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Research Article

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Application of constructed wetland to partial nitrification process: Relations betweenparameter values and effluent outcome using response surface methodology

Guangxu Qin, Yancheng Li, Yi Han, Jianbing Zhang, Jian Zhou*, Li Chen and Benzhou Gong

Key laboratory of the Three Gorges Reservoir Region's Eco-environments, Ministry of Education,
Chongqing University, Chongqing, PR China

ABSTRACT

Partial nitrification has a unique advantage in dealing with low carbon/nitrogen (C/N) ratio streams but is rarely applied to streams with low-ammonia concentration. A constructed wetland was used to develop a partial nitrification system based on low-ammonia stream. Response surface methodology was employed, with temperature (X), filler thickness (Y), and filler size (Z) identified as the independent variables, whereas ammonia oxidation rate (AOR) and nitrite accumulation rate (NAR) were the response variables. Using the Box–Benhnken design and second-order polynomial, following response equations were obtained: $AOR=51.44+10.82X-0.15Y-8.15Z-0.26XZ-0.14X^2+0.69Z^2$; $NAR=-3.31+11.67X-0.54Y+5.03Z+0.03XY-0.37X^2-0.32Z^2$*.Analysisofvariance indicatedthat the equations could appropriately describe their corresponding relations. The equations can illustratethe parameter value selection of the reactorto make the effluent stream suitable for post anaerobic ammonia oxidation or for post short-cut denitrification.*

Keywords: constructed wetland; partial nitrification; wastewater treatment; advanced nitrogen removal; response surface methodology

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INTRODUCTION

Most wastewater treatment plants at the Three Gorge reservoir area apply a total nitrogen discharge standard of 20 mg/L. Thus, discharge of these plants will pollute the reservoir area. Advanced nitrogen removal for these plants is necessary. The drain stream of a wastewater plant is characterized by low C/N ratio, thus making traditional nitrification-denitrification processes unsuitable [1,2]. Hence, another method should be considered.

Partial nitrification is widely applied to the treatment of streams with a low C/N ratio. Combined with short-cut denitrification, the process can save 25% O demand and 40% C demand relative to traditional denitrification [3]. Partial nitrification combines with anaerobic ammonia oxidation (ANAMMOX) in autotrophic N removal, which can accomplish nitrogen removal without C [4]. Several parameters can influence partial nitrification: free ammonia [5, 6], pH [7], temperature [8], DO concentration [9, 10] etc. The doubling speed of ammonia--oxidizing bacteria (AOB) is higher than that of nitrite-oxidizing bacteria (NOB) when the temperature exceeds 20 °C [11, 12]. Meanwhile, the O saturation constant of AOB is lower than that of NOB [13]. Several partial nitrification approaches have been developed using the difference between the two bacteria [14, 15].Currently, partial nitrification is mainly used for strong streams. Developing a partial nitrification system that can be applied to low-ammonia stream will provide new method for advanced nitrogen removal in wastewater plants.

The O supplement of constructed wetland mainly relies on air re-aeration. Thus, the DO of the constructed wetland system is usually limited [16, 17]. For better O affinity of AOB, partial nitrification can be applied to constructed wetlands [9, 10].This research attemptsto develop and optimize a new constructed wetland partial nitrification system.

With the adoption of response surface methodology (RSM), reactor parameterswould be analyzed. Then models would be establishedto quantifythe parameters and the efficiency of the reactor. Results could support the engineering application of the system and would provide a new treatment process for the streams with both low C/N ratio and low-ammoniaconcentration.

EXPERIMENTAL SECTION

2.1 Reactor description:

Laboratory-scale constructed wetland was adopted, as shown in Figure1. The inner diameter of the wetland is 200 mm. This wetland has no plants. In addition, the filler consists entirely of solid gravel without soil, making this wetland difficult to block. The filler gravel came from a local quarry. Three series of diameters are listed in Table 1 for the analysis of filler size. Experiments were all run in a thermostatic chamber for temperature control. Three different heights (45, 85, and 125 cm) of the reactor are employed to match corresponding filler thickness (40, 80, and 120 cm). The constructed wetland was operated as a sequencing batch. The cycle continued for 24 h as follows: settle (2 h) →influent (0.25 h) →attach (21.5 h) → drain (0.25 h).

