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Nitrogen and phosphorus removal in pilot-scale anaerobic-anoxic oxidation ditch system

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Abstract

To achieve high efficiency of nitrogen and phosphorus removal and to investigate the rule of simultaneous nitrification and denitrification phosphorus removal (SNDPR), a whole course of SNDPR damage and recovery was studied in a pilot-scale, anaerobic-anoxic oxidation ditch (OD), where the volumes of anaerobic zone, anoxic zone, and ditches zone of the OD system were 7, 21, and 280 L, respectively. The reactor was fed with municipal wastewater with a flow rate of 336 L/d. The concept of simultaneous nitrification and denitrification (SND) rate (r_{SND}) was put forward to quantify SND. The results indicate that: (1) high nitrogen and phosphorus removal efficiencies were achieved during the stable SND phase, total nitrogen (TN) and total phosphate (TP) removal rates were 80% and 85%, respectively; (2) when the system was aerated excessively, the stability of SND was damaged, and r_{SND} dropped from 80% to 20% or less; (3) the natural logarithm of the ratio of NO_x to NH_4^+ in the effluent had a linear correlation to oxidation-reduction potential (ORP); (4) when NO_3^- was less than 6 mg/L, high phosphorus removal efficiency could be achieved; (5) denitrifying phosphorus removal (DNPR) could take place in the anaerobic-anoxic OD system. The major innovation was that the SND rate was devised and quantified.

Key words: oxidation ditch; biological nitrogen removal; biological phosphorus removal; simultaneous nitrification and denitrification (SND); pilot scale; municipal wastewater

Introduction

On account of the introduction of effluent standards getting more strict, for nutrients in particular, many existing wastewater treatment plants are about to be upgraded. The oxidation ditch process is an economic and efficient technique for biological wastewater treatment. In controlling eutrophication, oxidation ditches are competitive with other activated sludge processes (Hao *et al*., 1997).

In recent years, simultaneous nitrification and denitrification (SND) have become the research focus bacause they have higher nitrogen removal efficiency (Holman and Wareham, 2005; Meyer *et al*., 2005); however, the few literature available to give an effective method to quantify SND. Zeng *et al*. (2003) have successfully demonstrated a process in an anaerobic/aerobic reactor where nitrification and denitrification occur simultaneously with phosphorus (P) uptake, under low oxygen oncentration. This novel integrated process has been called simultaneous nitrification, denitrification, and phosphorus removal (SNDPR). SNDPR has some advantages in the wastewater biological nitrogen removal field, such as, removing high efficiency of nitrogen and phosphorus, aeration energy saving, alkalinity production, and so on. In SNDPR, the acetate is taken up under anaerobic conditions, accompanied by phosphorus release. During the following aerobic period, phosphorus is fully taken up, whereas, NH_4^+ is converted through simultaneous nitrification and denitrification to gaseous nitrogen without accumulation of nitrite or nitrate intermediates (Lemaire *et al*., 2006). It has recently been demonstrated that enhanced biological phosphorus removal (EBPR) could be incorporated in SND process by encouraging the denitrification to be mediated by polyphosphate-accumulating organisms (PAOs) (Zeng *et al*., 2003; Meyer *et al*., 2005). In the simultaneous nitrification-denitrification-phosphorus removal (SNDPR) system in the present study, high efficiency phosphorus can be removed with nitrogen removal.

Besides denitrifying, phosphorus removal became another research focus because of higher nitrogen and phosphorus removal efficiency (Robert *et al*., 2003; Hu *et al*., 2003; Peng *et al*., 2006). Mino *et al*. (1998) claimed that a significant fraction of PAOs could take up phosphate in the anoxic phase. Meinhold *et al*. (1998) hypothesized that the biological phosphorus removal population comprised of at least two groups: one group was capable of utilizing either oxygen or nitrate as an electron acceptor

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(denitrifying PAOs), and the other group was capable of utilizing only oxygen (aerobic PAOs). However, because of the lower efficiency in energy production with nitrate compared to that with oxygen, a lower cell yield value was reported for the anaerobic-anoxic sequencing batch reactor (SBR) than the aerobic-aerobic SBR (Murnleitner *et al*., 1997). Despite lower efficiency, good phosphorus removal performance was reported for systems enriched with denitrifying PAOs (Robert *et al*., 2003; Peng *et al*., 2006). If the denitrifying PAOs took up and stored phosphate, using nitrate as an electron acceptor, the organic carbon substrate could be used simultaneously for both phosphorus and nitrogen removal. This was of significance, as organic carbon content in most of municipal wastewater was often limited to phosphorus and nitrogen removal. Employing denitrifying PAOs in the biological nutrient processes also made it possible to reduce sludge production and aeration demand (Peng *et al*., 2006).

