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Performance evaluation of single-sludge reactor system treating high-strength nitrogen wastewater

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Abstract

In the single-sludge reactor system treating high-strength nitrogen wastewater (similar to anaerobically pretreated piggery wastewater), the NH_4^+ -N removal efficiencies (98–82%) are higher than total nitrogen removal efficiencies (71–43%). The mixed liquor recycle ratio only imposes a slight effect on total nitrogen removal efficiency. The alkalinity change data could be used for monitoring and control of the reactor system. To evaluate the performance of the single-sludge reactor system, a simplified nitrification–denitrification model (with nitrification capacity, denitrification capacity, and denitrification potential concepts) and a graphically analytical technique are proposed. It turns out that ammonia nitrification and total nitrogen removal efficiencies are strongly dependent on the process load and reactor configuration, and an optimal operating condition requires a proper match between nitrification and denitrification. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Ammonia nitrogen; Nitrification–denitrification; Single-sludge reactor system; Graphically analytical technique

1. Introduction

Ammonia nitrogen (NH_4^+ -N) with several milligrams per liter is known to impose a toxic effect on aquatic lives. If untreated or improperly treated NH_4^+ -N-containing wastewater discharges into water bodies, especially the drinking water source, it reacts with the disinfectant chlorine, resulting in the generation of the carcinogen trihalomethane. Thus, it is becoming increasingly important to control the discharge of ammonia nitrogen by proper design of wastewater treatment plants. Among a great many biological and

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Nomenclature

C_k	concentration of ammonia nitrogen in batch reactor ($\text{mg NH}_4^+ \text{-N dm}^{-3}$)
C_{k0}	ammonia nitrogen influent concentration ($\text{mg NH}_4^+ \text{-N dm}^{-3}$)
C_{ke}	ammonia nitrogen effluent concentration ($\text{mg NH}_4^+ \text{-N dm}^{-3}$)
C_n	concentration of oxidized forms of nitrogen in batch reactor ($\text{mg NO}_x^- \text{-N dm}^{-3}$)
C_{ne}	effluent concentration of oxidized forms of nitrogen ($\text{mg NO}_x^- \text{-N dm}^{-3}$)
C_{s0}	easily biodegradable COD influent concentration (mg COD dm^{-3})
$D_{c,ana}$	denitrification capacity of anaerobic compartment (mg N dm^{-3})
$D_{p,anx}$	denitrification potential of anoxic compartment (mg N dm^{-3})
E_1	nitrification efficiency
E_2	denitrification efficiency
F_k/M_{aer}	input ammonia nitrogen to microbes (in aerobic compartment) ratio for nitrifying autotrophs ($\text{mg NH}_4^+ \text{-N mg per VSS per day}$)
k_d	denitrification rate constant (per day)
k_n	nitrification rate constant (per day)
N_c	nitrification capacity of aerobic compartment (mg N dm^{-3})
Q	inflow rate (dm^3 per day)
r_d	denitrification rate ($\text{mg NO}_x^- \text{-N dm}^{-3}$ per day)
R_m	mixed liquor recycle ratio
R_s	sludge recycle ratio
V_{aer}	volume of aerobic compartment (dm^3)
V_{ana}	volume of anaerobic compartment (dm^3)
V_{anx}	volume of anoxic compartment (dm^3)
V_T	total volume of anaerobic, anoxic, and aerobic compartments (dm^3)
X	average biomass concentration in single-sludge reactor system (mg VSS dm^{-3})
X_{aer}	biomass concentration in aerobic compartment (mg VSS dm^{-3})
X_{ana}	biomass concentration in anaerobic compartment (mg VSS dm^{-3})
X_{anx}	biomass concentration in anoxic compartment (mg VSS dm^{-3})

Greek letters

α	volume fraction of anaerobic compartment
β	volume fraction of anoxic compartment
ϕ	proportionality constant
γ	volume fraction of aerobic compartment

physicochemical processes, biological nitrification–denitrification is the most cost-effective method for removing nitrogen from domestic and industrial wastewater.

Aerobic heterotrophs, strict aerobic nitrifiers and facultative aerobic denitrifiers frequently exist in the aerobic wastewater treatment system. The populations of the three different types of microorganisms vary with different wastewater characteristics and

operating conditions. They compete with one another, and eventually maintain a delicate stable relationship. To create conditions that favor desired reactions of carbon oxidation, nitrification and denitrification, several single-sludge processes such as A/O, A2/O, SBR, and VIP have been developed [1]. Although these reactor systems use the same form of the activated-sludge process, they employ different combinations of anaerobic, anoxic, and aerobic zones or compartments.

Sharma and Ahler [2] reviewed thoroughly the literature on nitrification and thereby concluded that the kinetics of multicomponent substrate removal has a bearing on nitrification by $\text{NH}_4^+\text{-N}$ and $\text{NO}_2^-\text{-N}$ oxidizers in the presence of other substrates and organisms. van Haandel et al. [3] and Warner et al. [4] used the zero-order kinetics to describe accurately the denitrification rate in anoxic reactor of the single-sludge reactor system. Henze et al. [5], Wentzel et al. [6], and Argaman [7] developed very complex models for the single-sludge reactor system. These models contained a large number of processes, components, and parameters, which must be evaluated before the simulation purpose. Zhao et al. [8] incorporated the concepts of nitrification capacity and denitrification potential to derive a model applied to the alternating activated sludge process. They also presented a graphical technique as a tool for a process dynamic analysis.

