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Optimization of partial nitritation in a continuous flow internal loop airlift reactor

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HIGHLIGHTS

- A central composite design (CCD) was applied.
- The factors influencing the NO_2^--N_{eff}/NH_4^+-N_{eff} ratio and NAR were investigated.
- Optimal conditions regarding DO, Alk/NH_4^+-N and NH_4^+-N_{inf} were determined.
- The validity of the response surface models was confirmed in verification trials.
- Different types of alkali were compared for use in the PN process.

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ABSTRACT

In the present study, the performance of the partial nitritation (PN) process in a continuous flow internal loop airlift reactor was optimized by applying the response surface method (RSM). The purpose of this work was to find the optimal combination of influent ammonium (NH_4^+-N_{inf}), dissolved oxygen (DO) and the alkalinity/ammonium ratio (Alk/NH_4^+-N) with respect to the effluent nitrite to ammonium molar ratio and nitrite accumulation ratio. Based on the RSM results, the reduced cubic model and the quadratic model developed for the responses indicated that the optimal conditions were a DO content of 1.1–2.1 mg L^{-1}, an Alk/NH_4^+-N ratio of 3.30–5.69 and an NH_4^+-N_{inf} content of 608–1039 mg L^{-1}. The results of confirmation trials were close to the predictions of the developed models. Furthermore, three types of alkali were comparatively explored for use in the PN process, and bicarbonate was found to be the best alkalinity source.

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1. Introduction

The anaerobic ammonium oxidation (ANAMMOX) process has attracted considerable attention in recent years as a substitute for the conventional nitrification–denitrification process due to several potential benefits (Mulder et al., 1995). The ANAMMOX process utilizes both ammonium and nitrite, at a molar ratio off 1:1.32, as reaction substrates (Strous et al., 1999). However, ammonium is frequently the main nitrogenous compound in the input stream, and a suitable substrate ratio for the ANAMMOX pathway therefore needs to be achieved through a pre-treatment step involving partial nitritation (PN). This method employs an effluent nitrite to ammonium molar ratio (NO_2^--N_{eff}/NH_4^+-N_{eff}) of 1.0–1.32, which converts 50–57% of the influent ammonium (NH_4^+-N_{inf}) into nitrite and prevents the excess production of nitrate (Sliekers et al., 2003). A stable and efficient PN process is essential to establish a robust ANAMMOX procedure through a two-stage PN-ANAMMOX process (Li et al., 2011).

Many factors, such as the dissolved oxygen (DO) content, the alkalinity to influent ammonium ratio (Alk/NH_4^+-N) and the dose of NH_4^+-N_{inf}, are considered to impact PN performance (Hwang et al., 2000; Xing et al., 2013; Zhang et al., 2011). An appropriate combination of these factors is desirable to achieve a highly efficient and stable treatment. The response surface method (RSM) is a technique for designing experiments, building models, evaluating the effects of several factors and determining the optimal conditions for desirable responses, requiring a limited number of planned experiments (Yue et al., 2007; Zinatizadeh et al., 2010). This classical method offers a better alternative than the conventional method because it includes the influences of individual factors as well as their interactions. The RSM has been frequently employed in the field of wastewater treatment (Moon et al., 2013; Rastegar et al., 2011; Zhao et al., 2008). Lu et al. (2006) reported the combined effects of operational parameters such as pH, DO and NH_4^+-N on the performance of shortcut nitrification based on performing an orthogonal experiment. However, few

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studies have been reported employing the RSM to optimize PN process parameters. Therefore, in the present study, an attempt was made to optimize the key factors involved in the PN process using the RSM, thus allowing the interactions between parameters and the nonlinear dependencies among experimental variables to be studied and a real optimum to be achieved.

The main objective of this work was to evaluate the effects of operating parameters such as the DO content, Alk/NH_4^+-N ratio and NH_4^+-N_{inf} content on the NO_2^--N_{eff}/NH_4^+-N_{eff} ratio and the nitrite accumulation ratio (NAR) in a continuous flow internal loop airlift reactor (ILAR) and to search for the optimal operating parameters to achieve an NO_2^--N_{eff}/NH_4^+-N_{eff} ratio of 1.0–1.32 and a high NAR through applying the RSM using a central composite design (CCD). The appropriate type of alkalinity was also explored.

2. Methods

2.1. Synthetic wastewater, reactor and inoculum

The reactor was fed with a synthetic influent consisting of $NaHCO_3$, to provide alkalinity, and an inorganic carbon source supplement, ammonium and nutrients, similar to that described by Jin et al. (2008). The concentration of ammonium, supplied in the form of $(NH_4)_2SO_4$, and the dose of alkalinity depended on the Alk/NH_4^+-N ratio, applied as explained in the text.