This study seeks to characterize the SNDPR process with the aim of elucidating factors responsible for the course of SND damage and recovery though excessive aeration, and it is therefore the authors' goal to address how the SNDPR process can be managed.

1 Materials and methods

1.1 Pilot-scale plant

The experiments have been carried out in a pilot-scale anaerobic-anoxic OD process configuration process. As shown in Fig.1, this process consists of an inlet tank (200 L), OD bioreactor (280 L) with an anaerobic zone, anoxic zone, and a secondary clarifier (95 L). The bioreactor is composed of three compartments, the anaerobic zone (7 L), the anoxic zone (21 L), and the OD (280 L). The influent rate is 14 L/h, which gives a hydraulic retention time (HRT) of 0.5, 1.5, and 18 h respectively in the three zones. Thirty percent of the total returned activated sludge (RAS) is pumped to the anaerobic zone, and the remaining 70% is returned to the anoxic zone. A mixer is set up in the anaerobic zone and anoxic zone, and two other mixers are equipped in the ditches. An online dissolved oxygen (DO) monitor meter, pH monitor meter, and redox potential (ORP) monitor meter are equipped in the export of the OD. The pH is monitored, but is not controlled artificially. The aeration is controlled by manipulating the aeration valves. The inflow, with an influent flow of 336 L/d, and a sludge recycle flow are controlled with a peristalsis pump. The mixed liquor suspended solids (MLSS) are controlled at 4.5–6.0 g/L and the solid residence time (SRT) is 20–30 d. All experiments have been conducted at ambient temperature (18–25°C).

Four continuous phases were considered to show the four different conditions during SND damaging and recovering processes, the SND stabilizing phase (phase I), the SND damaging phase (phase II), the SND recovering phase (phase III), and the SND recovered phase (phase IV).

1.2 Sludge and wastewater

Both the sludge and wastewater were taken from the OD process of the Beijing Jiuxianqiao Wastewater Treatment Plant (WWTP). The wastewater was fetched from the washing grit basin. Table 1 shows the major characteristics of the influent.

1.3 Analysis

The analyses of chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), TP, PO_4^{3-}, and mixed liquor suspended solids (MLSS) were performed as described in the Standard Methods of APHA (APHA, 1995). DO, pH, ORP, and temperature were measured continuously using online probes (340i, WTW, German).

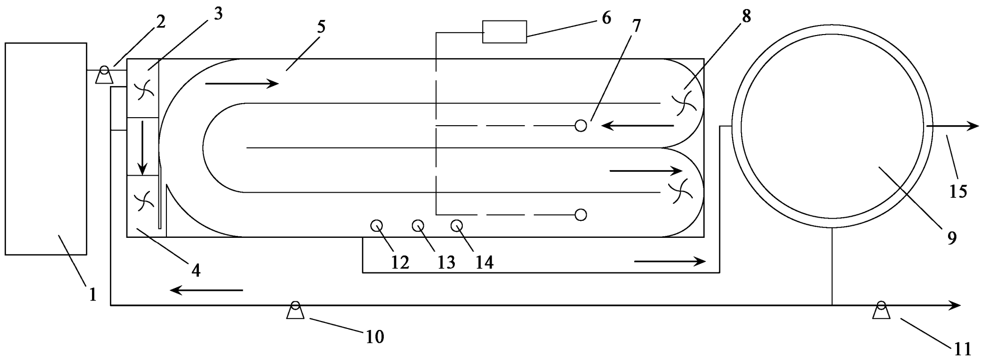

Fig. 1 Schematic diagram of the oxidation ditch system. (1) water tank; (2) influent pump; (3) anaerobic zone; (4) anoxic zone; (5) aerobic zone of OD; (6) air pump; (7) air diffuser; (8) mixer; (9) secondary clarifier; (10) returned activated sludge pump; (11) wasted activated sludge pump; (12) DO probe; (13) ORP probe; (14) pH probe; (15) effluent.