In this work, a single-sludge reactor system was conducted to treat high-strength nitrogen wastewater (similar to anaerobically pretreated piggery wastewater). To evaluate the performance of the single-sludge reactor system with different operating conditions, a simplified nitrification–denitrification model together with a graphically analytical technique are also proposed.

2. Simplified nitrification–denitrification model

Fig. 1 illustrates the flow diagram of the single-sludge suspended-growth reactor system which is designed for biological removal of organics and ammonia nitrogen from wastewater. The reactor system which consists of anaerobic, anoxic, aerobic, and settling compartments in sequence is operated with mixed liquor recycle and sludge recycle.

The validity of the simplified nitrification–denitrification model is based on the following assumptions:

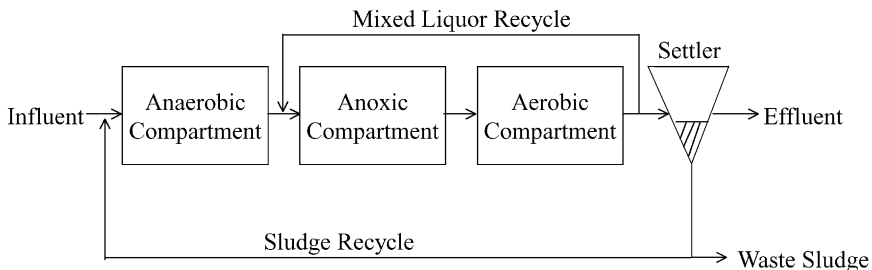


Fig. 1. Schematic diagram of the single-sludge reactor system.

1. *For nitrification:* The distribution of nitrifiers, denitrifiers, and heterotroph species in the aerobic compartment can be characterized by the value of loading (F_k/M_{aer}) [9]. That is, the rate of nitrification can be determined with loading.
2. *For denitrification:* The kinetic limitation by a low NO_x^- -N concentration is neglected due to the reportedly small value of the half saturation constant. That is, the denitrification rate can be approximated as a zero-order reaction.
3. No microbial activity occurs in the settling compartment. Thus, the soluble nitrogen content in the settling compartment and the effluent are the same as that in the aerobic compartment.
4. According to the chemical formula $\text{C}_5\text{H}_7\text{O}_2\text{N}$, nitrogen assimilation by microorganisms (in the reactor system with a high influent NH_4^+ -N concentration of 900 mg/l and sludge ages of longer than 10 days) was only 3.7–6.1%, so neglect it.

2.1. Nitrification in aerobic compartment

According to Sharma and Ahler [2], the Grau model [10] describes well the kinetics of multicomponent substrate removal. Thus, nitrification in the aerobic compartment can be expressed as

$$\frac{dC_k}{dt} = -k_n \frac{C_k}{C_{k0}} X \quad (1)$$

Based on assumption 1, the rate of nitrification can also be determined in terms of the loading. Thus, a material balance for NH_4^+ -N entering and leaving the aerobic compartment, where nitrification occurs, gives

$$\frac{Q(C_{k0} - C_{ke})}{V_{\text{aer}} X} = k_n \frac{C_{ke}}{C_{k0}} = \frac{k_n C_{k0}}{(C_{k0}(C_{k0} - C_{ke})/C_{ke}) + C_{k0}} = \frac{k_n (F_k/M_{\text{aer}})}{k_n + (F_k/M_{\text{aer}})} \quad (2)$$

where

$$X = \alpha X_{\text{ana}} + \beta X_{\text{anx}} + \gamma X_{\text{aer}} \quad (3)$$

$$\frac{F_k}{M_{\text{aer}}} = \frac{QC_{k0}}{\gamma V_T X} \quad (4)$$

$$\alpha = \frac{V_{\text{ana}}}{V_T}, \quad \beta = \frac{V_{\text{anx}}}{V_T}, \quad \gamma = \frac{V_{\text{aer}}}{V_T} \quad (5)$$

Eq. (2) can be rewritten as

$$\frac{C_{k0} - C_{ke}}{C_{k0}} = \frac{k_n}{k_n + (F_k/M_{\text{aer}})} \quad (6)$$

2.2. Denitrification in anaerobic and anoxic compartments

Abufayed and Schroeder [11] and Argaman [12] suggested that the rate of denitrification (r_d) by activated-sludge mixed liquor can be expressed as

$$r_d = k_d X \quad (7)$$

2.3. Nitrification capacity, denitrification capacity, and denitrification potential

For the single-sludge reactor system, three mass parameters were introduced: nitrification capacity, denitrification capacity, and denitrification potential [13]. Neglecting nitrogen assimilation, nitrification capacity (N_c) can be defined as

$$N_c = C_{k0} - C_{ke} \quad (8)$$

By placing Eq. (6) into Eq. (8), nitrification capacity can be rewritten as

$$N_c = \frac{C_{k0}k_n}{k_n + (F_k/M_{aer})} \quad (9)$$

To maintain the anaerobic compartment at anaerobic state, the insufficient amount of the oxidized forms of nitrogen has to be recycled from the settling compartment to the anaerobic compartment. It turns out that all the recycled oxidized forms of nitrogen can be completely denitrified. Denitrification capacity of the anaerobic compartment ($D_{c,ana}$), which is defined as denitrified nitrogen per unit influent flow, can be expressed as

