxygen} during the cultivation of *L. vannamei* [20,26]. The ratio of the standard error to experimental data, i.e., the coefficient of variation (*CV*), is a normalized measure of the degree of dispersion of the probability distribution. A *CV* < 10% is considered satisfactory, and the *CV* values of the data in the UR_{Oxygen} and Q_{Oxygen} groups in this study were 1.28% and 6.13%, respectively [27]. The *Prob* > *F* values < 0.0001 indicated that the models were statistically acceptable. Additionally, the *AP* values in the UR_{Oxygen} and Q_{Oxygen} groups were 29.456 and 34.757, respectively, with *AP* values > 4 considered feasible [20,27]. The comparisons between the predicted and actual values of the models with response values of UR_{Oxygen} and Q_{Oxygen} are shown in Figure 4a_1,a_2, while the normal % probability residual and external student residual are shown in Figure 4b_1,b_2. The linear relationship between the data proved that the established models could effectively predict the UR_{Oxygen} and Q_{Oxygen} of the U-tube oxygenator in the production scale operation of the *L. vannamei* RAS [19,20].

Table 3. The results of variance analysis.

Response Value	R^2	$Adj\text{-}R^2$	$Pred\text{-}R^2$	*CV* (%)	*Prob* > *F*	*AP*
Model 1: UR_{Oxygen}	0.9906	0.9773	0.9001	1.28	<0.0001	29.456
Model 2: Q_{Oxygen}	0.9883	0.9799	0.9197	6.13	<0.0001	34.757

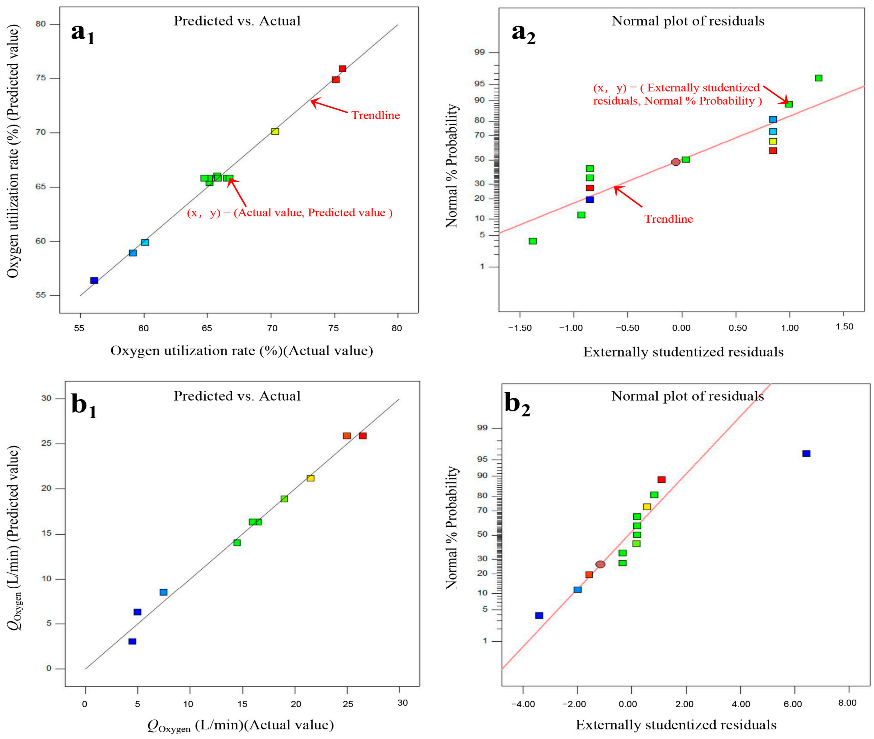

Figure 4. The predicted and actual values, normal % probability residuals, and external student residuals of the models ((**a**$_1$,**a**$_2$) UR_{Oxygen}; (**b**$_1$,**b**$_2$) Q_{Oxygen}).