Table 1 Major characteristics of the influent (unit: mg/L)

Parameter	COD	BOD_5	NH_4^+	TN	TP	SS
Average	331.6	173.4	36.5	50.8	5.88	187
Min./Max.	192.2/448.5	123.1/305.8	20.9/53.7	32.5/73.4	3.2/8.9	105/360

2 Results and discussion

2.1 Mass balance of nitrogen in the OD system

In general, the nitrogen loss in the OD system could be explained using four pathways: ammonia stripping, assimilation, denitrification, and SND. Ammonia stripping was assumed to be negligible as the pH of the mixed liquor in the ditch was usually below 7.5 (Hao *et al.*, 1997). Nitrogen removal by assimilation could be estimated through the quantity of wasted activated sludge (WAS). The amount of nitrogen removed by assimilation was limited by the amount of net growth, which in turn depended on the carbonaceous organic content of the wastewater and the operation in the system. The nitrogen content in the waste activated sludge would decrease because of endogenous metabolism. The nitrogen content was 8% at the SRT of 20 d (Sedlak, 1991). The amount of nitrogen assimilation was calculated via the waste sludge discharged. Total nitrogen removed via assimilation is described as Eq.(1).

$$R_{\text{TN-A}} = \frac{Q_{\text{WAS}} \times C_{\text{VSS}} \times K_{\text{A}}}{Q_{\text{IN}}} \quad (1)$$

where, $R_{\text{TN-A}}$ is the TN removal via assimilation (mg/L); Q_{WAS} is the inflow of waste activated sludge (L/d); C_{VSS} represents the volatile suspended solids concentration (mg/L); K_{A} represents the nitrogen content of biological volatile suspended solids; and Q_{IN} is the influent (L/d).

Total nitrogen removed via denitrification is described as Eq.(2).

$$R_{\text{TN-D}} = (C_{\text{NO}_{x\text{-E}}} - C_{\text{NO}_{x\text{-AE}}}) \times R \quad (2)$$

where, $R_{\text{TN-D}}$ is the total nitrogen removal via denitrification (mg/L); $C_{\text{NO}_{x\text{-E}}}$ is the effluent NO_x concentration (mg/L); $C_{\text{NO}_{x\text{-AE}}}$ is the effluent NO_x concentration of the anoxic zone (mg/L); and R is the return ratio.

SND has been achieved in the OD systems. SND rate (R_{SND}) is shown as the percent of the TN removal via SND, as described in Eq.(3).

$$R_{\text{SND}} = \frac{C_{\text{TN-IN}} - C_{\text{TN-E}} - R_{\text{TN-A}} - R_{\text{TN-DN}}}{C_{\text{TN-IN}} - C_{\text{TN-E}}} \times 100\% \quad (3)$$

where, R_{SND} is the TN removed via SND to the TN removed in the system ratio (%); $C_{\text{TN-IN}}$ is the influent total nitrogen concentration (mg/L); $C_{\text{TN-E}}$ is the effluent total nitrogen concentration (mg/L); $R_{\text{TN-A}}$ is the total nitrogen removal via assimilation (mg/L); $R_{\text{TN-D}}$ is the total nitrogen removal via denitrification (mg/L).

2.2 Biological nitrogen removal

Table 2 shows the operating conditions, average concentrations of COD, TN, NO_x, and NH_4^+ in the influent and effluent, ORP in the wastewater, R_{SND} and aeration during the SND stabilizing phase (phase I), SND damaging phase (phase II), SND recovering phase (phase III), and recovered phase (phase IV).

During the four phases, the TN in the influent and effluent, TN removal efficiency and ORP are shown in Fig.2. The effluent NO_x, NH_4^+, aeration, and R_{SND} profiles are shown in Fig.3. The system was stable during the 30–60 d period, and the average ORP was from –30 to 20 mV. TN in the effluent was below 15 mg/L, which meant that about 80% TN was removed. The aeration rate was changed at a small range, 0.50–0.58 m^3/h and NO_x and NH_4^+ in the effluent were 2–8 and 1–7 mg/L, respectively. R_{SND} was 60%–80% in this phase, which could be considered as high SND efficiency. The average aeration rate was increased from 0.54 to 0.70 m^3/h during the day and 60–78 after phase I. NO_x and TN in the effluent combined with ORP increased gradually, whereas, TN removal efficiency decreased with an increase in effluent NO_3^-. At the end of this stage the R_{SND} decreased to about 20%, which implied that the SND stable state had been destroyed. After that, some measures were taken to recover SND in phase III. Aeration was controlled firmly below 0.55 m^3/h. ORP, the effluent NO_x and TN were kept high and fluctuated