$$D_{c,ana} = R_s C_{ne} \quad (10)$$

In contrast, the sufficient amount of the oxidized forms of nitrogen is recycled from the aerobic compartment to the anoxic compartment. Thus, the oxidized forms of nitrogen are always present in the effluent from the anoxic compartment. Denitrification potential (i.e. the maximum mass of the oxidized forms of nitrogen that can be denitrified) of the anoxic compartment ($D_{p,anx}$) is then given by

$$D_{p,anx} = \frac{r_d \beta V_T}{Q} \quad (11)$$

Therefore, the concentrations of the oxidized forms of nitrogen in the effluent (C_{ne}) can be obtained by using a material balance equation, as shown below:

$$C_{ne} = N_c - D_{c,ana} - D_{p,anx} = \frac{N_c - D_{p,anx}}{R_s + 1} \quad (12)$$

Also, the effluent NH_4^+ -N concentration (C_{ke}) can be calculated from Eq. (8). That is,

$$C_{ke} = C_{k0} - N_c \quad (13)$$

Moreover, from the definitions of nitrification capacity, denitrification capacity, and denitrification potential, the nitrogen removal or nitrification efficiency (E_1), and total nitrogen (TN) removal efficiency (E_2) can be expressed as follows:

$$E_1 = \frac{\text{nitrified nitrogen}}{\text{total influent } \text{NH}_4^+\text{-N}} = \frac{N_c}{C_{k0}} = \frac{k_n}{k_n + (F_k/M_{aer})} = \frac{k_n}{k_n + (QC_{k0}/\gamma V_T X)} \quad (14)$$

$$\begin{aligned}
 E_2 &= \frac{\text{denitrified nitrogen}}{\text{total influent } \text{NH}_4^+ \text{-N}} = \frac{D_{p,\text{anx}}}{C_{k0}} + \frac{D_{c,\text{ana}}}{C_{k0}} = \frac{D_{p,\text{anx}}}{C_{k0}} + \frac{R_s}{R_s + 1} \left(E_1 - \frac{D_{p,\text{anx}}}{C_{k0}} \right) \\
 &= \frac{k_d X \beta V_T / Q}{C_{k0}} + \frac{R_s}{R_s + 1} \left(E_1 - \frac{k_d X \beta V_T / Q}{C_{k0}} \right) \quad (15)
 \end{aligned}$$

It must be stressed that Eq. (10) is valid only when the recycled oxidized forms of nitrogen in the anaerobic compartment are reduced to zero. If this condition is satisfied, there must be a maximum R_s that just causes the NO_x^- concentration in the anaerobic compartment not to be zero. Once NO_x^- appears in the effluent from the anaerobic compartment, the capacity of denitrification ($D_{c,\text{ana}}$) achieves a maximum value and the anaerobic condition is difficult to be maintained. Hence, at anaerobic state the amount of electron donors (organic material) should be greater than that of electron acceptors (NO_x^-) introduced from recycled sludge. Based on this configuration, it is assumed that the maximum denitrification capacity in the anaerobic compartment is proportional to the influent biodegradable COD concentration. That is,

$$D_{c,\text{ana,max}} = \phi C_{s0} \quad (16)$$

where the index 'max' refers to the maximum value.

It is noted that R_s must satisfy Eq. (17) if Eq. (10) is applied to calculate $D_{c,\text{ana}}$.

$$R_s C_{ne} < \phi C_{s0} \quad (17)$$

Moreover, there must be a minimum mixed liquor recycle ratio (R_m) that just causes the oxidized forms of nitrogen (in the effluent from the anoxic compartment) to be zero. Hence, the lower limit of R_m is derived. That is,

$$R_{m,\text{min}} C_{ne} = D_{p,\text{anx}} \quad (18)$$

where the index 'min' refers to the minimum value.

Also, R_m must satisfy Eq. (19) if the oxidized forms of nitrogen appear in the effluent from the anoxic compartment.

$$R_m C_{ne} > D_{p,\text{anx}} \quad (19)$$

2.4. Graphically analytical technique

In our study, an approach similar to that developed by Zhao et al. [8] (except that TN removal efficiencies of anaerobic and anoxic compartments were included) was applied to estimate the effects of operating parameters of the single-sludge reactor system on $\text{NH}_4^+ \text{-N}$ and TN removal efficiencies (E_1 and E_2) by means of Eqs. (14) and (15), respectively.