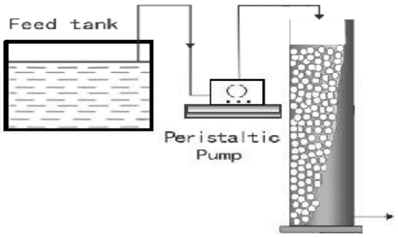

Figure 1: Reactor description

Table1: Three standards of the gravel filler

standard	fine	middle	coarse
Average diameter(mm)	2.5	7.5	12.5
Actual diameter(mm)	0 to 5	5 to 10	10 to 15

2.2 Influent water quality

Artificial wastewater was used to facilitate the Box–Benhnken design (BBD).The synthetic media was composed of the following (in mg/L): NH_4HCO_3, 25; KH_2PO_4, 6.25; EDTA, 6.25; $FeSO_4$, 6.25; $MgSO_4 \cdot 7H_2O$, 12.5; $CaCl_2$, 18.5; and trace solution (Zn, Co, Mn, etc.), 1.25. $NaHCO_3$ was added to regulate the pH of the influent stream to 8.0. Tap water was used as the solvent of the artificial wastewater. Thus, the influent stream also contained a few nitrates with concentration ranging from 1 mg/L to 2 mg/L.

2.3 Response surface methodology (RSM)

This method involves five steps: statistical design of experiments, data transformation, model selection, coefficient estimation, and applicability examination [18]. A statistical model generally needs to be developed for the practical application of RSM [19–21]. By using the BBD, the ammonia oxidation rate (AOR) and the nitrite accumulation rate (NAR) were identified as dependent variables in the experiment. Three parameters were selected as independent variables in accordance with the preliminary research: system temperature (X), filler thickness(Y), and filler size(Z).

$$\text{AOR} = (\text{influent ammonia} - \text{effluent ammonia}) / (\text{influent ammonia}) \times 100\% \quad \text{Eq. (1)}$$

$$\text{NAR} = (\text{effluent nitrite}) / (\text{effluent nitrite} + \text{effluent nitrate} - \text{influent nitrate}) \times 100\% \quad \text{Eq. (2)}$$

$$x_i = (X_i - X_0) / \Delta x \quad \text{Eq. (3)}$$

Wherex_i is the coded value of the i^{th} variable, X_i represents the uncoded value of the i^{th} test variable, and X_o is the uncoded value of the i^{th} test variable at the center point.

The actual value of the independent variable will be coded prior to RSM analysis. Each of the independent variables has three levels. Table 2 shows the coded values and their corresponding actual values. Equation 3 (Eq.3) shows how the actual value becomes a coded value.

Table 2 BBD and the experiment result

Run	A	B	C	Independent variables			Ammonia oxidation rate（%）	Nitrite accumulation rate（%）
				temperature（℃）	Filler thickness（cm）	Filler size（mm）		
1	-1	0	1	13	80	12.5	14.1	90.4
2	1	0	1	33	80	12.5	37.3	23.2
3	0	1	-1	23	120	2.5	71.1	95.9
4	1	0	-1	33	80	2.5	98.6	38.4
5	-1	0	-1	13	80	2.5	23	88.6
6	1	-1	0	33	40	7.5	54.4	19.3
7	0	0	0	23	80	7.5	40.5	106.5
8	0	0	0	23	80	7.5	41.1	105.8
9	0	0	0	23	80	7.5	41.1	104.4
10	0	1	1	23	120	12.5	32.9	109
11	0	0	0	23	80	7.5	40.5	104.7
12	0	-1	1	23	40	12.5	48.4	102.1
13	1	1	0	33	120	7.5	42.9	77.5
14	-1	-1	0	13	40	7.5	10.3	93.9
15	0	-1	-1	23	40	2.5	88.4	94.5
16	-1	1	0	13	120	7.5	7.8	97.8
17	0	0	0	23	80	7.5	39.7	105.8

Model selection is based on the results of the experiments [22, 23].According to the BBD, 17 experiments were conducted. The experimental scheme and result are listed in Table 2. Based on the experiment result, a second-order polynomial model was determined to be suitable for quantitative analyses between independent (temperature, filler thickness, and filler size) and dependent variables (AOR and NAR)[22-24]. Eq.4 shows the adopted quadratic model.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon$$

Eq. (4)

Where y is the predicted response; xi represents the coded variables; β0, βi, βii, βij are the regression coefficients and ε is the stochastic term, which is supposed to have Gaussian distribution.