Table 2 Operating conditions, average concentrations of influent and effluent during the four phases

Phase	Phase I	Phase II	Phase III	Phase IV
Influent COD (mg/L)	390	265	282	403
Effluent COD (mg/L)	46	43	45	50
Influent TN (mg/L)	60.21	42.34	45.98	58.22
Effluent TN (mg/L)	9.38	14.29	17.36	11.43
Effluent NO_x (mg/L)	4.31	11.18	11.02	4.01
Effluent NH_4^+(mg/L)	3.63	1.46	4.76	6.38
SND rate (%)	69.2	35.7	46.3	67.4
Aeration (m^3/h)	0.52	0.68	0.48	0.52
ORP (mV)	–1	64	42	–10

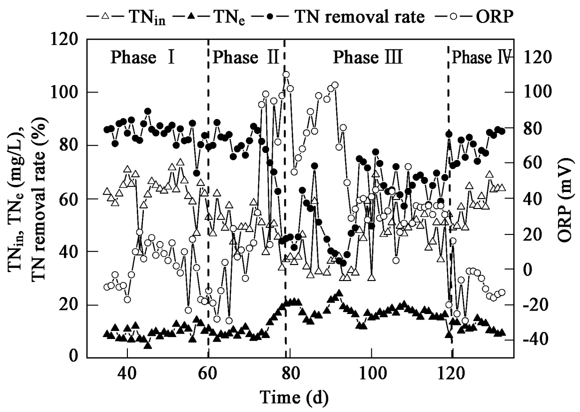

Fig. 2 Influent and effluent TN, TN removal rate, and ORP profiles.

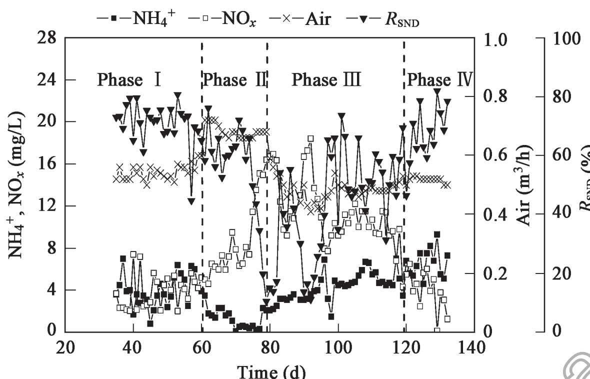

Fig. 3 Effluent NH_4^+, NO_x, R_{SND}, and aeration profiles.

acutely, and NH_4^+ increased constantly during the day 79–100. The SND rate was low and unstable. During days 111–116, the ORP decreased and kept at 0–50 mV, and effluent TN, NO_x, NH_4^+, and R_{SND} kept at 15–20 mg/L, 6–12 mg/L, 4–7 mg/L, and 30%–60%, respectively. During this phase effluent TN, NO_x, and NH_4^+ were still high, and the TN removal efficiency of 60%–80%. After 117 d, the NO_x, ORP decreased, resulting from an increase in R_{SND} to 60%–80%, which could be considered as SND successfully recovered.

The oxidation ditch had a long hydraulic retention time and a completely mixed water flow minimizing the impact of a shock load or hydraulic surge. In this system, alkalinity produced by denitrification in the anoxic zone and the SND in the OD would complement about one half of that consumed by the nitrification process, which would keep the pH stable. The pH was 7.35–7.60 during the oxidation in the whole examination. Therefore, the OH^- concentration was steady in the OD. In addition, DO was 0.10–0.50 mg/L in the ditches. Therefore, the O_2/OH^- did not change much, and had little effect on the ORP. The correlation of ORP to $\ln(NO_x/NH_4^+)$ is plotted in Fig.4.