Fig. 2 shows a typical example of graphical representation on treatment performance of the single-sludge reactor system. In Fig. 2, a curve OA depicts the relationship (Eq. (1)) between E_1 (calculated by Eq. (14)) and aerobic volume fraction (V_{aer}/V_T), showing that E_1 increases abruptly with a slight increase in aerobic volume fraction. With a further increase in aerobic volume fraction, the increment of E_1 gradually declines and tends to reach a maximum value. In other words, when the aerobic volume fraction has been increased to a

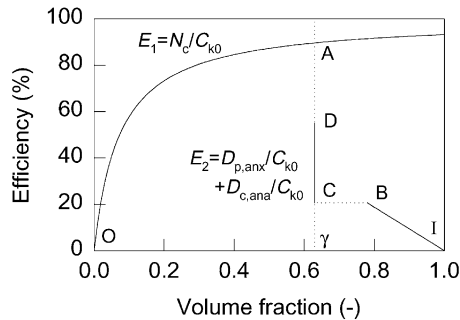


Fig. 2. Graphical representation on treatment performance of the single-sludge reactor system with process parameter values: $C_{k0} = 900 \text{ NH}_4^+ \text{-N dm}^{-3}$, $Q = 30 \text{ dm}^3$ per day, $X = 2000 \text{ mg VSS dm}^{-3}$, $V_T = 79 \text{ dm}^3$, $\alpha = 0.15$, $\beta = 0.22$, $\gamma = 0.63$, $R_s = 1$, $k_d = 0.16$ per day and $k_n = 2.34$ per day.

certain extent, a further increase of aerobic volume fraction results in a limited increment of E_1 . Point A represents E_1 at the aerobic volume fraction (γ), and thus, the percent $\text{NH}_4^+ \text{-N}$ remaining in the effluent can be calculated by subtracting E_1 from 100%. E_2 is separated into two parts: line IB (i.e. denitrification in the anoxic compartment; the first term in the right side of Eq. (15)) and line CD (denitrification in the anaerobic compartment; the second term in the right side of Eq. (15)). Line IB is a straight line (with a slope of $k_d X V_T / C_{k0} Q$) starting from point I to point B at the anoxic volume fraction ($\beta = 1 - \alpha - \gamma$). The length of horizontal line BC is just equal to the anaerobic volume fraction (α). The length of vertical line CD can be calculated by multiplying the length of line AC by $R_s / (R_s + 1)$. Point B represents the fraction of TN removal in the anoxic compartment, and point D represents TN removal of the single-sludge reactor system. Thus, the percent oxidized forms of nitrogen remaining in the effluent can be calculated by subtracting the E_2 value at point D from the E_1 value at point A.

3. Experimental

3.1. Reactor system

Two sets of identical laboratory-scale single-sludge reactor system (made of plexiglass) were used. Each reactor system consisted of anaerobic, anoxic, aerobic, and settling compartments with effective volumes of 12, 17, 50 and 9 dm^3 , respectively. Two sets of stainless steel mixing impellers (with a rotating speed of 50 rpm) were respectively installed in the anaerobic and anoxic compartments. The two compartments were equipped with covers (sealed on the top to prevent the intake of air) but provided with gas vents and sampling ports. The aerobic compartment was thoroughly aerated with a diffuser to maintain the dissolved oxygen concentrations at 3–4 mg dm^{-3} . During the operation of the reactor system, sludge was constantly recycled ($R_s = 1$) from the bottom of the settling compartment to the anaerobic compartment. Meanwhile, mixed liquor was constantly recycled ($R_m = 1, 2$ and 3) from the aerobic compartment to the anoxic compartment (Fig. 1). The reactor system was operated at room temperature (20–25°C).

To maintain the designate microbial cell residence time (MCRT) and the concentrations of mixed liquor volatile suspended solids (MLVSS) in anaerobic, anoxic, and aerobic compartments of the reactor system, a certain amount of excess sludge was wasted daily from the settling compartment. Prior to carrying out the first test run, the seeded sludge in the reactor system had been acclimatized for a 3-month period. To ensure the reactor system reached steady state, each of a total of six test runs was continuously operated for at least three-fold MCRT. Ammonia nitrogen, oxidized forms of nitrogen and chemical oxygen demand (COD) in the effluent and MLVSS in the reactor system were monitored for each test run. Steady state was assumed to be reached after test results of the four parameters were within 5% deviation for three consecutive samples (sampling twice weekly).

3.2. Feed wastewater

The ingredients of synthetic wastewater containing sucrose (2490 mg dm^{-3}), yeast extract (29 mg dm^{-3}), KH_2PO_4 (340 mg dm^{-3}), K_2HPO_4 (134 mg dm^{-3}), NH_4Cl (3440 mg dm^{-3}), NaHCO_3 (6720 mg dm^{-3}), Ni^{2+} (0.5 mg dm^{-3}), Fe^{3+} (0.5 mg dm^{-3}), Co^{2+} (0.3 mg dm^{-3}), Mo^{6+} (0.6 mg dm^{-3}), Zn^{2+} (0.5 mg dm^{-3}), Mn^{2+} (0.5 mg dm^{-3}) and Mg^{2+} (0.5 mg dm^{-3}) were prepared. The concentrations of COD, alkalinity, and $\text{NH}_4^+\text{-N}$ were 2800, 4040 (as CaCO_3), and 900 mg dm^{-3} , respectively, and the pH value was 7.5. It is noted that the concentrations of components (COD, $\text{NH}_4^+\text{-N}$, and total phosphorus) of prepared synthetic wastewater in the present work are quite similar to those of anaerobically pretreated piggery wastewater.

3.3. Analytical methods

Nitrate and nitrite were measured using the ion chromatography method by selecting Shim-pack IC-A3 as chromatographic column, $8.0 \text{ mM } p\text{-hydroxy benzoic acid}$ and 3.2 mM bis-Tris as mobile phase, and CDD-6A, 3.2 mS cm^{-1} FS as conductivity detector. COD, $\text{NH}_4^+\text{-N}$, and MLVSS were measured according to the standard methods [14].