3.2.2. The UR_{Oxygen} RSM

The relationships between Q_{RAS}, Q_{Oxygen}, and UR_{Oxygen} in the *L. vannamei* RAS are shown in Figure 5. The UR_{Oxygen} was directly proportional to Q_{RAS} and inversely proportional to Q_{Oxygen}. Specifically, when Q_{Oxygen} was 1 and 25 L/min, with an increase in Q_{RAS} from 240 to 340 m^3/h, the UR_{Oxygen} of the U-tube oxygenator increased from 59.73% and 48.33% to 83.78% and 65.45%, increasing by 24.05% and 17.12%, respectively. When Q_{RAS} was 240 and 340 m^3/h, with an increase in Q_{Oxygen} from 1 to 25 L/min, the UR_{Oxygen} of the U-tube oxygenator decreased from 59.73% and 83.78% to 48.33% and 65.45%, reducing by 11.40% and 18.33%, respectively. Xiao et al. (2019) reported that, due to the inability of the U-tube oxygenator to effectively remove nitrogen and CO_2, UR_{Oxygen} was found to be about 40% [7]. In this study, when the Q_{RAS} was 240–340 m^3/h and the Q_{Oxygen} was 1–25 L/min, the UR_{Oxygen} of the U-tube oxygenator was 48.33–83.78%, mainly due to the high Q_{RAS}, nano gas disk, and the FS and MBBR aeration process for CO_2 removal.

A quadratic regression model was determined between Q_{RAS}, Q_{Oxygen}, and the U-tube oxygenator UR_{Oxygen}: $UR_{Oxygen} = -105.3406 + 0.9911Q_{RAS} + 10.6202Q_{Oxygen} - 0.05964Q_{RAS}Q_{Oxygen} - 1.2628 \times 10^{-3}{Q_{RAS}}^2 - 0.1821\,{Q_{Oxygen}}^2 + 6.8888 \times 10^{-5}{Q_{RAS}}^2Q_{Oxygen} + 6.3993 \times 10^{-4}Q_{RAS}{Q_{Oxygen}}^2$. A total of 37 sets of data were collected from the production scale *L. vannamei* RAS. The actual and simulated values of the AP effluent, MBBR effluent, AP inflow, shrimp OCR, and UR_{Oxygen} during the cultivation of *L. vannamei* are shown in Table 4. Moreover, according to Formula (3), the correction coefficient θ of the model was 0.9626. The modified RSM model was $UR_{Oxygen} = 0.9626 \times (-105.3406 + 0.9911Q_{RAS} + 10.6202Q_{Oxygen} - 0.05964Q_{RAS}Q_{Oxygen} - 1.2628 \times 10^{-3}{Q_{RAS}}^2 - 0.1821{Q_{Oxygen}}^2 + 6.8888 \times 10^{-5}{Q_{RAS}}^2Q_{Oxygen} + 6.3993 \times 10^{-4}Q_{RAS}{Q_{Oxygen}}^2)$.

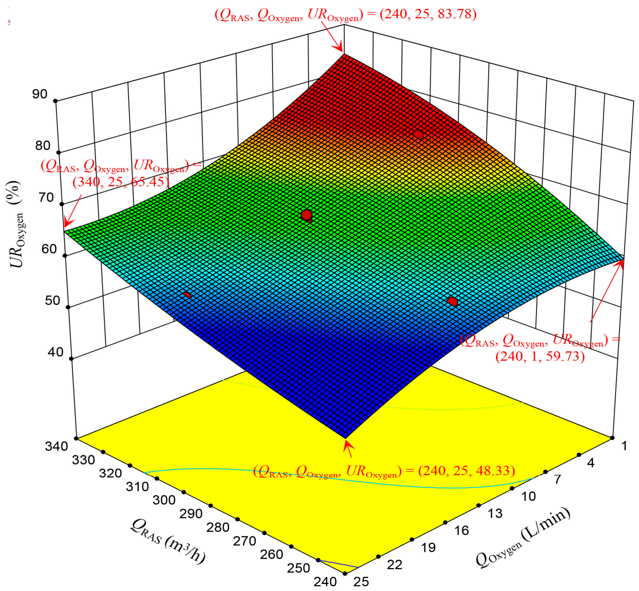

Figure 5. Effects of the RAS flow (Q_{RAS}) and pure oxygen addition (Q_{Oxygen}) on the U-tube oxygenator oxygen-utilization rate (UR_{Oxygen}).