A linear correlation implied that the ORP could act as a parameter to denote the effect of nitrification and denitrification. The linear regression equation is described in Eq.(4).

$$ORP = 10.43 + 19.14 \times \ln(NO_x/NH_4^+) \tag{4}$$

ORP value was mainly determined by NO_3^-/NH_4^+ (generally prevailing) and NO_2^-/NH_4^+ when the O_2/OH^- equilibrium was constant (Bertanza, 1997). The linear correlation implied that ORP could be used as the parameter to denote the extent of nitrification and denitrification.

Most of the ORP is a parameter to control simultaneous nitrification and denitrification in the sequence bioreactor, but less used in the continuous flow process. Fuerhacker *et al.* (2000) observed that ORP was in the range of 60 to 198 mV, and included optimal setpoints for simultaneous nitrification and denitrification. The range was too large, and was not suitable as a reference value in the continuous flow. It was observed that the ORP range of –30 to 30 mV was the optimal set point for simultaneous nitrification and denitrification.

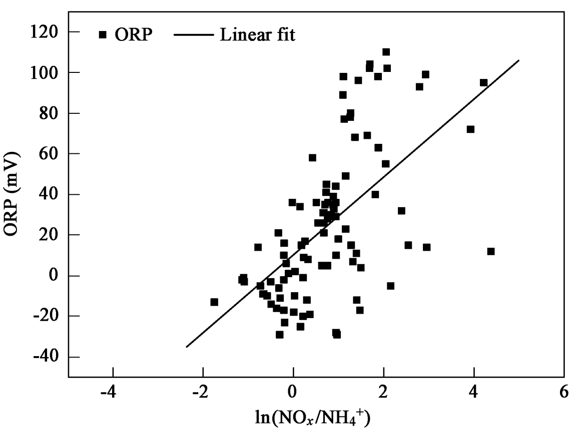

Fig. 4 Correlation between ORP and $\ln(NO_x/NH_4^+)$.

2.3 Biological phosphorus removal

TP in the influent and effluent, TP removal efficiency, and the R_{SND} are shown in Fig.5. TP removal rate was more than 80% during phase I and IV, during which SND performed well, whereas, biological phosphorus removal changed unsteadily with low average TP removal rate during phases II and III. When R_{SND} was more than 40%, NO_x in the returned activated sludge flowed into the preanoxic zone was much less, which provided a strict anaerobic environment and improved biological phosphorus removal capability in the system.

TP removal rate changing with effluent NO_3^- is shown in Fig.6. The TP removal efficiency was more than 80% when NO_3^- in the returned activated sludge was less than 6 mg/L. However, it was low and uneven when NO_3^- was more than 6 mg/L. The anaerobic zone, where the NO_3^- was more than 10 mg/L, could not keep the anaerobic environment, which resulted in surplus NO_3^- in the effluent of the anaerobic zone. NO_3^- would affect anaerobic phosphorus release. The reasons were as follows: first, denitrification organisms have a stronger capability of plundering the biodegradable COD which is easier than PAOs. Second, the poly-hydroxy-butyrate (PHB) stored in the PAOs had worn off because of excessive aeration. Third, NO_3^- inhibited phosphorus release by PAOs. In the SNDPR system of the OD, wastewater was fed into the

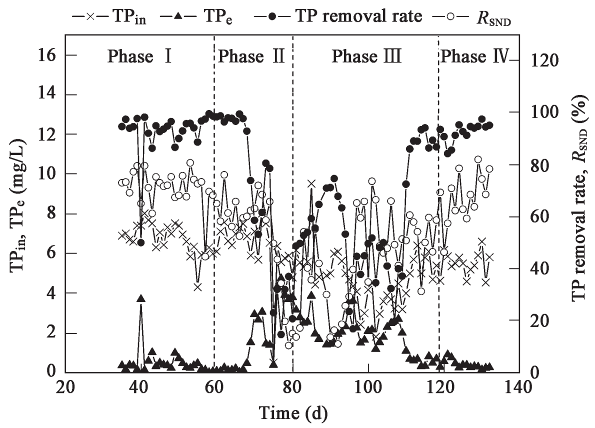

Fig. 5 Influent and effluent TP, TP removal rate, and ORP profiles.