4. Results and discussion

4.1. Reactor performance evaluation with laboratory operating data

4.1.1. Nitrogen removal

The laboratory operating data of the single-sludge suspended-growth reactor system are shown in Table 1. When the influent $\text{NH}_4^+\text{-N}$ concentration of 900 mg dm^{-3} , MCRT of 11–20 days, and hydraulic retention times (HRT) of 6.6–1.6 days, and nitrogen loadings of $0.16\text{--}0.48 \text{ kg NH}_4^+\text{-N kg per VSS per day}$ were maintained, the $\text{NH}_4^+\text{-N}$ removal efficiencies (98–82%) were higher than total nitrogen (TN) removal efficiencies (71–43%). This can be explained by two reasons. First, the single-sludge reactor system was continuously fed with high-strength $\text{NH}_4^+\text{-N}$ -containing wastewater ($\text{NH}_4^+\text{-N}/\text{COD} = 0.32$), resulting in denitrification being deficient in COD. Siebritz et al. [13] pointed out that, if complete

Table 1
Operating parameters and main results of the single-sludge reactor system

Run	Q (dm ³ per day)	MLVSS (mg dm ⁻³)	MCRT (days)	F_k/M_{aer} (kg NH ₄ ⁺ -N kg per VSS per day)	R_s	R_m	NH ₄ ⁺ -N removal (%)	TN removal (%)	$\Delta\text{COD}_{\text{exp}}/\Delta\text{TN}_{\text{exp}}$	$\Delta\text{Alk}_{\text{cal}}/\Delta\text{Alk}_{\text{exp}}$
1	12	1350	20	0.16	1	2	98	71	4.16	1.09
2	30	3230	20	0.17	1	2	92	63	4.68	1.06
3	42	2320	14	0.33	1	1	90	43	6.74	1.07
4	42	2570	14	0.29	1	2	87	48	6.00	1.08
5	42	1890	11	0.40	1	3	85	47	6.06	1.07
6	50	1890	11	0.48	1	2	82	45	6.30	1.04

denitrification is expected to reach in a single-sludge reactor system, the NH₄⁺-N/COD ratio should be maintained at no greater than 0.07–0.08. Secondly, the aerobic compartment is the last biological reactor of the single-sludge reactor system, and thus, a part of the generated NO_x⁻-N should flow out of the reactor system. Table 1 also shows that the declining degree of TN removal (71–43%) with an increase in nitrogen loading (0.16–0.48 kg NH₄⁺-N kg per VSS per day) was much higher than that of NH₄⁺-N removal (98–82%).

By observing treatment performance of the reactor system in test runs 3–5 (Table 1), the mixed liquor recycle ratio only imposed a slight effect on TN removal efficiency. van Haandel et al. [3] also pointed out that, if the oxidized forms of nitrogen were detected in the effluent from the anoxic compartment, the denitrification rate should reach a maximum value (i.e. zero-order kinetics with respect to the concentration of the oxidized forms of nitrogen). Accordingly, the denitrification rate would not increase with a further increase in mixed liquor recycle ratio.

4.1.2. $\Delta\text{COD}/\Delta\text{TN}$

Based on the transfer of one electron equivalent for dissimilative reduction of nitrate (i.e. denitrification), the reduction of 1 g of NO₃⁻-N requires the consumption of 2.86 g of COD. In the present work, the $\Delta\text{COD}/\Delta\text{TN}$ ratios within the reactor system were all larger than 2.86 (Table 1). This implies that the substrate (COD) was not only consumed in denitrification, it also was consumed by either microbial synthesis or other aerobic heterotrophs. In addition, the $\Delta\text{COD}/\Delta\text{TN}$ ratio within the reactor system increased with an increase in nitrogen loading (F_k/M_{aer}). This is mainly because a higher F_k/M_{aer} (i.e. a shorter hydraulic retention time) caused insufficient denitrification in the anoxic compartment. Consequently, the excess substrate was oxidized (by aerobic heterotrophs) in the aerobic compartment, resulting in a lower nitrification efficiency.

4.1.3. Alkalinity change

Nitrification–denitrification in the single-sludge reactor system is accompanied by alkalinity consumption or release. According to the stoichiometry of these biochemical reactions, 1 g NH₄⁺-N consumes 7.14 g of alkalinity, and 1 g NO₃⁻-N releases 3.57 g of alkalinity. Nitrogen conversion data from our study were used to calculate the change in alkalinity within the reactor system and compared with measured values (Table 1). The $\Delta\text{Alk}_{\text{cal}}/\Delta\text{Alk}_{\text{exp}}$ ratios ranged from 1.04 to 1.09, showing good agreement between the

measured and predicted values. This suggests that the alkalinity data could be used for monitoring and control of the reactor system.

4.2. Biokinetic constants

By using the test results shown in Table 1, the nitrification rate constant (k_n) can be obtained after Eq. (14) is rearranged in a linear form as follows:

$$\frac{1}{E_1} - 1 = \frac{1}{k_n} \frac{F_k}{M_{aer}} \quad (20)$$

By performing linear regression of the experimental results obtained from six test runs, the k_n obtained was 2.34 per day.