Table 4. Changes in the pure oxygen addition (Q_{Oxygen}), dissolved oxygen (DO) concentration, and oxygen-utilization rate (UR_{Oxygen}) during the cultivation of *Litopenaeus vannamei.*

Q_{RAS} (m^3/h)	$M_{Feeding}$ (kg/d)	$M_{Biomass}$ (kg)	Q_{Oxygen} (L/min)	AP Effluent (mg/L)	MBBR Effluent (mg/L)	AP Influent (mg/L)	AP DO Loss (g/h)	O_2 Addition (g/h)	RAS DO Increase (g/h)	UR_{Oxygen} (%)	
										A_i	P_i
248	19.7	197	7.0	8.58	7.61	9.16	143.84	600.00	384.40	64.07	62.10
248	19.7	180	6.0	8.21	7.38	8.75	133.92	514.29	339.76	66.06	62.34
248	21.2	190	6.0	8.10	7.47	8.72	153.76	514.29	310.00	60.28	62.34
248	21.2	215	6.0	8.02	7.35	8.61	146.32	514.29	312.48	60.76	62.34
286	22.2	222	3.6	7.34	7.15	7.86	148.72	308.57	203.06	65.81	71.94
286	23.2	242	6.0	7.94	7.37	8.58	183.04	514.29	346.06	67.29	70.04
286	25.4	274	3.2	7.25	7.25	7.94	197.34	274.29	197.34	71.95	72.26
248	26.6	300	4.0	7.47	7.46	8.35	218.24	342.86	220.72	64.38	62.67
266	26.6	336	4.0	7.46	7.42	8.28	218.12	342.86	228.76	66.72	67.27
266	26.6	356	4.0	7.37	7.46	8.26	236.74	342.86	212.8	62.07	67.27
266	26.8	368	4.0	7.35	7.42	8.25	239.40	342.86	220.78	64.39	67.27
266	26.8	368	6.0	7.66	7.42	8.63	258.02	514.29	321.86	62.58	66.29
248	27.4	394	3.5	6.95	7.32	8.07	277.76	300.00	186.00	62.00	62.73
248	27.4	431	4.0	6.92	7.28	8.11	295.12	342.86	205.84	60.04	62.67
248	27.4	500	4.0	7.06	7.42	8.28	302.56	342.86	213.28	62.21	62.67
286	31.8	550	9.0	7.95	7.48	9.21	360.36	771.43	494.78	64.14	67.67
248	38.5	600	10.0	8.09	7.55	9.62	379.44	857.14	513.36	59.89	61.10
298	40.7	641	9.5	7.66	7.34	9.11	432.10	814.29	527.46	64.78	68.80
304	44.5	741	9.5	7.41	7.22	8.95	468.16	814.29	525.92	64.59	69.50
298	40.7	670	8.5	7.46	7.34	9.01	461.90	728.57	497.66	68.31	69.68
248	44.3	740	12.0	8.01	7.46	9.94	478.64	1028.57	615.04	59.80	60.21
248	50	840	16.0	8.28	7.31	10.45	538.16	1371.43	778.72	56.78	57.85
248	52.6	880	17.0	8.05	7.26	10.32	562.96	1457.14	758.88	52.08	57.14
286	68.6	2830	16.0	7.18	7.21	10.41	923.78	1371.43	915.20	66.73	62.21
286	68.6	3000	20.0	7.63	7.39	11.05	978.12	1714.29	1046.76	61.06	59.14
298	72.6	3460	23.0	8.01	7.48	11.56	1057.90	1971.43	1215.84	61.67	58.59
298	72.6	3630	24.5	8.21	7.67	11.86	1087.70	2100.00	1248.62	59.46	57.65
298	72.6	3630	25.0	8.25	7.68	11.79	1054.92	2142.86	1224.78	57.16	57.35
286	73.2	3660	18.0	6.73	7.18	10.45	1063.92	1542.86	935.22	60.62	60.67
286	73.2	3660	21.0	7.26	7.31	10.97	1061.06	1800.00	1046.76	58.15	58.37
337	77.3	3865	24.0	7.64	7.26	11.14	1179.50	2057.14	1307.56	63.56	64.83
290	79.2	3960	24.0	7.28	7.28	11.39	1191.90	2057.14	1191.9	57.94	56.70
290	79.2	4160	26.0	7.72	7.31	11.78	1177.40	2228.57	1296.3	58.17	55.28
301	84.7	4435	29.5	8.06	7.51	12.38	1300.32	2528.57	1465.87	57.97	55.54
337	85	4650	23.5	7.74	7.43	11.37	1223.31	2014.29	1327.78	65.92	64.86
337	85	4950	25.0	7.75	7.38	11.55	1280.60	2142.86	1405.29	65.58	64.82
301	86.4	5220	26.0	7.35	7.36	11.55	1264.20	2228.57	1261.19	56.59	57.32