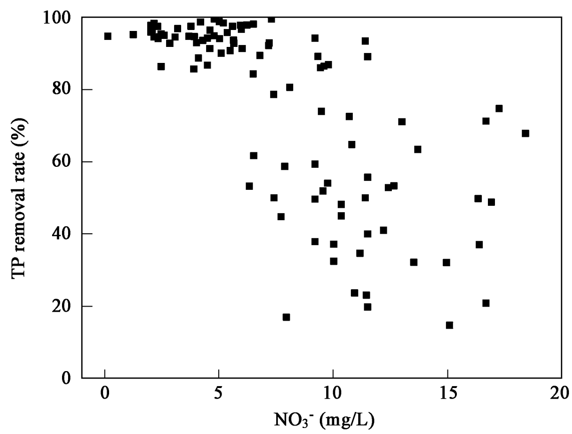

Fig. 6 Scatter of TP removal rate to effluent NO_3^-.

initial anaerobic period and carbon could selectively be taken up by PAOs and stored as PHB. In the following anoxic and aerobic periods, SNDPR was facilitated by the presence of adjacent anoxic and aerobic zones and the microanoxic zones in the microbial aggregates caused by mass transport limitation of oxygen, provided conditions for SND (Brdjanovic *et al*., 1999). Denitrification with simultaneous P uptake was carried out by PAOs using the PHB stored in the previous anaerobic period as a carbon source. The returned activated sludge and fresh municipal wastewater were mixed and exposed to the anaerobic conditions for 2 h, followed by one half being exposed to aerobic conditions, and the other to the anoxic ones on the day 126. Phosphorus release and uptake under anaerobic aerobic and anaerobic anoxic conditions are shown in Fig.7.

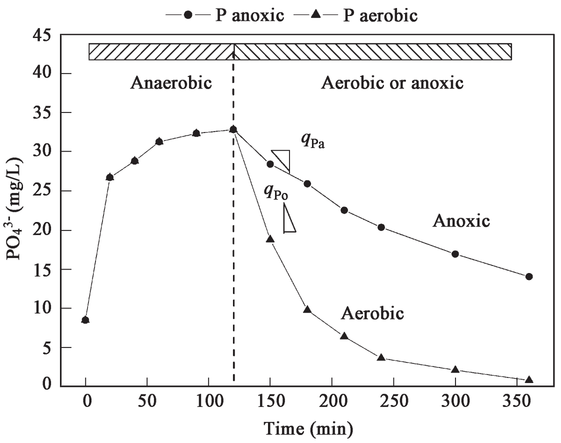

Fig. 7 Phosphorus release and uptake under anaerobic-aerobic and anaerobic-anoxic conditions.

The internal poly-P was depleted and the PHA level in the biomass increased in anaerobic conditions. Anoxic conditions were maintained by instant addition of nitrate to 20 mg/L. Oxygen and nitrate supply to the reactors was surplus in the following aerobic and anoxic phases. The P uptake rate under aerobic and anoxic conditions were 169.08 and 53.28 mg PO_4^{3-}/(gVSS·d), respectively. The relative proportion of denitrifying dephosphation activity in the phosphorus removing organisms was 0.32, which indicated that denitrifying phosphorus removal took place in the OD system.

3 Conclusions

According to the results, it could be concluded that SNDPR was suitable to remove nitrogen and phosphorus in the anaerobic-anoxic OD process. High phosphorus removal efficiency was achieved during SND stable phase, with TN and TP removal efficiency of 80% and 85%, respectively. When the aeration was excessive, the stable SND situation was damaged, which resulted in increased TN in the effluent, and less than 40% R_{SND}. Meanwhile, TN and TP removal rate dropped from 80% and 95% to 40% and 20%, respectively. However nitrogen and phosphorus removal efficiency increased step by step with aeration rate decreased during the SND recovering phase until high efficiency of SNDPR was recovered.

The values of ORP, DO, and pH detected at the end of the aeration tank fluctuated feebly when the system was stable, and at the same time the natural logarithm of the ratio of NO_x to NH_4^+ in the effluent had a linear correlation to ORP, with coefficient R of 0.58.

When NO_3^- was less than 6 mg/L, NO_3^- in the returned activated sludge was taken into the anaeroxic zone, which provided a strict anaerobic environment and improved BPR in the system.

It was also found that P-uptake rates under aerobic and anoxic conditions, after the returned activated sludge underwent anaerobic P-release with feed municipal wastewater, were 169.08 and 53.28 mg PO_4^{3-}/(gVSS·d), respectively, which indicated that denitrifying phosphorus removal (DNPR) took place in the anaerobic-anoxic OD system.

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