Because the feed wastewater flowed first into the anaerobic compartment of the single-sludge reactor system, it would provide sufficient substrate for complete denitrification in the anaerobic compartment. A suspended-growth batch reactor was then utilized to determine the denitrification rate constant (k_d). Into the batch reactor, 2 dm³ sludge (taken from the anaerobic compartment in run 6), NO₃⁻ and sucrose were added, and then diluted to 5 dm³ with deionized water. As shown in Fig. 3(a), a nonlinear relationship was found in the time course of the reduction of NO₃⁻-N or NO₂⁻-N. However, a linear relationship was found in the time course of the reduction of the oxidized forms of nitrogen NO_x⁻-N. In other words, denitrification in the anaerobic compartment followed zero-order kinetics with a rate constant (k_d) of 1.6 g NO_x⁻-N g per VSS per day.

$$\frac{dC_n}{dt} = -k_d X \quad (21)$$

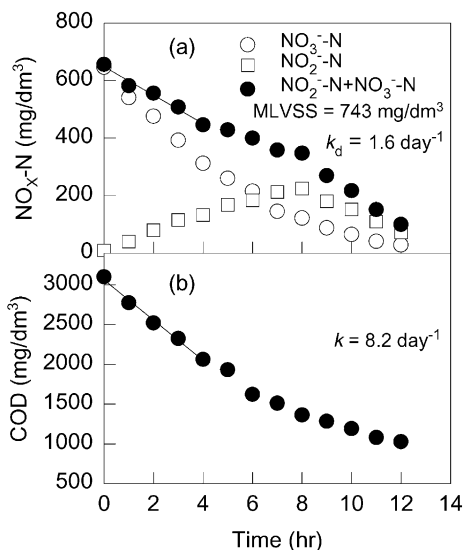


Fig. 3. Kinetic analysis of denitrification in a suspended-growth batch reactor (anaerobic sludge).

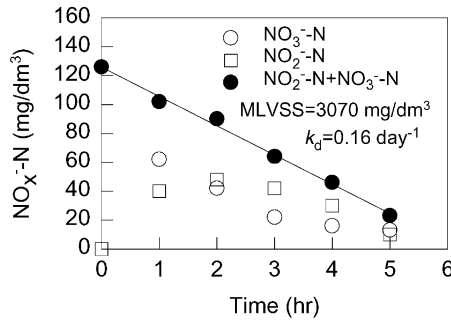


Fig. 4. Kinetic analysis of denitrification in a suspended-growth batch reactor (anoxic sludge).

Moreover, Fig. 3(b) shows that the degradation of the substrate (expressed in COD) in denitrification also followed zero-order kinetics with a rate constant of 8.2 g COD g per VSS per day. Therefore, the estimated ratio of NO_x^- -N reduction to organic material degradation is $1.6/8.2 = 0.195$ (i.e. ϕ value in Eq. (16)). van Haandel et al. [3] reported an estimated ϕ value of 0.1168. In our six test runs, the obtained $R_s C_{ne}$ values ranged from 243 to 423 mg dm^{-3} (i.e. less than the ϕC_{s0} value of 546 mg dm^{-3}) and thereby satisfied the required condition in Eq. (17). Also, the NO_x^- -N concentrations were not detected from the anaerobic compartment in all six test runs. Accordingly, the anaerobic compartment was well maintained at anaerobic state.

On the other hand, a suspended-growth batch reactor, into which the settled sludge (taken from the anoxic compartment in run 6) and the supernatant (taken from the aerobic compartment in run 6) were added, was utilized to determine the denitrification rate constant (k_d). The kinetics of NO_x^- -N denitrification in the anoxic batch reactor (Fig. 4) is similar to that in the anaerobic batch reactor. Thus, denitrification in the anoxic compartment can also be considered zero-order kinetics with a rate constant of 0.16 g NO_x^- -N g per VSS per day. The obtained k_d value is close to the finding of van Haandel et al. [3], who obtained a denitrification rate constant of 0.1 g NO_x^- -N g per VSS per day when a slowly biodegradable organic material was utilized as the carbon source. Accordingly, the carbon source contained in the anoxic compartment of the single-sludge reactor system in our study can be regarded as a slowly biodegradable organic material, and the denitrification rate in the anoxic compartment is much slower than that in the anaerobic compartment (with sufficient carbon source). Moreover, in our six test runs, the obtained $R_m C_{ne}$ values ranged from 423 to 1026 mg dm^{-3} (i.e. greater than the $D_{p,anx}$ values of 103–306 mg dm^{-3} , which was calculated by using k_d) and thereby satisfied the required condition in Eq. (19). Also, the NO_x^- -N concentrations were detected from the anoxic compartment in all six test runs. Accordingly, the anoxic compartment was well maintained at anoxic state.