3.2.3. The Q_{Oxygen} RSM

During the cultivation of *L. vannamei*, when the DO concentration of the AP effluent was 6.9 ± 0.4 mg/L, the required Q_{Oxygen} under different Q_{RAS} and $M_{Feeding}$ conditions is shown in Figure 6. The required Q_{Oxygen} was directly proportional to $M_{Feeding}$ and inversely proportional to Q_{RAS}. Specifically, when Q_{RAS} was 240 and 340 m^3/h, with an increase in $M_{Feeding}$ from 20 to 100 kg/day, Q_{Oxygen} increased from 0 to 32.65 and 24.18 L/min, respectively. Interestingly, when Q_{RAS} was 240–340 m^3/h and $M_{Feeding}$ was 24.6–28 kg/day, there was no need to add pure oxygen. Due to the relatively low biomass in the RAS in the early stage of aquaculture, the gas–water exchange processes of the FS and MBBR could supplement the required DO. As $M_{Feeding}$ increased, the effects of Q_{RAS} on Q_{Oxygen} significantly increased. When $M_{Feeding}$ was 100 kg/d, Q_{RAS} increased from 240 to 340 m^3/h, and Q_{Oxygen} decreased by 25.94%. There were two main reasons for this: (1) adding Q_{RAS} improved the UR_{Oxygen} of the U-tube oxygenator and (2) increasing Q_{RAS} enhanced the removal efficiency of the organic particulate matter in the aquaculture water, thereby reducing the DO consumption caused by the oxidation and decomposition of the organic matter [7,18].

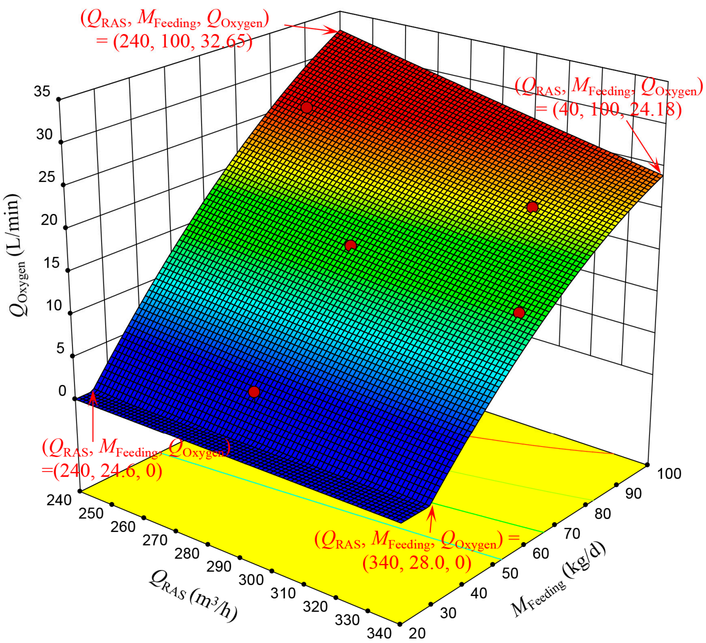

Figure 6. Effects of the RAS flow (Q_{RAS}) and daily feeding rate ($M_{Feeding}$) on the pure oxygen addition (Q_{Oxygen}) during the cultivation of *Litopenaeus vannamei.*

A quadratic regression model was obtained between Q_{RAS}, $M_{Feeding}$, and Q_{Oxygen}: $Q_{Oxygen} = -12.8633 - 0.02793Q_{RAS} + 0.9369M_{Feeding} - 8.9286 \times 10^{-4}M_{Feeding}Q_{RAS} + 5.6122 \times 10^{-5}Q_{RAS}^2 - 2.3281 \times 10^{-3}M_{Feeding}^2$. Table 5 shows the actual and model-predicted values of Q_{Oxygen} during the cultivation of *L. vannamei*. Table 5 compares the actual value and the RSM-predicted values of Q_{Oxygen} and indicates that the model could effectively predict Q_{Oxygen} during the cultivation of *L. vannamei*. According to the Formula (3), the correction coefficient (θ) of the model was 1.09 ($M_{Feeding}$ > 28.0 kg/day). Therefore, the RSM was revised to $Q_{Oxygen} = 1.09 \times (-12.8633 - 0.02793Q_{RAS} + 0.9369M_{Feeding} - 8.9286 \times 10^{-4}M_{Feeding}Q_{RAS} + 5.6122 \times 10^{-5}Q_{RAS}^2 - 2.3281 \times 10^{-3}M_{Feeding}^2)$.