A laboratory-scale ILAR was used in this study, following the description of Xing et al. (2013). The reactor had a reaction capacity of 3.8 liters, with an internal diameter of 15 cm and a height/diameter ratio of 7/3. The bioseed for the ILAR was collected from a local municipal wastewater treatment plant (Hangzhou, China). The contents of suspended solids (SS) and volatile suspended solids (VSS) in the seeding sludge in the reactor following inoculation were 14.34 and 5.02 g L^{-1}, respectively. After approximately 10 months of operation, enrichment of ammonia-oxidizing bacteria (AOB) and a stable PN were achieved through initial complete nitrification followed by adjustment of the Alk/NH_4^+-N ratio from 7.14 to 3.57, thus corresponding to an initial complete nitrification and subsequent partial nitrification strategy (Xing et al., 2013). The stabilized effluent with an NO_2^--N/NH_4^+-N ratio of 1.15 ± 0.06 was suitable for the subsequent feeding of the ANAMMOX process.

Table 1
Relationship between the coded and actual values of a factor.

Code (x_i)	Actual value of factor (X_i)
$-\alpha$	X_{min}
-1	$\frac{(\alpha-1)X_{max}+(\alpha+1)X_{min}}{2\alpha}$
0	$\frac{X_{max}+X_{min}}{2}$
+1	$\frac{(\alpha-1)X_{min}+(\alpha+1)X_{max}}{2\alpha}$
$+\alpha$	X_{max}

X_{min} and X_{max}: minimum and maximum values of X, respectively.

2.2. Operation of ILAR

The reactor was located in a thermostatic chamber at 30 ± 1 °C, and the hydraulic retention time was set at a constant 21 h. Following reactor start-up, experiments were conducted to investigate the effects of DO, the Alk/NH_4^+-N ratio and NH_4^+-N_{inf} on the NO_2^--N_{eff}/NH_4^+-N_{eff} ratio and NAR. Variation of the effluent nitrogen concentration within ±3% in each run was considered the criterion for reaching a pseudo-steady state before changing to the next condition. Only results obtained in a pseudo-steady state were reported. After optimization of PN was accomplished, confirmation experiments were undertaken to validate the optimal process parameters and the developed model. Finally, three types of alkali ($NaHCO_3$, Na_2CO_3 and NaOH) with the same alkalinity level were comparatively explored.

2.3. Experimental design and data analysis

A CCD is a very efficient design tool for the fitting of second-order models and is rotatable by changing the value of α (Trinh and Kang, 2011; Yue et al., 2007). An α value of 1.682 for three independent factors each at five levels assured rotation of the CCD in this case. The relationship between the coded (x_i) and actual (X_i) values of the factors is shown in Table 1, in which the range of factor values is expressed by the values of X_{min} and X_{max}. The ranges and levels of the independent input variables DO, Alk/NH_4^+-N and NH_4^+-N_{inf} are presented in Table 2. The factors and the experimental levels for each factor were selected based on values presented in the literature and results from preliminary experiments. The range of DO was set according to Ruiz et al. (2003) and Antileo et al. (2006), while the range of Alk/NH_4^+-N values was selected as suggested by Zhang et al. (2011) and Liang et al. (2011), and the NH_4^+-N_{inf} range was determined from preliminary experiments. DO content of more than 3.0 mg L^{-1} was not favor for the nitrite accumulation in the PN process, and the NH_4^+-N_{inf} was nearly fully oxidized at the Alk/NH_4^+-N ratio approximately 7.14. In addition, the dose of NH_4^+-N_{inf} higher than 1232 mg L^{-1} was not helpful for the stable operation of PN prior to ANAMMOX in an ILAR according to Xing et al. (2013). The NO_2^--N_{eff}/NH_4^+-N_{eff} ratio and NAR acted as the dependent output variables. The levels of the input variables are given in Table 2. The CCD applied in this work is presented in Table 3, which provides the experimental conditions and their responses. Twenty experiments were run in a random manner to minimize the effect of uncontrolled variables on the obtained responses.

To determine whether a relationship existed between the factors and the responses, the collected data were analyzed statistically through regression analyses. Regression analysis was performed using the following second-order polynomial empirical model (Rastegar et al., 2011; Trinh and Kang, 2010):

$$Y = X_0 + X_1A + X_2B + X_3C + X_{12}AB + X_{13}AC + X_{23}BC + X_{11}A^2 + X_{22}B^2 + X_{33}C^2 \quad (1)$$

where Y is the response variable, i.e., the NO_2^--N_{eff}/NH_4^+-N_{eff} ratio or NAR; X_0 is a constant coefficient; X_1, X_2 and X_3 are linear interaction coefficients; X_{12}, X_{13} and X_{23} are second-order interaction

Table 2
Experimental range and levels of independent test variables.

Variable	Low axial −1.682 (-α)	Low factorial (−1)	Center point (0)	High factorial (+1)	High axial +1.682 (+α)
DO(mg L^{-1}): A	0.4	0.9	1.7	2.5	3.0
Alk/NH_4^+-N: B	0	1.45	3.57	5.69	7.14
NH_4^+-N_{inf} (mg L^{-1}): C	280	473	756	1039	1232

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