4.3. Parametric sensitivity

To assay biokinetic parameter values (k_n and k_d) used in model calculation later on (Section 4.4), parametric sensitivity analyses with process parameter values ($C_{k0} = 900 \text{ mg NH}_4^+\text{-N dm}^{-3}$, $Q = 30 \text{ dm}^3$ per day, $X = 2000 \text{ mg VSS dm}^{-3}$,

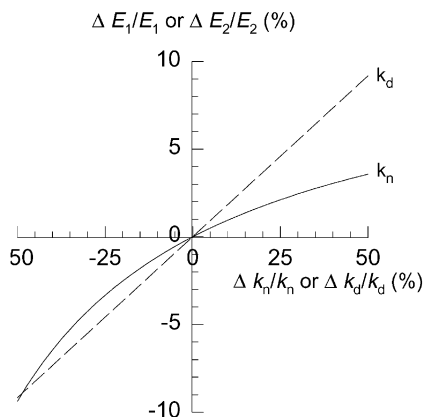


Fig. 5. Parametric sensitivity with process parameter values as in Fig. 2.

$V_T = 79 \text{ dm}^3$, $\alpha = 0.15$, $\beta = 0.22$, $\gamma = 0.63$, $R_s = 1$, $k_d = 0.16$ per day, and $k_n = 2.34$ per day) were performed. By varying each parameter value within a range of -50 to $+50\%$, the variations in NH_4^+ -N removal efficiency (E_1) and total nitrogen removal efficiency (E_2) with its basis can be calculated by using Eqs. (14) and (15), respectively. As shown in Fig. 5, the relative variations of E_1 and E_2 are -9.4 to $+3.6$ and -9.2 to 9.2% , respectively. Accordingly, if the relative errors between the calculated and experimental nitrification efficiencies (or total nitrogen removal efficiencies) are within a range of $\pm 10\%$, the parameter values k_n and k_d used in model calculation could be $\pm 50\%$ deviated from the true parameter values.

4.4. Reactor performance evaluation with graphically analytical technique

With the graphically analytical technique described earlier, variations in treatment performance of the single-sludge reactor system with different operating conditions (MLVSS concentration, aerobic volume fraction, inflow rate, influent NH_4^+ -N concentration and sludge recycle ratio) can be evaluated.

4.4.1. MLVSS concentration

As shown in Fig. 6(a), when the MLVSS concentration is increased from 2000 to 3000 mg dm^{-3} by reducing sludge wastage rate, the NH_4^+ -N and TN removal efficiencies increase from 89.7 (A_1) to 92.9% (A_2) and from 54.9 (D_1) to 61.5% (D_2), respectively. This indicates that an increase of MLVSS concentration can improve treatment performance of the single-sludge reactor system. However, in such an operating condition, the operation cost of aeration and the occurrence of uneasily settled sludge (resulted from a long period of microbial cells residence time) have to be taken into account.

4.4.2. Aerobic volume fraction

As shown in Fig. 6(b), when the volume of aerobic compartment decreases from 50 to 40 dm^3 and the volume of anoxic compartment increases from 17 to 27 dm^3 , the NH_4^+ -N

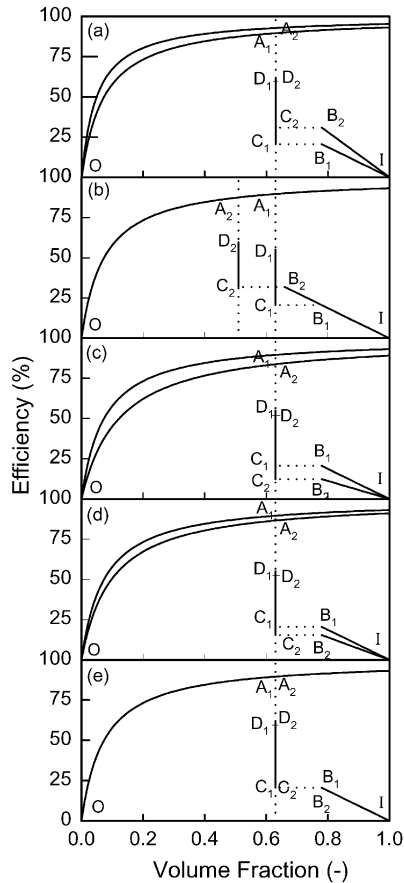


Fig. 6. Effects of operating parameters on treatment performance with the basis process parameters (plot subscripted as 1): $C_{k0} = 900 \text{ mg NH}_4^+\text{-N dm}^{-3}$, $Q = 30 \text{ dm}^3$ per day, $X = 2000 \text{ mg VSS dm}^{-3}$, $V_T = 79 \text{ dm}^3$, $\alpha = 0.15$, $\beta = 0.22$, $\gamma = 0.63$, $R_s = 1$, $k_d = 0.16$ per day and $k_n = 2.34$ per day. The varied parameters (plot subscripted as 2): (a) $X = 3000 \text{ mg VSS dm}^{-3}$; (b) $\beta = 0.34$, $\gamma = 0.51$; (c) $Q = 50 \text{ dm}^3$ per day; (d) $C_{k0} = 1200 \text{ mg NH}_4^+\text{-N dm}^{-3}$; (e) $R_s = 1.5$.

and TN removal efficiencies vary from 89.7 (A_1) to 87.4% (A_2) and from 54.9 (D_1) to 59.7% (D_2), respectively. In other words, with a decrease in aerobic volume fraction and with an increase in anoxic volume fraction, the $\text{NH}_4^+\text{-N}$ removal efficiency decreases and the TN removal efficiency increases. To avoid the occurrence of uneasily settled bulking sludge, Henze et al. [5] reported out that the non-aerated volume fraction (i.e. anaerobic and anoxic compartments) should be controlled at <50% of total.