Table 5. The daily feeding rate ($M_{Feeding}$), RAS flow (Q_{RAS}), microscreen drum filter (MDF) backwashing period (T_{MDF}), and pure oxygen addition (Q_{Oxygen}) during the cultivation of *Litopenaeus vannamei*.

No.	$M_{Feeding}$ (kg)	Q_{RAS} (m^3/h)	T_{MDF} (s)	Q_{Oxygen} (L/min)			No.	$M_{Feeding}$ (kg)	Q_{RAS} (m^3/h)	T_{MDF} (s)	Q_{Oxygen} (L/min)		
				a	b	c					a	b	c
1	18.5	241	1800	0.0	-	-	51	56.5	311	268	13.0	13.7	13.6
2	20.0	248	1674	0.0	-	-	52	58.5	311	257	14.0	14.5	14.1
3	19.7	248	1714	0.0	-	-	53	46.5	318	343	12.5	9.3	10.8
4	21.2	248	1565	0.0	-	-	54	46.5	318	339	12.5	9.3	10.9
5	27.9	248	1319	2.0	-	-	55	47.5	318	325	13.0	9.7	11.4
6	27.4	248	1241	2.0	-	-	56	49.0	318	300	13.0	10.4	12.3
7	28.2	248	1286	2.0	-	-	57	51.5	318	284	13.0	11.4	13.0
8	27.4	248	1000	2.0	-	-	58	54.0	318	260	13.5	12.4	14.0
9	27.4	248	1014	2.0	-	-	59	57.0	318	239	14.5	13.6	15.0
10	27.4	248	966	2.0	-	-	60	58.0	318	237	15.0	14.0	15.1
11	26.6	266	1047	1.5	-	-	61	60.0	318	225	16.5	14.8	15.7
12	27.0	266	1094	2.0	-	-	62	61.5	318	219	17.5	15.3	16.0
13	26.8	266	1140	2.5	-	-	63	63.0	318	214	18.0	15.9	16.2
14	26.8	266	1125	2.5	-	-	64	50.4	325	237	13.5	10.7	15.1
15	20.7	286	947	0.0	-	-	65	52.3	325	235	14.0	11.5	15.2
16	21.2	286	930	0.0	-	-	66	54.5	325	243	15.5	12.3	14.8
17	21.2	286	905	0.0	-	-	67	56.5	325	224	16.5	13.1	15.7
18	22.2	286	889	0.5	-	-	68	59.0	325	214	17.0	14.1	16.2
19	23.2	286	882	1.0	-	-	69	60.5	325	210	17.5	14.6	16.5
20	25.4	286	857	1.5	-	-	70	62.0	325	205	17.5	15.2	16.7
21	27.0	286	828	2.0	-	-	71	63.4	325	201	18.0	15.7	17.0
22	29.4	297	688	2.0	1.6	2.7	72	64.8	325	199	18.0	16.1	17.1
23	30.5	297	667	2.5	2.1	3.1	73	65.4	325	192	17.5	16.4	17.5
24	31.4	297	649	3.5	2.6	3.4	74	64.6	337	190	17.0	15.5	17.6
25	33.0	297	617	4.0	3.5	4.0	75	61.0	337	208	16.0	14.3	16.6
26	34.2	297	591	4.5	4.1	4.5	76	62.0	337	202	16.5	14.6	16.9
27	35.5	297	576	5.0	4.7	4.8	77	62.5	337	202	16.5	14.8	16.9
28	37.4	297	541	5.5	5.7	5.5	78	62.0	337	205	16.5	14.6	16.7
29	39.5	297	522	5.5	6.7	5.9	79	63.0	337	201	17.0	15.0	17.0
30	40.7	297	497	5.5	7.3	6.5	80	64.5	337	198	17.0	15.5	17.1
31	37.9	297	539	5.5	5.9	5.5	81	65.5	337	190	17.0	15.8	17.6
32	42.5	297	466	6.5	8.2	7.2	82	67.5	337	186	17.5	16.5	17.9
33	44.8	297	407	9.5	9.2	8.8	83	67.5	337	183	17.5	16.5	18.0
34	44.7	297	424	7.0	9.2	8.3	84	64.0	337	195	17.0	15.3	17.3
35	44.5	304	402	9.5	8.9	8.9	85	64.0	337	200	17.0	15.3	17.0
36	46.5	304	391	9.5	9.8	9.3	86	65.0	337	190	17.5	15.6	17.6
37	46.5	304	382	10.0	9.8	9.5	87	66.0	337	190	18.0	16.0	17.6
38	47.5	304	365	10.0	10.2	10.1	88	69.0	337	185	18.0	16.9	17.9
39	48.5	304	350	10.5	10.7	10.5	89	72.5	337	175	18.0	18.0	18.6
40	49.5	304	342	10.5	11.1	10.8	90	74.0	337	168	18.5	18.4	19.0
41	50.5	304	336	10.5	11.5	11.0	91	75.0	337	162	19.5	18.7	19.5
42	52.0	304	313	11.0	12.2	11.8	92	75.5	337	157	19.5	18.9	19.8
43	52.5	304	310	11.5	12.4	11.9	93	76.5	337	158	19.5	19.2	19.7
44	53.5	304	300	11.5	12.8	12.3	94	75.5	337	154	19.0	18.9	20.0
45	53.5	311	287	11.5	12.5	12.8	95	76.0	337	155	19.5	19.0	20.0
46	53.5	311	290	12.0	12.5	12.7	96	78.5	337	150	20.5	19.7	20.3
47	53.5	311	291	12.5	12.5	12.7	97	78.0	337	152	20.5	19.6	20.2
48	53.0	311	292	12.5	12.3	12.6	98	75.0	337	155	20.0	18.7	20.0
49	54.0	311	279	12.5	12.7	13.2	99	76.0	337	154	21.0	19.0	20.0
50	56.0	311	269	13.0	13.5	13.6	100	76.0	337	150	21.0	19.0	20.4