RESULTS AND DISCUSSION

3.1 Equations and analysis of variance (ANOVA)

Thesecond-order polynomial model (Eq.4) applied to the experiments resulted inEqs.5 and 6. Eq.5 describes the relation between AOR and the three independent variables, whereasEq.6 describesNAR. ANOVA is then applied.Table 3 showsthe ANOVA results of Eqs.5 and 6.

$$\mathrm{AOR} = -51.44 + 10.82\mathrm{X} - 0.15\mathrm{Y} - 8.15\mathrm{Z} - 0.26\mathrm{XZ} - 0.14\mathrm{X}^2 + 0.69\mathrm{Z}^2 \quad \text{Eq. (5)}$$

$$\mathrm{NOR} = -3.30 + 11.68\mathrm{X} - 0.54\mathrm{Y} + 5.02\mathrm{Z} + 0.033\mathrm{XY} - 0.37\mathrm{X}^2 - 0.32\mathrm{Z}^2 \quad \text{Eq. (6)}$$

Table 3: Analysis of variance (ANOVA)

Source	Sum of squares (Eq5/ Eq6)	Df (Eq5/ Eq6)	Mean square (Eq5/ Eq6)	F Value (Eq5/ Eq6)	P-value (Eq5/ Eq6)
Model	9796.20/13195.04	6/6	1632.70/2199.17	95.76/33.52	< 0.0001/< 0.0001
X	3960.50/5751.28	1/1	3960.50/5751.28	232.29/87.65	<0.0001/< 0.0001
Y	294.03/579.70	1/1	294.03/579.70	17.25/8.84	0.0020/0.140
Z	2816.25/6.48	1/1	2816.25/6.48	165.18/0.099	<0.0001/0.7598
Std. Dev.=4.13/8.10		R^2=0.9829/0.9526		Adj R^2=0.9726/0.9242	
Pre R^2=0.9212/0.752318		C.V.=9.57%/9.46%		AdeqPrecision=37.664/16.658	

The p-value (Prob> F) of the two models were both relatively low ($p < 0.0001$), indicating that the models were significant. The other indices must be in accordance with R^2>0.95, (Adj R^2- Pre R^2) <0.2, C.V. <10%, Pre R^2>0.7, Adeq Precision >4.011 [22, 23]. Table 3 shows the index of Eqs.5 and6, which could both satisfy the requirements. Therefore, both equations are appropriate for describing the relation between the parameter values and the response outcome.

3.2 Analyses for AOR and NAR

According to Eq.5, temperature, filler thickness, and filler size all have significant effects on AOR. The effect degree of the three parameters can be ranked as: temperature>filler size>filler thickness. No XY and YZ terms are present in Eq.5, which indicates that filler thickness has no significant interaction with temperature and filler size. Thus, filler thickness affects AOR independently. Furthermore, calculations of the derivation of Eq.5 results in Eq.7, which indicates an inverse correlation between filler thickness and AOR. This finding corresponds with the re-aeration capability of the wetland. When filler thickness increases, the re-aeration capability of the wetland will decrease. Thus, AOR decreases.

$$\frac{\partial AOR}{\partial Y} = -0.15 \qquad \text{Eq. (7)}$$

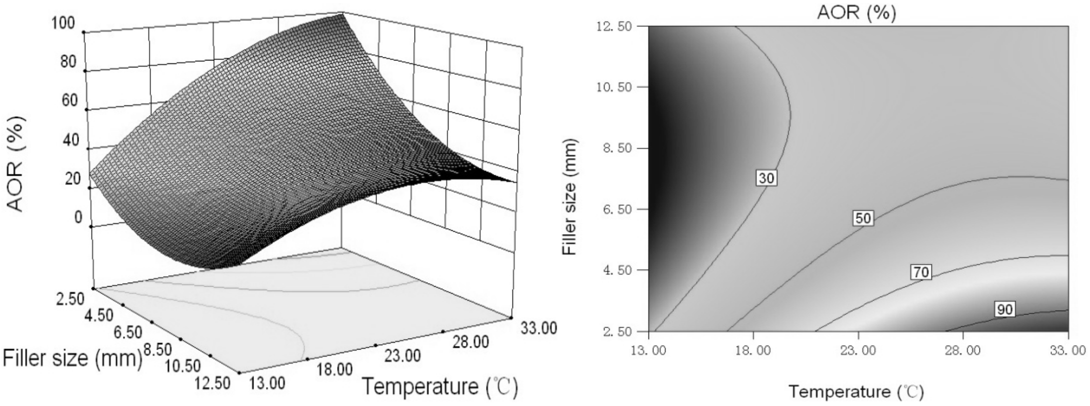

Figure 2: Influence of temperature and filler size on AOR

Temperature interacted with filler size significantly, as shown in Figure2. When filler size is constant, AOR increases with increasing temperature. When temperature is below 15 °C, AOR is less than 40%, which indicates that the function stem will have low activity under low temperature. As filler size rises, AOR initially decreases and then increases. When filler size is 2.5 mm, AOR achieves the maximum value.