4.4.3. Inflow rate and TKN influent concentration

As shown in Fig. 6(c), when the inflow rate is increased from 30 to 50 dm^3 per day, the $\text{NH}_4^+\text{-N}$ and TN removal efficiencies decline from 89.7 (A_1) to 83.9% (A_2) and from

54.9 (D₁) to 48% (D₂), respectively. In other words, an increase of inflow rate gives lower NH₄⁺-N and TN removal efficiencies. Meanwhile, as shown in Fig. 6(d), when the influent NH₄⁺-N concentration increases from 900 to 1200 mg dm⁻³, the NH₄⁺-N and TN removal efficiencies decline from 89.7 (A₁) to 86.7% (A₂) and from 54.9 (D₁) to 50.9% (D₂), respectively. In other words, an increase of influent NH₄⁺-N concentration results in lower NH₄⁺-N and TN removal efficiencies. Moreover, if the influent COD concentration does not increase with an increase in influent NH₄⁺-N concentration, the reduction of TN removal efficiency will be higher.

4.4.4. Sludge recycle ratio

As shown in Fig. 6(e), when the sludge recycle ratio is increased from 1 to 1.5, the NH₄⁺-N removal efficiency remains unchanged but the TN removal efficiency increases from 54.9 (D₁) to 61.9% (D₂). In other words, an increase of sludge recycle ratio gives a higher TN removal efficiency if complete denitrification occurs in the anaerobic compartment.

5. Conclusions

1. From the performance data of the single-sludge reactor system, the NH₄⁺-N removal efficiencies (98–82%) are higher than TN removal efficiencies (71–43%); the mixed liquor recycle ratio only imposes a slight effect on TN removal efficiency.
2. The $\Delta\text{COD}/\Delta\text{TN}$ ratio within the reactor system increases with an increase in nitrogen loading; good agreement between the measured and predicted alkalinity change suggests that alkalinity data could be used for monitoring and control of the reactor system.
3. By using the graphically analytical technique, the mixed liquor recycle ratio only imposes a slight influence on nitrogen removal of the single-sludge reactor system; the MLVSS concentration, aerobic volume fraction, inflow rate, influent nitrogen concentration, and sludge recycle ratio significantly affect NH₄⁺-N and TN removal efficiencies.
4. From linear regression of the performance data of the reactor system, the obtained nitrification rate constant (using Grau model) is 2.34 per day.
5. From two independent batch studies, denitrification of NO_x⁻-N follows zero-order kinetics with rate constants of 1.6 g NO_x⁻-N g per VSS per day (sludge from anaerobic compartment) and 0.16 g NO_x⁻-N g per VSS per day (sludge from anoxic compartment).

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References

- [1] Metcalf and Eddy Inc., Wastewater Engineering Treatment: Disposal, and Reuse, 3rd Edition, McGraw-Hill, New York, 1991.
- [2] B. Sharma, R.C. Ahler, Nitrification and nitrogen removal, Water Res. 11 (1977) 897–925.

- [3] A.C. van Haandel, G.A. Ekama, G.V.R. Marais, The activated sludge process. III. Single-sludge denitrification, *Water Res.* 15 (1981) 1135–1152.
- [4] A.P.C. Warner, G.A. Ekama, G.V.R. Marais, The activated sludge process. IV. Application of the general kinetic model to anoxic–aerobic digestion of waste activated sludge, *Water Res.* 20 (1986) 943–958.
- [5] M. Henze, C.P.L. Grady Jr., W. Gujer, G.V.R. Marais, T. Matsuo, A general model for single-sludge wastewater treatment systems, *Water Res.* 21 (1987) 505–515.
- [6] M.C. Wentzel, G.A. Ekama, G.V.R. Marais, Processes and modelling of nitrification denitrification biological excess phosphorus removal systems: a review, *Water Sci. Tech.* 25 (1992) 59–82.
- [7] Y. Argaman, A steady-state model for the single-sludge activated sludge system. I. Model description, *Water Res.* 29 (1995) 137–145.
- [8] H. Zhao, S.H. Isaacs, H. Soeberg, M. Kummel, An analysis of nitrogen removal and control strategies in an alternating activated sludge process, *Water Res.* 29 (1995) 535–544.
- [9] S.E. Jørgensen, M.J. Gromiec, *Mathematical Models in Waste Treatment*, Elsevier, New York, 1985.
- [10] P.M. Grau, M. Dohanyos, J. Chudoba, Kinetics of multicomponent substrate removal by activated sludge, *Water Res.* 9 (1975) 637–642.
- [11] A.A. Abufayed, E.D. Schroeder, Kinetics and stoichiometry of SBR/denitrification with a primary sludge carbon source, *J. Water Pollut. Control Fed.* 58 (1986) 398–405.
- [12] Y. Argaman, Nitrogen removal in a semi-continuous process, *Water Res.* 20 (1986) 173–183.
- [13] I.P. Siebritz, G.A. Ekama, G.V.R. Marais, A parametric model for biological excess phosphorus removal, *Water Sci. Tech.* 15 (1983) 127–152.
- [14] APHA, AWWA, WEF, *Standard Methods for the Examination of Water and Wastewater*, 18th Edition, American Public Health Association, Washington, DC, 1992.