Note: In the Q_{Oxygen} column, a, b, and c represent the actual value, RSM-predicted value, and feedback-control model predicted value, respectively.

3.2.4. The Q_{Oxygen} Feedback-Control Model

During the operation of an RAS, T_{MDF} is mainly influenced by $M_{Feeding}$ and Q_{RAS} [7,18]. The results given in Section 3.2.3 showed that Q_{Oxygen} was also associated with $M_{Feeding}$

and Q_{RAS}. Previous studies have shown that the operating parameters of the automatic control of some water-treatment units in an RAS can be guided by the working status of the MDF, such as the electrocoagulation reactors [6,18]. Therefore, constructing a model of the relationship between T_{MDF} and Q_{Oxygen} will help to achieve the automatic control of the U-tube oxygenator during the cultivation of *L. vannamei*. Table 5 shows the T_{MDF} and Q_{Oxygen} during the cultivation process of *L. vannamei*. The 92 sets of data in Table 5 were fitted, as shown in Figure 7. The relationship between T_{MDF} and Q_{Oxygen} was a logarithmic function: $Q_{Oxygen} = -11.57\ln(T_{MDF}) + 78.319$, $R^2 = 0.9782$. Table 5 compares the actual value and the Q_{Oxygen} feedback-control model predicted values of Q_{Oxygen} and indicates that the model could effectively manage the Q_{Oxygen} during the cultivation of *L. vannamei*.