As regards NAR, the effect degree of the three parameters is in the following order: temperature>filler thickness>filler size. Filler size affects NAR independently, as shown in Eq.8. Whenfiller size is equal to 7.8 (5.02/0.64) mm, NAR achieves themaximum value. Afiller size less than 7.8 mm positivelycorrelates with NAR. If filler size is greaterthan 7.8mm, aninversecorrelation is observed.

$$\frac{\partial NAR}{\partial Z} = -0.64Z + 5.02 \qquad \text{Eq. (8)}$$

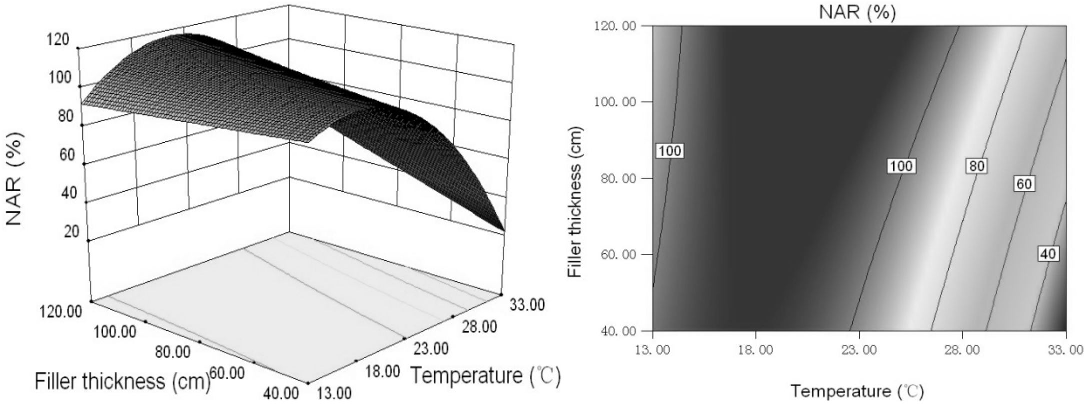

Figure 3: Influence of temperature and filler thickness on NAR

Figure 3 indicates that temperature interacts with filler thickness. The contour line tends to be straight, which suggests that this interaction is extremely significant. Thus, once one of the two parameters negatively affects NAR, the other could be regulated to counterbalance such effect. NAR positive correlates with filler thickness, and this correlation is more significant with higher temperature.

3.3Optimization

Two kinds of effluent streams of the wetland could be needed, for post anaerobic ammonia oxidation or for post partial denitrification. The former stream requests an AOR of around 55.6%, while the latter requests the AOR near to 100%. Both streams need the NAR as higher as possible. According to Eq.5 and Eq.6, lots series of the possible solutions of the parameters could be proposed for the both streams. This can give guidance when new wetland is set up. Table 4 gives some solutions for both streams based on the equations (first 3 for post anaerobic ammonia oxidation, the other for post partial denitrification).

Table 4 Some solutions

Order	Temperature (℃)	Filler thickness(cm)	Filler size(mm)	AOR (%)	NOR (%)
1	23.59	43.60	7.12	50.16	96.49
2	24.95	81.92	6.30	51.37	99.89
3	27.37	110.50	5.97	53.24	97.84
4	27.33	112.53	2.51	85.49	90.83
5	26.32	86.66	2.50	87.03	87.01
6	24.05	41.10	2.53	87.27	85.89

CONCLUSION

RSM was applied to analyze the efficiency of the partial nitrification of a constructed wetland. Temperature, filler thickness, and filler size significantly influence the wetland. When filler thickness and filler size are at low levels while temperature is at a high level, AOR will be high. When filler thickness is high or temperature is less than 30 °C, NAR will be high. The equations could provide guidance in the establishment of a new reactor that can release effluent stream as expected. Effluent ammonia/effluent nitrite can be approximately 1.26, which is suitable for post ANAMMOX. Likewise, nitrite can dominate the effluent stream, which is suitable for post partial denitrification.

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