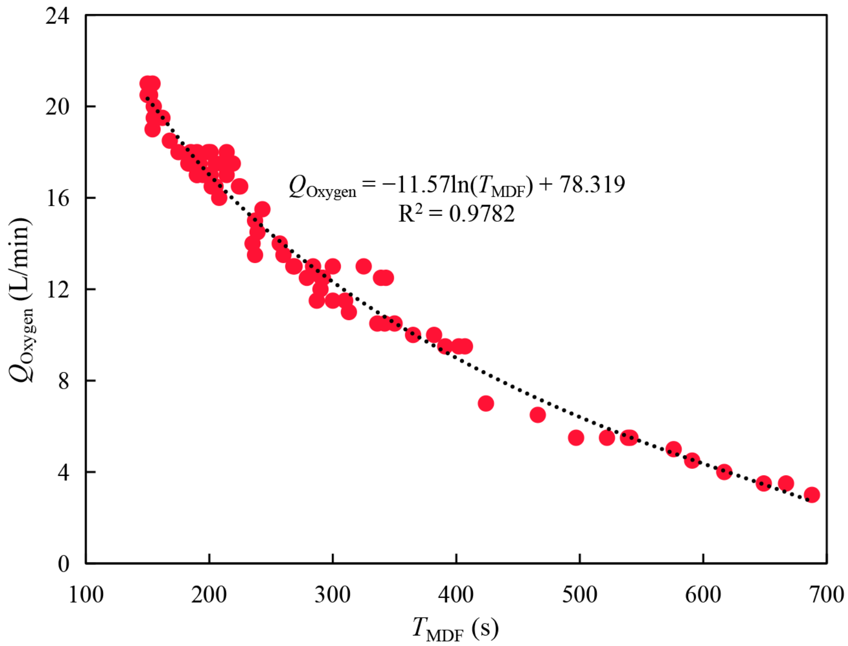

Figure 7. The microscreen drum-filter (MDF) backwashing period (T_{MDF}) and pure oxygen addition (Q_{Oxygen}) during the cultivation of *Litopenaeus vannamei.*

3.3. Analysis of the RAS Oxygenation Cost

Table 6 shows the oxygenation cost of the cultivation of *L. vannamei* and a comparison with other cases. The oxygen addition, total feeding amount, yield, and cost of the RAS during the cultivation of *L. vannamei* were 2368 kg O_2, 4987 kg, 4488 kg, and CNY 0.42 kg shrimp, respectively. Compared to other oxygenation methods, the lowest cost was achieved with the use of pure oxygen.

Table 6. The oxygenation cost during the cultivation of *L. vannamei.*

Aquaculture Mode	Oxygenation Method	Oxygen Addition/Energy Consumption	Total Feeding Amount (kg)	Shrimp Yield (kg)	Oxygenation Cost (CNY/kg Shrimp)	Reference
RAS (384 m^3)	Pure oxygen	2296 kg O_2	4987	4488	0.42	This study
RAS (338 m^3)	Pure oxygen + Roots blower	452 kg O_2 + 4579 kWh	4368	3956	1.25	[4]
Factory water exchange farming (272 m^3)	Roots blower	3540 kWh	2372	1590.8	2.33	[5]
Semi-intensive pond farming (1 ha)	Paddle-wheel aerators	2681 kWh	-	2520	1.06	[28]

Note: The unit prices for oxygen and electricity are CNY 0.83/kg and CNY 1.0/kWh, respectively.

4. Conclusions

This study focused on the efficient management of DO in an *L. vannamei* RAS. The application of a U-tube oxygenator in an RAS was investigated, and models were constructed to predict the automatic control of DO in an RAS. The results showed that the U-tube oxygenator met the DO requirements for the high-density cultivation of *L. vannamei*, with an oxygenation energy consumption of CNY 0.42/kg shrimp. More importantly, the established Q_{Oxygen} RSM could predict and guide the addition of oxygen, and the Q_{Oxygen} feedback-control model could achieve the automatic regulation of Q_{Oxygen} during the cultivation of *L. vannamei*. The results of this study reduced the cost of oxygen augmentation during the cultivation of *L. vannamei*, achieving the precise addition of oxygen and efficient management of DO in an RAS, thus improving its stability and automation. The models constructed in this study were based on M_{Feeding}. If M_{Feeding} was abnormal during the cultivation of *L. vannamei*, the DO automatic management system needed to be closed, and Q_{Oxygen} was adjusted based on the actual DO concentration. In addition, the results of this study can provide a reference for the management of DO during the recirculating aquaculture of the fish.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

DO	dissolved oxygen
RAS	recirculating aquaculture system
$\text{UR}_{\text{Oxygen}}$	oxygen-utilization rate
Q_{Oxygen}	pure oxygen addition
Q_{RAS}	RAS flow
$\text{M}_{\text{Feeding}}$	daily feeding rate
MDF	microscreen drum filter
T_{MDF}	MDF backwashing period
RSM	response-surface model
AP	aquaculture ponds
FS	foam separator
MBBR	moving bed biofilm reactor
OCR	oxygen-consumption rate
CCD	central composite design
CV	coefficient of variation
AP	adequate precision
m_{shrimp}	the average weight of shrimp

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